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16. Abstract

This report provides an overview of travel surveys, including literature review and background, as well as the motivation for the research and development of the Global Positioning System Automated Travel Diary (GPS-ATD). The system requirements and specifications for the device development are presented and discussed. In addition, the detailed architecture, hardware, software, and user interface design are included. Vehicular and personal GPS-ATD systems were developed to support comprehensive traveler behavior studies. The GPS-ATD provides an intuitive user interface to capture trip activity information (trip purpose, travel mode, etc.), with minimal user input and burden during travel surveys. Each survey participant interacts with their own personal GPS-ATD, and information is automatically coordinated between personal and vehicular GPS-ATD units via ZigBee wireless. The system captures and logs data from the High-Sensitivity GPS (HSGPS) receiver, allowing subsequent identification of corridors, route lengths, and regional and inter-regional trips. The primary sensor is the HSGPS receiver. For the vehicular GPS-ATD, inertial sensing (MEMS gyro and accelerometers) is also provided to fill in the gaps during GPS outages and cold starts. To obtain vehicle sensor information, the GPS-ATD uses ZigBee wireless communications to the car computer On-Board Diagnostics connector (OBD-II). Following the design discussion, complete system testing, results, and user feedback are discussed. The report concludes with recommendations for future work related to the GPS-ATD and its use in the 2010 California Statewide Household Travel Survey.

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DEVELOPMENT OF VEHICULAR AND PERSONAL UNIVERSAL LONGITUDINAL TRAVEL DIARY SYSTEMS USING GPS AND NEW TECHNOLOGY*

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ABSTRACT

This report provides an overview of travel surveys, including literature review and background, as well as the motivation for the research and development of the Global Positioning System Automated Travel Diary (GPS-ATD). The system requirements and specifications for the device development are presented and discussed. In addition, the detailed architecture, hardware, software, and user interface design are included. Vehicular and personal GPS-ATD systems were developed to support comprehensive traveler behavior studies. The GPS-ATD provides an intuitive user interface to capture trip activity information (trip purpose, travel mode, etc.), with minimal user input and burden during travel surveys. Each survey participant interacts with their own personal GPS-ATD, and information is automatically coordinated between personal and vehicular GPS-ATD units via ZigBee wireless. The system captures and logs data from the High-Sensitivity GPS (HSGPS) receiver, allowing subsequent identification of corridors, route lengths, and regional and inter-regional trips. The primary sensor is the HSGPS receiver. For the vehicular GPS-ATD, inertial sensing (MEMS gyro and accelerometers) is also provided to fill in the gaps during GPS outages and cold starts. To obtain vehicle sensor information, the GPS-ATD uses ZigBee wireless communications to the car computer On-Board Diagnostics connector (OBD-II). Following the design discussion, complete system testing, results, and user feedback are discussed. The report concludes with recommendations for future work related to the GPS-ATD and its use in the 2010 California Statewide Household Travel Survey.

EXECUTIVE SUMMARY

This report provides a basic background and brief summary of longitudinal travel surveys, the use of the Global Positioning System (GPS) in previous surveys, and new technological developments that can improve surveys by increasing GPS availability and reducing the cost of conducting a survey. It is fundamentally important that surveys can be carried on for a long duration while maintaining the survey data accuracy and integrity, and yet minimizing the burden on survey respondents. Therefore, a new method is needed for comprehensive, highly automated and efficient data collection for individual travelers. The survey data are crucial for modeling trip generation, predicting the effects of transportation policy changes, and supporting the decision making process at the Federal, State, county and city level. In this project, a new solution was developed to address known deficiencies of previous approaches.

The mismatch between existing methods and the stated needs of travel surveyors drove the Global Positioning System Automated Travel Diary (GPS-ATD) system specifications and developments. Previously, typical travel survey duration was one or two days; however, researchers have shown benefits if the duration is extended to beyond one or two weeks. Therefore, the GPS-ATD was designed with storage to handle four weeks of data. For prior attempts at applying GPS receivers for travel surveys, long GPS startup time and signal blockage in urban canyons were major obstacles—thus Micro-Electro-Mechanical Systems (MEMS) inertial sensors were used for dead-reckoning to calculate position solutions when GPS is not available. The report documents the well-balanced GPS-ATD system design, which meets data, storage, and cost constraints while minimizing the survey respondents' burden. Readers are strongly encouraged to read the references cited herein along with a sampling of the papers cited in these references to gain a deeper understanding of longitudinal travel surveys and the benefit provided by the GPS-ATD system.

This report provides an overview of travel surveys, including literature review and background, as well as the motivation for the research and development of the GPS-ATD. The system requirements and specifications for the device development are presented and discussed. In addition, the detailed architecture, hardware, software, and user interface design are included. Vehicular and personal GPS-ATD systems were developed to support comprehensive traveler behavior studies. The GPS-ATD provides an intuitive user interface to capture trip activity information (trip purpose, travel mode, etc.), with minimal user input and burden during travel surveys. Each survey participant interacts with their own personal GPS-ATD, and information is automatically coordinated between personal and vehicular GPS-ATD units via ZigBee wireless. The system captures and logs data from the High-Sensitivity GPS (HSGPS) receiver, allowing subsequent identification of corridors, route lengths, and regional and inter-regional trips. The HSGPS receiver is the primary sensor. For the vehicular GPS-ATD, inertial sensing (MEMS gyro and accelerometers) is also provided to fill in the gaps during GPS outages and cold starts. To obtain vehicle sensor information, the GPS-ATD uses ZigBee wireless communications to the car computer On-Board Diagnostics connector (OBD-II). Following the design discussion, complete system testing, results, and user feedback are discussed. The report concludes with recommendations for future

work related to the GPS-ATD and its use in the 2010 California Statewide Household Travel Survey.

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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California – Davis, and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
ABS	Acrylonitrile Butadiene Styrene
ACMS	Advanced Construction and Maintenance Systems
AHMCT	Advanced Highway Maintenance and Construction Technology
AOR-W	Atlantic Ocean Region-West
ASCII	American Standard Code for Information Interchange
BGA	Ball-Grid Array
Caltrans	California State Department of Transportation
CASI	Computer-Assisted Self-Interview
CATI	Computer-Assisted Telephone Interview
CDMA	Code-Division Multiple Access
CNC	Computer Numerical Control
COTS	Commercial-Off-the-Shelf
CPU	Central Processing Unit
DAC	Digital-to-Analog Converter
DGPS	Differential Global Positioning System
DOD	Department of Defense
DOP	Dilution-of-Precision
DOT	Department of Transportation
DR	Dead Reckoning
DRI	Division of Research and Innovation
DSL	Digital Subscriber Line
EL	Electroluminescent
EMI	Electromagnetic Interference
ESR	Equivalent Series Resistance
ETD	Electronic Travel Diary
FAA	Federal Aviation Administration
FBGA	Fine Ball-Grid Array
FHWA	Federal Highway Administration
FM	Frequency Modulation
GB	Gigabyte
GIS	Geographic Information System
GPS	Global Positioning System
GPS-ATD	GPS-Automated Travel Diary
GSM	Global System for Mobile communications
HDOP	Horizontal Dilution of Precision
HMI	Human-Machine Interface
HSGPS	High-Sensitivity GPS
HTML	HyperText Markup Language
I^2C	Inter-Integrated Circuit
IC	Integrated Circuit
IGEB	Interagency GPS Executive Board
IMU	Inertial Measurement Unit
ITS	Intelligent Transportation Systems
ITSA	Intelligent Transportation Society of America
IV	Intelligent Vehicle
LCD	Liquid Crystal Display
Li-ion	Lithium-ion
LNA	Low-Noise Amplifier
MB	Megabyte
MEMS	Micro-Electro-Mechanical Systems

Acronym	Definition
MF	Medium Frequency
MP	Milepost
MPO	Metropolitan Planning Organization
NDGPS	Nationwide Differential GPS
NiMH	Nickel-Metal-Hydride
NMEA	National Marine Electronics Association
OBD	On-Board Diagnostics
OS	Operating System
OSS	Open-Source Software
PAPI	Paper and Pencil Interview
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
PDF	Portable Document Format
PLAN	Position Location and Navigation
POR	Pacific Ocean Region
RAM	Random Access Memory
RF	Radio Frequency
RFI	Radio Frequency Interference
RoHS	Restriction of Hazardous Substances
RTOS	Real-Time Operating System
SA	Selective Availability
SBC	Single Board Computer
SDRAM	Synchronous Dynamic Random Access Memory
TMC	Transportation Management Center
TSI	Transportation System Information
TSOP	Thin Small Outline Package
TUCF	Trip Underreporting Correction Factor
UART	Universal Asynchronous Receiver / Transmitter
UCD	University of California-Davis
UI	User Interface
USB	Universal Serial Bus
USDOT	United States Department of Transportation
USNO	United States Naval Observatory
UTC	Coordinated Universal Time
VDOP	Vertical Dilution of Precision
VMT	Vehicle Miles Traveled
WAAS	Wide Area Augmentation System
WGS	World Geodetic System
YAFFS2	Yet Another Flash File System (version 2)
ZIF	Zero-Insertion-Force

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CHAPTER 1:
INTRODUCTION AND BACKGROUND

This chapter provides a brief introduction to objective longitudinal traveler surveys, including previous methods of conducting surveys and their findings. The objectives are to:

- Summarize travel survey goals and define the data needed for travel demand forecasting.
- Identify the challenges inherent in longitudinal travel surveys and pitfalls encountered in previous GPS-aided longitudinal travel surveys.
- Summarize previous major travel surveys.
- Highlight the reference research and literature.

In addition, details of GPS and other relevant new technological developments are provided. The authors recommend review of all the cited references to gain a deeper understanding. The aim is to illuminate the key findings of the past research to foster ongoing discussion and understanding of the context and need for the GPS-Automated Travel Diary (GPS-ATD).

Longitudinal Traveler Survey and Demand Forecast / Modeling

There is a need for finer-grained understanding of traveler behavior than current data collection techniques allow. Traditional cross-sectional survey methods are somewhat coarse and seek to provide traffic measurements for a single point of a road or intersection, thus providing traffic loading at a specific location over time. While this may support conclusions regarding the capacity of a particular location, it does not provide needed information on traveler behaviors such as trip purpose, trip frequency and schedule, route selection, and speeds used throughout the entire route. Many factors can contribute to a driver’s reasons for choosing a particular route. A system which can monitor current traveler location, time, speed, and current and next tasks is required. Longitudinal surveys directly measure traveler behavioral change at the level of the individual traveler, and provide information that can lead to a better understanding of the factors that influence and direct personal travel behavior. These data are critical in:

- developing travel demand models and forecasting future demand,
- predicting the number of trips generated by households as a function of demographics, socioeconomics, and location relative to employment and commercial centers [31],
- estimating travel mode choice and traffic volumes on various roads,
- measuring and understanding trends in population behavior,

- assessing the impact of changes in transportation policy or the transportation system [7,23,30],
- predicting emissions from motor vehicles and input for air quality analysis [31],
- and calibrating regional models.

Previous Travel Surveys

Household-level travel surveys collect three categories of data: household information, household member personal information, and travel activity information for a particular day or range of days (see Table 1 and Table 2). Travel diaries are the standard method used to capture participating household travel activity information. Travel diaries have progressed over the last few decades due to improved understanding of trip generation, as shown in Table 3. The most recent trend in travel surveys is the use of the “place-based” survey instead of a trip-based or activity-based survey [31]. “Place-based” surveys focus on respondent movements from one place to another during the survey period [31]. Survey methods evolved from the mail-out / mail-back Paper and Pencil Interview (PAPI) in the 1960’s, through the Computer-Assisted Telephone Interview (CATI) in 1980’s, to the Electronic Travel Diary (with or without GPS) of today [31]. Computer-Assisted Self-Interview (CASI) methods, in which respondents input their travel information directly into a computer, have become widely used [17]. However, respondents are required to have access to a computer and the Internet. Each method improved upon the previous approaches by better capturing incidental trips, reducing underreporting, improving data accuracy, and minimizing respondent burden and fatigue. Nevertheless, gathering complete information from travelers has been problematic. Drawbacks of self-administered paper-based survey designs are well-known, and this approach is not suited for long-term mobility pattern observations. Moreover, multi-day personal surveys often suffer the ill-effects of survey fatigue and low response rates typical in longer survey durations [23]. It is common for respondents to underreport or to provide incorrect data due to poor memory, misunderstanding instructions, or carelessness. Short or infrequent trips that occur during the day are the most often not reported [23].

Table 1: Fixed (static) information collected in a travel survey

Information Categories	Specific information
Household Information	Physical address location
	Housing unit type
	Length of residence
	Number of vehicle
	Vehicle details (vehicle type, fuel type, ownership, etc)
	Household size
	Total household income
Household Member Personal Information	Relationship to other household member
	Gender
	Ethnicity
	Age
	Employment status
	Occupation
	Weekly work schedule
	Transportation taken to work
	Education level

Table 2: Dynamic travel diary information collected for given trip(s)

Category	Data Element / Sub Element	
Activity	Type of activity	
	Start time	
	End time	
	Origin location	
	Destination	
Travel Mode	Switching travel mode	
	Reason of mode choice	
	Personal Vehicle	Vehicle used
		Driver or passenger
		Vehicle occupancy
		Parking cost
		Other toll costs
		Distance
		OBD-II data
	Transit	Transit fare
		Location of access
		Location of egress
		Wait time
		Number of transfers
	Walk	Distance
	Bicycle	Use of bicycle lanes
		Distance
		Means of securing bicycle at destination

Table 3: Summary of previous travel surveys

Location	Year	Duration	Sample Size	Survey Methods
Uppsala, Sweden	1971	35 days	149 individuals	Paper and Pencil Interview (PAPI)
Lexington, KY	1996	1 week	100 households	Vehicle-only GPS / PDA with 2-3 sec sampling period
California	2000-2001	Oct 2000 and Dec 2001, one 24 hr. weekday, one 48 hr. weekend. 20 weeks with passive GPS logger	58 counties and 17,040 households	Computer Assisted Telephone Interview (CATI) on all respondent and passive GPS monitoring on 292 households. Used GPS to determine underreporting factor.
Atlanta, Georgia	2000	5 days	250 households with Electronic Travel Diary (ETD) & GPS, 50 households with ETD, GPS, & OBD-II, 250 households with passive GPS	All methods were used [33]
Mobidrive, Germany	Spring & Fall 1999	6 weeks	362 persons in 162 households	Paper and Pencil Interview (PAPI)
Swedish Intelligent Speed Adaptation, Borlange, Lund, and Lidkoping	June 2000 to March 2002	~ 80 weeks	186 vehicle, and 49,667 vehicle days	Passive GPS with vehicle engine on/off sensing
Puget Sound Household Travel Survey	July & Nov. 1999	48 hrs	6,000 households	Paper and Pencil Interview (PAPI)

Previous longitudinal surveys have shown that there are day-to-day and seasonal variations in travel behavior that can only be captured by a multi-week longitudinal survey. Furthermore, multi-day travel survey data have been found to be more efficient and accurate estimators of trip generations. Pendyala [23] provided a detailed literature review on day-to-day variability in travel behavior. He noted there are two sources of day-to-day travel behavior variability: people's needs and desires vary from day to day, and behavior varies because of feedback from the transportation system. In supporting his hypothesis, he cited the research work of Hanson and Huff [9-11] using the 1971 Uppsala (Sweden) household survey data (35 days long, 149 individuals using self-administered travel diaries); Pas and Koppelman's [14,19-22] analysis of both 1973 Reading, England and 1989 Seattle, Washington travel survey data; and Kitamura and Van der Hoorn's [13] examination of Dutch National Mobility panel data. Previous research suggests that there is substantial day-to-day variability in travel behavior. Furthermore, Richardson suggested that the number of sample households may be reduced if the study duration increases [25]. In order to accurately capture the full spectrum of travel behavior, it is fundamentally important that surveys can be carried on for a long duration while maintaining the survey data accuracy and minimizing the burden on the respondents.

Table 4: Summary of previous GPS-aided travel survey diary hardware

Researcher	**Survey Year**	**Description**
Lexington, KY	Fall 1996	Sony MagicLink PIC-2000 with interface software that controlled the recording of GPS data and allowed respondents to enter trip information (2 MB storage)
Transport Research Centre (AVV), Netherlands	Winter 1998 – Spring 1999	ETD with handheld data logging devices equipped with a combined GPS / DGPS receiver and battery pack
Austin, Texas	1997-1998	Passive in-vehicle GPS-system
Quebec city, Canada	Dec. 1998-March 1999	In-vehicle GPS only
Georgia Institute of Technology	2000	ETD and comprehensive in-vehicle data collection system with both GPS technology and an engine-monitoring device, >100 lbs [34]
Georgia Institute of Technology Handheld Travel Diary	1999	Psion WORKABOUT handheld, 16 MB storage, 240x100 pixel display with key input, 11.46 ounces, 2 AA batteries [8]
Stopher's pilot experiment	1999	Vehicle passive logging with Garmin GPS III, max 1900 point [29]
GeoStats Logger		Passive logger using Garmin 35 GPS sensor with 4 MB max storage, 1.0 or 0.2 Hz logging rate, 1 lbs
McNally, UC Irvine, CA	2002	X86 133 MHz CPU running embedded Linux with 16 MB for 28 hours data logging, GPS & CDPD modem. Estimated cost, size & power: $1,200 - $1,400, 7"x9"x4", ~4 watt. Limited to Vehicular use only. Used in a survey of 25 Orange County households in which all homes are newly built in a new residential development [17].

Previous longitudinal surveys utilizing GPS (refer to Table 4) have shown great potential [1,3,7,23,33]. GPS-based surveys are more accurate and minimize the respondent burden. In addition, GPS digital data can be readily imported into computer analysis programs. This approach captures route choice, path, and speed profile information, items not feasible with traditional paper surveys [7,23]. These data may be used to measure the level of congestion of a particular highway [2,27]. GPS travel diaries used in the past may be classified into two types: *interactive* and *passive* [6,28]. An *interactive* electronic travel diary requires the respondent to interact with the hand-held computer to input survey information such as marking trip start and end, trip purpose, cost of trip, and travel mode. A *passive* travel diary requires essentially no interaction with the respondent—respondents only need to carry and turn on the device whenever they travel. Other essential trip information is collected through paper survey or follow-up phone call, or is estimated by computer-aided software based on the GPS data. Passive travel data loggers have been used to determine a Trip Underreporting Correction Factor (TUCF) which was used to adjust the statistical results of a larger-sample paper survey [3,35]. Some methodical GPS data post-processing approaches have been developed to successfully extract temporal trip start and end, trip purpose, and travel mode from the passive GPS data collected [3,6,28,32,35]. Determining the cost of a given trip from GPS data was not done in previous research. However, toll and parking costs could be extracted based on the vehicle route and stop duration, if detailed toll and parking fee structures in the traveled area are known. Nevertheless, the number of passengers, vehicle type, fuel type, and identity of the driver cannot be determined without the input of the respondents or an image of the vehicle interior.

Replacing traditional self-administered paper travel diaries with interactive GPS-aided travel diaries has shown significant reduction in the resulting respondent burden. Battelle reports that 75% of respondents took less than one minute to enter all required trip information into an interactive electronic travel diary [1]. On the other hand, respondents would generally spend 10 minutes on a paper diary or 20-25 minutes on a follow-up phone call. Therefore, a GPS-aided interactive travel diary could save both surveyors and respondents time and money.

Previously, all GPS-aided travel surveys were performed on a relatively small scale (sample size < 300). Moreover, all GPS-aided electronic travel diary devices were developed by loosely integrating commercial off-the-shelf items. Typically, a GPS receiver was connected to a data logger or a Personal Digital Assistant (PDA) hand-held computer [1,3,6-8,29,32]. Data were entered using touch screen or keypad interfaces. Each device had its own power source. These GPS travel diary data loggers used in previous surveys have their drawbacks. A high percentage of the units failed to achieve full data collection capability due to:

- Hardware failure:
    - Broken cable connection between the GPS and the data logger or PDA [1,32];
    - Respondent failure to provide power [3];

- Respondents not carrying the unit due to:
    - Weight and size [8];
    - Difficult to carry when bicycling [1];
- Software bugs [1];
- Inability to differentiate vehicle stop at the end of a trip vs. a stop caused by congestion or pedestrian crossing [3,29];
- Loss of GPS signal due to urban canyons, improper GPS antenna orientation on the respondent body, and signal blockage inside vehicles such as buses [1,6];
- and loss of GPS data during GPS receiver cold-start period [6,7].

Nevertheless, the GPS-aided electronic travel diary has the strongest potential to fully capture all travel behavior exactly for accurate modeling. The drawbacks of previous GPS-aided travel diaries and loggers have been overcome in the current project's GPS-ATD system by tight component integration, additional sensors, longer lasting backup batteries, and increased onboard processing power and intelligence.

CHAPTER 2:
RECENT EMERGENCE OF SUPPORTING TECHNOLOGIES

Recent technological developments and improvements in the Global Positioning System (GPS), low-cost small Micro-Electro-Mechanical Systems (MEMS) inertial sensors, low-power embedded computers, high-capacity storage devices, wireless communications, and high-speed Internet have converged to make a portable and low-cost data collection system a feasible reality. Each of these technical areas will be discussed in detail in this chapter.

Current Global Positioning System (GPS) Status

The Global Positioning System (GPS) is a space-based radio-navigation system consisting of a constellation of satellites and a network of ground stations used for monitoring and control. A minimum of 24 GPS satellites orbit the Earth at an altitude of approximately 11,000 miles, providing land, sea, and airborne users with accurate information on position, velocity, and time anywhere in the world and in all weather conditions, with precision and accuracy far better than other radio-navigation systems available today or in the foreseeable future (see http://gps.faa.gov). Currently, there are 30 operational GPS satellites in orbits. They circle the Earth twice per day. The space and ground control GPS segments are operated and maintained by the Department of Defense (DOD). In 1996, a Presidential Decision Directive, later passed into law, transferred "ownership" from DOD to an Interagency GPS Executive Board (IGEB), co-chaired by senior officials of the Departments of Transportation and Defense to provide management oversight to assure that GPS meets both civil and military user requirements.

GPS receivers collect signals from the satellites in view (a.k.a line-of-sight). They provide the user's position, velocity, and time, and some receivers give additional data, such as distance and bearing to selected waypoints or digital charts after further processing of the positional and time solutions. Without going into full detail, each satellite transmits an accurate position and time signal. The user's receiver measures the time delay for the signal to reach the receiver, which provides a direct measure of the apparent range (called a "pseudorange") to the satellite. Measurements collected simultaneously from a minimum four satellites are processed to solve for the three dimensions of position (latitude, longitude, and altitude) and precise time. Position measurements are in the World Geodetic System WGS-84 geodetic reference system, and time is with respect to a worldwide common U.S. Naval Observatory (USNO) time reference. For more information, see Hoffmann-Wellenhof, et al [12].

Until recently, Selective Availability (SA) was used to protect the security interests of the United States and its allies by globally denying the full accuracy of the civil system to potential adversaries. SA was turned off at midnight on May 1, 2000, and it is not the intent of the U.S. to use SA ever again. Currently, with removal of SA, accurate position (< 25 m), time, and speed can be obtained throughout the country using small and low-cost GPS receivers.

GPS is continuously being modernized with additional radio frequency and transmission power resulting in more reliable and accurate positional and time solution. However, civilian users will not benefit from the effects of in-progress and planned GPS modernization until 2008.

Free Nationwide Differential GPS (DGPS) Services

GPS accuracy can be improved by additional information provided by fixed ground GPS monitoring stations. The Wide Area Augmentation System (WAAS) and the Nationwide Differential GPS (NDGPS) are two free differential GPS services available in the United States. Both systems provide improved GPS accuracy and integrity monitoring services.

NDGPS is a land-based GPS augmentation that typically provides 1- to 3-meter positioning accuracy to receivers capable of receiving the differential correction via a Medium Frequency (MF) signal transmitted by a ground station. It is an expansion of the U.S. Coast Guard's Maritime DGPS network. NDGPS is now providing single-station coverage over about 80% of the landmass of the continental U.S. and is expected to be fully operational with dual-station coverage throughout the continental U.S. in the near future. To ensure accuracy, integrity and continuity, NDGPS is managed and monitored 24 hours a day, 7 days a week from the Coast Guard’s Navigation Center in Alexandria, Virginia. NDGPS also provides GPS integrity monitoring capability; it gives an alarm to users within 6 seconds of detecting a fault with the signal from any GPS satellite in view. NDGPS receivers are generally much bigger and consume more power because of the extra MF (150 - 175 kHz) radio modem.

