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GPS AND NEW TECHNOLOGIES TO IMPROVE LONGITUDINAL TRAVEL SURVEYS*

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16. Abstract

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 in supporting the decision making process at the federal, state, county and city level. In the current research, a new solution is proposed to address known deficiencies of previous approaches. This report will serve as guide to making informed trade-offs in the design of the novel GPS-Automated Travel Diary (GPS-ATD).

The mismatch between existing methods and the stated needs of travel surveyors will drive the 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 will be 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 inertial sensors will be used for dead-reckoning to calculate position solutions when GPS is not available. We present a well-balanced preliminary GPS-ATD system design at the end of the report. The current design meets the data, storage, and cost constraints while minimizing the survey respondents' burden. Specific design details will be discussed further with Caltrans to achieve the final optimum design meeting the current needs. 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 proposed GPS-ATD system design.

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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
ACMS	Advanced Construction and Maintenance Systems
AHMCT	Advanced Highway Maintenance and Construction Technology
AOR-W	Atlantic Ocean Region-West
Caltrans	California State Department of Transportation
CASI	Computer-Assisted-Self-Interview
CATI	Computer-Assisted Telephone Interview
CDMA	Code-Division Multiple Access
CPU	Central Processing Unit
DGPS	Differential Global Positioning System
DOD	Department of Defense
DOP	Dilution-of-Precision
DOT	Department of Transportation
DR	Dead Reckoning
DSL	Digital Subscriber Line
EMI	Electromagnetic Interference
ETD	Electronic Travel Diary
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
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
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
MB	Megabyte
MEMS	Micro-Electro-Mechanical Systems
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
PAPI	Paper and Pencil Interview
PDA	Personal Digital Assistant
PLAN	Position Location and Navigation
POR	Pacific Ocean Region
RF	Radio Frequency
RFI	Radio Frequency Interference
RTOS	Real-Time Operating System
SA	Selective Availability

Acronym	Definition
SBC	Single Board Computer
SDRAM	Synchronous Dynamic Random Access Memory
TMC	Transportation Management Center
TSI	Transportation System Information
TUCF	Trip Underreporting Correction Factor
UCD	University of California-Davis
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

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SECTION 1: INTRODUCTION

This report provides a brief introduction to objective longitudinal traveler surveys, including previous methods of conducting surveys and their findings. The report 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 further discussion and the finalization of the specification for the GPS-Automated Travel Diary (GPS-ATD) to be developed.

SECTION 2: 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.

SECTION 3: 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 has 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 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: Travel Diary Information Collected for Given Day(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 of Survey**	**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 are 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; herein, 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 (35 days long, 149 individuals using self-administered travel diaries) data, 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, 1900 point max [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	X686 133 MHz CPU running embedded Linux with 16 MB for 28 hours data logging, GPS & CDPD modem. User interface is under development. 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 a picture 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 fail 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 can be overcome by tight component integration, additional sensors, longer lasting backup batteries, and increased onboard processing power and intelligence.

SECTION 4:
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 section.

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 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. It was turned off at midnight on May 1, 2000. It is not the intent of the U.S. to ever use SA 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 a 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 serving the WAAS area (Inmarsat IIIs: POR (Pacific Ocean Region) and AOR-W (Atlantic Ocean Region-West). 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 NDGPSenabled 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.

