Development of a

Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior

Final Report

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TABLE OF CONTENTS

List of Figures

List of Tables

Abstract

Regional travel surveys are conducted worldwide to collect the data required for travel demand models, which are then used to make decisions on high-cost transportation network improvements. These regional travel estimates are also used to predict emissions from motor vehicles and serve as primary input data for air regional quality analyses. One element missing from air quality modeling, however, is the relationship between the driver and the vehicle, which is also directly related to emission levels, but to date has largely been unexamined due to the lack of data.

The objective of this research effort is to provide a means of integrating travel behavior studies and vehicle activity studies by developing an instrumentation system which allows for the simultaneous monitoring and capture of trip characteristics and vehicle / engine operating conditions. Components of this system include a handheld electronic travel diary, a global positioning system receiver and antenna, an onboard engine monitor, an interface computer, and a power supply. This system is capable of capturing all traditional travel diary information as well as second-by-second GPS coordinates and engine activity data.

During the development of this prototype system, research was conducted both at the component and system level. Key findings include:

- Route choice accuracy is a function of GPS accuracy; differential GPS will be required for successful map matching to the Atlanta street network.
- Additional component research is required to find an onboard engine diagnostics unit able to meet all requirements.
- Temperature conditions in Atlanta during the summer present additional challenges in finding components able to withstand trunk temperatures that reach or exceed 140°F.
- Further research is needed on reducing power demand of the various components and on new battery technologies.

1. EXECUTIVE SUMMARY

Urban and regional planners use travel demand models to estimate changes in transportation activity over time. These models predict the number of trips generated by households as a function of various demographic and socioeconomic considerations and also predict the number of trips attracted to various employment and commercial centers. Estimates for vehicle mode choice, distribution of trip destinations across the metropolitan region, and traffic volumes on various roads also come from these travel demand models. Regional travel surveys, or travel diary studies, are used to collect the data necessary to build travel demand models. Randomly-selected survey participants record trip information over a one-day, three-day, or one-week period. Data collected from thousands of households across the region are then analyzed to develop travel demand models. These regional travel estimates are then used to predict emissions from motor vehicles and serve as primary input data for air regional quality analyses.

Emissions from motor vehicles are directly related to the amount of vehicle activity undertaken. Increased miles or hours of travel results in increased emissions. Emissions are also strongly related to the percentage of dirty vehicles operating in a region. However, even the emissions from “clean vehicles” that normally pass standard smog checks are a function of the way in which the vehicles are operated. Emissions are not only a function of miles driven, but a function of such trip characteristics as time lag between engine starts and the number of hard acceleration activities. Determining the operating characteristics of onroad vehicles is critical to understanding vehicle emissions behavior. Furthermore, some vehicle operating characteristics are likely to be correlated with driver behavior. For example, young male drivers may be more likely to undertake high-speed hard-acceleration activities which significantly increase vehicle emissions. Current emissions models do not take into account driver interaction with the vehicle and vehicle controls because such data are not available for analysis.

To date, vehicle activity studies and travel behavior studies have never been coordinated. This research effort focused on the development of electronic monitoring equipment that would allow such studies to be undertaken jointly. The new equipment will allow simultaneous monitoring of trip characteristics and vehicle and engine operating conditions. Hence, data collected with equipment developed in this research effort will help model developers understand the linkages between travel decisions and vehicle operating conditions. This, in turn, will lead to the development of improved algorithms for predicting emissions as a function of vehicle characteristics, onroad traffic conditions, and household/driver demographics.

A literature review was undertaken to investigate the various aspects of developing an integrated vehicle instrumentation package. Topic areas covered in this review include past and present travel survey methodologies, trends in the field of travel behavior research, results of other vehicle instrumentation studies, availability of useful technologies, survey bias and response rate issues, and traveler route choice studies. One of the greatest benefits of this review was the sharing of research findings among the limited number of researchers currently conducting automated travel diary and vehicle instrumentation studies.