The Federal Aviation Administration (FAA) Wide Area Augmentation Service (WAAS) GPS differential correction signals enable even higher positional accuracy (1-3 m), without the need for an additional FM radio. WAAS broadcasts correction signals by geostationary satellites, and uses a system of ground stations to provide necessary augmentations to the GPS navigation signal. A network of approximately 25 precisely surveyed ground reference stations are strategically positioned across the country–including Alaska, Hawaii, and Puerto Rico–to collect GPS satellite data. The system is then able to estimate the amount of signal delay and error that is the result of the ionospheric and/or solar activity. This information is then passed on to the user as a part of the WAAS navigation message to correct GPS signal errors. These correction messages are then broadcast through communication satellites to GPS receivers using the same frequency (L1, 1575.42 MHz) as GPS. WAAS is designed to provide the additional accuracy, availability, and integrity necessary to enable users to rely on GPS within the territory of the United States. The FAA commissioned the Wide Area Augmentation System at 12:01am on July 10, 2003. At present there are two geo-stationary satellites (Inmarsat IIIs) serving the WAAS Pacific Ocean Region (POR) and Atlantic Ocean Region-West (AOR-W). The FAA is pursuing dual geo-satellite coverage throughout the U.S. to eliminate a possible single point-of-failure and increase system reliability. The West Coast currently has dual-satellite coverage, as can be seen in Figure 1. Although WAAS was originally designed for aviation use, it provides benefits beyond aviation to all modes of transportation, including maritime, highway, and rail. Small low-power WAAS-enabled GPS receivers are more widely available than NDGPS-enabled GPS receivers. WAAS vertical accuracy over the United States is illustrated in Figure 2—horizontal accuracy (of most interest for travel surveys) is approximately three times better than vertical, due to geometric configuration. As with coverage, the West Coast has excellent WAAS accuracy.

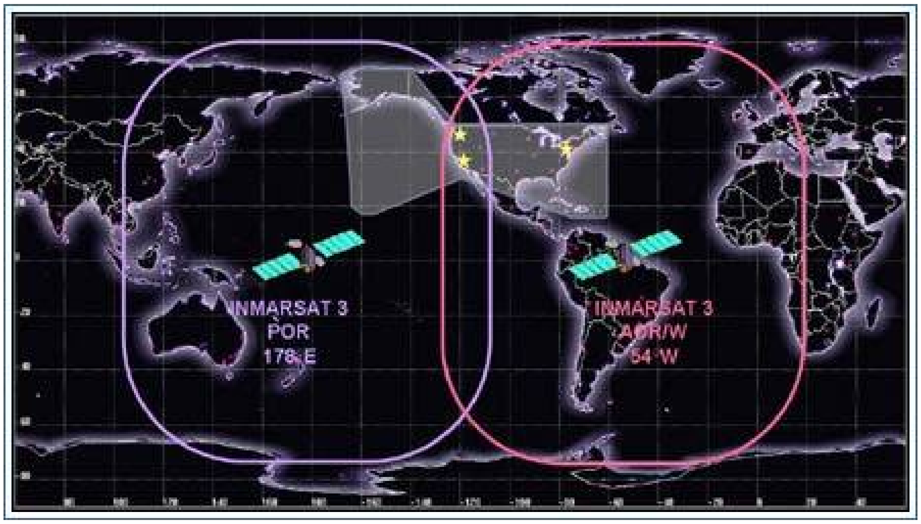

Figure 1: WAAS geostationary satellites coverage map (http://gps.faa.gov/CapHill/geosat.htm)

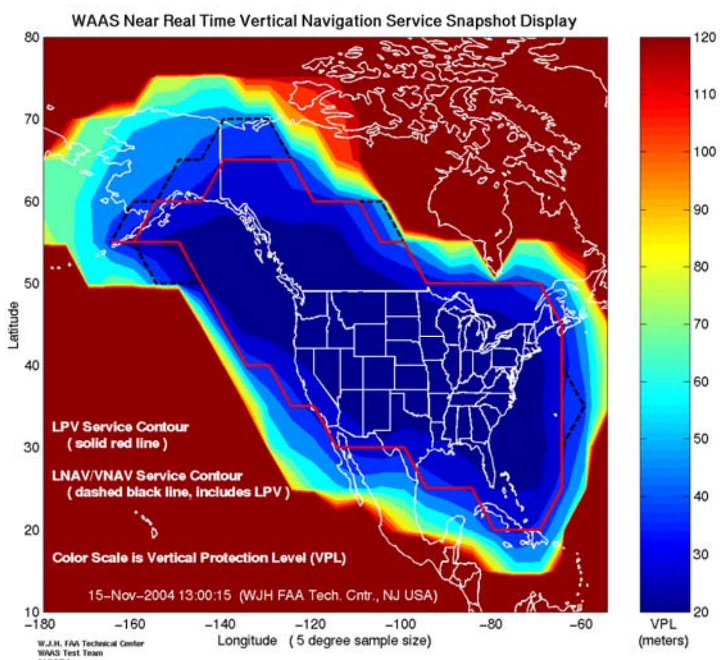

Figure 2: WAAS GPS vertical accuracy map (http://www.nstb.tc.faa.gov/vpl.html)

GPS Vulnerability

Many factors can degrade GPS performance. GPS receivers require a direct line-of-sight to the satellites in order to obtain a signal representative of the true distance from the satellite to the receiver. Therefore, any object in the path of the fairly weak GPS signal has the potential to interfere with its reception. Objects which can block a weak GPS signal include tree canopies, buildings, and terrain features. Similarly, the WAAS geostationary satellite signal can also be blocked. Furthermore, reflective surfaces can cause the GPS signals to bounce before arriving at a receiver, thus causing an error in the distance calculation. This problem, known as multipath, can be caused by a variety of materials, including water, glass, and metal. Even the water contained in the leaves of vegetation can produce multipath error. In some instances, operating under heavy and wet forest canopy can degrade the ability of a GPS receiver to track satellites. Typically, lower-elevation GPS satellites' signals are most likely to be blocked. In this situation, GPS receivers track only the highest satellites in the sky, as opposed to those satellites which provide the best Dilution-of-Precision (DOP)—a measure of the satellite geometry error sensitivity. Thus, the positional accuracy decreases. Unfortunately, there will be locations where the minimum required four GPS satellite signals simply are not available due to obstruction such as urban canyon—in these cases, no general GPS solution can be obtained.

GPS Sensors

There are many GPS receiver manufacturers—some options and form factors are shown in Figure 3. Each manufacturer may have its own signal tracking, positional solution, and filtering algorithms. Receivers may perform differently during startup, reacquisition of signal, and in various terrains such as urban canyons and under tree canopies. Nevertheless, most GPS receivers output the position and time solution in ASCII text standard National Marine Electronics Association (NMEA) 0183 format via an RS232 serial port. NMEA output sentences contains Coordinated Universal Time (UTC) date and time, latitude, longitude, and altitude in the WGS-84 coordinate system, geoidal separation, number of visible satellites, speed, heading, horizontal DOP (HDOP), and solution status. Some GPS receivers give additional information such as estimated positional accuracy. Moreover, most receivers can also communicate solution data using proprietary binary communication protocols at a higher baud rate, allowing more data or more frequent updates.

Most GPS users would still not know where they are given their position in latitude, longitude, and altitude—with this raw data, most users can at best tell whether they are in the northern or southern hemisphere. A digital map or a Geographic Information System (GIS) database is required to determine the user's state, city, and street location. Some receivers have incorporated mapping functions and GIS database. They have more memory, Flash storage, and powerful processors. However, most handheld units can only store a coarse state map or a detailed city map. Digital maps and GIS databases vary in size depending on the number of detailed entries. For example, Microsoft MapPoint software has a 1 Gigabyte (GB) GIS database map for all of North America.

Each GPS receiver has its own power-on sequence where it downloads almanac data (such as GPS satellite orbital information) before establishing a position and time fix. This start-up time is referred as cold-start time (typically between 45 sec to 5 min). Some receivers have a “sleep” mode in which the receiver keeps all the almanac data in memory using a low-power consumption mode. Thus, the long start time may be eliminated. Furthermore, keeping the receiver on may eliminate the cold-start time. In addition, the reacquisition time—the time to reacquire the satellite signal lock when the signal was temporarily blocked—varies from 1 to 3 seconds for different manufacturers. Moreover, GPS receivers perform differently in GPS-challenged areas like urban canyons or heavily wooded areas. Their size and power consumption varies as well. These factors were closely examined in the project’s GPS receiver testing and evaluation phase discussed in Chapter 4.

Figure 3: Example commercial GPS receivers

Some GPS receivers can track weaker GPS signals better than other models. A newly-developed class of GPS receiver, the High-Sensitivity GPS (HSGPS), can operate in urban canyons with weak GPS signals, supporting traveler behavior data collection in areas previously thought ill-suited for GPS [18,26]. Experiments conducted by the PLAN (Position Location and Navigation) Group of the University of Calgary show that a high-sensitivity GPS receiver achieved 100% positional solution availability, while a traditional high-performance dual-frequency survey-type GPS receiver could only provide 30% availability in the same downtown Calgary urban canyon [18]. However, by their very nature, HSGPS errors are typically larger (100 ~ 200 m) in hostile GPS signal environments [18]. Nevertheless, these large positional errors can be eliminated by map-matching and/or use of inertial sensors such as a rate gyro [4,15,24].

GPS receiver performance varies for different models and manufacturers. They all have different internal proprietary positional solution routines and Kalman filtering for invalid GPS positional solutions [18]. Therefore, intensive testing on different GPS receivers must be performed to determine the model best-suited for the traveler behavior survey data collection application. Commercially available GPS receivers and components were evaluated on their:

- size, power consumption, and weight,
- cold-start acquisition and re-acquisition time in open sky as well as in harsh GPS signal environments,

- and availability and accuracy in various indoor situations such as metal and concrete buildings, concrete parking structures, household garages, as well as outdoors in urban canyons, heavy tree cover, and open sky.

In addition, various GPS antennas were tested for performance in different conditions, particularly for signal loss at various orientations, and the effects of human tissue in changing the antenna signal gain pattern [16]. Size and weight were also compared.

Low-Cost Inertial Sensors for Dead Reckoning

Dead reckoning (DR) is a navigation method used in ships, aircraft, and, more recently, mobile robots. Essentially it is used to estimate an object's position based on the distance traveled in the current direction from its previous position. A simple dead reckoning system measures acceleration and angular rates and estimates heading and speed, then integrates to obtain position. For a vehicle, heading could be measured by compass and/or gyro, and the speed may be obtained through accelerometer or wheel rotational speed. DR will provide position information if GPS is not available for a short period of time. Since DR relies on integration of sensor measurements, error increases as usage duration increases—this is referred to as drift. The error can be corrected with a positional update from the GPS receiver. Traditionally, DR is used to estimate current position based on previous position in time. However, a non-causal technique can be used to back-calculate to obtain a previous position based on the current position given by the GPS receiver. Thus, during post-processing, the user position can be determined during the long GPS cold start-up time if the system logs inertial data.

Small and low-cost MEMS gyro and accelerometer chips (see e.g. Figure 4) available today make low-cost DR possible. In addition, MEMS gyros and accelerometers can measure vehicle acceleration, detect lane changes, and provide dead-reckoning to increase GPS availability in a complementary fashion. Combining these technologies, a system can collect positional and temporal data automatically and accurately with high availability. Furthermore, in some cases acceleration and speed profiles and other driving characteristics could be used to determine driver identity.

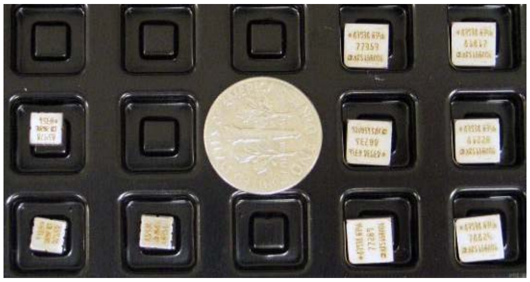

Figure 4: Analog Devices MEMS gyro and accelerometer chips

Other New Technologies to Improve Travel Surveys

Vehicle On-Board Diagnostic (OBD) Interface

All 1996 and later vehicles are equipped with a standard On-Board Diagnostic (OBD) version II data bus, including an OBD-II Diagnostic Link Connector which enables a diagnostic scan tool to communicate with OBD-II compliant control units via protocol ISO9141-2, J1850-PWM or J1850-VPW, depending on the make of the vehicle. According to the 2000-2001 California Statewide Travel Survey, 62.7% of the vehicles are less than 10 years old, implying that approximately 62.7% of vehicle currently on the road have an OBD-II interface. This percentage will increase over time, and can be expected to be higher when the next Statewide travel survey is conducted. OBD-II provides real-time vehicle operating parameters such as engine coolant temperature, calculated load, fuel trim, fuel pressure, engine RPM, vehicle speed, intake air temperature, throttle position, oxygen sensor output, and vehicle identification [5]. These data may be useful in estimating vehicle emissions. In addition, vehicle speed could be input to a Kalman filter to improve dead-reckoning and provide an estimate of vehicle miles traveled (VMT) when the GPS signal is not available.

Wireless Technology Developments

Coarse data may be transmitted automatically in real-time via CDMA (Code-Division Multiple Access) or GSM (Global System for Mobile communications), and high-resolution sampled data may be stored for subsequent automatic transfer without any user input via a high-speed wireless network (Bluetooth or WiFi—802.11) and high-speed Internet connection (Digital Subscriber Line (DSL) or cable modem) once the vehicle is parked at the end of the trip. Data may also be stored in internal solid-state Flash memory for later retrieval if a data-link is not available. Real-time vehicle data transfer allows the vehicle to act as a probe for traffic congestion [2,17]. These data would be valuable to a Transportation Management Center, although this was not addressed in the current research.

These technological advancements have increased the system's robustness and availability, and reduce survey costs and needed user interaction. The result is a physically small, low-cost, embedded system which is easily installed and which creates minimum impact or burden on the respondent while providing the maximum accurate and complete data collection.

CHAPTER 3:
SYSTEM OVERVIEW OF THE GPS-AUTOMATED TRAVEL DIARY

Automation is the key to reduced respondent burden and increased accuracy and data integrity. To lower the cost, weight, complexity, and power consumption of the GPS-Automated Travel Diary (GPS-ATD), its required tasks should be minimized. Therefore, longitudinal travel surveys should be divided into two phases, as shown in Figure 5: data collection and data post-processing. The GPS-ATD should collect all necessary raw data, leaving further processing for the subsequent data post-processing and analysis phase. Researchers and analysts may then process and re-process the raw data with various criteria, methods, and GIS information updates in the post-processing phase.

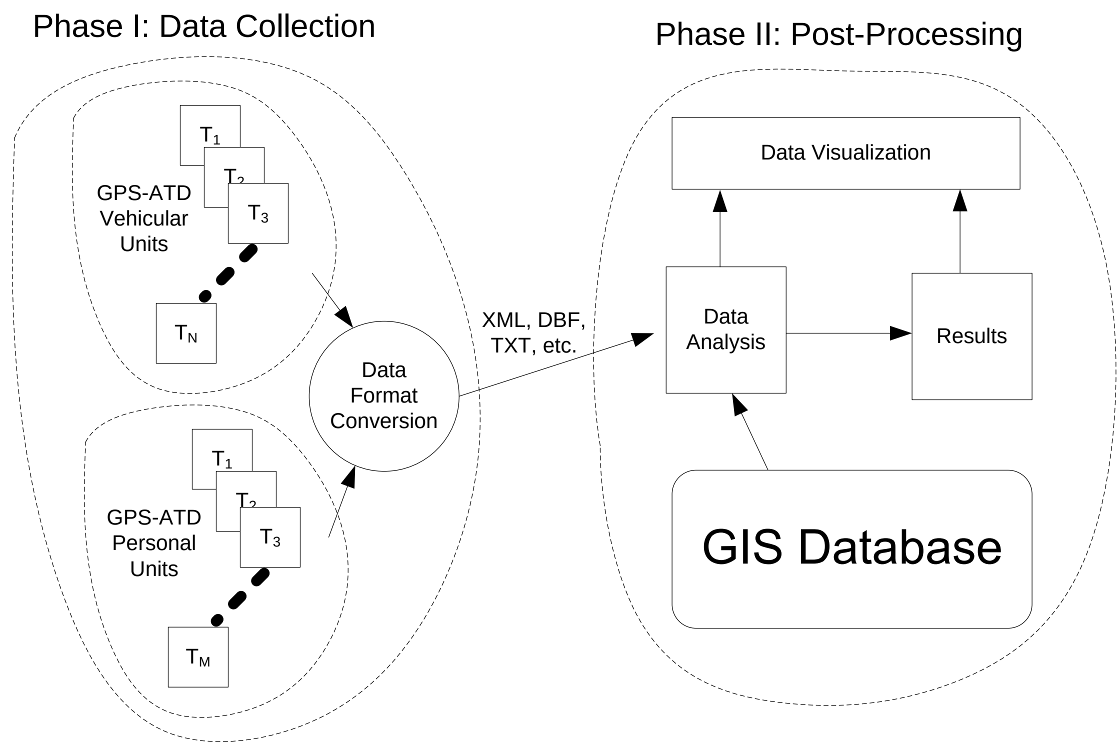

Figure 5: System architecture including data collection and post-processing phases

Recommended GPS-Aided Electronic Travel Diaries Systems

The current project focuses on development of the data collection units, i.e. on the Phase I portion of the architecture. Vehicular and personal GPS-Automated Travel Diary (GPS-ATD) systems have been developed to address the need for comprehensive travel behavior study data collection. The devices support *interactive*, *passive*, and *hybrid* operating modes (*hybrid* implies any of a variety of modes between interactive and passive). Ideally, the system would capture all pertinent data over the entire survey period without zero burden on the user in question; clearly this is never the case, and we seek to approach a reasonable set of criteria. These features are summarized below in Table 5, and are based on user responses in exit surveys and analysis conducted in prior research referenced in this report. The objective was to provide internal and external decision makers and stakeholders with current, accurate, reliable, and spatially dense traveler behavior data at a significantly reduced cost.

Table 5: System features

Travel Diary	Long or quick trip data collection
	4-week data capture
	Internal data Flash
	Intuitive user interface
	Reduced user burden
	Lightweight (~12 oz)
	Low-power, operational time > 3 days
	Wireless interface
	Upgradeable (firmware)
	Easy installation
	Suitable for vehicular, walking, or biking use
	Little or no cabling
	Compact for security
Display	LCD Graphic display, 160x240 resolution
	Backlit
	Automatic contrast control
GPS	High Sensitivity
	Integrated
	Easy-mount GPS antenna
	Dead reckoning for GPS startup and low signal availability
Gyro/Accel	User position for GPS startup
	User position for GPS low signal availability
Vehicle Interface	OBD-II vehicle telemetry
Wireless	Unit-to-unit communication

The travel diary contains all of the necessary sensors and interfaces to reliably collect the needed information with low user burden over the specified survey period. Based on previous research, the minimum survey period should be approximately four weeks in length. This allows capturing the various patterns of the average traveler. Intra-week surveys tend to only capture quick and short-term travel patterns, and fail to fully sample long-term long trip travel patterns. Additionally, to account for seasonal travel pattern variations, this four-week survey should be repeated quarterly. These requirements suggest a compact data collection device which is easily deployable and installed by the end-user, i.e. the survey participant.

In general there will be two diary units: one for the vehicle, and one portable unit for each user. These two units share common features and functionality. Both vehicular and wearable personal versions are based on a shared modular system architecture. Furthermore, both vehicular and personal GPS-ATD units can operate in *passive*, *interactive*, or *hybrid* mode. Moreover, they are simple to use, robust, compact, low-power, light-weight, simple to install, esthetically pleasing, rugged, and low-cost for easy implementation in a wide array of vehicles, or travel modes for the portable units. The units are entirely self-contained with all of the sensors integrated into a single package. The sensor outputs—positional and temporal data—are collected automatically by an onboard embedded processor and stored in solid-state memory.

Human-machine interfaces (HMI) that are overly complicated or tedious are viewed negatively, and can impact the data collection and the survey results. The HMI can address biases of potential language barriers, literacy, or technology illiteracy. Use of customizable icons and menus has been successful in the past. Previous electronic travel diary HMI approaches were used as a reference and baseline guide. The user interface is based on a Liquid Crystal Display (LCD) and application-specific buttons. The user make menu choices with the application specific keypad. This interface will be intuitive, fast, and result in reduced user burden. In interactive mode, an automatic sequence of requests for data could be made after the car is started in the case of the vehicle unit, or by simply pressing a start button in the case of the wearable personal unit.

The wearable personal GPS-ATD captures all modes of transportation. In addition, it is light-weight and has rechargeable batteries that can be recharged from either the home station or an auto-charger. Its GPS receiver antenna is less sensitive to orientation. Several mounting and carrying options for the personal GPS-ATD are provided to let the respondents use the unit in many situations (walking, biking, and motorcycling) with ease.

The vehicular GPS-ATD has additional sensors, OBD-II interface and backup batteries which are rechargeable from vehicle power. The heart of the system uses a HSGPS receiver for positional data collection. When a GPS system initially starts up or suffers intermittent satellite signal loss, dead reckoning can be used to supplement the positional data. This data is calculated from MEMS inertial sensor (gyroscope and accelerometers) measurements during a loss of positional fix by the GPS receiver. As shown in Table 8, the sample rate of these sensors will be increased during the GPS blackout interval. Larger backup batteries can power the GPS receivers for extended periods and reduce the likelihood that loss of GPS data occurs at the beginning of a trip due to potentially long GPS cold-start time. Moreover, the MEMS inertial sensor data is also collected and stored in solid-state memory. The vehicular GPS-ATD can determine the starting and shutting off of the vehicle by monitoring the power input voltage, and via other means. Typically, a vehicle's "12-Volt" source will have a voltage greater than 13 Volts when the engine is started. Thus, the vehicle stopping at the beginning and end of a trip can be easily separated from traffic jam stops or stops at rail and pedestrian crossing. Finally the vehicle system contains an interface to the OBD-II port on all new vehicles (1996 and later). The OBD-II interface provides access to vehicle telemetry and diagnostics to determine vehicle speed, engine characteristics, and dynamic emissions. The features of the two GPS-ATD versions are compared in Table 6.

Table 6: Comparison of vehicular and personal versions of GPS-ATD

Data	Vehicular Ver.	Personal Ver.
Personal Identity	√	
Trip Purpose	√	√
Travel Begin Time	√	√
Travel End Time	√	√
Route Choice & Speed Profile by GPS	√	√
Trip Distance by GPS	√	√
Cost of Trip (fees, parking, toll, etc.)	√	√
Mode of Transportation		√
Switching Mode of Travel		√
Reason of Mode Choice		√
Number of Passengers	√	
OBD-II Interface Data	√	
Acceleration	√	√
Yaw Rate	√	
Temperature	√	√

By automating the collection of accurate and objective data, GPS-ATD units may eliminate traditional paper diaries altogether. Furthermore, previous research has shown that given appropriate GIS information, trip purpose, travel mode, travel duration, travel mode switch, speed, acceleration, deceleration, trip origin and destination, trip cost (parking and toll), regional or interregional travel, vehicle miles traveled, trip start and end time may all be determined by either post-processing of the data or by respondent input. The GPS-ATD satisfies the needs of the modern longitudinal travel survey.

System Implementation

Table 7 shows the hardware requirements to implement the features in Table 8. The Central Processing Unit (CPU) is a 32-bit 266 MHz ARM chip with the program Flash layered on top of the CPU die for a smaller package. This chip runs the embedded Linux operating system (OS). At boot-up, the program stored in the on-chip Flash will be loaded into the 32 Megabyte (MB) Synchronous Dynamic Random Access Memory (SDRAM) for execution. The internal 256 MB non-volatile Flash stores the data shown in Table 8. In general, the GPS data is sampled once per second (1 Hz), parsed, and the pertinent data stored in an efficient binary format in Flash. The other sensors are adaptively sampled as required with the resultant data also stored in binary format for maximum memory utilization. The wireless interface is based on the familiar ZigBee technology and is used for unit-to-unit communication. The user interface is based primarily on a 160x240 resolution LCD graphic display with backlighting and automatic contrast control to ease user burden. The main input is by application-specific custom buttons. In the case of the portable device, the system will be powered by Lithium-ion battery and will include a built-in charger. The system will be connected to a power supply, similar to cell phones, for recharging. Power calculations and lab tests suggest that the portable system should be able to run for three days during business hours, i.e.

approximately 8 hours per day. Longer operational periods could be achieved by powering down in certain scenarios, e.g. when the user/device is at rest, or is riding in a car with a vehicle system already gathering data.

Table 7: GPS-ATD system hardware

CPU	266 MHz 32-bit
RAM	32 MB SDRAM
Flash	256 MB
Wireless Interface	ZigBee
GPS	DGPS
Vehicle Interface	OBD-II
Accelerometer	2 G max with 5 mG resolution
Gyroscope	75 deg/sec max
User Interface	160x240 backlit automatic contrast control
	Application-specific buttons
Power	Lithium-ion battery
	Switching supply, 95% efficiency
	Built-in charger

The data budget shown in Table 8 provides the various data and related sampling rates. The duty-cycle represents the percent time that the sensors in question are sampled. These are realistic sampling rates which assume a maximum of 8 hours of usage per day resulting in approximately 30 days of storage utilizing 128 MB of internal Flash. It is important to note that the user and/or trip information is taken only once, while the bulk of the data gathered is GPS-based. To ensure high positional data confidence, the gyroscope and accelerometer are adaptively sampled (i.e. at varying rate depending on conditions) to complement the GPS data. The vehicle data will also be sampled adaptively. It is important to always keep in mind that one of the major goals of this work is to reduce the user burden and maintain the data quality. One way this can be achieved is to drastically reduce the amount and difficulty of end-user data input, which can be achieved by deriving as much information as possible in post-processing. This goal was always in the forefront when analyzing the various systems suitable for this development.