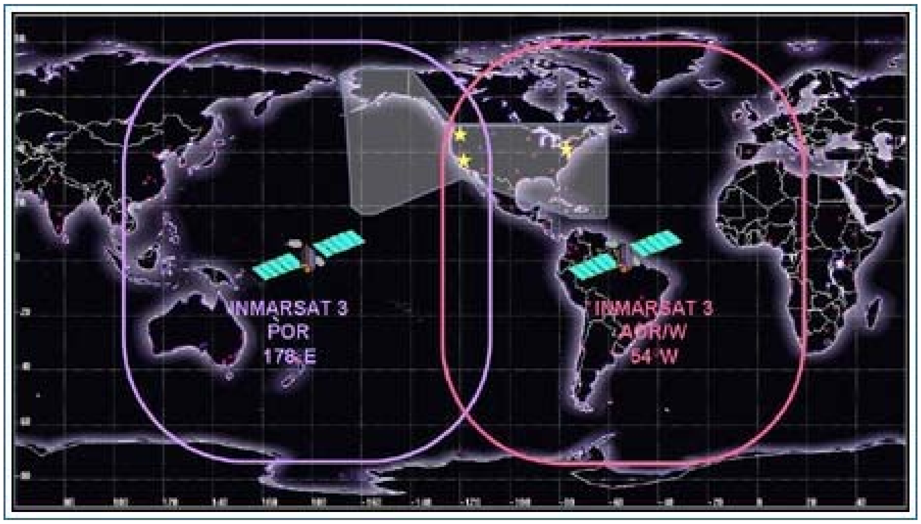

Figure 1: WAAS Geostationary Satellites Coverage Map (http://gps.faa.gov/CapHill/geosat.htm)

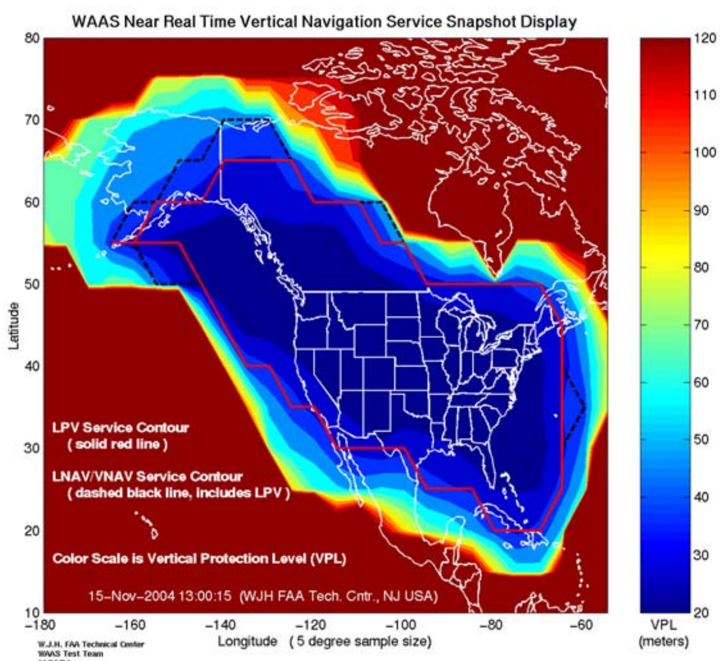

Figure 2: WAAS GPS Vertical Accuracy Map (http://www.nstb.tc.faa.gov/vpl.html)

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. 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 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, 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 only 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 processor. 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 will be closely examined in the project's GPS receiver testing and evaluation phase.

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 will be 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 will be 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]. Their size and weight will also be 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.

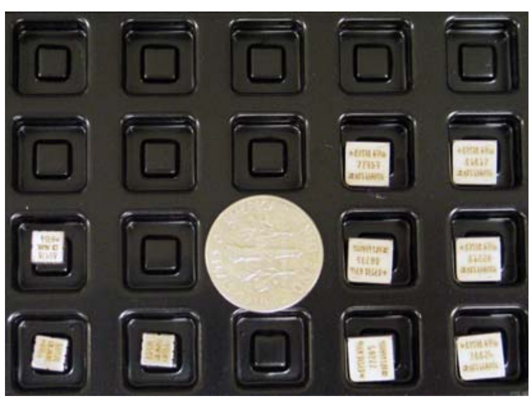

Figure 4: Analog Devices MEMS Gyro and Accelerometer Chips

SECTION 5:
OTHER NEW TECHNOLOGIES TO IMPROVE TRAVEL SURVEYS

Vehicle On-Board Diagnostic (OBD) Interface

All vehicles built after 1996 have been 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, 54% of the vehicles are younger than 8 years, implying that approximately 54% 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 surveys are 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 is not the subject of the current research.

These technological advancements will increase the system's robustness and availability, and reduce survey costs and needed user interaction. The result would be 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.

SECTION 6:
PROPOSED GPS-AIDED ELECTRONIC TRAVEL DIARY SOLUTION

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-aided electronic travel diary, 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-aided electronic travel diary should be designed just to collect all necessary raw data 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.