To collect all required data streams for use in travel model development and validation, the integrated vehicle instrumentation package must contain a handheld travel diary, global positioning system, onboard engine monitor, interface computer, and power supply. Because many manufacturers and models within each equipment class had the potential to meet minimum design and performance criteria, the research team first developed a set of system goals in the form of functional specifications (Wolf, Guensler et al., 1999b). These functional specifications served to narrow the field of potential equipment that would meet project requirements. Given a smaller set of potential equipment solutions, the research team reviewed the detailed technical specifications for the most promising equipment options. The technical specifications analysis is contained in Wolf, Guensler, et al., 1999c. The most promising components identified and reviewed were then selected for purchase and field testing.

Each class of equipment was first tested separately to determine superior performers within each class. To facilitate competitive testing, the research team identified those factors that may influence the accuracy and ease of use of each equipment type. With this knowledge in mind, the team then developed standardized test scripts and testing procedures that would challenge the ability of equipment to perform under real-world test conditions. The descriptions of the test metrics and the performance of each individual component are summarized in the test plans and results document (Wolf, Guensler, et al., 1999d). The selection of individual components, final assembly of the prototype system, and software development were based upon these test results.

This final report summarizes the project in its entirety. Information presented in the four previous project volumes is summarized throughout this report. An review of each system component that is in the final prototype package is given, including the original specifications, test plans and results, and final recommendations. The testing of the final prototype unit is summarized in this final report as well. The functionality of the assembled unit is reviewed and shortcomings that must be overcome before such a system is fully deployed are identified.

The literature review and communications with other related research initiatives revealed several problem areas for instrumentation projects. Project development and testing exposed additional issues that should be taken into consideration in future electronic travel diary and vehicle instrumentation research efforts. These problem areas and issues include:

- Manufacturer support for various equipment components is highly variable. Many of the candidate components identified for testing, and some of those actually procured for testing, were no longer being manufactured one year later. The replacement models (if any are available) will not always meet system specifications. In addition, several vendors went out of business in the midst of negotiating with the project team – this reflects the unstable nature of new, specialized technologies.
- Technical expertise at many equipment companies is not readily available; in fact, the research team often found that there was only one person within a given company who could answered detailed questions regarding equipment specifications.
- Route choice accuracy is a function of GPS accuracy. Field tests dramatically demonstrated the importance of using GPS units that provide accurate position under conditions of Selective Availability (purposeful degradation of the satellite signals by the military to reduce position accuracy). The research team determined that a unit capable of data post-

processing (correction of the signal to compensate for military signal degradation) is required for future systems.

- An alternative to post-processing GPS data, which is both time and resource intensive, is the use of GPS equipment that can receive position corrections via radio signal. For use in metropolitan area studies, these units need to be capable of receiving the correction signal throughout the region. The research team is currently testing two units in Atlanta under a separate research effort.
- GPS units do not all initialize with the same time stamp when they are powered on, resulting in a potential clock offset between two separate units. Clock drift was also noted across the variety of GPS units tested, indicating that the units employ different internal algorithms for tracking the passage of time. Any research effort aimed at integrating data based on time (matching the location of an event and the environmental conditions associated with that event) must consider clock drift. An independent, single time stamp should be applied to all recorded data streams if second-by-second matching of these streams is a post-processing requirement.
- The onboard engine diagnostics units currently available on the market do not yet provide an optimal solution. Currently, the OTC scanner provides the best capabilities for vehicles. However, the OTC has to be specifically configured for each vehicle. When operated in a generic onboard diagnostics (OBDII) mode, engine data are only reported every three-seconds, which is insufficient to provide accurate acceleration data. New systems are entering the market this year and should be considered for future studies.
- Onboard computers and other components must be capable of performing under very high temperature conditions if they are to be located in the vehicle trunk. Few computers are available which can perform at temperatures exceeding 140°F.
- Equipment durability is a critical issue. Component failure during data collection efforts will result in the loss of all data for the duration of the equipment outage. A warning interface to notify the driver of component or system failure should be built into future systems.
- Off-the-shelf 12-volt deep cycle batteries are not capable of storing their rated charge. Batteries must be fully discharged and recharged 30 times, before their rated charge can be met. Field study teams need to purchase and "season" batteries well in advance of any studies being undertaken.
- The power demand of the current prototype system is such that a single battery charge will only power the unit for three days. Adding a second battery will extend the duration of tests, but adds significant weight to the vehicle and may influence the response of the engine to various driving conditions by adding to vehicle load. Hence, future system research should continue to focus on reducing the power demand of the various components and on new battery technologies.