Table 8: Data elements and update rates

		bytes	freq (Hz)	byte/sec	duty cycle	adjusted bytes/sec
GPS	date	2	0.001	0.002	1	0.002
	time	2	1	2	1	2
	latitude	4	1	4	1	4
	longitude	4	1	4	1	4
	altitude	4	1	4	1	4
	number_satellites	4	1	4	1	4
	velocity	4	1	4	1	4
	heading	4	1	4	1	4
	HDOP	2	1	2	1	2
	quality	2	1	2	1	2
OBD-II	speed	4	10	40	0.1	4
	intake_temperature	4	1	4	1	4
	coolant_temperature	4	1	4	1	4
	oxygen_sensor_1	4	10	40	0.1	4
	oxygen_sensor_2	4	10	40	0.1	4
	oxygen_sensor_3	4	10	40	0.1	4
	oxygen_sensor_4	4	10	40	0.1	4
	throttle_position	4	10	40	1	40
	RPM	4	10	40	1	40
Temp	temperature	2	1	2	1	2
Gyro	horizontal	4	20	80	0.1	8
Accel	accel_lateral	4	20	80	0.1	8
	accel_longitudinal	4	20	80	0.1	8
Identity	name	2	0.001	0.002	1	0.002
	mode_travel	2	0.001	0.002	1	0.002
	mode_reason	2	0.001	0.002	1	0.002
	mode_switch	2	0.001	0.002	1	0.002
	number_passengers	2	0.001	0.002	1	0.002
Trip	purpose	2	0.001	0.002	1	0.002
	Link trip / drop off	2	0.001	0.002	1	0.002
					total bytes/sec	164.01

duty cycle	0.3
storage size (MB)	128
maximum days	31.57

Design Tradeoffs

Table 9 represents the relationships between the system features and their influence on weight, size, cost, user burden, data quality, battery duration and survey duration. The system features are the row headings and the major constraints are the column headings. The colors and numbers represent the effects of including or increasing one of the features, with red, or -3, representing a very negative (bad) effect, and blue, or +3, representing a very positive (good) effect. As an example, by increasing the display size feature, we see that the weight would be slightly increased (negative), the size would be more increased (more negatively impacted), and the cost would be greatly increased (very negatively impacted). We see that by increasing the display size the user burden is somewhat reduced (positively effected). The battery duration is negatively effected as larger screens use more power. However this negative effect can be somewhat offset by the fact that the display is powered down in the portable version to conserve power when not in use. At the bottom of Table 9 we see an "importance" table which is a weighting for the various system constraints. The above constraint matrix is multiplied by the weighting vector resulting in the total weighted sum on the right of the table. A more positive number represents a more efficient feature, and a more negative number represents a less efficient feature. The highlighted weighted sums represent features which are most highly recommended in Table 9.

Features		Effect							
		Weight	Size	Cost	User Burden	Data Quality	Battery Duration	Survey Duration	Total
Human Interface	Display Size	-1	-2	-3	2	0	-2	0	-10
	Backlit	0	0	-2	3	1	-1	0	8
	Graphics	0	0	-2	2	2	0	0	12
	Menu Content	0	0	0	3	3	0	0	27
	Interface Method	-1	-2	-2	3	2	0	0	13
Data Storage	Onboard Flash	-1	-1	-1	2	0	-2	3	6
	Removable Flash	-1	-1	-2	1	0	-2	3	-1
Data Collection Method	Serviceman Download	-1	-1	-3	-2	0	0	-2	-25
	Flash Card Pickup	0	0	-3	-1	0	0	-2	-19
	Flash Card Mail	0	0	-1	-3	-2	0	-2	-31
	Remote Batch Transfer	-1	-1	-2	2	1	-1	2	8
	Real-time Transfer	-1	-1	-3	2	3	-2	3	15
	Unit-to-Unit Transfer	-1	-1	-1	2	1	-1	1	8
Sampled Data	GPS	-1	-2	-3	3	3	-1	0	12
	OBD-II	-1	-1	-1	2	3	-1	0	15
	Accelerometer	-1	-1	-1	2	3	-1	0	15
	Gyro	-1	-1	-3	2	3	-1	0	9
	Temperature	-1	-1	-1	0	1	-1	0	-3
Power	Battery Size	-3	-1	-1	0	0	3	3	11
	Battery Type	1	0	-3	0	0	3	3	10
	Rechargability	-1	-1	-1	2	0	0	0	3

-3	-2	-1	0	1	2	3
Worse			**Same**			**Better**

Importance (1-5)

Weight	Size	Cost	User Burden	Data Quality	Battery Duration	Survey Duration
1	1	3	4	5	3	3

Table 9: Feature cost-benefit tradeoff analysis

CHAPTER 4:
COMPONENT TESTING AND EVALUATION

GPS Sensor Test Results

The GPS receiver is the most critical sensor on the GPS-ATD. A newly-developed class of GPS receiver, the High-Sensitivity GPS (HSGPS), can track weaker GPS signals better than previous GPS receivers and provide positional solution in challenging GPS environments such as urban canyons, some indoor areas, and parking structures. It can support traveler behavior data collection in areas previously thought ill-suited for GPS [18,26] such as inside a bus or train. Experiments conducted by the PLAN (Position, Location and Navigation) Group of the University of Calgary show that a high-sensitivity GPS receiver achieved 100% positional solution availability, while a traditional high-performance dual-frequency survey-type GPS receiver could only provide 30% availability in the same downtown Calgary urban canyon [18]. However, by their very nature, HSGPS errors are typically larger (100 ~ 200 m) in hostile GPS signal environments [18]. Nevertheless, these large positional errors can be eliminated by map-matching and/or use of inertial sensors such as a rate gyro [4,15,24]. These recent developments will greatly improve Longitudinal Travel Behavior surveys.

Intensive testing on different GPS receivers was performed to determine the model best-suited for the traveler behavior survey data collection application. Commercially available GPS receivers and components were evaluated on their:

- size, power consumption, and weight,
- cold-start acquisition and re-acquisition time,
- and positional solution availability in various GPS challenge conditions such as inside buildings, concrete parking structures, household garages, in urban canyons, and under heavy tree cover.

GPS World magazine provides a comprehensive list of existing GPS equipment makers in its annual survey—this served as a basis for the selection process. The GPS-ATD requires the use of a small and low-power GPS module to keep the size and weight down while providing long run-time using battery power. Therefore, any GPS sensors bigger than 2 sq. inches or consuming more than 200 mW were eliminated. Following GPS World's GPS hardware list, each manufacturer's product line was examined in detail to identify likely candidates. In addition, web searches were carried out to find other GPS modules makers not on the GPS World annual survey. Due to the rapid change in technology and roll-out of new GPS chipsets, most printed GPS test results are quickly out of date and obsolete. On the other hand, GPS enthusiast websites, such as http://www.gpspassion.com, provide current GPS news and test results for popular GPS receivers, as well as industry trends.

The GPS industry is very much like the computer industry. Even though there are many computer makers, there are only a few CPU makers. Similarly, there are relatively few GPS chipset makers (the chipset is the processing engine of the GPS receiver). GPS receivers using the same GPS chipset tend to perform very similarly. Since GPS receiver modules are usually more difficult to obtain, COTS (commercial off-the-shelf) GPS receivers were used in the initial testing. The main objective of the initial test was to determine which GPS chipset performance best under various conditions. The major embedded GPS chipset makers are (as of 2007) Garmin, SiRF, Sony, NemeriX, Tyco, Trimble, and Atmel/u-blox. Note that throughout this report, trademarks and copyrights are property of their respective owners, and are omitted for conciseness.

To reduce testing time, the GPS chipset selection process was conducted on an elimination basis, with the goal to find the most suitable GPS chipset for GPS-ATD use, rather than fully characterize the performance of each GPS chipset under any conceivable conditions. GPS chipset performances were directly compared. If a GPS chipset performed poorly vs. the other GPS chipsets in one test, it was immediately dropped from further testing. Since the handheld personal GPS-ATD with be used in particularly challenging GPS environments, availability of the solution is far more important than accuracy.

The final GPS test candidates were: Garmin 18 GPS, Holux GR212 (SiRF II Xtrac), iTrek BT (NemeriX 1st-generation chipset), Sony GXV5005 GPS module, San Jose Navigation FV-25 (ATMEL/u-blox ANTARIS chip), and Holux GPSlim236 (SiRF III GPS chipset). Generally, all the tested GPS performances achieved similar performance under relatively open sky such as on highways and suburban residential streets. The effect of trees on residential streets was comparatively small vs. previous generations of GPS. All GPS test candidates were able to provide good positional solutions under heavy tree cover. The SiRF III chipset GPS was able to maintain lock to all GPS satellites in view while other chipset GPS could lose lock on some GPS satellites in view.

Figure 6: GPS test setup

On the other hand, performance varied significantly under GPS challenge conditions such as urban canyon, inside parking structure, under a bridge, and indoors. Firstly, the Garmin 18 and Atmel ANTARIS GPS chipset GPS lost track of GPS satellites when placed under any large structure such as a bridge. The Atmel ANTARIS GPS stopped providing solution when it lost track of GPS satellites. However, the Garmin 18 provided a (typically poor) “extrapolated” solution based on previous speed and heading for several seconds. Based on these results, these receivers were eliminated from further testing.

Figure 7: Residential streets with tree blockage

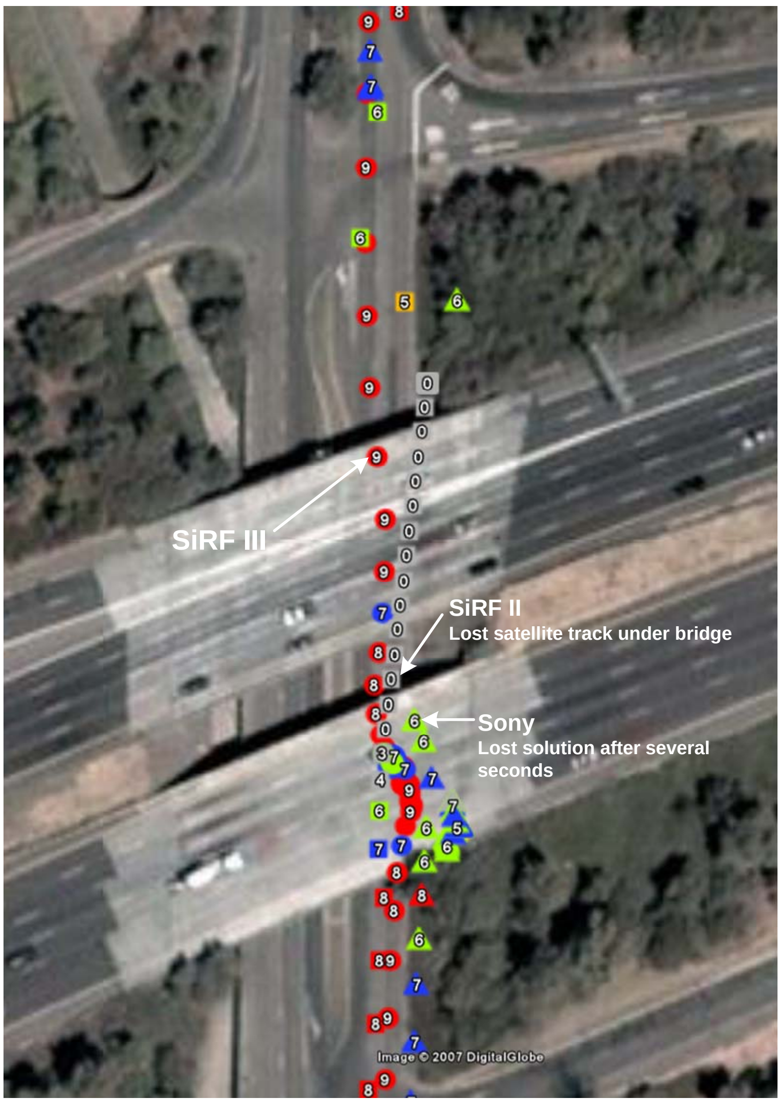

Figure 8 Bridge test results for SiRF II, SiRF III and Sony GPS receivers (number on symbol indicates number of satellites used for position calculation)

The remaining systems were tested in the basement and first levels of a parking structure. The SiRF III was the only GPS that continuously tracked GPS signals and provided good positional solutions in both the first and basement levels of the parking structure. Other GPS modules generally lost track and could not provide solutions midway into the parking structure. Moreover, the remaining GPS were tested in an urban canyon environment, specifically downtown Sacramento, California. The SiRF III was the only GPS that could continuously provide solutions. Other GPS modules would lose track near tall buildings.

Figure 9: UC Davis parking structure

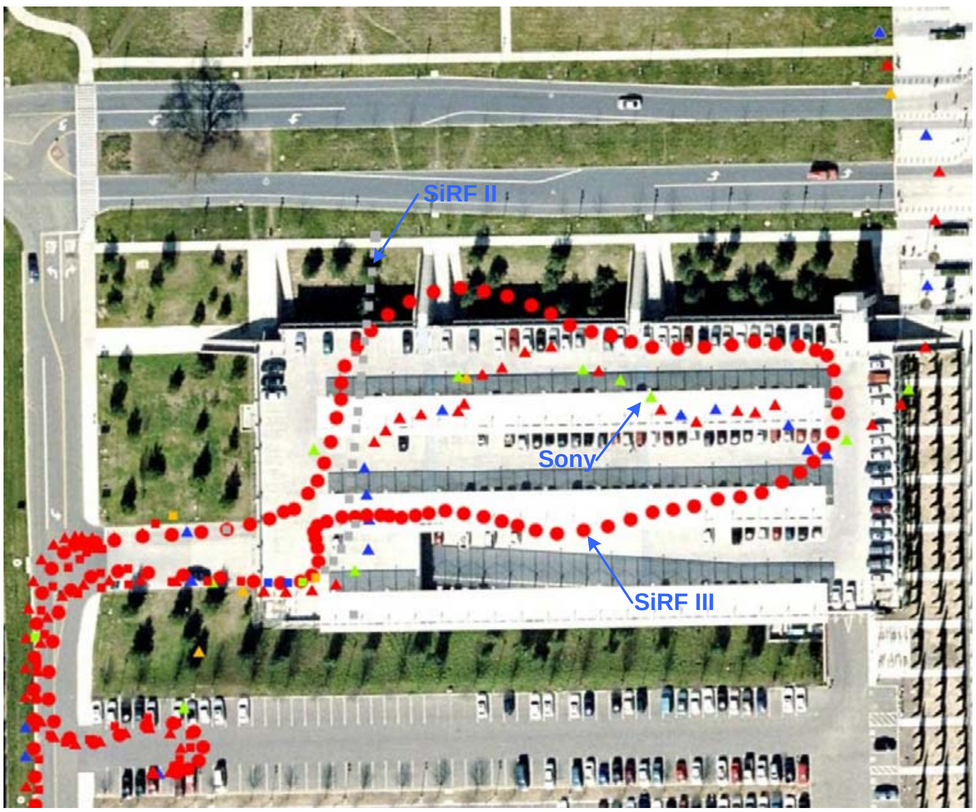

Figure 10: Parking structure GPS receiver test results in the basement level

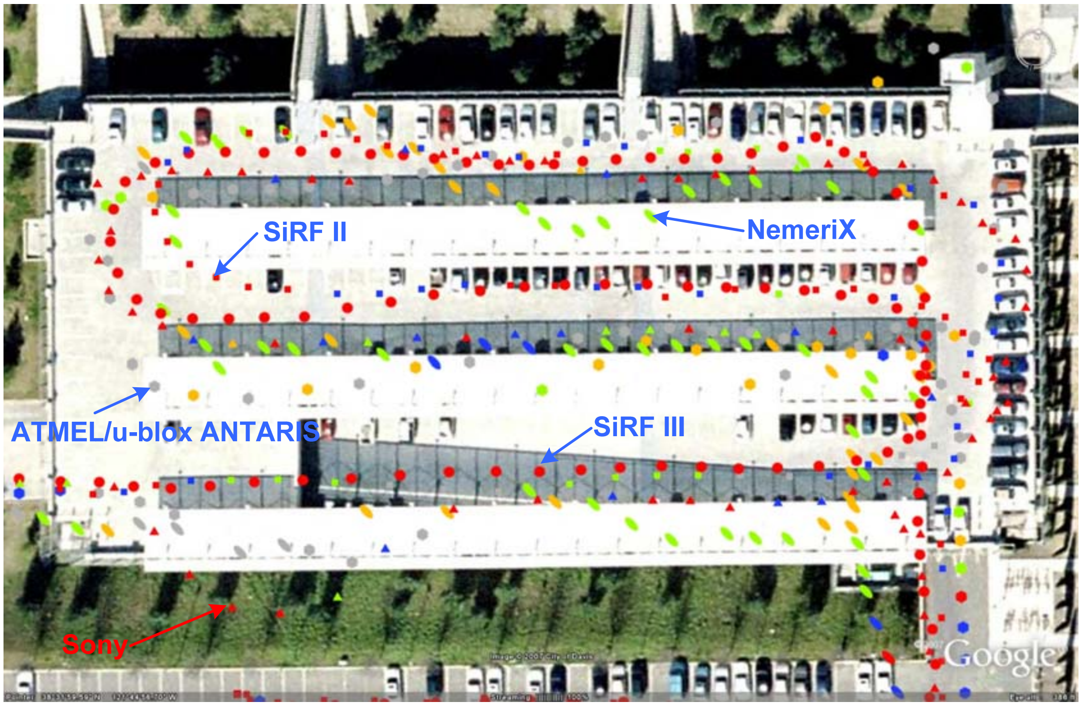

Figure 11: Parking structure GPS receiver test results in the first level

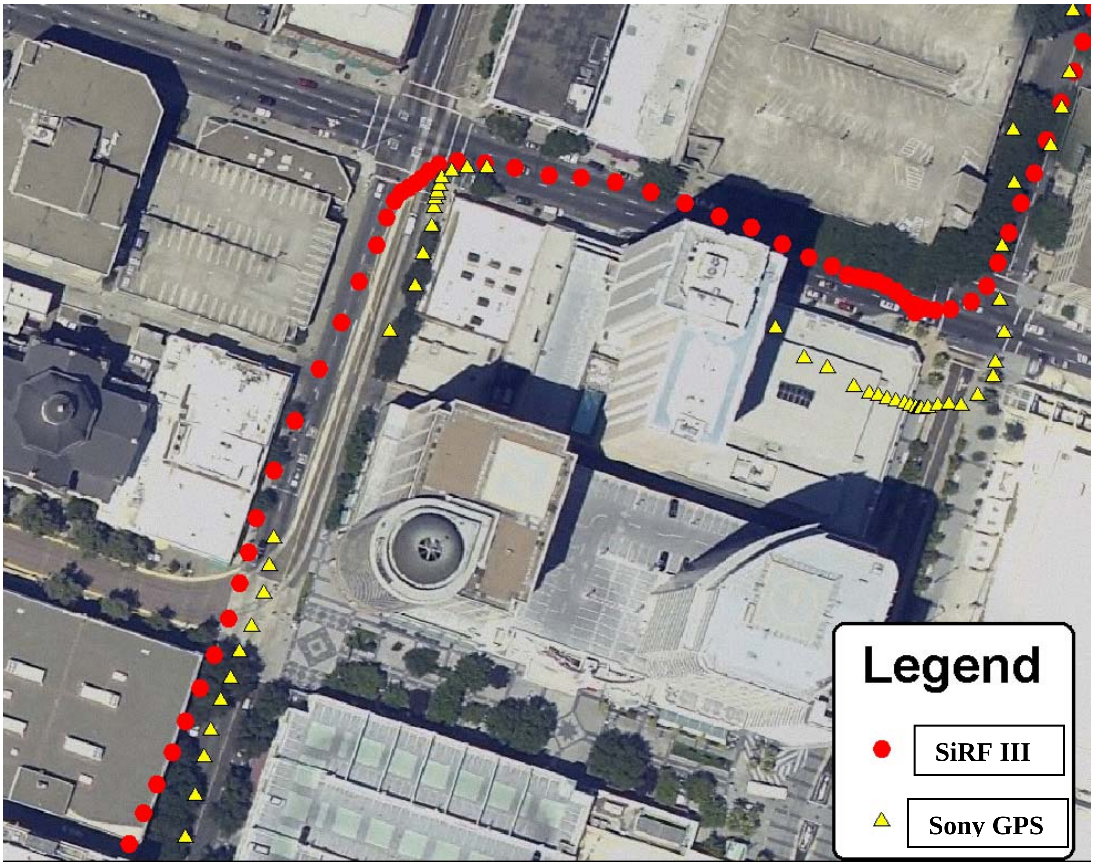

Figure 12: Downtown Sacramento GPS receiver test results

As such, we selected a SiRF III-based GPS chipset module to be incorporated in the GPS-ATD design, based mainly on its urban canyon and underground parking structure performance. Note that several new GPS receiver chipsets became available twelve months after our GPS testing, but too late in the GPS-ATD development cycle. According to www.gpspassion.com, users found that MTK chipset-based GPS units perform as well as the SiRF III chipset, and in some cases better. The MTK GPS chipset also consumes 50% less power than SiRF III. In addition, there is now a low-power version of the SiRF III chipset which consumes half the power of the previous version. Thus, the GPS-ATD battery run-time may be further extended using the new low-power MTK or SiRF III modules. However, these new generation modules were not available until the current project's development was complete.

GPS Antenna Test Results

The Sarantel GeoHelix antenna is a new generation of GPS antenna designed specifically for handheld device applications. It offers several advantages over a traditional patch GPS antenna: compact size, omni-directionality, light weight, and less susceptibility to interference by the human body and hand [16]. Both the Sarantel GeoHelix and a patch antenna were connected to an identical SiRF III module to compare their performance on the open highway and in a parking structure. The performance of the SiRF III GPS with Sarantel GeoHelix antenna is slightly less than with a patch antenna. The GPS signal received is about 3 db less with the GeoHelix antenna. However, the GeoHelix antenna should out-perform the patch antenna if the patch antenna is oriented sideways or upside-down, according to manufacturer's literature. Thus, the Sarantel GeoHelix is better-suited for handheld applications, where orientation varies. Therefore, it was selected for the personal GPS-ATD. Based on the same tests, a patch antenna was selected for the vehicular GPS-ATD.

Figure 13: Sarantel GeoHelix GPS antenna

GPS Antenna Placement Simulations

Simulations were run to determine the performance degradation of placing the GPS patch antenna on the dashboard instead of the roof. The vehicle metallic roof was simulated as a perfect GPS signal block. The effect of the metallic roof blockage depends on the vehicle travel direction. The effect is less when the vehicle is traveling south, as shown in Table 10 and Figure 14. Generally, the vehicle metallic roof will block one to two satellites. However, the GPS antenna still receives more than four satellites to give a positional solution. Based on the simulation results, we concluded that the ease and convenience of GPS antenna installation on the dashboard outweighs the performance gained by placing the GPS antenna on the roof.