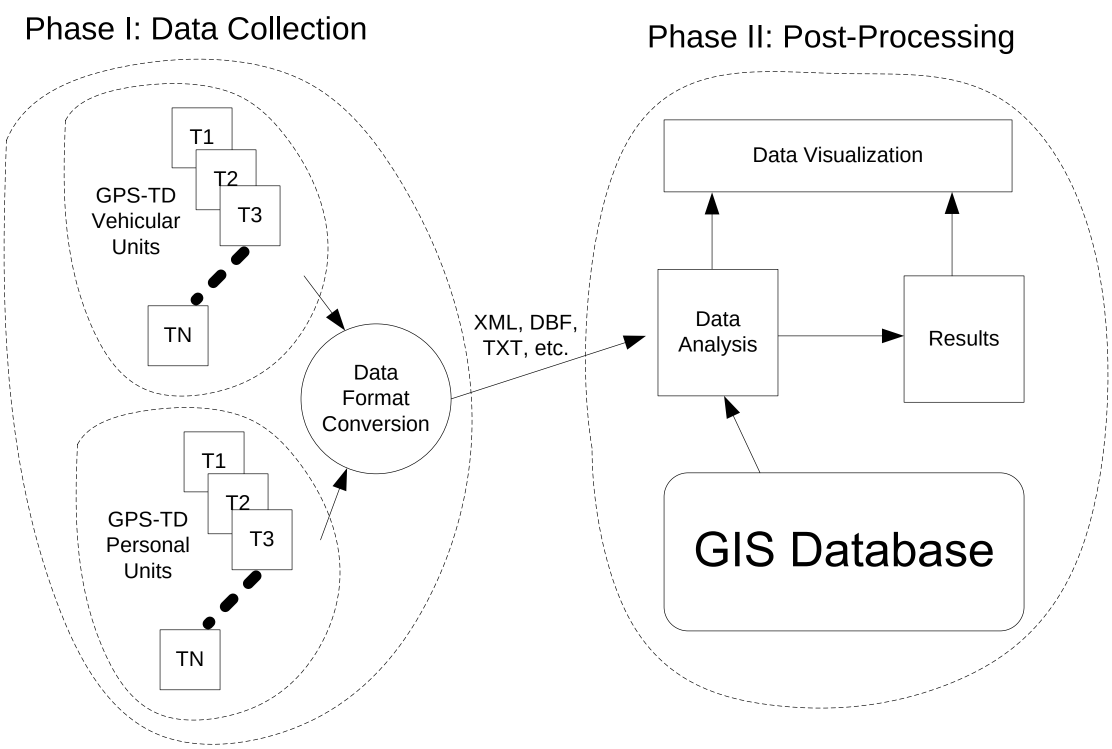

Figure 5: System Architecture including Data Collection and Post-Processing Phases

<u>Recommended GPS-Aided Electronic Travel Diaries Systems</u>

The current research focuses on development of the data collection units, i.e. on the Phase I portion of the architecture. We envision vehicular and personal GPS-Automated Travel Diary (GPS-ATD) systems to be developed to address the need for comprehensive travel behavior study data collection. The devices will support "interactive", "passive", and "hybrid" operating modes ("hybrid" implies any of a variety of modes between interactive and passive). Ideally, this system should be able to capture all pertinent data over the entire survey period without creating any 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. The recommended system features are based on user responses in exit surveys and analysis conducted in prior research referenced in this report. The objective is 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: Recommended 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 accuracy
	Integrated
	Easy-mount GPS antenna
	Dead reckoning for GPS startup and low signal availability
	WAAS differential GPS correction
Gyro/Accel	User position for GPS startup
	User position for GPS low signal availability
Vehicle Interface	OBD-II vehicle telemetry
	OBD-II vehicle diagnostics
Wireless	Data download
	Real-time data download
	Remote upgrade
	Unit-to-unit communication

The travel diary should contain 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, we believe 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 will share common features and functionality. Both vehicular and wearable personal versions will be based on a shared modular system architecture. Furthermore, both vehicular and personal GPS-ATD units could operate in "passive", "interactive", or "hybrid" mode. Moreover, they must be 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 will be entirely self-contained with all of the sensors integrated into a single package. The sensor outputs—positional and temporal data—would be collected automatically by an onboard embedded processor and stored in solid-state memory. The overall system will be easily installable by the end-user, and will support several methods of remote administration. A wireless interface will be provided for use in conjunction with popular Bluetooth-capable cellular phones to support real-time administration and data transfer from vehicular units. Personal units could be setup to transfer data to a master vehicle unit when in close proximity and thus make the data available for remote batch download.