This final report also summarizes the linkage between this project, sponsored by the Federal Highway Administration and Georgia Department of Transportation and the ongoing research effort associated with the development of the year 2000 travel survey in the Atlanta metropolitan region (SMARTRAQ).

2. PROJECT OVERVIEW

In travel diary studies, randomly selected survey participants from a metropolitan region manually record information about each trip that they make during a one-day to one-week period. Participants log trip origin, destination, time, mode, and other characteristics into their travel diaries. After collecting representative samples from households across a metropolitan region, travel demand modelers use the recorded travel data to derive statistical representations of travel behavior. The resulting statistical models become trip generation algorithms within travel demand models. These models are then used to forecast travel patterns, such as the number of daily trips, trip purpose frequencies, trip origins and destination selection, trip duration distributions, and temporal distributions.

Motor vehicle emissions are a function of the number of trips made and miles driven. However, the emissions from “clean vehicles” that pass normally pass standard smog checks are also a strong function of the manner in which the vehicle operates. A small fraction of high acceleration activity or moderate acceleration activity at high speeds lead to combustion conditions (“enrichment”) that increase emission rates by 10 to 1000 times for short periods (Kelly and Groblicki, 1993; LeBlanc, et al., 1995). In addition, some engine computers on modern vehicles that control air:fuel ratios (directly impacting emissions) monitor the rate of change in throttle position. This means that driver interaction with the vehicle through the throttle can also lead to elevated emissions.

Travel behavior studies and vehicle activity studies have never been coordinated. Researchers note differences in driver behavior across demographic groups in travel behavior studies and differences in vehicle activity patterns across cities in vehicle studies. However, separating the impacts of driver behavior and driving patterns on emissions is not possible without detailed driver studies that simultaneously monitor vehicle and engine operating conditions. This research effort focused on the development of electronic monitoring equipment to simultaneously collect information needed to understand travel decisions and vehicle operating conditions.

2.1 Goals and Objectives

The primary goal of the comprehensive electronic travel diary project is to develop an instrumentation package that will automate the capture and integration of travel activity (trip-level data) and vehicle and engine operating conditions. An ideal monitoring system should be easy to install in any personal vehicle (automobiles or trucks), should not require the participation of a certified mechanic, and should be unobtrusive. Data are to be collected and stored electronically.

The ultimate objectives of the comprehensive travel diary system are to: 1) automate the manual travel diary process, producing more and more accurate data for use in transportation planning model development, and 2) capture vehicle and engine operating conditions concurrently for use in motor vehicle emissions model improvement. Emissions models can be improved once the relationships between driver behavior, vehicle operations, engine operations, and vehicle emissions are determined through studies that employ the new equipment.

The system has been designed to capture or compute the following data elements:

- All driver and passenger travel activities that would normally be captured using manual travel diary or telephone survey methods. For each trip, this information includes: vehicle (or other mode) identification, driver identification, passenger identification, driver and passenger trip purposes, trip start time, finish time (or duration), origin location, destination location, and distance traveled. In addition to these traditional elements, route choice, travel speed, and functional classification of each link (with traffic conditions) can be determined by tying GPS data to a GIS database, greatly enhancing the original data collected.

- All vehicle and engine operating conditions affecting emissions that can feasibly be captured via an onboard engine computer monitor. These data include such variables as vehicle speed, acceleration, engine rpm, manifold absolute pressure, throttle position, catalyst temperature, gear selection, air/fuel ratios, and coolant temperature.