Table 10: Number of available satellite summary statistics

	No Blockage		Southern Blockage		Northern Blockage		Eastern Blockage		Western Blockage	
City	Mean	STD Dev	Mean	STD Dev	Mean	STD Dev	Mean	STD Dev	Mean	STD Dev
Los Angles, CA	10.61	0.05	8.83	0.06	9.33	0.05	8.12	0.06	8.16	0.06
Fresno, CA	10.54	0.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
San Francisco, CA	9.50	0.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sacramento, CA	9.50	0.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Redding, CA	9.48	0.05	8.71	0.06	9.28	0.05	7.82	0.07	8.12	0.05

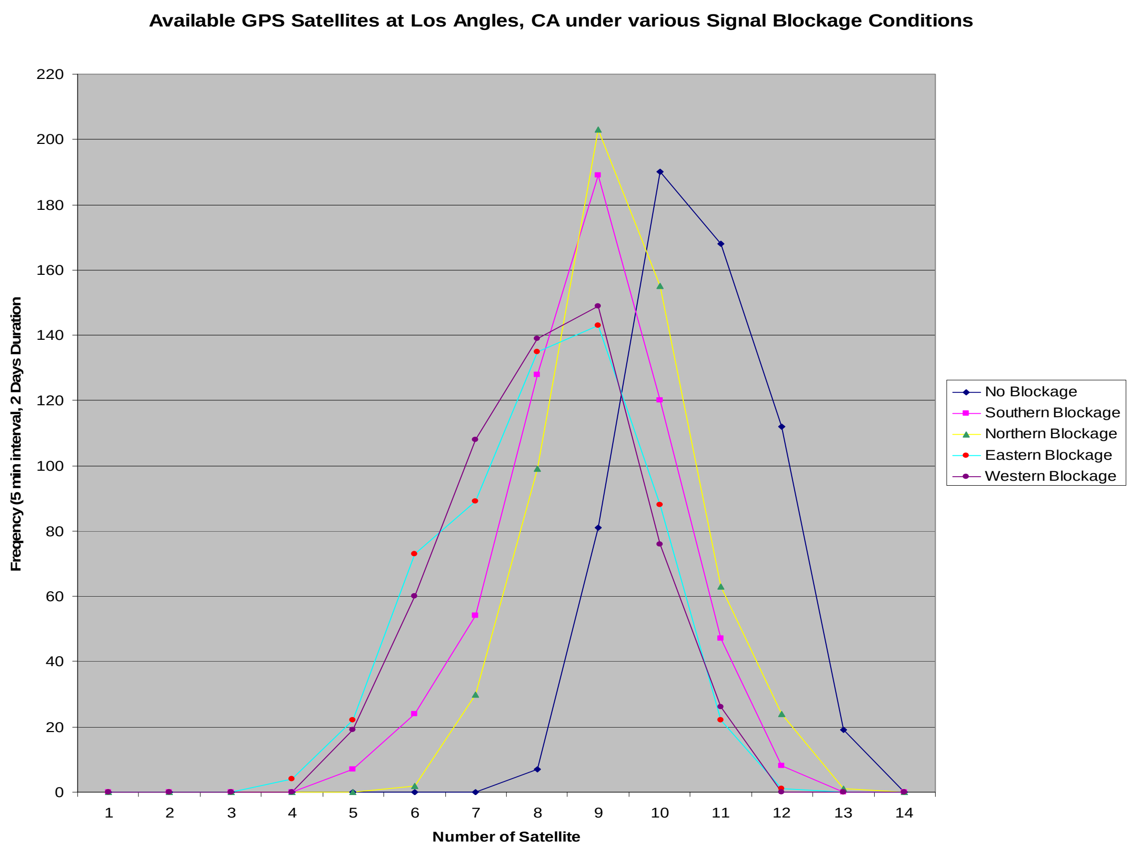

Figure 14: Simulated effect of placing the GPS antenna on the dashboard vs. on the roof (No blockage line represents GPS antenna on the vehicle roof, and the others represent GPS antenna on the vehicle dashboard traveling in various directions)

CHAPTER 5: HARDWARE DESIGN AND IMPLEMENTATION

The system design, shown in Figure 15, was driven by the design requirements. Hardware design focused on portability, light-weight, small size, and low power consumption. Once the actual system architecture was developed, appropriate components to implement the system functions could be selected. The GPS-ATD is composed of following major components: ABS plastic case, LCD display panel with built-in backlight, custom membrane switch user interface, 1800 mAh Lithium-ion battery, and the main circuit board with all the electronics. The LCD panel and battery are assembled into the GPS-ATD unit with little modification. The battery capacity was limited by the size of the GPS-ATD case. Other components are custom design or COTS with major modifications. Component selection principles were based on availability, package size, power consumption, technical specification and cost. No single criterion is necessarily more important than any other. In order to extend the battery run-time as long as possible, each component's power usage must be scrutinized carefully. The GPS receiver module, SDRAM (synchronous dynamic RAM), and CPU were the major power-consuming devices on-board. In addition to selecting inherently low-power components, one must also select components that allow lower voltage supply levels. Components that quickly change binary states, such as the CPU, use power based upon the voltage supply and the digital communication data bus voltage to other components. Therefore, SDRAM and 32-bit ARM processor based on a 1.8 V memory bus were selected, with the CPU core requiring a 1.5 V rail. The processor data bus connected to the 256 MB NAND Flash device was also 1.8 V; therefore the *optimal* design used a 1.8 V NAND Flash device.

Part availability in both small and large quantity is a major issue, especially if the part is new or being used in popular devices such as PDA, portable GPS navigation devices, and MP3 players. A new part may not be up to full production for months after the manufacturer's announcement of availability. The resulting short supply is often sold before manufacture, and often the minimum order is 10,000 units or more. Larger customers are given preferential treatment and higher shipment priority on available stocks. In some cases, large customers may have exclusivity with the component manufacturer. For example, the proliferation of pocket electronics has put an enormous load on the NAND Flash industry, so that it is virtually impossible for prototype developers to obtain any current-generation Samsung Flash devices. Despite Samsung's superior Flash specification, the only option left is to design using previous-generation parts at higher cost, larger package size, higher power requirements, and more associated "glue" circuitry. Availability changes with market conditions and industry trends, which led to design changes throughout the project for certain major components.

Finally the selected components must be compatible with available manufacturing technologies. Small package components usually have finer pitch and smaller electrical contacts for soldering onto the main printed circuit board (PCB). The finer the component's pitch, the more costly it will be to place onto a PCB by pick-and-place machines. Even though new low-power components may cost less because of smaller die and package, resulting increased manufacturing difficulty may negate any cost savings.

Thus, component selection is an iterative process whereby the designer must balance power, cost, size, manufacturability, and availability.

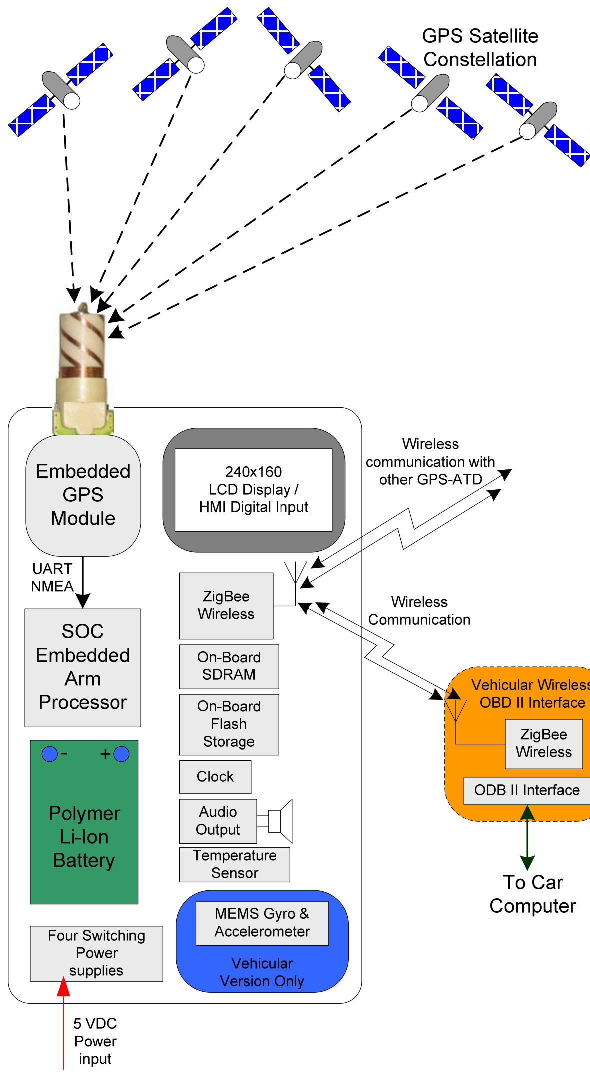

Figure 15: GPS-ATD system block diagram

Once major components are selected, schematic design may start. However, the detail design is carried out simultaneously with the component selection process because of interdependences: component selection affects schematic detail, and conversely. Once the system-level functional design is defined, the system level blocks can then be synthesized into a component-level design. Since the CPU connects to most components, the CPU system block design is initiated first. This block contains a 266 MHz Freescale i.MX21 32-bit ARM processor in a 256-pin Fine Ball-Grid Array (FBGA) package configured to operate at 1.5 V with memory buses running at 1.8 V, and all other interfaces running at 3.3 V. This design provided the lowest operational power requirements for this system block. Further reductions in the system power consumption can be attained by further throttling the software-configurable operating frequency from the initial clock frequency of 133 MHz—we opted to run the chip at half-speed for power savings. The remaining CPU dependencies are clock crystals, SDRAM, NAND Flash storage, and necessary power rails and sequencing requirements. Clock crystals are available from several manufacturers and suppliers in a variety of sizes, generally at low cost. Based on initial software run-time memory requirement estimate, 32 MB of RAM was selected using two 1.8 V Micron SDRAM 128 Mbit x 16-bit wide bus in a 54-ball FBGA chip package. These were widely available through several distributors.

Choosing the NAND Flash was much more complicated. The CPU can operate all memory interfaces at 1.8 V or 3.3 V. The only available 256 MB NAND Flash components used a 3.3 V interface, not the desired 1.8 V interface. The CPU memory bus can be configured to operate at 3.3 V to work with more power-consuming 3.3 V SDRAM and 3.3 V Flash. Alternatively, the CPU can be configured to interface with 1.8 V SDRAM and 3.3 V NAND Flash through a 1.8 V to 3.3 V transceiver. The latter design increases part count by about 30, and raises cost and complexity, but has lower power consumption than the first alternative, and was the option selected for the GPS-ATD. A Micron 3.3 V 256 MB NAND Flash memory with 48-pin TSOP (Thin Small Outline Package) Type 1 package was selected. The last major dependency of the CPU is the power supply rails and the sequencing of these rails during system power-up and down. The CPU has a specific requirement of turning on higher voltages before lower voltages, so that reverse biases are not exceeded during startup and conversely during power down. Therefore, the power supply sequencing circuitry must meet the CPU power sequencing requirements.

Furthermore, all power supplies were designed as high-efficiency step-down switching regulators to maximize battery life. These power-switching supplies, along with other digital switching circuitry, add noise to the system. Mitigation of this noise depends on proper design of the various switching power supplies as well as the selection of bypass capacitors at device operating frequencies. Substantial analysis and simulation of the system components were needed to determine the optimum set of bypass capacitors, with the goal to select low ESR (equivalent series resistance) capacitors that are resonant at the noise frequency in question, thus shorting that frequency to ground. These bypass capacitors were then populated throughout the PCB and placed as close as possible to the supply pins of the various integrated circuit chips. As the noise frequency being bypassed increases, the distance between the bypass capacitors and supply pin must decrease. At 266 MHz the bypass capacitors must be within 10 mm of the supply pin. However, at 33 MHz the bypass capacitors may be moved up to 100 mm away from the supply pins. Since the PCB is smaller than 100 mm in any dimension, the bypass capacitor can be placed anywhere on the board for any frequency below 33 MHz. Proper noise control is not only important for digital circuitry but extremely important for analog circuitry. Power supply noise in most analog circuits is modulated into the analog signal. In the case of low-noise amplifiers (LNA) used in the front end of low sensitivity GPS receivers, the power noise would directly affect the signal to noise ratio of the received GPS signal and reduce the sensitivity of the receiver. Therefore, adequate attention must be applied to the design and isolation of the various RF circuits from the rest of the system components. Noise may come in from of conducted noise through the power supply rails and ground planes as well as radiated noise through coupling of adjacent circuit traces. The supply rails must be adequately filtered so that existing noise does not modulate into the signal path and so that RF energy doesn’t travel to the supply rails.

This may be accomplished by inductive components and traces supplying the voltage to the LNAs. In the GPS-ATD design, a two-stage LNA was created and placed in front of the SiRF III based GPS receiver module. Our front-end used good RF design techniques to match to the Sarantel antenna and GPS receiver while maximizing gain and minimizing noise figure. Currently, the GPS module power supply is isolated from the main system power supply using a bypass capacitor. A better design would include a series inductor to the GPS module power supply input.

A ZigBee transceiver was implemented to enable wireless communication between personal and vehicular GPS-ATD, and the ZigBee OBD-II reader. Initially, a fully-integrated single-chip Chipcon ZigBee CPU+transceiver design was selected. However, availability forced redesign using the previous generation Chipcon transceiver, resulting in a two-chip design with a Silicon Labs CPU interfacing to a Chipcon transceiver. A minimal radio frequency (RF) circuit and dipole antenna was designed following Chipcon application notes. Consequently, PCB block area usage, power consumption, and cost doubled for the ZigBee block design.

Table 11: GPS-ATD system hardware

CPU	32-bit ARM Freescale i.MX21
RAM	32 MB SDRAM
NAND Flash	256 MB
Wireless	ZigBee
GPS	SiRF III
Vehicle Interface	OBD-II via ZigBee
PC Interface	USB 2.0
Accelerometer	2 G max with 5 mG resolution
Gyroscope	75 deg/sec max
User Interface	Microtips 160x240 grayscale with EL backlight
	4 application-specific buttons
Power	1800 mA-h Li-Ion polymer battery
	4 Switching supplies
	Built-in charger and battery protection
Weight	4.5 oz (Vehicular GPS-ATD) 5 oz (Personal GPS-ATD)
Size	2.62”x4.4”x0.83”

Remaining major components are summarized here, and the main hardware components selected are listed in Table 11. A USB 2.0 data interface was implemented to support high-speed data download. An 1800 mAh Li-ion (Lithium-ion) polymer rechargeable battery was selected because of its high power-density compared to other rechargeable batteries, as well as form-factor allowing a better fit inside a COTS plastic case. A grayscale 160x240 resolution LCD was selected rather than color due to better readability in all lighting conditions, particularly under bright sunlight. A four-button membrane custom keypad was designed by the AHMCT team and fabricated by a custom keypad maker. The system can be charged by a power supply via a mini-USB connector commonly found in digital cameras and mobile phones.

To maintain low unit cost, a COTS ABS plastic case (part #: 1593TBK) made by Hammond Manufacturing was selected. The case is composed of three pieces. Each case top cover requires CNC machining to create the LCD display window opening, keypad connection opening, and recess for the LCD display. Two different case front panels were CNC machined for the vehicular and personal version of GPS-ATD. In the case of the personal GPS-ATD, openings for the mini-USB connector and GPS antenna are required. For the vehicular GPS-ATD, openings for the mini-USB connector and GPS antenna MCX connector were machined into the front panel. A custom fixture was designed and fabricated to speed up the CNC machine process. All the mount posts in the case interior (top and bottom cover) are removed to allow room for the circuit board, battery, and LCD display. Details of the 1593TBK modifications are available in a supplement.

A custom membrane switch was found to be the most cost effective and esthetically pleasing way to add a custom user interface; hence a custom membrane switch was designed and manufactured for the GPS-ATD. It has four application-specific spherical embossed buttons with 12 mm diameter, 340 g force stainless steel dome custom made by Intermountain Technologies, Inc according to AHMCT design specification. These switches are connected to the built-in keyboard interface of the iMX21 ARM processor. In addition, it has an adhesive back that is used to fasten onto the top cover recess area of the GPS-ATD plastic case. A window opening for the LCD display was designed into the membrane cover. Furthermore, the keypad has a three-inch built-in ribbon cable with a 1 mm pitch zero–insertion-force (ZIF) connection at the end. The ribbon cable is passed through an opening in the top cover and connected to the main circuit board during assembly. Details of the custom membrane switch are available in a supplement

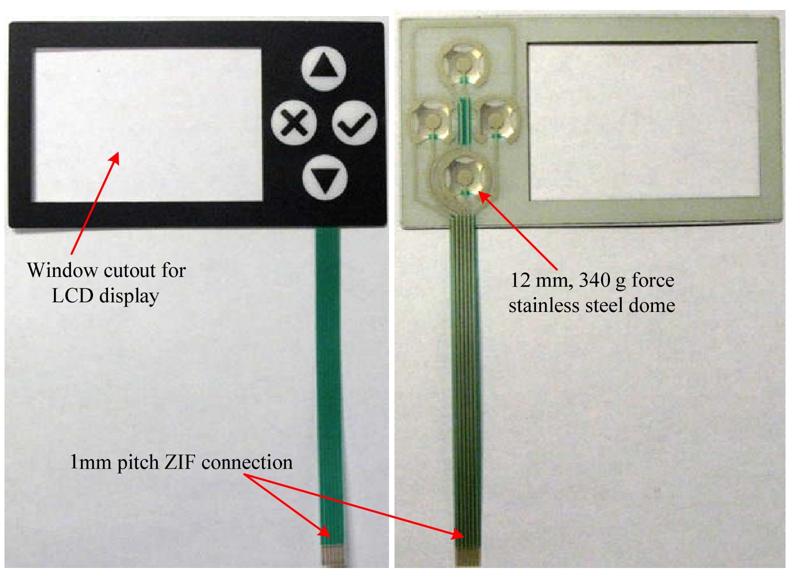

Figure 16: GPS-ATD membrane switch user keypad

A monochrome 8-bit grayscale LCD with 240x160 resolution and built-in electroluminescent (EL) backlight was selected due general readability in all light conditions. A color LCD display would require much brighter backlight under bright sunlight conditions, and thus would decrease battery life. The high-resolution displays text clearly for the user. A touch screen interface was not employed because it tends to add glare and adversely affects the readability. The LCD panel is directly connected to the iMX21 LCD interface via an 18-pin 1 mm pitch ZIF socket. The detailed electrical circuit design is provided in a supplement.

Circuit Board Design

Because of the overall size constraints, a custom 6-layer main circuit, shown in Figures 16 to 20, was designed to connect all the electronic components. Furthermore, the circuit board has components on both sides, totaling 130 components and 470 parts. The bottom side of the circuit board, shown in Figure 21, contains five power supplies, battery charging and protection circuits, and connectors to LCD and custom keypad. The top side of the circuit board houses the CPU, RAM, NAND, and GPS module.

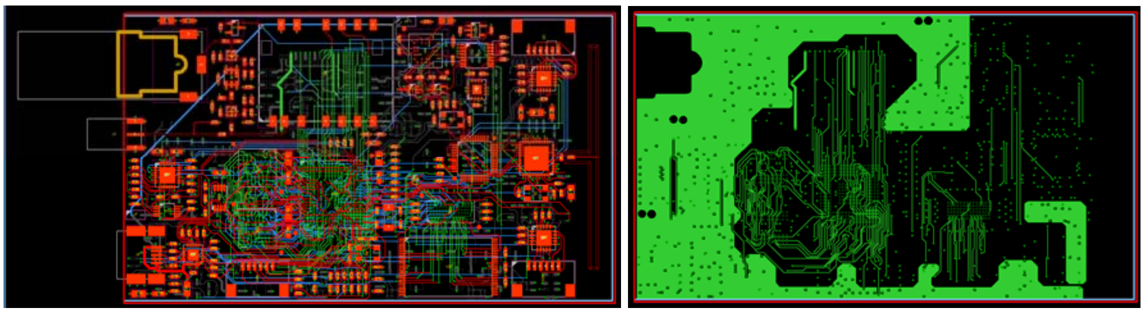

Figure 17: All layers and layer 3 of the GPS-ATD circuit board

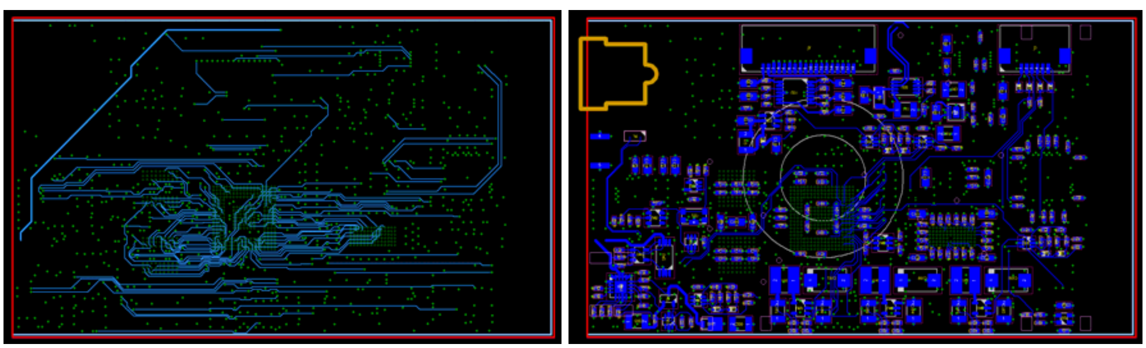

Figure 18: Layer 4 and layer 5 of the GPS-ATD circuit board

When capturing the design to schematics, each component must be defined as a part for Mentor Graphics' DxDesigner. We have developed an extensive in-house database containing all of our desired parts, part specifications, cost, size, power, availability, RoHS (Restriction of Hazardous Substances) status, and inventory. This database interfaces directly with the Library Manager of DxDesigner, which uses the part attributes from the database, and then associates the part to a specific DxDesigner symbol. Although these schematic symbols can be created manually in DxDesigner, our automated process using software developed in-house improved productivity and reduced human errors. This software uses Microsoft Excel as the base application due to its excellent ability to manage information in a row-column format, and implements custom operations in Visual Basic for Applications code. First, tabular or grid data from the component PDF or HTML datasheet is copied and pasted into a blank Excel spreadsheet.

After that, the user assigns symbolic pin locations and arrangements to the various pin names and numbers. The pin list is then consolidated. Finally the symbol is written to file and imported to the Mentor Graphics Library Manager. The Library Manager associates this symbol and the part attributes, and provides the part data to DxDesigner for placement. This process and workflow reduces human error in data entry.

After the entire system is captured to schematic attributes such as trace timing, crosstalk, trace width, and minimum spacing, these parameters are then exported to the layout tool, Mentor Graphics Expedition. Expedition uses these parameters to control characteristics of the final PCB, such as signal timing and noise. In Expedition the board outline is drawn, and parts can be initially placed on the top and bottom layers. For the GPS-ATD, primarily, all functional IC's were placed on the top layer and all power supplies, bypass capacitors, pull-up resistors, and simple control circuitry were placed on the bottom layer. The main placement constraints were the location of the GPS RF circuitry which had to be in the upper left corner based on the case design, and the ZigBee IC's and antenna, which had to be placed at the other end. Naturally the CPU was placed in the middle of the PCB since it connects to almost everything, and, based on timing/noise constraints, the SDRAM was placed as close as possible to the CPU. Also the level transceiver and the NAND Flash were placed relatively close to the CPU. Other system IC's were placed as space permitted with the pull-up resistors and capacitors spread around the PCB following the rule for maximum distance between bypass capacitors and supply pins described above. Our typical trace/space (trace width and trace spacing) was 0.1 mm for all signal lines. This value was not arbitrarily chosen; rather it was a result of layout dependencies of the 14x14 mm 0.65 mm pitch CPU Ball-Grid Array (BGA) and the PCB layer count.

Since we sought to keep the PCB layer count low for cost considerations, we chose a 6-layer 0.062"-thick PCB stack-up. Primarily, the PCB stack-up would be made of the top and bottom component layers, a power layer, a ground layer, a vertical signal layer, and a horizontal signal layer. With the CPU package having a pitch of 0.65 mm, we chose via holes to be 0.2 mm in 0.35 mm pads with 0.55 mm anti-pads based on manufacturing tolerances. However this setup did not allow avoidance of all necessary pins using standard via locations; hence, we used via-in-pad for the CPU. This presented some manufacturing challenges for the PCB fabricator, both in cost and time. It turns out that caps on the in-pad vias (used so that the BGA sees a flat circular pad) can pop up during reflow process if any gases are trapped during the via fill-and-cap process. This choice allowed us to continue with the 6-layer design and escape the majority of pins in the two signal layers, with some less critical pins escaped on the top and bottom layers. Since the Flash level transceiver was an 0.65 mm pitch BGA, via-in-pad was again required for pin escape. Since the via process worked well, it was also used for the larger 0.80 mm pitch SDRAM BGA which allowed for much easier pin escape.

All routing between the CPU and memory devices was constrained, routed, simulated, and met timing and noise requirements. The SDRAM was designed to operate at 133 MHz and the NAND Flash at 66 MHz. The design was simulated on Agilent ADS software and laid out accordingly on the PCB. The two-stage LNA (Low-Noise Amplifier) was placed as close as possible to the PCB-mount antenna and the LNA output was as close as possible to the GPS module input. The ZigBee CPU was placed near the transceiver, which was placed as close as possible to the center-tapped folded dipole antenna. The power was distributed to all components on the PCB through eight different power nets. Three power planes were implemented on the power layer, two on the vertical signal layer, and three more on the bottom layer. The ground plane was uniform and limited to the ground layer.

Although we had significant prior in-house experience with the manufacturing of fine-pitch components onto PCB's, this project turned out to be vastly more difficult than any of our prior efforts. The trace/space was fine but not anything that most PCB fabricators cannot handle; however, the via-in-pad was something relatively new to most of them. This raises an interesting application-oriented question: the only way to avoid the via-in-pad requirement for fine-pitch devices is to drastically increase the layer count. The primary PCB cost design decision boils down to which is a more economical alternative: a via-in-pad low layer-count PCB, or a no via-in-pad high layer-count PCB. We opted for the former alternative, as it is simultaneously more advanced and more cost-effective within the constraints of our prototype environment.