Human-machine interfaces (HMI) that are overly complicated or tedious will also be viewed negatively, and may impact the data collection and the survey results. The HMI will 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 will be used as a reference and baseline guide. The user interface will be based on a Liquid Crystal Display (LCD) and a thumbwheel, as well as application-specific buttons. The user will select various graphical icons and make menu choices with the thumbwheel. 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 will capture all modes of transportation. In addition, it will be light-weight and have rechargeable batteries that could be recharged from either the home station or an auto-charger. Its GPS receiver antenna will be less sensitive to orientation. Several mounting and carrying options for the personal GPS-ATD will be designed to let the respondents use the unit in many situations (walking, biking, and motorcycling) with ease.

The vehicular GPS-ATD will have additional sensors, OBD-II interface and backup batteries which are rechargeable from vehicle power. The heart of the system uses a WAAS-enabled differential GPS receiver for positional data collection. When a GPS system initially starts up or suffers intermittent satellite signal loss, dead reckoning will 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 could 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 will also be 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 will contain an interface to the OBD-II port on all new vehicles (made after 1996). The OBD-II interface will provide 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 proposed GPS-ATD will satisfy 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 200 MHz ARM chip with the program flash layered on top of the CPU die for a smaller package. This chip can run the embedded Linux operating system (OS). At boot-up, the program stored in the on-chip flash will be loaded into the 16 Megabyte (MB) Synchronous Dynamic Random Access Memory (SDRAM) for execution. The internal 128 MB non-volatile flash will store the data shown in Table 8. In general, the GPS data will be sampled once per second (1 Hz), parsed, and the pertinent data stored in an efficient binary format in flash. The other sensors will be adaptively sampled as required with the resultant data also stored in binary format for maximum memory utilization. The wireless interface will be based on the familiar Bluetooth technology and would be used for data transfer and unit-to-unit communication. The user interface will be based primarily on a 160x240 resolution LCD graphic display with backlighting and automatic contrast control to ease user burden. The main input device will be a thumb wheel. This device is used on many popular portable devices today. In the case of the portable device, the system will be powered by 3 AA Nickel-Metal-Hydride (NiMH) batteries and will include a built-in charger. The system will be connected to a power supply or cradle, similar to cell phones, for recharging. Preliminary power calculations 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: Features Synthesized with the Following Hardware

CPU	200 MHz 32-bit
RAM	16 MB SDRAM
Flash	128 MB
Wireless Interface	Bluetooth
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
	Thumb wheel and application specific buttons
Power	2-3 AA NiMH batteries
	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 is 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 Tradeoff

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 utilize 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 mostly recommended in Table 9.

Table 9: Feature Cost-Benefit Tradeoff Analysis

Features		Weight	Size	Cost	User Burden	Data Quality	Battery Duration	Survey Duration	Total
		Effect							
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

SECTION 7: CONCLUSION

The current research in this area has been reviewed and key articles have been cited. The current and future needs have been reviewed, and a recommended system has been presented. This system is the result of performing rigorous feature, power, cost, size, weight, and data analyses resulting in the system represented in Table 7. Although this system is close to optimal, it is by no means the final system. According to the relationships shown in Table 9, the various system parameters can be adjusted and tradeoffs can be made. The goal of this development is to create an information gathering system which, in the end, will provide the highest quality data for purposes of analysis and model creation. The fundamental purpose of this preliminary report is to provide the needed background and technical tradeoff information so that the research team and Caltrans can finalize the system functional requirements and specifications, leading to a design that best supports future travel behavior surveys.

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APPENDIX A: ATD MENUS

(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

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

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

Strikethrough are confidential fields

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