By having the unique ability to measure and record trip-making characteristics, exact origins, destinations, routes, and times, we make available a host of new research opportunities to better understand human travel behavior, and its impact on congestion and emissions. By combining the proposed instrumentation package with other tools such as household stated preference surveys or commercial/retail surveys, a great deal can be learned about the effectiveness of many transportation strategies and policies. The elasticity of parking pricing and availability could be explored explicitly (both spatially and temporally). The effectiveness of carpool strategies could be determined by instrumenting carpool vehicles before and after participation to compare trip making. High occupancy vehicle (HOV) lane effectiveness could be studied explicitly in a similar fashion. Finally, vehicles could be instrumented for long periods of time, say several months, to explore seasonal trip making behavior, and its impact on route choice, and trip origins and destinations. Finally, the instrumentation package provides the capability of implementing a Nielsen Family of cars in major urban areas (Guensler, 1993).

2.2 Scope and Deliverables

The goal of this research initiative was to develop, assemble, and test a vehicle instrumentation package for use in monitoring individual tripmaking behavior. The research contract called for prototype instrumentation development and submission of a final report summarizing the activities of the research team. To support the preparation of the final project report, four separate reports were prepared:

- **Literature Review (GTI-R-99001)**
  This review examines travel diary methodologies and trends in the field of travel behavior research. Several stated preference surveys and travel diary surveys used in the U.S. are included. This report presents other projects focused on travel diary automation or vehicle instrumentation. The literature review also includes a review of suspected travel survey bias issues.
- **Project Overview and Functional Specifications (GTI-R-99002)**
  This report presents the original goals, objectives, and scope of the project. Functional specifications are given for the system as a whole, as well as for each individual component. Specific data elements captured by each component are defined, data-processing requirements are reviewed, and subsequent data analyses to be performed are presented.
- **Technical Specifications and Analysis (GTI-R-99003)**
  This report presents various system configuration options considered, the technical requirements for the integrated system, and the detailed technical requirements for each component and the corresponding specifications for each product considered.
- **Test Plans and Results (GTI-R-99004)**
  This document summarizes the criteria used to evaluate each major class of equipment (electronic travel dairy, GPS, onboard engine scanner, and other components) and reports the field trial performance of each component. Performance test results were used to select individual components in each class of equipment.

2.3 State of the Practice

In developing the specifications for the electronic travel diary, the research team performed a literature review on state-of-the-practice travel survey methods. The team reviewed previous travel diary studies in Atlanta and other major metropolitan areas. The review of research literature focused on accuracy issues and suspected travel survey biases that could be avoided in future studies. The researchers also reviewed technologies and methodologies employed in previous automated diary and instrumented vehicle studies, including those that use GPS only and those that use onboard monitoring devices. The complete literature review is contained in a separate report (Wolf, Guensler, et al, 1999a).

2.3.1 Travel Diary Studies

Travel diary studies are one of the most common methods for collecting data for use in travel demand model development. As mentioned previously, travel diary studies randomly select survey participants from a metropolitan region and ask them to manually record the characteristics of each trip that they make in a standard paper diary. These data are then used to model travel behavior throughout the region and to forecast travel patterns for use in transportation systems planning, a process which often results in multi-million dollar infrastructure decisions.

Within the past several decades, the traditional paper-and-pencil interview (PAPI) method of travel diary data collection has been supplemented or replaced with computer-assisted-telephone interviews (CATI). CATI involves telephone interviewers using specialized software who call survey respondents and asks them to provide details of all trips taken on a prior day – the respondents may have been given a paper diary when recruited to assist in this recall process. Most recently, computer-assisted-self-interview (CASI) methods are being evaluated. There are numerous references available which review the traditional diary instruments and the transition to automated data collection methods (see Stecher et al., 1996; Kalfs and Saris, 1997; Sarusua and Meyer, 1996). Two recent European research projects have examined handheld PC's (Haubold and Axhausen, 1998) and Internet-based web sites for long distance travel data collection (Plaxton, et al., 1999). Additional U.S. studies have begun to examine the opportunities of using GPS and GIS technologies in travel studies (see Abdel-Aty et al., 1995; Greaves, 1997; Czerniak and Reilly, 1998).