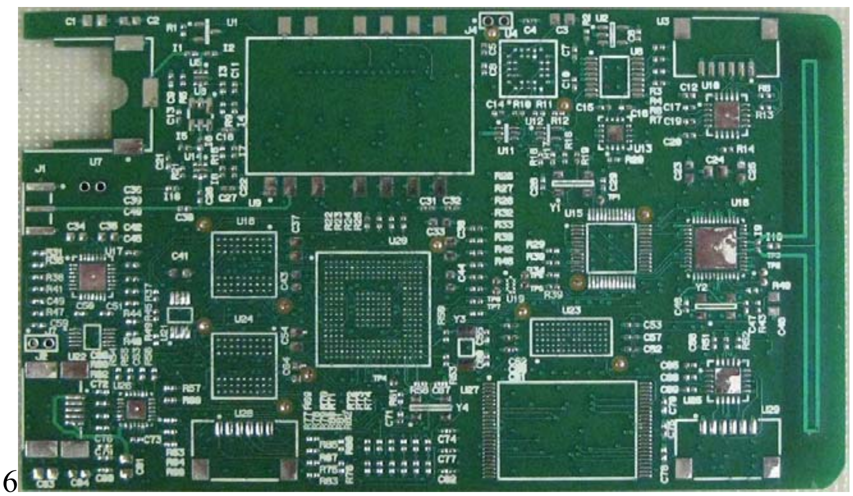

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Figure 19: GPS-ATD circuit board

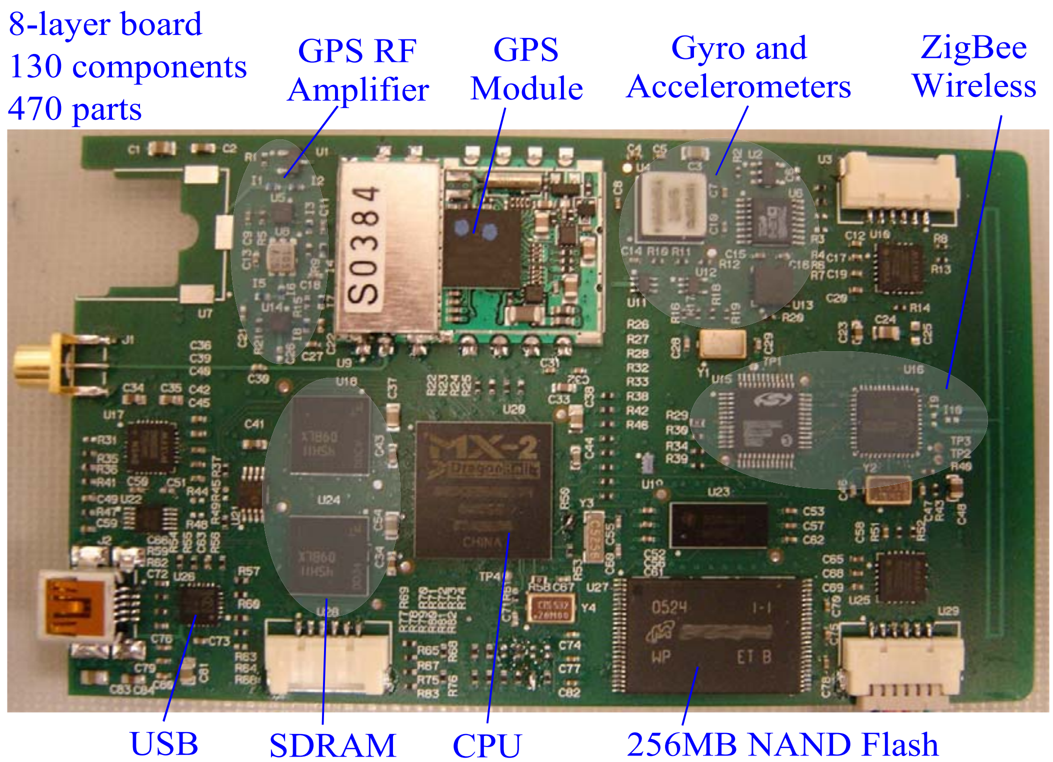

Figure 20: Assembled GPS-ATD circuit board (top side)

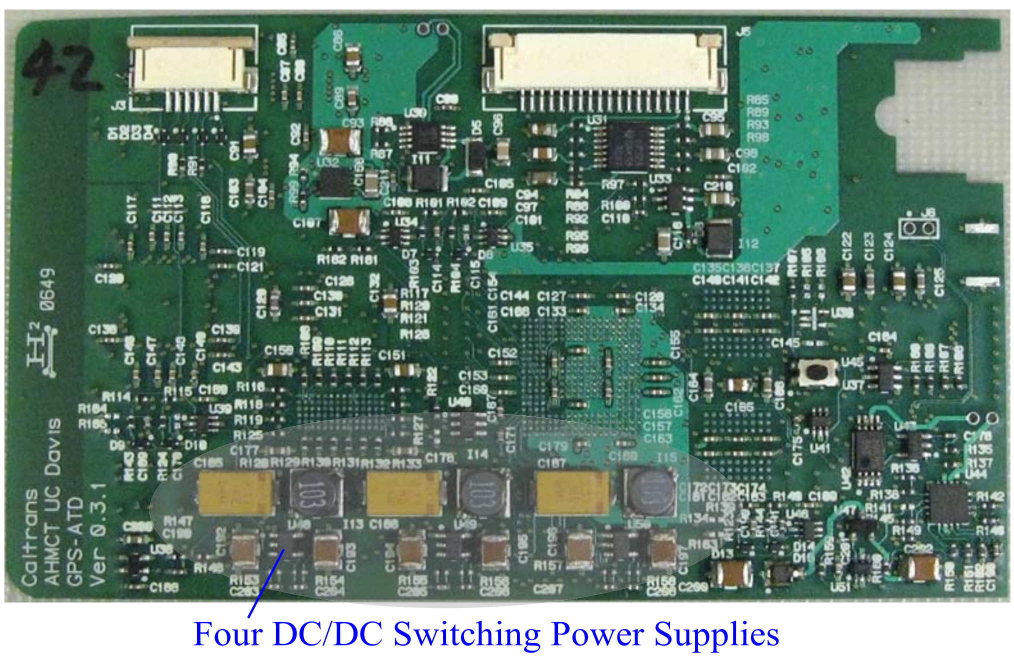

Figure 21: Assembled GPS-ATD circuit board (bottom side)

GPS-ATD Manufacturing

Due to the small volume of GPS-ATD fabrication, the main GPS-ATD boards were assembled in AHMCT's Sensing and Communications Lab. This was a significant manufacturing challenge due to small component package size, system complexity, high number of parts, and, mainly, the new Restriction of Hazardous Substances (RoHS) soldering process required by the new semiconductor packages. The small component package size and large part count increased the assembly time (approximately 4 to 6 hours per side). Most significantly, the RoHS soldering process caused low yield and decreased reliability. RoHS soldering processes are much less robust compared to traditional lead-based soldering processes. New solder paste must be used, and this paste is very sensitive to temperature variation and has a much shorter shelf-life. All semiconductor parts are subjected to higher solder temperature profile. Months were spent to refine and improve the RoHS soldering process to an acceptable yield and reliability.

Since all of the parts were RoHS-compliant, previous lead-based solder paste and reflow procedures could not be employed. The first test boards were soldered using these procedures, and the resulting assembled boards were very unreliable, with many marginal or bad solder joints. Through six months of experimentation and trial and error, a new lead-free soldering process was refined and improved to provide acceptable yield and reliability. We determined that it is critical to use very freshly-made lead-free paste and follow a strict optimal reflow profile to avoid BGA pin disconnects. Through repeated tests using a thermocouple on the circuit board to verify the reflow temperature profile, the oven temperature profile was carefully adjusted. Lead-free solder paste is much more sensitive to temperature variation on the circuit board during the reflow process. In addition, it is vital that an appropriate amount of lead-free solder paste is applied, preferably using a laser-cut mask as shown in Figure 22.

Circuit Board Assembly Process

The bottom side of the GPS-ATD circuit board is assembled first, in part because the components and assembly are less sensitive to the second reflow for the top side. After testing and validation of the power supplies of the fully-assembled bottom circuit, the top side is then assembled. The assembly process for both board sides is very similar. First, the proper amount of lead-free solder paste is applied to the soldering area of the circuit board, with time and labor significantly reduced using the laser-cut stencil, shown in Figure 22. A CNC (computer numerical control) machined fixture, shown in Figure 23, was used to hold the circuit board in a fixed position relative to the stencil. After the board is placed into the fixture, the stainless steel stencil is placed on top. Solder paste is then spread across the stencil surface. Next, the stencil is carefully lifted, and the circuit board is removed from the fixture. Each part is then hand-placed onto the circuit board. Finally, the fully-populated board is baked inside a reflow oven following a precise temperature profile. This process is repeated for the top side of the circuit board.

Each fully-assembled board, shown in Figure 24 and 25, then goes through a board validation process. The GPS antenna and GPS module are then hand-soldered. The complete GPS-ATD is then assembled, with the board, LCD, and battery placed into the plastic case as shown in Figures 24. Finally, another series of full-system validation tests are performed on the complete GPS-ATD unit.

In large volume production, a pick-and-place machine would dramatically speed up the assembly process. However, it would require an extensive one-time machine programming and physical machine setup. The time and cost of board assembly largely depends of the number of parts on the board.

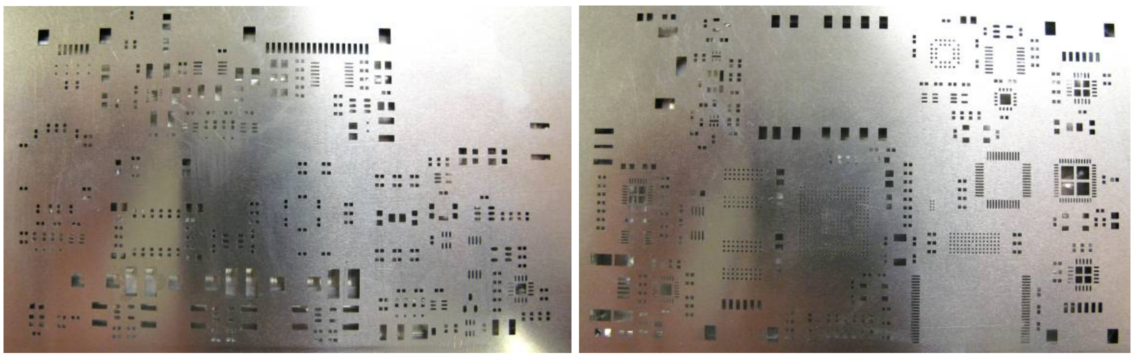

Figure 22: GPS-ATD circuit board bottom and top stencil

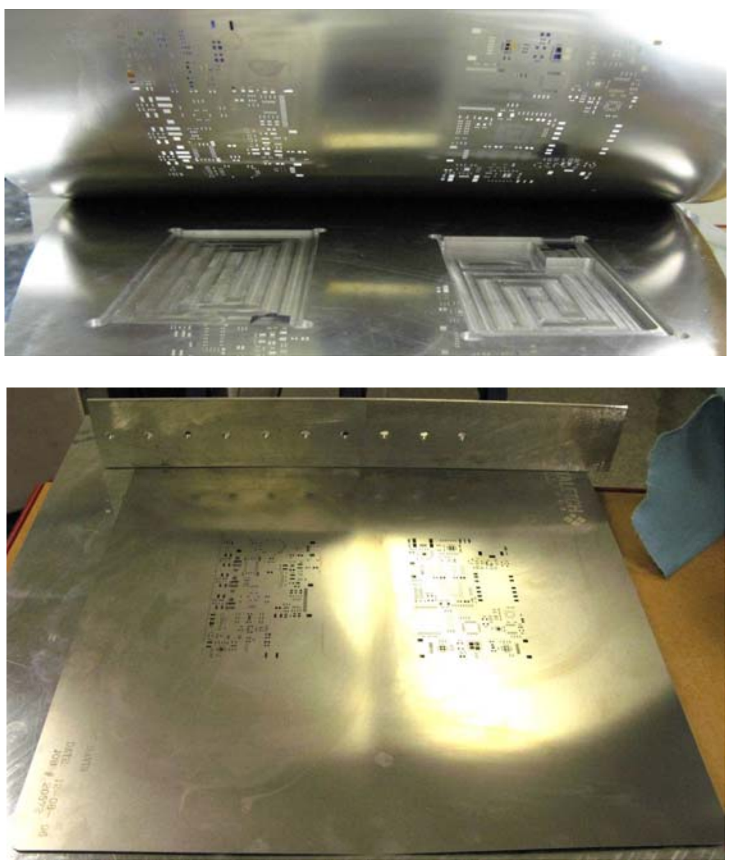

Figure 23: GPS-ATD circuit board fixture for applying RoHS solder paste

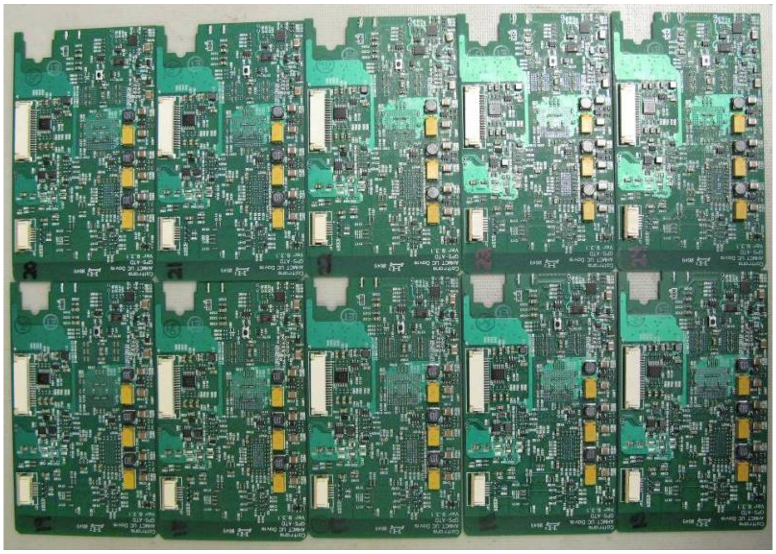

Figure 24: Fully-assembled GPS-ATD bottom-side circuit boards (qty 10 shown)

Figure 25: Fully-assembled GPS-ATD unit internals

CHAPTER 6:
GPS-ATD FIRMWARE

The GPS-ATD firmware consists of the Linux 2.6 kernel, custom GPS-ATD applications, Trolltech Qtopia Core 4, uClibc 0.9.29 libraries, and in-house developed device drivers including: bootloader, NAND Flash storage, keyboard, I^2C (inter-integrated circuit), USB interface, and LCD. Figure 26 shows the GPS-ATD software layers. Since all software components are either Open-Source license or were developed in-house, the complete firmware could be made available under an Open-Source license, avoiding additional software licensing cost in mass production.

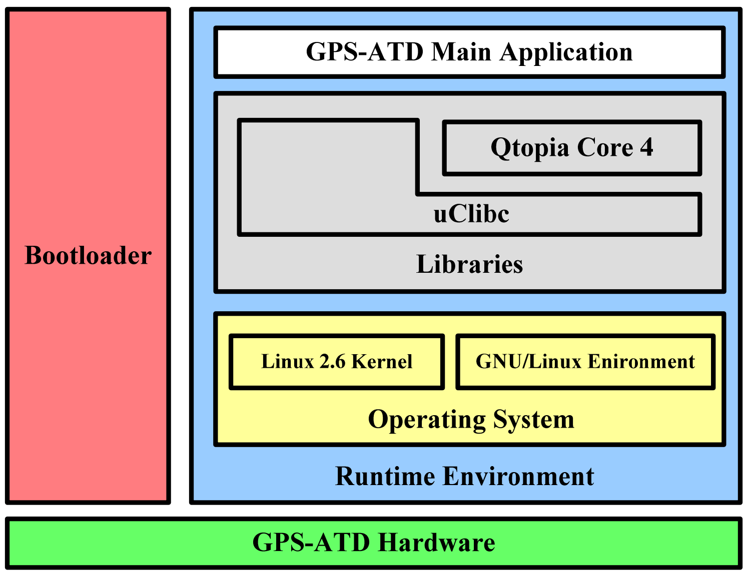

Figure 26: GPS-ATD firmware architecture

The device's firmware image consists of a three-stage bootloader and a runtime environment. The main task of the bootloader is to initialize the CPU, memory system, and other hardware, and to load and boot the kernel from NAND Flash. It also supports various administrative functions via the serial port, such as test and debug routines, and flashing new firmware images. The runtime environment is based on a Linux 2.6 kernel and a minimal GNU/Linux OS. Drivers and patches were developed against Linux 2.6 to support the following functionality: i.MX21 CPU, Microtips LCD, GPS-ATD keypad, Micron NAND Flash (MT29F2G08AABWP and MT29F2G08AACWP), I^2C bus, serial UART, custom digital control lines, YAFFS2 file system, and Universal Serial Bus (USB). The I^2C bus connected to Analog Devices A/D converter (AD7994), battery monitor, temperature sensor (TCN75A), and Maxim IC audio DAC control interface (MAX9850). The serial UARTs are linked to the Globalsat ET-301 SiRF III GPS module, the ZigBee CPU controller, and the debug console. The custom digital control lines allow the power management software to enable and disable power to LCD display, LCD backlight, GPS module, audio devices, MEMS inertial sensors, and ZigBee wireless.

The two most significant libraries on the system are uClibc and Qtopia Core 4. uClibc is a C library that has been optimized for embedded systems and was chosen for its small memory footprint, stability, and large user-base and hence better support community. Trolltech's Qtopia Core is a heavily-used cross-platform application framework that is well-suited to embedded Linux devices. We developed Qtopia Core 4 patches to support our custom GPS-ATD LCD display driver. The data is stored in files on a dedicated YAFFS2 (Yet Another Flash File System, version 2) file system, specifically designed for NAND Flash, on the GPS-ATD 256 MB NAND Flash. The data files are in a custom log format that is interpreted by post-processing tools after they are downloaded from the device.

The primary function of the GPS-ATD survey application is to collect and record data from the onboard sensors along with information obtained interactively from the user. The interactive user interface behavior is governed by state machines, each of which was designed by the Caltrans TSI group to collect the desired information for a particular mode of operation. The behavior of the application and its menus can be switched among various modes, each of which can be described by a text file, and the device could support other data collection activities with appropriate application and interface development.

User Interface

The GPS-ATD user interface is shown in Figure 27. The LCD display is divided into three areas: the GPS-ATD status area located at the top; the travel survey question area located in the middle within a rectangle graphic; and the survey answer menu selection area located on the bottom of the display. The user-selected item is highlighted. User (survey respondent) inputs are provided though four application-specific keys located to the right of the LCD display. The user can move the desired selection item by pressing the "Up" ▲ or "Down" ▼ key. The user can cancel the selection and go back to the previous menu by pressing the "Back/Cancel" × key, and can pick the selected menu item by pressing the "OK/Select" ✓ key. In a typical trip, there are two sets of questions to be answered. The first set should be answered right before the beginning of a trip. The second set of questions is to be answered at the end of the each leg of a trip. At the beginning of each trip, the user should select "Begin a new trip" by pressing ✓. After that, the user will enter the mode of travel and/or the trip activities/purpose. The user should follow the menu and answer each question. The number of questions varies from three to seven, depending on selected answers and options. Detailed GPS-ATD operation is provided in the GPS-ATD user guide, which can be found in the appendix, along with the GPS-ATD menu structure.

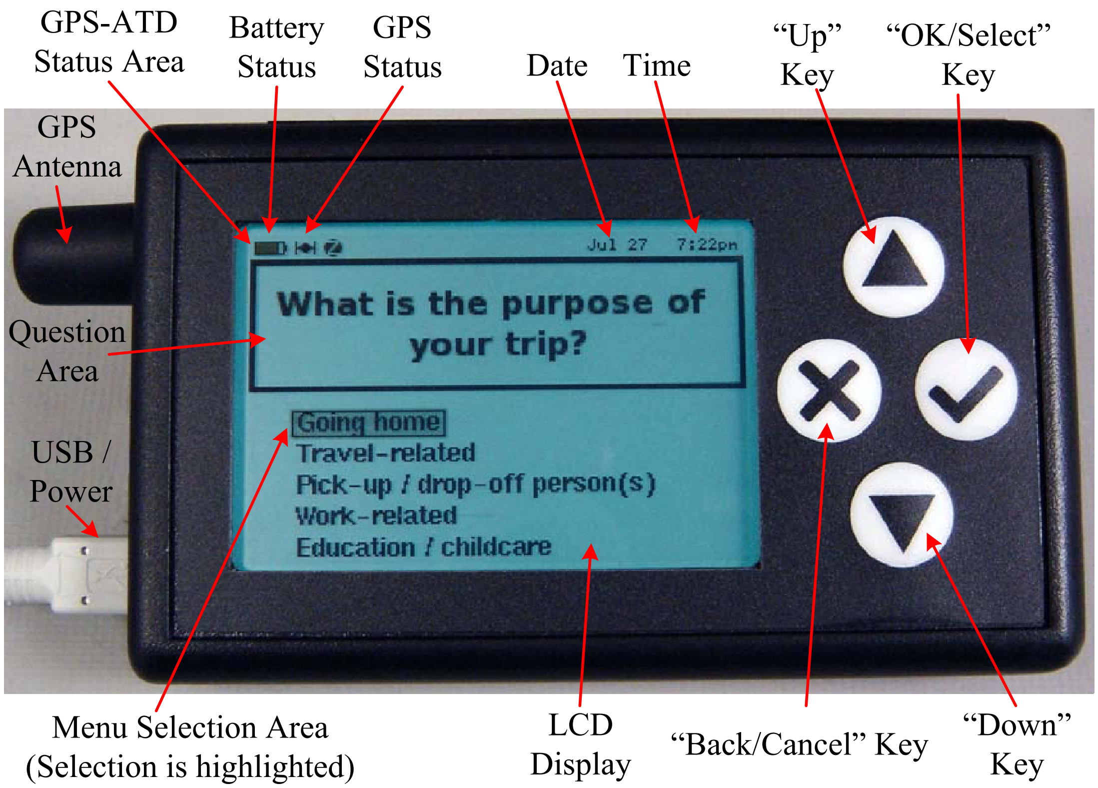

Figure 27: GPS-ATD user interface

CHAPTER 7:
GPS-ATD TESTING AND EVALUATION

The prototype boards performed as designed with respect to timing. All high-speed circuitry worked flawlessly. However the system power noise was higher than predicted based on the manufacturer's power supply design and simulation software. The noise impact on the GPS signal LNA circuitry was higher than anticipated, which degraded GPS receiver performance significantly. Although the GPS-ATD units do vary slightly with respect to noise performance, the major contribution to noise is believed to be a function of design choices, rather than manufacturing and component tolerance variation.

Figure 28: Personal GPS-ATD

Figure 29: Personal GPS-ATD with optional patch antenna

A typical fully-charged battery provides twelve hours of continuous GPS-ATD operation, significantly exceeding the initial design requirement of eight hours. Continuous run-time may be further extended by adding power management software. The user can recharge the battery at any time by plugging the AC adapter into the GPS-ATD mini-USB port on the side of the unit next to the GPS antenna. Charging takes approximately four hours for a completely discharged internal battery. The GPS-ATD battery management circuitry prevents over-charging or discharging of the internal Lithium-ion battery. Figure 30 shows a typical battery voltage charging curve. The battery charging circuit charges a fully discharged Li-ion battery from 3.5 V to a fully charge voltage of 4.15 V. At 4.15 V, the battery charging circuit automatically disconnects the battery from the power source, and hence prevents any over-charging of the Li-ion battery. Figure 31 shows a typical battery voltage discharging curve. The battery discharges from a fully-charged state of 4.15 V to a fully-discharged state of 3.5 V. At 3.5 V, the battery protection circuit automatically disconnects the battery from the load, and hence prevents any over-discharging of the Li-ion battery.

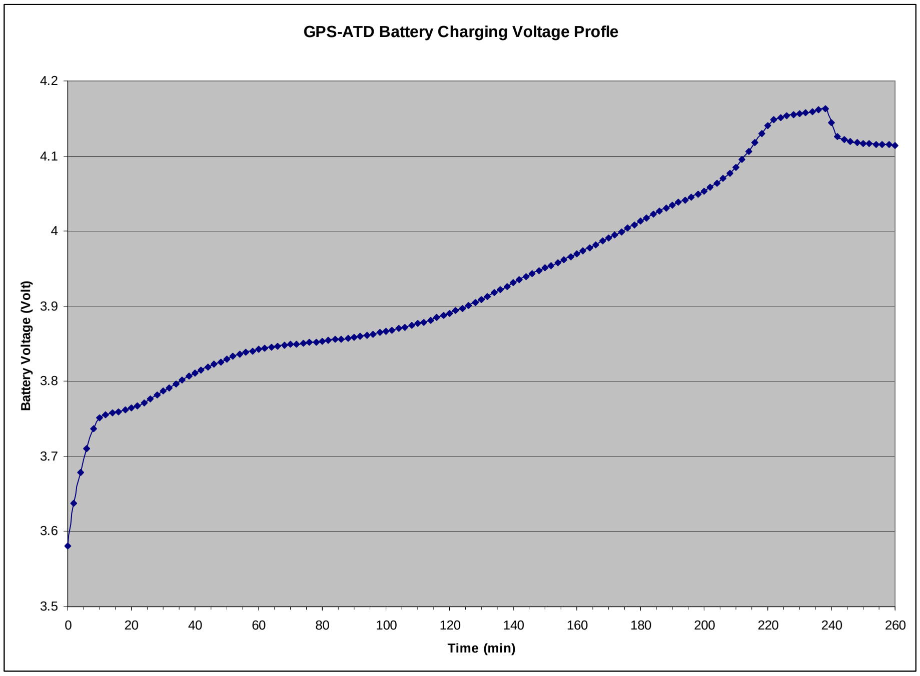

Figure 30: GPS-ATD battery charging curve

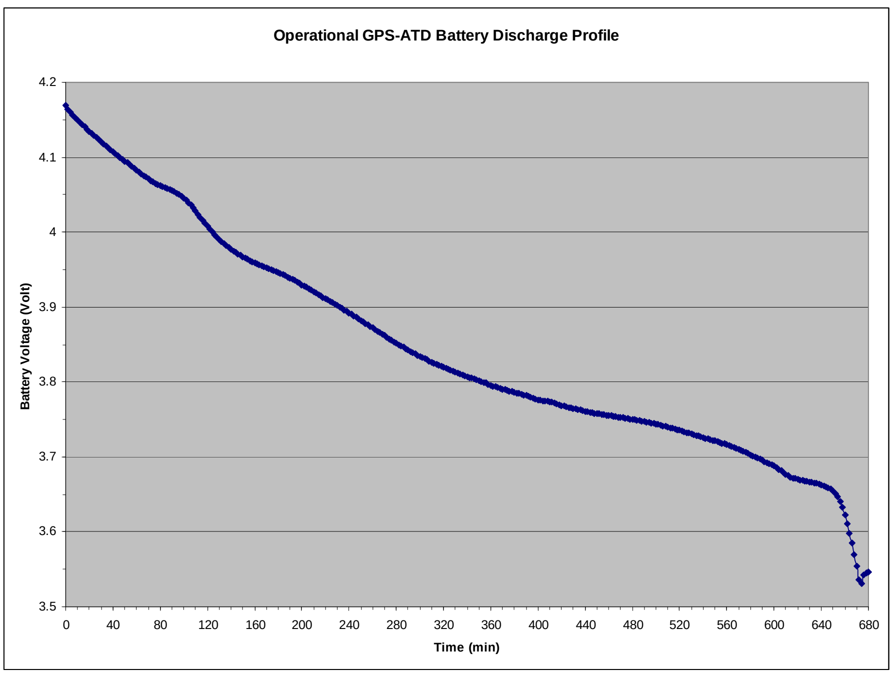

Figure 31: GPS-ATD battery discharging curve

Initial pilot testing by the Caltrans TSI team found that the units are very portable and easy to use. It generally takes the user one to two minutes to answer all trip-related questions. AHMCT is now conducting on-going prototype field-testing with Caltrans, and early field-testing feedback is positive. A COTS PDA-holder may be used hold and mount the personal GPS-ATD in a vehicle, or on a bicycle (shown in Figure 32) or motorcycle. The personal GPS-ATD also fits well in shirt and jacket pockets as well as hand bags. Thus, survey respondents may carry it in all modes of transportation. Moreover, the initial GPS-ATD menu requires fine-tuning to improve ease-of-use. For example, the initial menu structure does not allow for respondents to change their mind regarding their destination and trip activity type in the middle of the trip.

Figure 32: GPS-ATD on a bicycle mount

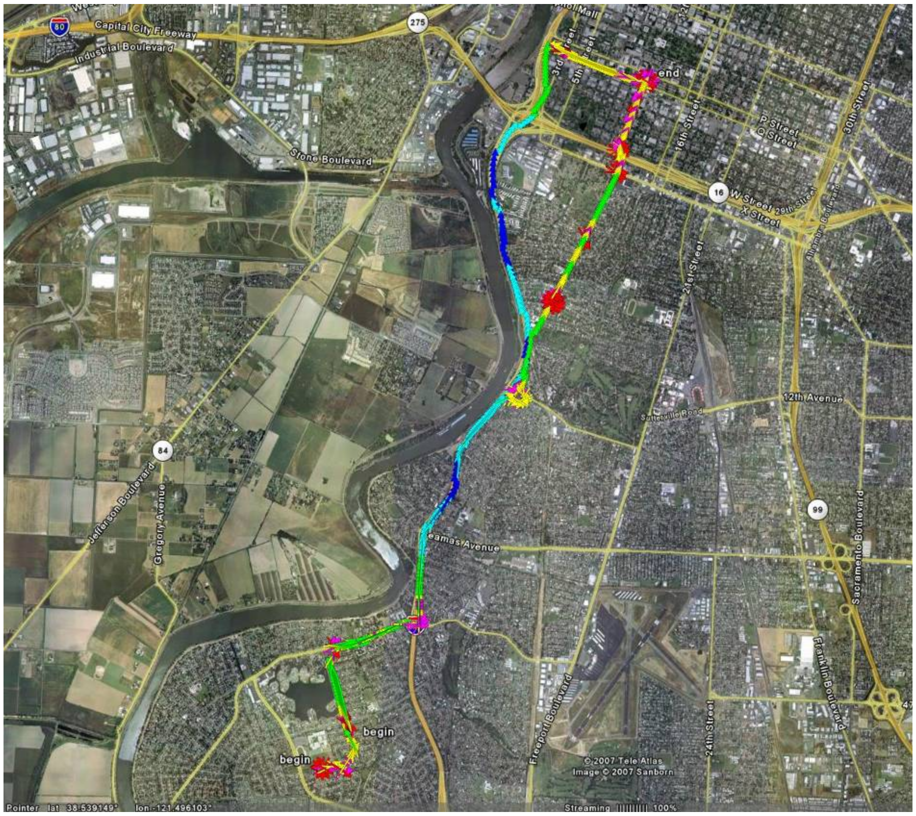

Figure 33: Trip information displayed in Google Earth
(two individual trips with same origin and destination using different route)

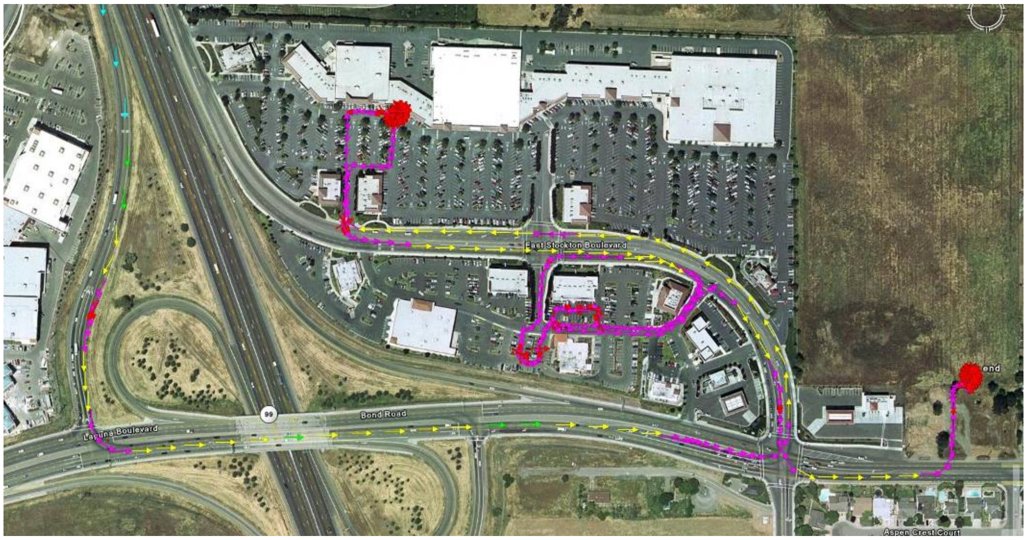

Figure 34: Trip information displayed in Google Earth
(example short trips often not reported)

CHAPTER 8:
CONCLUSIONS AND FUTURE WORK

The goal of this development was to create an information gathering system which, in the end, will provide the highest quality data for purposes of analysis and model creation. This report provides background and technical tradeoff information, functional requirements and specifications, and a design and prototype development that best supports future travel behavior surveys. The GPS-ATD is a highly-integrated and custom-designed system with HSGPS as its core component technology. Two GPS-ATD versions (vehicular and personal) have been developed to capture the complete spectrum of traveler behavior. The versions share most components, differing only with respect to inertial sensors and GPS antenna selection. The GPS-ATD provides an intuitive user interface to capture trip activity information (trip purpose, travel mode, etc.), with minimal user input—a key design goal for the system. Each survey participant interacts with their own personal GPS-ATD, and information is automatically coordinated between personal and vehicular GPS-ATD units via ZigBee wireless. The system captures and logs data from the GPS receiver, allowing subsequent identification of corridors, route lengths, and regional and inter-regional trips. Because of the advanced and highly-integrated design, the GPS-ATD can provide many enhancements beyond previous travel survey methods:

- reduce the user burden by automating data collection and reducing data entry;
- provide activity-time-space relationships;
- minimize under-reported trips;
- capture all modes of transportation and mode connectivity changes;
- provide vehicle position during GPS outages using inertial sensors (vehicular GPS-ATD);
- provide second-by-second detailed vehicle position, speed, acceleration, and emissions information;
- provide wireless synchronization; and allow survey duration up to 30 days.

The prototype was designed to be mass produced and deployable for future full-scale household survey. The resulting improved surveys will provide decision makers with current, accurate, and reliable traveler behavior data.

Recommendation for Future Research

The current GPS-ATD is a first-generation proof-of-concept prototype, and several improvements are required before mass production and final deployment. Future improvements would affect the cost, size, and technical performance of the overall system. The first subsystem to be improved would be the NAND Flash. Currently the 256 MB Flash is implemented as a 3.3 Volt TSOP Flash, necessitating a level translator to 1.8 Volt signaling and "glue" logic. Future revisions should use recently-available NAND Flash with 1.8 V and a new smaller BGA package; consequently, the size requirements in the PCB area would reduce, and the total part count and associated assembly cost would be reduced by eliminating the level translator and glue logic. The new Flash chip would likely be cheaper than the older one due to obsolescence. Furthermore, Freescale has recently released a lower-cost i.MX27 CPU which is exactly like the i.MX21 CPU, except for support for some peripherals that are not used in GPS-ATD. Although they are pin-compatible, some board design and software changes may be required to use the new i.MX27 CPU.

The personal unit's GPS performance is sub-optimal. The GPS signal amplification sub-sections, primarily the LNA, are subject to interference from other on-board components. Future revisions must provide better isolation from noise radiated by other on-board circuitry through proper physical shielding of both the GPS signal LNA and the GPS module. Furthermore, future revision must better mitigate any conducted power noise to both the GPS signal LNA and the GPS receiver module through better power filtering and ground-plane isolation; this can be achieved by connecting the RF ground-plane to the digital ground-plane through narrow traces that act inductively. In addition, any new design should employ newly available lower-power GPS receiver modules using SiRF III LP or MTK chipsets.

Due to time limitations, some software and hardware features, such as ZigBee OBD-II reader, a more efficient data storage format, ZigBee communication software, audio prompting software, and power management software, were not implemented. These features would enhance the GPS-ATD capability considerably.

Of most importance, for the full-scale use of the GPS-ATD in a real-world travel behavior survey, such as the pending 2010 California Statewide Household Travel Survey, the Phase II post-processing and automation will be essential. A Stage II research effort would develop data analysis automation tools suited for a longitudinal travel behavior survey that uses the GPS-ATD units. While it is clear that the GPS-ATD prototypes have achieved the goals of the Stage I study and provide substantial data collection benefits and reduced user burden, a survey using these units will produce large and complex sets of spatiotemporal data. Analysis of this data will require development of appropriate techniques and tools to support and facilitate extraction and reporting of useful survey data. These tools will enable planners to effectively search and query the large set of data to generate general statistics. The final results of this Stage II effort will be the needed analysis tools to support data extraction and reporting of survey results, as well as a much larger set of enhanced prototype GPS-ATD units, all ready for transition to deployment and/or commercialization, and for use in the Caltrans 2010 Longitudinal Travel Behavior Survey.

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APPENDIX A: GPS-ATD MENU TABLES

(as provided by Caltrans Division of Transportation System Information)

HOUSEHOLD INFORMATION

Table 1

(Pre Entered Data)

Code	Specific Information
	Household Region
1	TBD
2	TBD
3	Etc.
	Household Address
	~~Street address, or nearest intersection if street address not available (do not enter a P.O. Box address)~~
	City
	County **(Pre entered menu option, i.e. 1=Alameda, 2=Alpine etc.)**
	State
	Zip code
	Type of Dwelling Unit
1	Unattached single family home
2	Duplex
3	Apartment
4	Condominium or townhouse
5	Mobile home or trailer
6	Group quarters (dorms, barracks, etc.)
7	Other
99	Don't Know / Refused
	Owner/Renter Status
1	Own
2	Rent
7	Other
99	Don't Know / Refused
	Number of Persons in Household
1-98	Ordinal Variable
99	Don't Know / Refused
	Number of Vehicles in Household
1-98	Ordinal Variable
99	Don't Know / Refused

Strikethrough are confidential fields

HOUSEHOLD INFORMATION

Table 1 (continued)

(Pre Entered Data)

Repeat for each household's vehicles	**Code**	**Vehicle ID Number**	
	Veh 1	Vehicle ID Number (1, 2,…n)	
		Code	**Vehicle Model Year**
		Text	Vehicle Make and Model (Honda, Accord, etc.)
		4 Digit #	Model Year
		98	Don't Know
			Vehicle X -Body Type
		1	Automobile
		2	Van
		3	RV
		4	Sport utility vehicle (SUV)
		5	Pick-up truck
		6	Other truck
		7	Motorcycle/Moped
		97	Other, specify
		98	Don't Know
			Vehicle X-Fuel type
		1	Gasoline
		2	Diesel
		3	Electricity
		4	Hybrid
		97	Other
		98	Don't Know
			Owned or Leased
		1	Owned by a household member
		2	Owned by a person not in your household
		3	Leased by a member of your household
		4	Rented by a member of your household
		98	Don't Know

Strikethrough are confidential fields

HOUSEHOLD INFORMATION

Table 1 (continued)

(Pre Entered Data)

Code	Specific Information
5	To be close to a family member or friend receiving medical care in a medical facility.
6	Looking for permanent housing.
7	Other
	Annual Household Income (Wages, salary, commissions, bonuses or tips from all jobs. Report amount before deductions for taxes, bonds, dues or other items.)
1	<$10,000
2	$15,000-$24,999
3	$25,000-$34,999
4	$35,000-$49,999
5	$50,000-$74,999
6	$75,000-$99,999
7	$100,000-$149,999
8	$150,000-$199,999
9	$200,000+
99	Don't Know / Refused
	Language(s) Spoken in the Home (up to 3 languages)
1	English
2	Spanish
3	Tagalog
4	Chinese
5	Japanese
6	Vietnamese
9	Other

PERSON INFORMATION
Table 2
(Pre Entered Data)

Code	Specific Information
	Person X - Name
	First Name
	Middle Initial
	~~Last Name~~
	Person X - Sex
1	Male
2	Female
99	Refused
	Person X - Age (Ordinal Variable)
1-97	Actual Age (If less than one year of age, enter 1)
98	Age 98+
99	Don't Know / Refused
	Annual Person Income (Wages, salary, commissions, bonuses or tips from all jobs. Report amount before deductions for taxes, bonds, dues or other items.)
~~1~~	~~<$10,000~~
~~2~~	~~$15,000-$24,999~~
~~3~~	~~$25,000-$34,999~~
4	~~$35,000-$49,999~~
~~5~~	~~$50,000-$74,999~~
~~6~~	~~$75,000-$99,999~~
~~7~~	~~$100,000-$149,999~~
~~8~~	~~$150,000-$199,999~~
~~9~~	~~$200,000+~~
~~99~~	~~Don't Know / Refused~~
	Person X – Relation to the Head of Household
1	Self
2	Spouse/Partner
3	Son/Daughter (includes Stepchildren)
4	Mother/Father/Mother-in-Law/Father-in-Law
5	Other relative
6	Not related
99	Don't Know / Refused
	Residence During the Year (How many months a year do members of this household stay at this address?)
0	Less than one month
1-12	One or more months (Ordinal Variable)
	Reason for Residence (What is the main reason members of this household stay at the address given for the household?)
1	This is their permanent address.
2	This is their seasonal or vacation address.
3	To be close to work.
4	To attend school or college.

Strikethrough are confidential fields

PERSON INFORMATION
Table 2 (continued)
(Pre Entered Data)

Code	Specific Information
	Person X-Race (Indicate all that this person considers himself/herself to be.)
1	White alone, but not Hispanic
2	Hispanic
3	Black or African American alone
4	Asian alone (Asian Indian, Chinese, Filipino, Japanese, Korean, Vietnamese, Other Asian)
5	Native Hawaiian or other Pacific Islander alone
6	American Indian or Alaska Native alone
7	Other race alone (specify during interview)
98	Combination of two or more of the above categories
99	Don't Know / Refused
	Person X – Education (Highest level of education completed.)
1	No schooling completed
2	Nursery school/Preschool
3	Kindergarten
4	Actual Grade 1 to Grade 12
7	High school graduate
8	Some college, no degree
10	Undergraduate/Bachelors degree
11	Some graduate school/no degree
12	Master's degree
13	Professional degree
14	Doctorate or higher degree
99	Don't Know / Refused
	Person X – Education (What grade or level is this person attending?)
1	Nursery school/Preschool
2	Kindergarten
3	Actual Grade 1 to Grade 12
6	College undergraduate years (freshman to senior)
7	Graduate or professional school (e.g., medical, dental or law school)
8	Trade/Vocational
9	Post graduate
10	Military (Advanced training)
11	Other, specify
99	Don't Know / Refused
	Person X – Work Address
1	~~Street Address, or nearest intersection if street address not available (Do not accept a P.O. Box number)~~
2	City
3	County
4	State
5	Zip code

Strikethrough are confidential fields

Strikethrough are confidential fields

PERSON INFORMATION

Table 2 (continued)

(Pre Entered Data)

Code	**Person X – Industry of Employment (Industry of primary job.)**
1	Agriculture, Forestry, Fishing and Hunting, and Mining
2	Construction
3	Manufacturing
4	Military
5	Wholesale Trade
6	Retail Trade
7	Transportation and Warehousing, and Utilities
8	Information
9	Finance, Insurance, Real Estate, and Rental and Leasing
10	Professional, Scientific, Management, Administrative, and Waste Management Services
11	Educational, Health, and Social Services
12	Arts, Entertainment, Recreation, Accommodation, and Food Services
13	Other Services (except Public Administration)
14	Public Administration / Government
	Person X – Occupation (Occupation of primary job) (Employed civilian population 16 years and over.)
1	Management, Professional, and Related Occupations
2	Service Occupations
3	Sales and Office Occupations
4	Farming, Fishing, and Forestry Occupations
5	Construction, Extraction, and Maintenance Occupations
6	Production, Transportation, and Material moving occupations
	Person X – Class of Worker (Class of worker of primary job.)
1	Private wage and salary workers
2	Government worker
3	Self-employed workers in own not incorporated business
4	Unpaid family workers

Strikethrough are confidential fields

VEHICLE

Table 3 (User Input)

Code	Vehicle ID Number
Ordinal Variable	Vehicle ID Number (from Table 1)
98	Don't Know

Strikethrough are confidential fields

MODE OF TRANSPORTATION

Table 4

(User Input)

Code	Mode
	Auto/Truck/Van
1	Driver
2	Passenger in car/truck/van
	Transit
3	Local bus
4	Express bus / Commuter Bus
5	Light rail/Street car/Trolley
6	Cable car
7	Coaster
8	Ferry
9	Metro Blue Line
10	Metro Green Line
11	Metro Red Line
12	BART
13	Metro Link
14	Heavy Rail (CALTRAIN, Amtrak)
15	Dial-A-Ride/Para transit
16	School Bus/Chartered bus for school activities
	Other Modes
17	Walk
18	Bicycle
19	Motorcycle/moped
20	Taxi/shuttle bus/limousine
21	Greyhound / Trailways (Intercity bus)
22	Airplane-commercial
23	Airplane-private
97	Other
99	Don't Know / Refused

Will you use more than one mode of transportation for this trip?

No   Yes

Strikethrough are confidential fields

TRIP ACTIVITY

Table 5A (Active Mode)

(User Input)

Strikethrough are confidential fields

Code	Trip Activity
	Home
1	Working at home (related to primary or second job)
2	Shopping at home (ordering by telephone or internet from TV/Internet promotions)
3	Other at home
	Travel
3	Get on vehicle/ Wait for a ride
4	Leave/Park a vehicle
5	Boarding airplane, rail, intercity bus
6	Deboarding airplane, rail, intercity bus
	Pick-up/Drop-off
7	Pick up someone or get picked up (# of person)
8	Drop off someone or get dropped off (# of person)
	Work
9	Work (include regular scheduled and volunteer work)
10	Work related (sales calls, business meeting, errand, travel, etc.)
	Education/Childcare
11	School (preschool, K-12th grade)
12	School (post secondary – college, vocational)
13	Childcare, day care, before/after school care
	Dining
14	Eat out (restaurant, etc.)
15	Drive-through
	Medical
16	Medical appointment /surgery/treatment/pick up prescription
	Recreation/Entertainment
17	Fitness activities (gym, health club, playing sports)
18	Recreational (vacation, sightseeing tour, camping, picnic etc.)
19	Entertainment (movies, dance club, spectator sports, bar, etc.)
	Social/Civic/Religious
20	Visit friends/relatives
21	Community meetings, political/civic event, public hearing, voting, etc.
22	Occasional volunteer work
23	Church, temple, religious meeting
	Personal
24	Buy fuel for vehicle (gasoline/diesel station)
25	Incidental shopping (groceries, house wares, over counter drugs. etc.)
26	Incidental eating/drinking (i.e. coffee)
27	Major shopping (house, furniture, clothes, purchase a vehicle, etc.)
28	ATM, banking, post office, utilities.
29	Other
	Ground Access to Airport
30	Home-Airport, Airport-Home
31	Hotel-Airport, Airport-Hotel
32	Business-Airport, Airport- Business
	Other Out of Home
33	With another person at their activity

Strikethrough are confidential fields

TRIP PURPOSE

Table 5B (Hybrid Mode)
(User Input)

	Pick-up/Drop-off
1	Pick up someone or get picked up (# of person)
2	Drop off someone or get dropped off (# of person)

TRIP PURPOSE

What is the purpose of this Trip?