Global positioning systems can add a new spatial dimension to tripmaking, by tracking actual route choice. Research projects investigating automated diaries with GPS include the completed FHWA-sponsored Lexington study (Wagner, 1997) and ongoing travel surveys conducted in the Netherlands (Draijer, 1998). These two projects are the first to combine electronic travel diaries with GPS receivers to gain exact temporal and spatial details of each trip. Several other projects have installed passive GPS receivers in automobiles (Casas, 1999) and in trucks (Wagner, et al., 1998) to capture travel route information. Finally, several European research projects have evaluated GPS receiver performance in London (Ochieng, 1998) and in Paris (Flavigny, et al., 1998).

CASI methods such as electronic diaries provide the potential to expand recorded choices, making electronic diaries suitable for use in activity-based or tour-based travel demand modeling. In addition, the automated capture of time and location data provided by a GPS receiver should produce great improvements in travel data accuracy compared to manual methods. Specifically, an electronic travel diary (ETD) combined with GPS data collection should overcome several problems related to manual travel diary studies:

- Paper survey participants may not keep accurate records (either accidentally or intentionally), which result in misreported or underreported travel, including the omission of entire trips (Richardson, et al., 1996). The screen flow of electronic travel diaries will prevent the omission of individual trip data elements and the GPS component can be used to detect the omission of entire trips. In addition, help screens can be coded to add clarification where necessary.
- Due to the time-intensive nature of manual travel diaries, participants often feel fatigued or hassled by the process, which makes it difficult to collect extended panels of data (most manual travel diary studies collect either one or three days of travel data per household). The electronic travel diary's nesting of screens can reduce the respondent's impression of the overall burden because the respondent sees only those screens necessary for the collection of data for the given trip.
- Actual route choice is rarely captured in travel diary studies due to the increased respondent burden. This burden is eliminated with passive GPS data collection. The ETD with GPS should be able to collect data for periods up to a week without imposing any additional requirements on the respondent.

Because manual travel surveys potentially suffer from these reporting biases and limitations, new methods for obtaining personal tripmaking behavior can help minimize or reduce the impact of these biases on the estimation of trip generation rates. Consequently, Most automated travel diaries currently used in studies around the world are designed to:

- Collect all driver and passenger travel activities that would normally be captured using manual travel diary or telephone survey methods. For each trip, this information includes: vehicle (or other mode) identification, driver identification, passenger identification, driver and passenger trip purposes, trip start time, finish time (or duration), origin location, destination location, and distance traveled.
- Provide a portable, handheld device with independent data collection capabilities so that the unit can be employed for walking, cycling, and other trips made outside of the primary vehicle.
- Link route choice, travel speed, and functional classification of each link to the characteristics of each trip by linking trip data on the handheld diary to the GPS data collected simultaneously. A GIS provides the route matching routines that link trip origin/destination through the road network database.
- Provide the capability to store GPS data directly on the handheld device.
- Provide a user-friendly interface.

2.3.2 Instrumented Vehicle Studies

Researchers cannot use current travel dairy study data to explain driving patterns explicitly. It is impossible to separate the impacts of driver behavior from those of infrastructure, speed limit posting and enforcement, land-use, jobs-housing balance, vehicle fleet composition, etc. Interaction effects of driver, vehicle, and infrastructure characteristics on driving patterns also cannot be ascertained without the development of enhanced data collection techniques. Over the past decade, several research projects have instrumented vehicles in order to capture vehicle and engine activity data. These projects include the Canadian Autologger, which is a vehicle data collection device (Taylor, 1991), research in France conducted in 1983 and 1990 with 55 instrumented vehicles (André, 1995), and several instrumented vehicle studies conducted in the United States (DeFries and Kishan, 1992; Ross, et al., 1994; and Benjamin, 1997.

Collection of spatially-resolved motor vehicle activity in instrumented vehicle studies is critical for estimating travel demand and properly allocating vehicle emissions throughout an urban area. Vehicle emissions are a function of the number of vehicle trips, vehicle miles of travel, and the onroad operating conditions under which travel is undertaken. Vehicle is often under-reported in standard surveys, overlooking many very short trips with high emissions. Because the comprehensive vehicle instrumentation package will automatically log trip details, current air quality models will benefit from the improved accuracy of trip and engine start counts, soak-time distributions, vehicle activity profiles, and on- and off-network activities. New motor vehicle emissions models now predict emission rates as a function of vehicle speed, acceleration, and engine/vehicle technology characteristics. While laboratory testing has defined the relationship between these variables and emission production, real-world vehicle activity and onroad technology characteristics must be made available as inputs to run the models. Hence, instrumented vehicle studies improve travel demand estimates, provide better data on modes of vehicle operation, and significantly improve resulting air quality impact assessments performed for transportation projects.

The new instrumentation package links vehicle characteristics (e.g. size and horsepower), vehicle operating conditions (e.g. speed and acceleration), and engine operating conditions (e.g. engine rpm, and throttle position), with driver characteristics (e.g. age and gender) , trip purpose (e.g. work and shopping), and route choice (e.g. freeway and local road, as indicated by monitored geographic position). The wealth of data collected by such a system provides the opportunity to learn a great deal about driver and households relationships with respect to trip generation, trip chaining, route choice, and driver behavior. A wide variety of emissions related research questions that are currently intractable due to lack of data can be addressed once the new instrumentation package is online. For example, the emission characteristics of various vehicle types operating under various roadway conditions can be discerned through analysis of data collected by the instrumentation package. The interactions of driver characteristics, vehicle characteristics, speed, acceleration, change in throttle position, and vehicle enrichment can all be studied.

2.4 Related Research Contacts

The research team has reviewed reports related to the following related projects to gain knowledge of lessons learned and to better differentiate our project from these projects. A list of these projects, along with contact names, phone numbers, and email addresses is provided below.

1) Battelle and Federal Highway Administration (FHWA) - Lexington Project
   (Elaine Murakami, 202-366-6971,elaine.murakami@fhwa.dot.gov)

2) Battelle, California Air Resources Board (CARB), and FHWA - California Project
   (David Wagner, 614-424-4388)

3) CARB - Use of GPS for Collection of Motor Vehicle Activity Data
   (Michael Benjamin, 818-459-4385,mbenjami@arb.ca.gov)

4) Netherlands - PDA Travel Diary Project
   (Geert Draijer, G.J.A.Draijer@AVV.RWS.minvenw.nl)

5) Texas Transportation Institute – Austin Household Travel Survey 1998
   (Dave Pearson, 409-845-9933, david-pearson@tamu.edu)

6) European TEST - Long Distance Travel Diary (Kay Axhausen, axhausen@ivt.baum.ethz.ch)

7) National Cooperative Highway Research Program (NCHRP) Synthesis 258: Applications of GPS for Surveying and Other Positional Needs in Departments of Transportation

3. COMPONENT EVALUATION

To accomplish the instrumentation goals of this project, the integrated system must contain a handheld travel diary, a global positioning system receiver and antenna, an onboard engine monitor, a computer, and an independent power supply. There are many manufacturers and models within each equipment class that had the potential to meet minimum design and performance criteria. To limit the field of potential equipment for purchase and field testing, the research team first developed a set of system goals in the form of functional specifications (Wolf, Guensler et al., 1999b). The desired functional and performance specifications served as the screening criteria for selecting a candidate pool of technologies. The technical specifications for individual pieces of equipment within each equipment class that appeared to be able to meet functional specification goals were reviewed by the research team. The technical specifications and result of technical analyses are presented in Wolf, Guensler, et al., 1999c. The most promising components identified and reviewed were then selected for purchase and testing. This section of the final report summarizes information about each system component that was tested, including the original specifications, test plans and results, and final recommendations with respect to incorporating the equipment into the integrated package.

3.1 ETD (Handheld Device)

The driver interface is an essential component of the comprehensive electronic travel diary system. The driver interface allows the vehicle operator to record relevant trip data (driver name, passenger names, trip time, trip purpose, etc.). These data, collected during a large sampling program across an entire urban area, are used in travel demand model development.

3.1.1 ETD Original Specifications

During the initial requirements definition and component evaluation phase of this research project, researchers decided to evaluate only those handheld devices that supported keypad data entry. This decision was based on two primary issues: 1) the sponsor had just completed an electronic diary test with a touch screen device and was interested in the evaluation of non-touch screen technologies; and 2) the data capture requirements included provision of alphanumeric data entry for the respondents. In addition, the potential expansion of the project's scope to include non-vehicle trips dictated the need for a stand-alone device.