From		To
1	Home	1
2	Work place	2
3	Work related	3
4	Social or entertainment	4
5	Recreation (national parks, theme park, etc.)	5
6	Shop	6
7	School	7
8	Other (use other for anything not shown above)	8

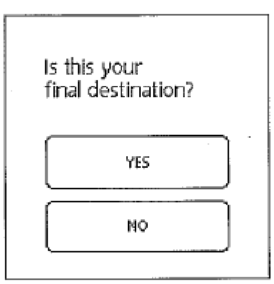
TRIP

Table 6

(User Input)

Strikethrough are confidential fields

Code	Trip
	Vehicle Occupancy
Number	How many total people were in the vehicle at the start of your trip (including yourself)?
99	Don't Know / Refused
	Personal Vehicle Parking Cost
$#, ##0.00	Parking Cost Unit (in dollar amount)
	How Do You Pay for Parking?
1	Hourly
2	Daily
3	Weekly
4	Monthly
5	Quarterly
6	Annually
7	None
8	Subsidized
9	Other
	Personal Vehicle Daily Cost of Tolls (bridge tolls/toll roads)
$#, ##0.00	Toll Cost (in dollar amount)
	Toll Pay Method
1	Cash
2	Fastrak
3	None
4	Subsidized
9	Other
	Transit Cost
Ordinal Variable	Transit Fare
1	Single Fare
2	Daily
3	Weekly
4	Monthly
5	Quarterly
6	Annually
7	None
8	Subsidized
9	Other
	Transit Information
Text	Station of access (How long does it take you in minutes to walk to this station?)
Text	Station of egress (How long does it take you in minutes to walk to your final destination?)
	Wait time at the station
Ordinal Variable	Number of transfers



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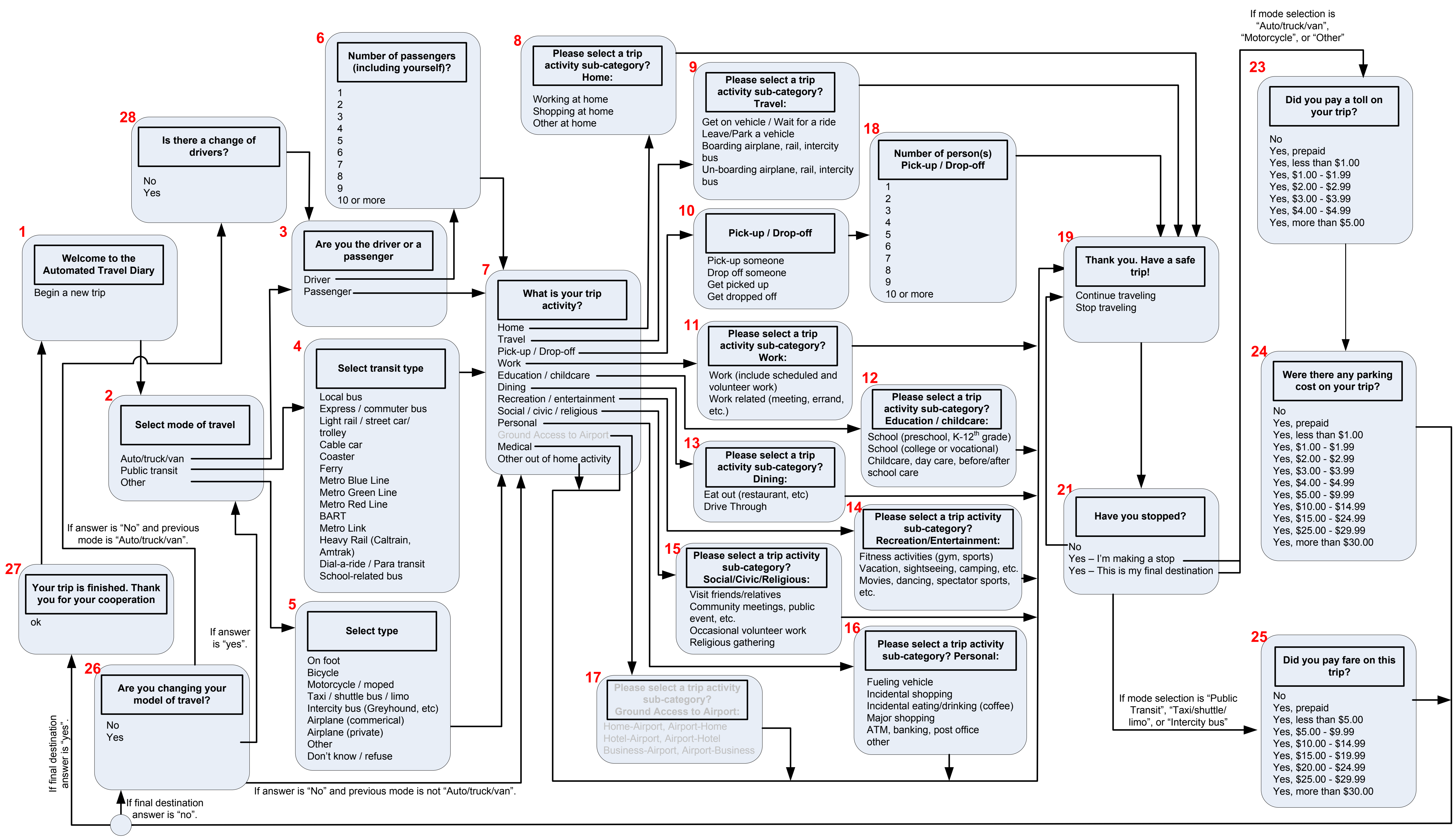
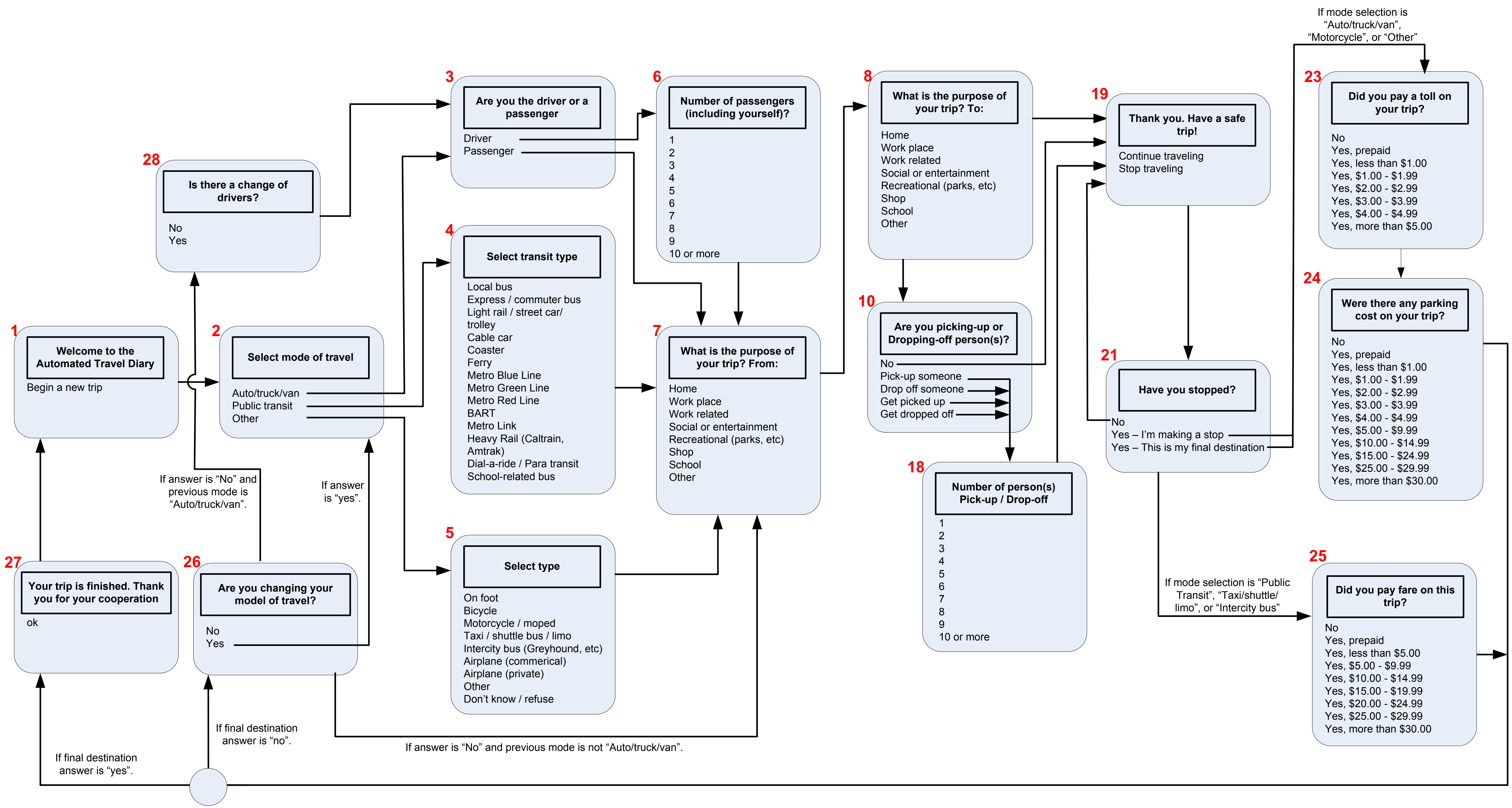
APPENDIX B: GPS-ATD MENU FLOWCHART

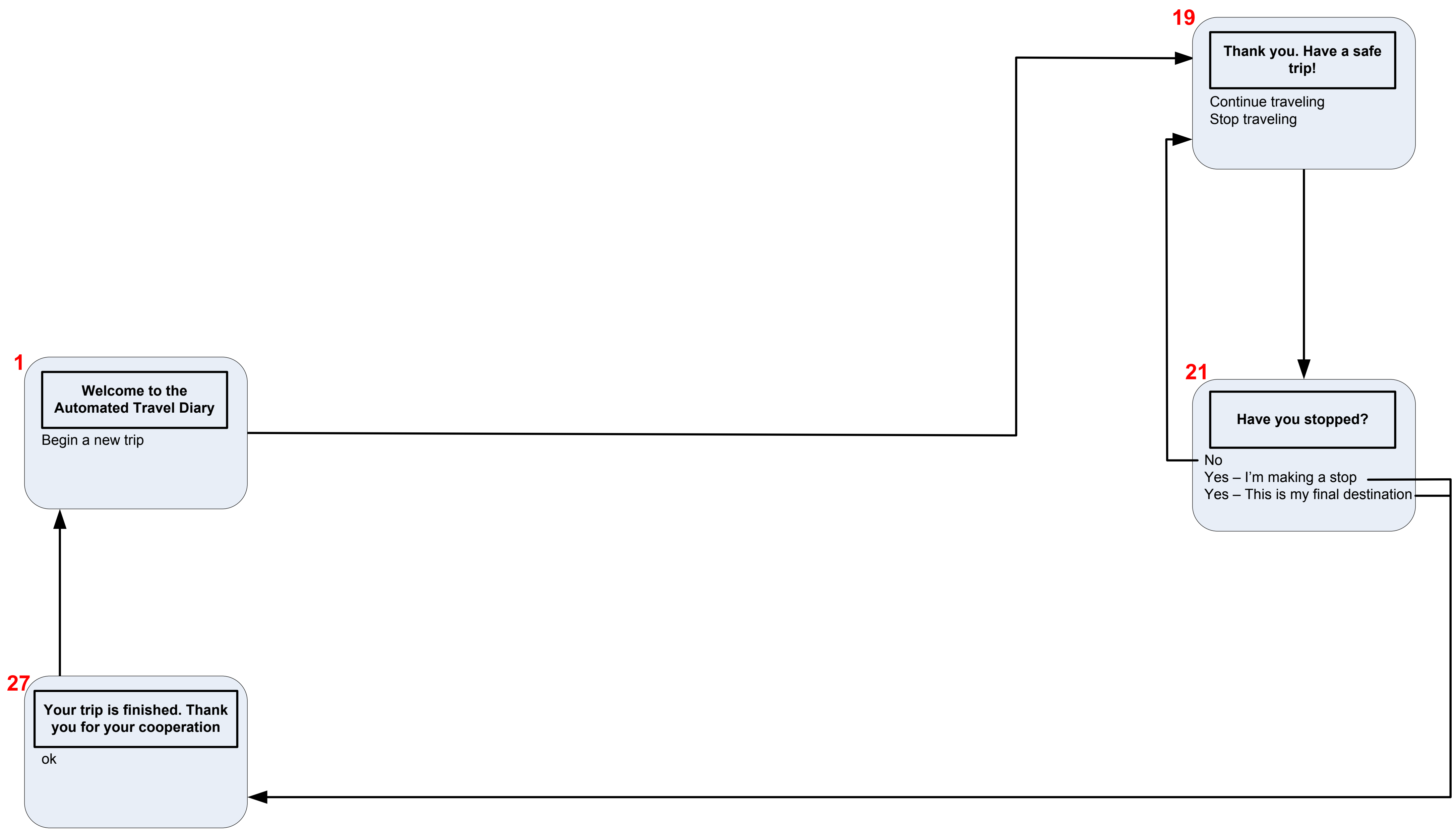
GPS-ATD Active Mode Menu Flowchart



GPS-ATD Hybrid Mode Menu Flowchart



GPS-ATD Passive Mode Menu Flowchart



APPENDIX C: GPS-ATD USER GUIDE

California AHMCT Program
University of California at Davis
California Department of Transportation

GPS Automated Travel Diary
User Guide for Caltrans*
(Firmware Version 0.1.0)

Kin S. Yen, Stephen M. Donecker,
Kimball Yan, Travis Swanston, Bahram Ravani, &

Ty A. Lasky, Principal Investigator

AHMCT Research Report
UCD-ARR-06-12-31-01 Appendix C

December 29, 2006

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USAGE WARNING

Do not interact with the GPS-ATD while driving a vehicle! Please enter the answer the survey before driving or after you have stopped your vehicle.

SAFETY PRECAUTIONS

This manual contains safety instructions that must be observed in order to avoid potential hazards that could result in personal injuries, damage to the GPS-ATD, or loss of data.

Warning

- If you notice any abnormal conditions, such as odor, smoke, or overheating, disconnect the AC or Auto charger adapter. Continued use of the GPS-ATD may result in fire, electronic shock or burn, and serious injury.
- If water or other liquid gets inside the GPS-ATD, immediately disconnect the AC or Auto charger adapter. Please return the GPS-ATD for service as soon as possible. Continued use of the GPS-ATD may result in fire, electronic shock or burn, and serious injury.
- If you drop or damage the GPS-ATD, please return the GPS-ATD for service as soon as possible. Continued use of the GPS-ATD may result in fire, electronic shock or burn, and serious injury.
- Do not disassemble, modify, or repair the GPS-ATD unit. Any modification may result in fire, electronic shock or burn, and serious injury.
- Do not allow any foreign objects, such as water, metal, or liquids, to enter or drop into the GPS-ATD connector ports or other openings or gaps. Such objects may result in fire electronic shock or burn, possibly in serious injury.
- Do not use the GPS-ATD on an airplane or near medical equipment, or in any other location where use of personal electronics is expressly limited.
- Do not use the GPS-ATD in a place that is exposed to water.
- Do not use the GPS-ATD in a bathtub or shower.
- Do not interact with the GPS-ATD while walking, driving a vehicle, riding a motorcycle, or riding a bicycle. You may fall or cause a traffic accident, possibly resulting in serious injury.
- If you notice leaking fluid or odor from the GPS-ATD, immediately move the GPS-ATD away from any source of fire. The fluid from the GPS-ATD is leaking from the built-in battery. In the event of battery leakage, the fluid may ignite and cause an explosion, possibly resulting in serious injury.

- If you discover leakage from the GPS-ATD, do not touch the fluid. The leakage from the GPS-ATD is fluid from the built-in battery. Battery fluid contacting the eye or the skin can result in serious eye injury or skin damage. If battery fluid enters your eye, rinse your eye thoroughly with clean water, and seek immediate medical attention. If battery fluid should contact your skin or clothes, immediately rinse it away with clean water, and seek immediate medical attention.

- Do not charge or discharge the GPS-ATD near fire or under the hot sun. The built-in battery may leak, causing fire or explosion, possibly resulting in serious injury.

- Do not place the GPS-ATD in a hot location. Placing the GPS-ATD under direct sunlight, near a stove, etc., can result in heat generation or fire, possibly resulting in serious injury.

- Do not subject the GPS-ATD to impact. Impact may result in a damaged display, broken glass, or leaking fluid, possibly resulting in serious injury.

- Store and operate the GPS-ATD out of reach of small children.

- Do not cover the GPS-ATD with a cloth, paper, or cushion.

- Do not use the supplied AC adapter with any device other than GPS-ATD.

- Use only the supplied AC adapter or Auto charger to charge the GPS-ATD.

- Insert the AC adapter power plug firmly into the power outlet.

- When removing the power plug from the power outlet, do not pull directly on the cable. Always hold the plug to remove it.

- Do not connect or disconnect the power plug with a wet hand.

- Connect the power plug of the AC adapter only to a 120 Volt AC source. Connecting the power plug of the AC adapter to a power outlet power source other than 120 VAC may result in fire or electric shock, possibly resulting in serious injury.

- Do not attempt to disassemble, modify, or repair AC adapter. Any modification may result in fire, electronic shock or burn, and serious injury.

- Do not cover the AC adapter with cloth, paper, or cushion, or place it near a heater or on carpet when the adapter is conducting current.

- Do not subject the AC adapter power cable to any of the following:

    - Scratching, extending, or otherwise modifying

- Heating
- Pulling, placing below a heavy object, or pinching
- Bending with force, twisting, or bundling.

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DISCLAIMER/DISCLOSURE

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology
Caltrans	California State Department of Transportation
CATI	Computer-Assisted Telephone Interview
CPU	Central Processing Unit
DGPS	Differential Global Positioning System
DOT	Department of Transportation
ETD	Electronic Travel Diary
GPS	Global Positioning System
GPS-ATD	GPS-Automated Travel Diary
LCD	Liquid Crystal Display
NDGPS	Nationwide Differential GPS
NMEA	National Marine Electronics Association
OBD	On-Board Diagnostics
OS	Operating System
SDRAM	Synchronous Dynamic Random Access Memory
TSI	Transportation System Information
UCD	University of California-Davis
UTC	Coordinated Universal Time
VMT	Vehicle Miles Traveled
WAAS	Wide Area Augmentation System
WGS	World Geodetic System

SECTION 1:
WELCOME & INTRODUCTION

Included accessories:

- AC adapter

- Auto charger adapter

- USB cable with mini-B USB connector (only included for Authorized Administrators)

- GPS-ATD

- GPS-ATD user manual (this document)

About the GPS-ATD

The GPS-ATD is specially-designed to conduct a travel survey and reduce users' burden. It prompts the user (travel survey respondent) with questions and allows the user to select the appropriate answer from a list. It has a built-in GPS to automatically log the user's travel path. All data are stored internally in flash memory. The data are vigorously protected again any unauthorized downloading.

SECTION 2:
PART DIAGRAM

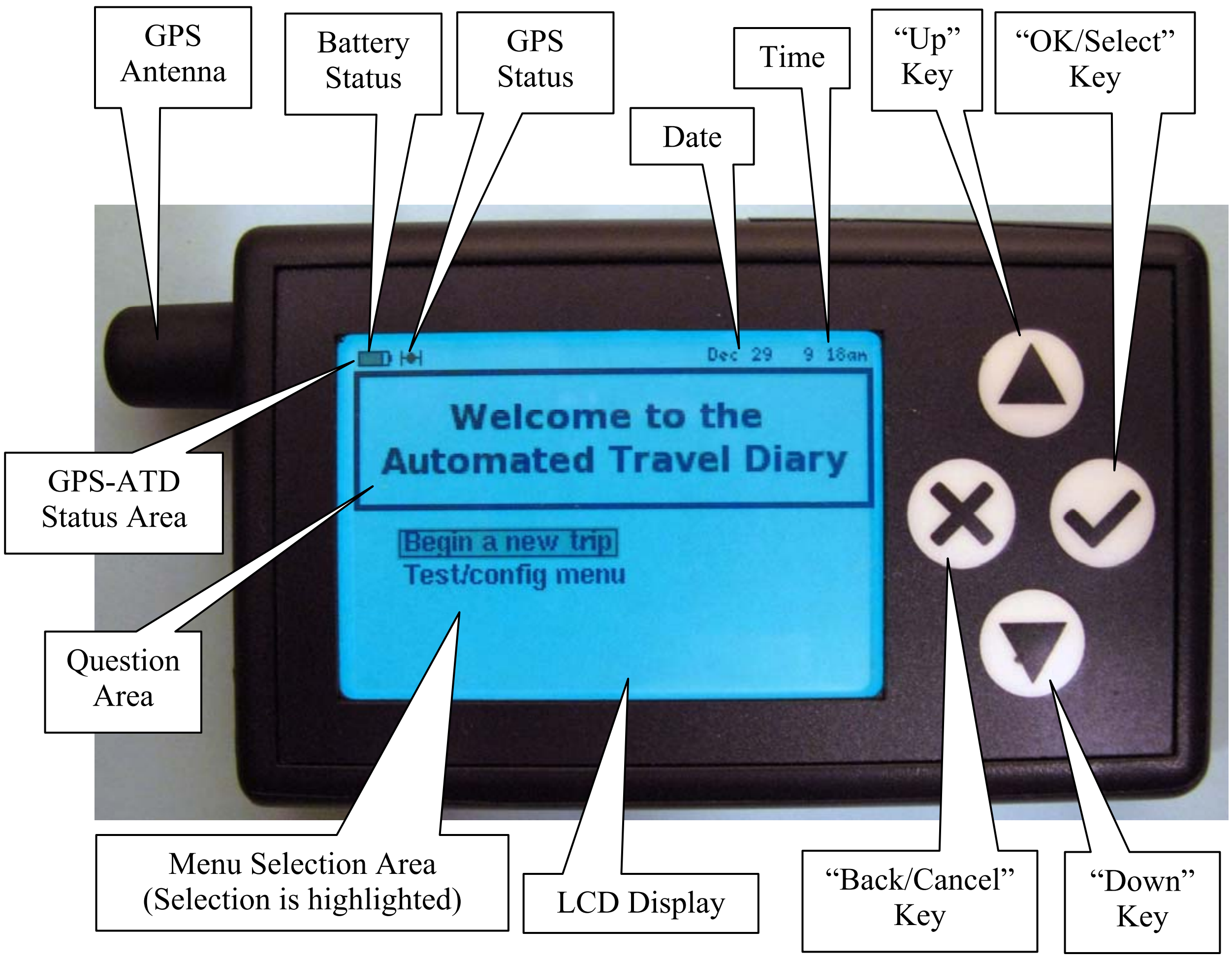


Figure 1: GPS-ATD Usage Diagram

Figure 2: GPS-ATD Side View

The GPS-ATD has an LCD display which is divided into three areas:

- GPS-ATD status area located at the very top,
- "Question" area located in the middle within a rectangle, and
- "Menu Selection" area located on the bottom of the display. Please note that the selected item is highlighted.

The GPS-ATD has four keys located next to the LCD display:

- The user moves the desired selection item by pressing the "Up" or "Down" key,
- the User may cancel the selection and go back to the previous menu by pressing the "Back/Cancel" key, and
- the user picks the selected menu item by pressing the "OK/Select" key.

Do not forcibly press in the buttons on the front surface. The user should hear and feel a "click" when the button is activated.

Do not place the GPS-ATD in a trouser pocket. When you sit down, the GPS-ATD could receive a strong impact and be damaged.

A typical fully-charged battery will allow for eight hours of continuous GPS-ATD operation. The user can recharge the battery at any time by plugging the AC adapter to the GPS-ATD power charging port located on the side of the unit next to the GPS antenna, shown in Figure 2 and 3. The user should then plug the AC adapter to the AC wall outlet. The unit may also be charged with an Auto charger adapter using any 12 VDC vehicle power outlet. It takes approximately four hours to fully charge a completely discharged internal battery. The GPS-ATD has battery management circuitry to prevent over-charging or discharging of the internal Lithium-Ion Battery. The user can charge the battery at anytime. The GPS-ATD has no "off" switch. It turns itself off when the battery is low.

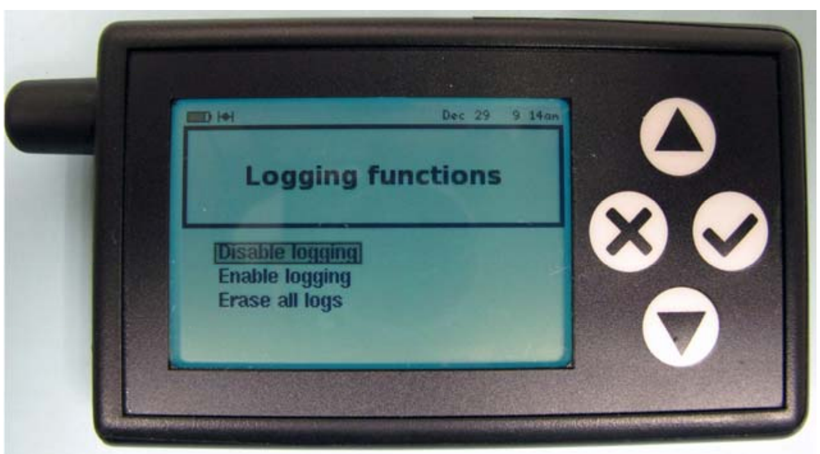
Figure 3: Charging the GPS-ATD

SECTION 3:
SETUP

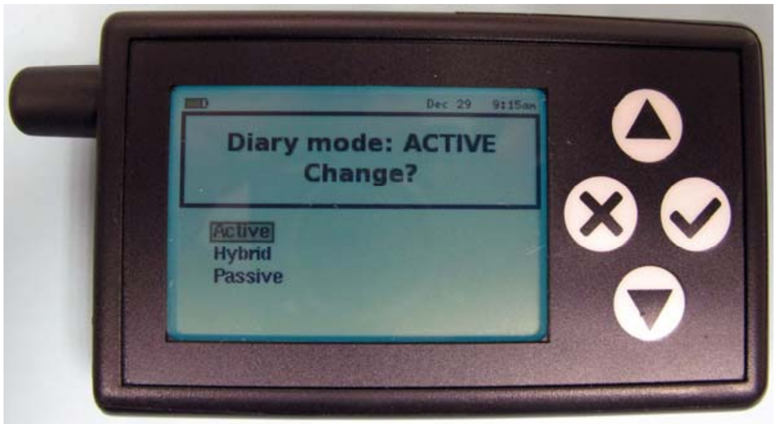
Setup should only be performed by trained authorized personnel. Data can be lost permanently if setup is performed incorrectly. The very first screen menu will show "Begin a new trip" or "Test / config menu" as shown below. The "Test / config" menu will not appear in the final version of the firmware of the GPS-ATD as sent to the end users. The "Test / config menu" is made available to allow easy change between "Active", "Hybrid", and "Passive" modes (refer to the main project report for discussion of modes) by Caltrans TSI personnel during the evaluation process.

After selecting the "Test / config menu", the administrator will see the menu shown in the following figure. The administrator can test the GPS, delete data logs, change diary mode (active, hybrid, and passive), or display the firmware version as shown in the figure below.

Under the "GPS test" sub-menu, the GPS-ATD will display the current user position, time, and number of satellites used as shown above.



Under the "Logging" sub-menu, the administrator can enable or disable GPS logging and erase all previous logs (used when the internal flash storage is full) as shown above.



Under the "Change diary mode" sub-menu, the administrator can switch the GPS-ATD into "Active", "Hybrid", or "Passive" mode as shown above.

Under the "Firmware version" sub-menu, the unit displays the current firmware version. Each GPS-ATD also has a serial number located on the bottom of the device.

Other menu selections may be available to support diagnostics by AHMCT personnel. These should not be used except by AHMCT.