The original functional specifications included the option of having a driver device that was essentially a dumb terminal connected directly to the equipment package computer. A tradeoff analysis was conducted comparing features of a stand-alone device against a dumb terminal and it was decided to proceed with the stand-alone evaluation in order to allow for future scope expansion to capture non-vehicle trips.

Once the decision was made to evaluate stand-alone devices, the following handheld features were defined as desirable:

- The travel diary screens should support at least four rows of text or two rows of objects in a user-friendly format / presentation.
- Screen display should support backlighting with adjustable contrast for night and sunlight viewing.

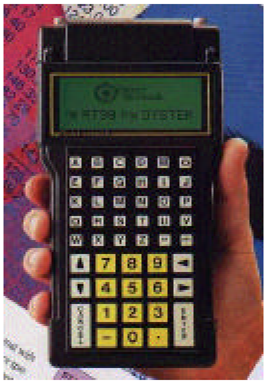
- The keypad must support data entry or selection of the driver name, passenger names, trip origin, trip destination, and trip purpose. Therefore, keypad must be alphanumeric.
- The keys should be positioned in a logical manner with adequate spacing between keys. Avoid dual-use keys.
- The device must be easy to use and non-intrusive.
- Time to enter all data should be minimized (target 15 seconds maximum).
- Power should be provided by self-contained rechargeable batteries or by a cigarette lighter power adapter.
- The trip information recorded on the handheld device must be time stamped to allow for post-process matching of various data streams. The user must be allowed to verify and correct the date and time to assist with the detection of time drift and/or battery failure.

The research team then identified and obtained three stand-alone, handheld devices for testing: the Psion Workabout, the WPI Oyster Termiflex PT2000, and the Percon PT1000 (see Table 1).

3.1.2 ETD Test Plans and Results

To evaluate the functionality and flexibility of each driver interface device, the research team designed a standard set of interface screens through which drivers enter all trip information. Programmers specified data files for the storage of all household and trip information on each device and created test scripts representing two typical households with trips made over a three-day period. Since these steps were very detailed, the complete listing of the screens and supporting logic, data files, and the test scripts are contained in the appendix of the test results document (Wolf, Guensler et al., 1999d). Once programmed with the test screens and files, researchers ran the devices through the test scripts. The research team evaluated each device using a variety of performance measures (see Table 2). Finally, the devices were examined by FHWA personnel in Atlanta, who assessed ease of use for each device and selected the Psion Workabout as the best of the three.

Table 1: Three Handheld Devices Evaluated



WPI Oyster TermiFlex PT1000

The PT1000 is a programmable terminal with PCMCIA card capabilities. The display is 8 lines by 32 characters (with a 4x20 option) and has a 48-button keyboard with an internal RS232 port. The handheld is programmed in C or BASIC and has PC programming packages. Thirty-five hours of use is available between charges of NiCd batteries, and options include an in-vehicle cradle for charging (and communications) and easy RS232 connection. Price for the base unit is $700 with 32K RAM; for software, docking station, and accessories add $400.

Percon PT2000 (shown with docking station)

The PT2000 is a handheld portable data collection device with a 4-line by 16-character display. The keypad has 34 alphanumeric keys, including four programmable keys and 10 dual alpha/numeric keys that require the use of a shift button. Maximum storage on the unit is 1 Megabyte, with a specified operation range of 12 hours on internal batteries and a 10-day battery backup for data storage in memory. There is a PS/2 interface to allow for use as a keyboard wedge or connection via a RS232 port. A docking station can recharge the unit without having to remove batteries or make any connections. Prices for the PT2000 range from $600 with 128K memory to $1360 with 2 Mb memory. The docking station is $200 and software at $300 must be purchased to program the unit. An additional $350 is needed for accessories.