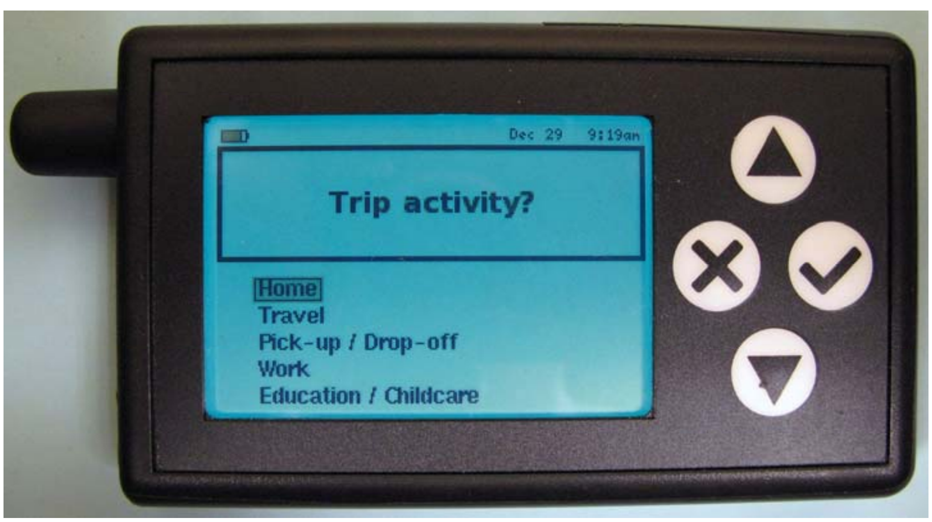
SECTION 4:
BASIC OPERATION FOR USERS

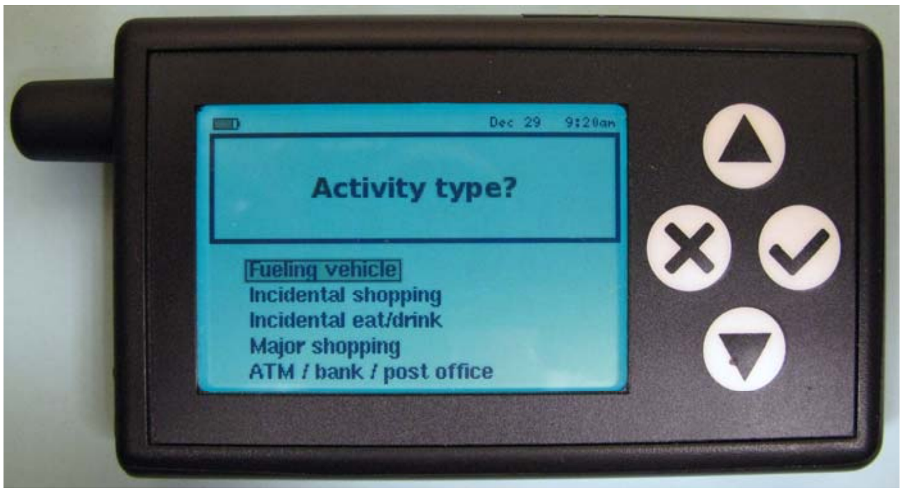
In a typical trip, there are two sets of questions to be answered. The first set of questions should be answered right at or before the beginning of a trip. The second set of questions is to be answered at the end of the each leg of a trip. At the beginning of each trip, the user (survey respondent) should select "Begin a new trip" by pressing the "OK/Select" button. After that, the user will enter the mode of travel and/or the trip activities/purpose. User should follow the menu and answer each question displayed. The number of questions varies from 3 to 7 depending on the selected answers and options.

Below figures shows a typical trip menu flow:


Dec 29 9:19am
Are you the driver or a passenger?
Driver
Passenger


Dec 29 9:21am
Number of passengers (including yourself)?
1
2
3
4
5

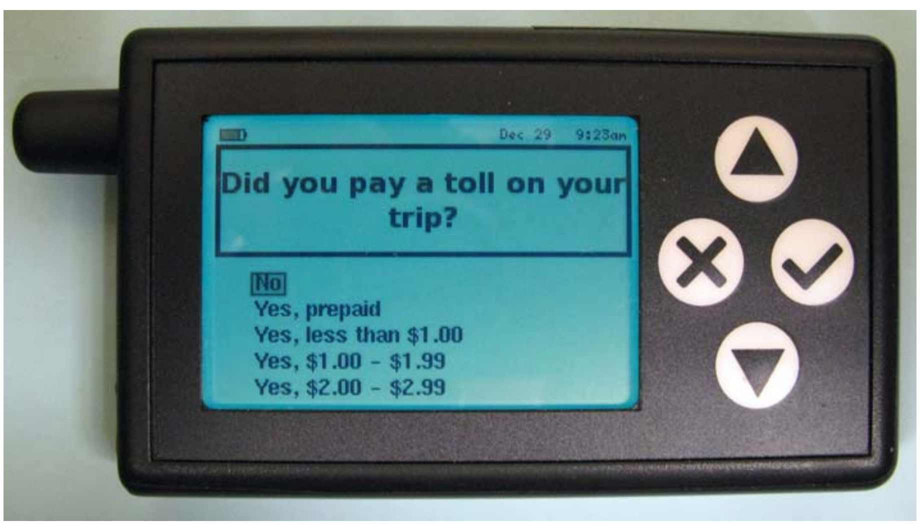

Dec 29 9:19am
Trip activity?
Home
Travel
Pick-up / Drop-off
Work
Education / Childcare

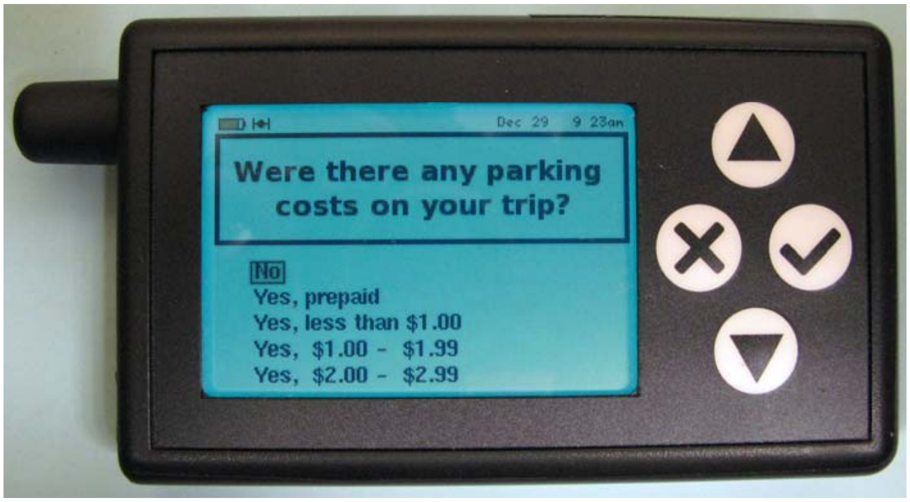


The following display marks the end of the first set of questions to be answered at the beginning of the trip. The user should not answer this question until the end of this leg of the trip. This "menu" structure is designed to trap any accidental button pressing when the user is traveling. When the user finishes the current leg of the trip, they should press the "down" button and then the "OK/Select" button to select the "Stop traveling" menu.

After that, the user has to confirm whether they have arrived at the end of this leg of the trip by selecting either "Yes – I am making a stop" or "Yes – This is my final destination". If the user selects "Yes – I am making a stop", the menu loops back and asks the user information about the next leg of the trip. If the user selects "No", the menu will loop back to the previous menu. This is designed to trap accidental key presses. If the user selects "Yes – This is my final destination" then the user is asked the "post-trip" questions as discussed below.

Next, the user will be asked to answer a set of "post-trip" questions related to cost of travel, such as fare cost, parking cost, or toll cost.





If the user has selected “Yes – This is my final destination” in previous menu, the following question / figure will be shown to the user. Once the user selects “OK” by pressing the “OK/Select” button, the user has completed the travel survey for this trip.

The complete menu flowcharts of all three modes are located in the appendix.

SECTION 5:
DOWNLOADING DATA

Travel Survey Respondents

GPS-ATD logged data are vigorously protected and may not be downloaded by end users or any unauthorized person.

Authorize GPS-ATD Administrator

GPS-ATD logged data are vigorously protected and may only be downloaded by an authorized administrator using special software and password through the USB port. See data download software instructions for further detail.

SECTION 6:
FREQUENTLY ASKED QUESTIONS

(TBD)

SECTION 7:
SPECIFICATIONS

Table 1 shows the hardware specification. The Central Processing Unit (CPU) is a 32-bit 200 MHz ARM chip. This chip runs the embedded Linux operating system (OS). At boot-up, the program stored in the on-chip flash will be loaded into the 32 Megabyte (MB) Synchronous Dynamic Random Access Memory (SDRAM) for execution. The internal 256 MB non-volatile flash stores the survey data (GPS, menu choices, and related). In general, the GPS data sampled and parsed once per second (1 Hz), with the pertinent data stored in an efficient binary format in flash. The other sensors are adaptively sampled as required with the resultant data also stored in binary format for optimal memory use. The wireless interface is based on the familiar ZigBee technology and is used for data transfer and unit-to-unit communication. The user interface is based primarily on a 160x240 resolution LCD graphic display, with backlighting and automatic contrast control to ease user burden. In the case of the portable device, the system is powered by a Lithium-Ion polymer battery and has a built-in charger. The system can be charged by a power supply in a manner similar to cell phones. Preliminary tests suggest that the portable system should be able to run for eight hours continuously when the user/device is at rest, or is riding in a car with a vehicle system already gathering data.

Table 1: GPS-ATD System Hardware

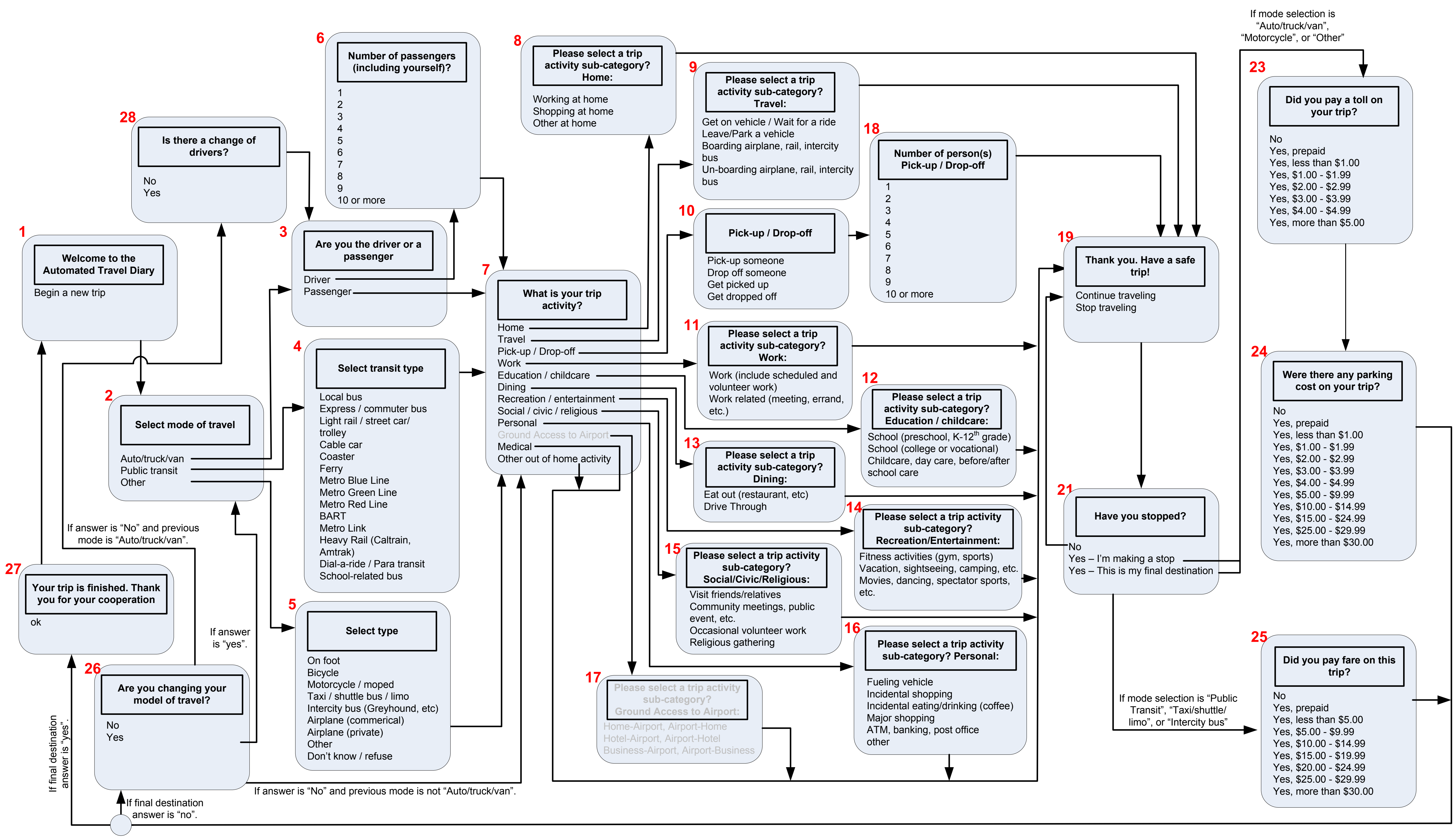
CPU	200 MHz 32-bit ARM
RAM	32 MB SDRAM
Flash	256 MB
Wireless Interface	ZigBee
GPS	Sirf III
Vehicle Interface	OBD-II
Accelerometer	2 G max with 5 mG resolution
Gyroscope	75 deg/sec max
User Interface	160x240 backlit automatic contrast control
	4 application-specific buttons
Power	Li-Ion polymer battery
	Switching supply
	Built-in charger and battery protection

Table 2: Comparison of Vehicular and Personal Versions of the GPS-ATD

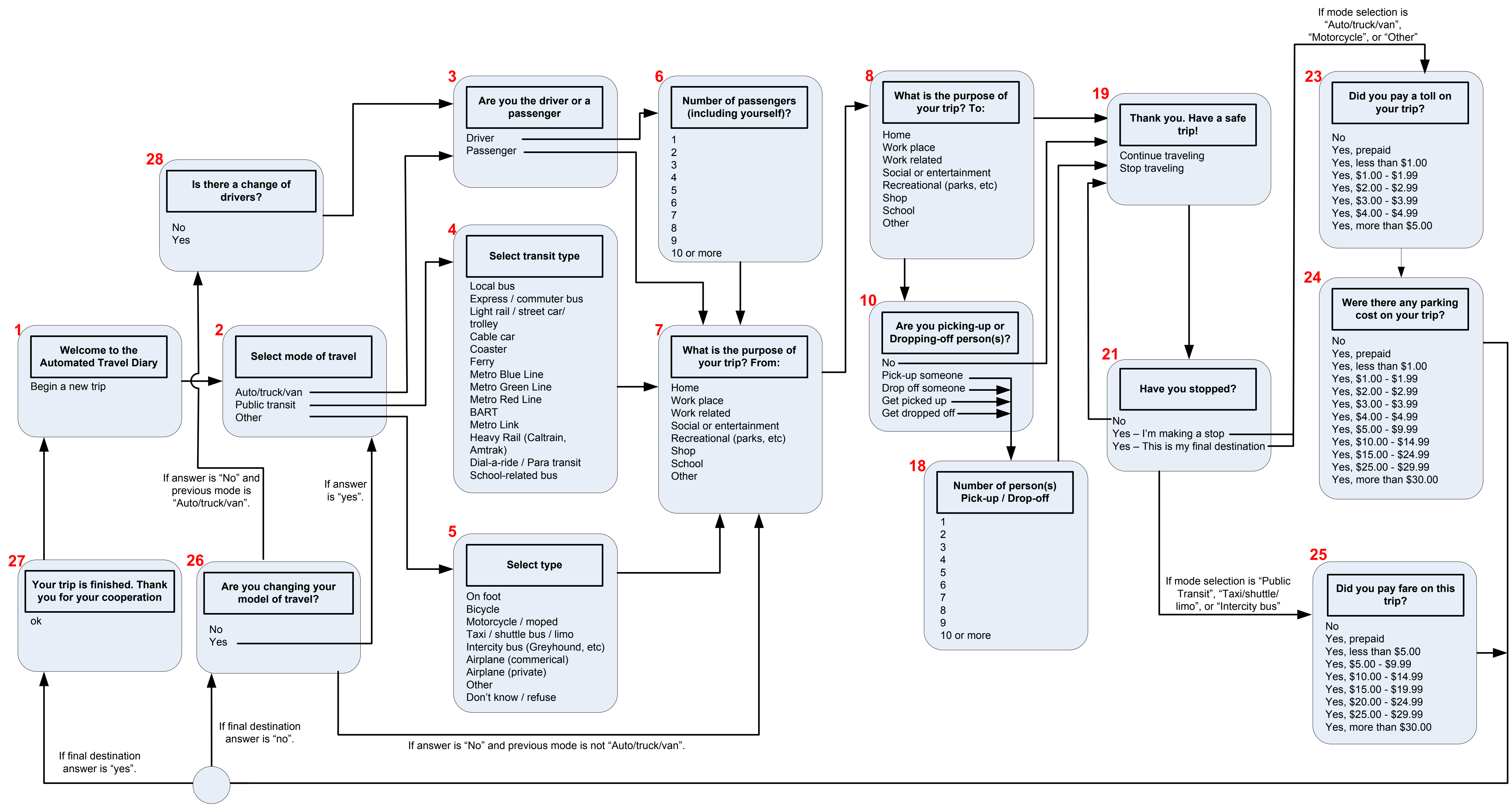
Data	Vehicular Ver.	Personal Ver.
Personal Identity	√	
Trip Purpose	√	√
Travel Begin Time	√	√
Travel End Time	√	√
Route Choice & Speed Profile by GPS	√	√
Trip Distance by GPS	√	√
Cost of Trip (Fees, Parking, Toll, etc.)	√	√
Mode of Transportation		√
Switching Mode of Travel		√
Reason for Mode Choice		√
Number of Passengers	√	
OBD-II Interface Data	√	
Acceleration	√	√
Yaw Rate	√	
Temperature	√	√

APPENDIX A: ATD MENUS FLOWCHART

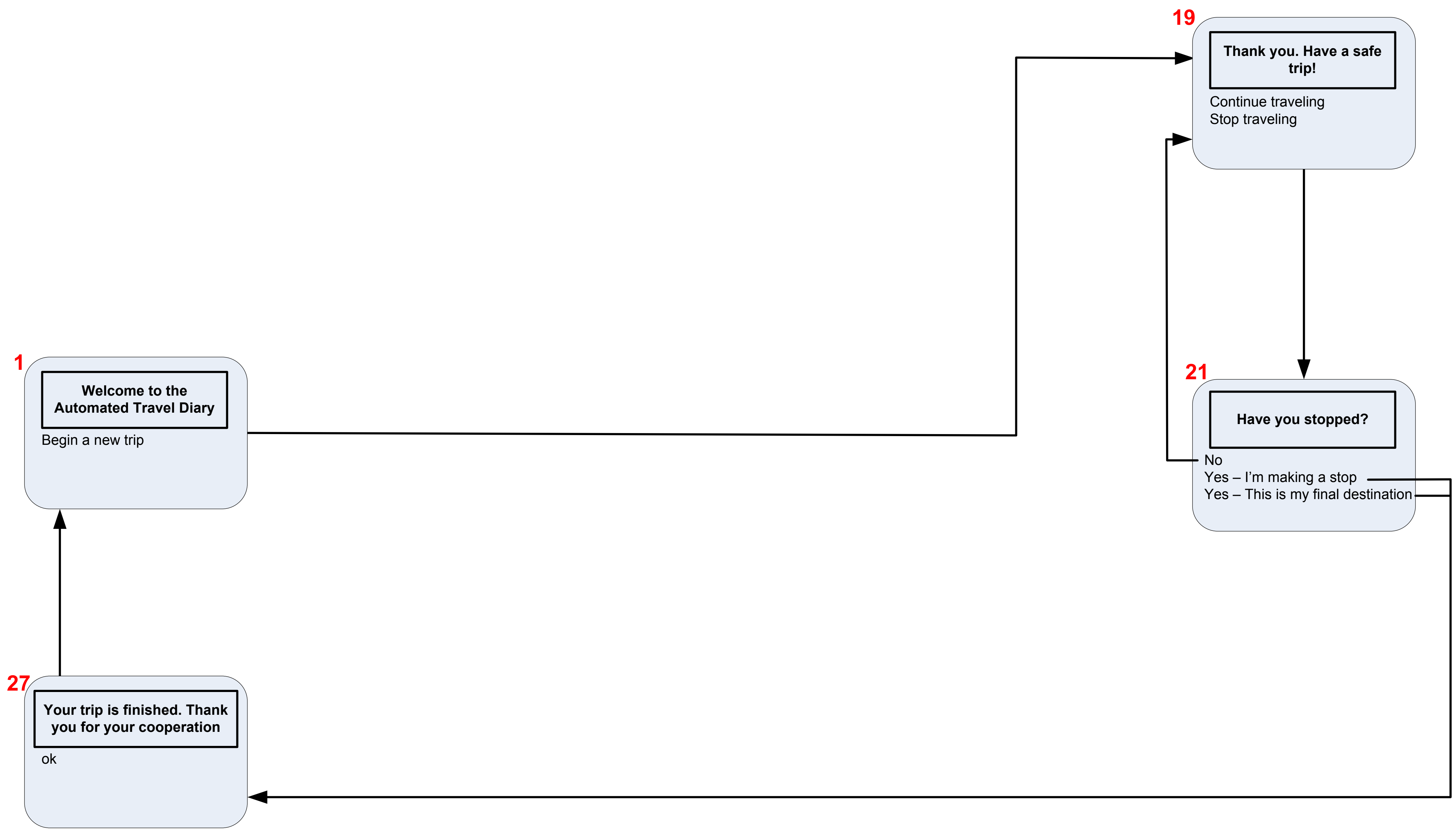
GPS-ATD Active Mode Menu Flowchart



GPS-ATD Hybrid Mode Menu Flowchart



GPS-ATD Passive Mode Menu Flowchart



APPENDIX D: DETAILED DELIVERABLES PROVIDED BY CALTRANS TSI

DELIVERABLES

The contractor shall, at a minimum, accomplish the following deliverables to meet the objectives of this contract:

1. **Review literature and products on:**

a - Human / Computer interaction - Identify types of household travel survey respondents who are representative of the target population by age group, language, ethnicity and technological skills for the use of GPS device. Classify survey participants by their capabilities and limitations to understand and use either the simple or more sophisticated GPS device. Rank the GPS devices, from high to low, according to the literacy and technological skills required to operate these GPS devices within the parameters of the survey. For highly skilled respondent a more sophisticated GPS device may be needed. For participants with the lesser technological skills, a totally automated GPS device, which requires minimum respondent interaction, may be appropriate.
In summary prepare a report on GPS selection criteria and recommended GPS application by various household types.

b – Develop protocols for collection and analyses of multi-modal trip data for multi-day longitudinal household travel survey:

1. Develop methodologies for downloading and processing trip data.
2. Provide GPS data output that is readable by GIS software.
3. Identify multi-modal trips and develop a method on how to combine all legs of the multi-modal trip information.
4. Develop Methodology on how to identify linked trips (e.g., change travel mode, drop off or pick up passenger).

c – Identify Trip Route from GPS data.

d – Develop guidelines to collect long distance trips for the statewide modeling by trip purpose (commute to work, business and recreation) and various trip modes [(i.e., Local bus, Express bus, Light rail/Street car/Trolley (San Francisco, San Diego, San Jose, Sacramento), Metro Blue Line, Metro Green Line, Metro Red Line, BART, Heavy Rail (Metrolink, CALTRAIN, Amtrak), School Bus, Passenger in car/truck/van, Motorcycle/moped, Driver, Taxi/shuttle bus/limousine, Greyhound (intercity bus), Airplane-commercial, Airplane-private].

e – Prepare summary report of findings – Evaluate various systems and recommend best alternatives for items a through d.

2. **Develop data collection and system requirements**

a – Trip information includes:

1. Mode of travel.

2. Trip activity

3. Trip purpose (Home-Other, Other-Other, Work-Other, Home- Work, Home-Shop, Business, Recreational).
4. Time of trip start and end
5. Route Identification
6. Trip duration
7. Date of travel and total trips made during survey period
8. Trip distance
9. Is this a linked trip (e.g., change travel mode, drop off or pick up passenger)? For linked trip definition, see page 296 of the *2000-2001 California Statewide Travel Survey*.
10. Public transit trip duration
11. Vehicle Mile Travel (VMT)
12. Speed
13. Origin and destination locations of each trip
14. Regional vs. interregional trips
15. Record crossing jurisdictional boundaries (e.g., city, county or region) and Traffic Analysis Zone (TAZ)
16. Vehicle type
17. Vehicle occupancy (number of people in vehicle)
18. Driver or passenger
19. Trip cost (out-of –pocket cost for instance parking and toll paid)
20. Delay factor (e.g., congestion, accident and railroad crossing)
21. Types of fuel

3. System architecture for both vehicular and personal Universal Longitudinal Travel Diary.

4. Component technology test results

5. Ten vehicular UnLTD units

6. Ten personal UnLTD

7. Final prototype test results and performance limitations

8. Develop GPS User Guideline for both vehicular and personal GPS device

9. Provide forty (40) copies of final reports in CD format and ten (10) printed copies including analysis and documentation