Psion Workabout (shown with Vehicle Interface Cradle)

The Workabout is a rugged handheld, programmable device with the ability to store up to 16 MB of data on flash memory installed in the machine. Two keypad options are available on the units, a 57 key alphanumeric layout (shown in unit in cradle) or a 35 numeric keypad layout which has larger keys. The display is 240x100 pixels, with the ability to display graphics on the LCD screen; 39 characters by 12 lines is the maximum text. A sound buzzer is included on the unit. Power is provided through internal batteries that can be recharged through a docking station (fast charge) or via a Vehicle Interface Cradle (trickle charge). An RS232 port is available for communications. The price of the unit is $1100 with 2MB RAM, the docking station is $400, the VIC is $275, software is $100, and accessories are $250.

Table 2: Driver Device Testing Summary

Test Element	WPI PT1000	Percon PT2000	Psion Workabout
1) Battery / Power Source			
Number / type of batteries and time before recharge	4 AA-size NiCd batteries, built-in, rechargeable (difficult to replace)	3 AA alkaline or third party rechargeable NiCd batteries	2 AA alkaline or third party rechargeable NiCd batteries
2) Recharge Options			
Direct AC Adapter	No direct AC adapter	Direct AC adapter	No direct AC adapter
Cigarette Lighter	No cigarette lighter adapter	No cigarette lighter adapter	Cigarette lighter adapter
In-home docking station	Docking Station	Docking station	Docking station
In-vehicle cradle	No vehicle cradle	No vehicle cradle	Vehicle cradle
3) Power Draw (Power On)	Programmable auto-off	Programmable auto-off	Programmable auto-off
Power Down (Auto Off)	2.5 sec - 10 minutes	Default at 10 minutes	1 minute – infinite
4) Time Keeping Ability	< 1 minute over a week	< 1 minute over a day	< 1 minute over a day
5) Screen functionality			
Accommodates full design	8x32 screen-full design	4x16, with scroll to 8x32	12 x 39, full design, graphics
Scroll up /down and left/right	No scrolling	Scroll feature is confusing, paging required for full design	Scroll available (but not necessary with object-oriented program)
Back lighting flexibility	Back lighting (2.5 sec - 10min)	No back lighting (push button)	Back lighting (push button)
Adjustable contrast	Adjustable contrast	No adjustable contrast	Adjustable contrast
6) Screen Visibility (Readable)			
Day, with sun	Easy (although slight glare)	Easy	Easy
Day, no sun	Easy	Easy	Easy
Night	Easy	Difficult (no back lighting)	Moderate
7) Key Usability			
Layout / single key access	Easy	Moderate (confusing dual use keys)	Moderate
Ease of key press	Easy	Easy (buttons are well spaced)	Moderate (keys are close together)
Visibility at night	Easy Dark gray letters on gold (numbers) and pale white (alpha, arrows, misc.)	Easy (white letters, dark gray keys)	Easy (dark gray numbers, light gray keys, white letters on dark gray keys, and gray on gold keys
8) Overall User Friendliness	Easy to Moderate	Moderate (screen size limitation)	Easy to Moderate (must scroll)
9) Ease of programming	Easy to Moderate - compiled BASIC	Easy to Moderate – compiled PPG	Difficult – compiled OVAL
10) Ease of file transfers	Easy - Moderate	Easy	Moderate
11) Hard disk requirements (Kb)			900k (O/S overhead)
Program size	11.3k	12k	33k
Data files	12.1k (200 trips,50 ODs,50 people)	12.1k (200 trips,50 ODs,50 people)	143k
12) Size	8” x 4.25” x 1.75”	8” x 4” x 1”	7.44" x 3.62" x 1.38"
Weight	1.3 pounds	12 ounces	11.46 ounces
13) Portability	Moderate (slightly bulky)	Excellent	Excellent

3.1.3 ETD Final Recommendation

The research team selected the Psion Workabout for use in the prototype system as it was the most versatile unit and provided the best user interface capabilities. The Psion is a rugged handheld, programmable device with the ability to store up to 16 MB of data on internal flash memory. The unit has a 57-key alphanumeric layout and key entry does not require the use of a shift button. However, the keys are smaller than those on other units, making button presses more slightly difficult for individuals with large fingers. The unit integrates a 240-pixel by 100-pixel graphics screen, displaying up to twelve lines of text (39 characters per line) at a time. The screen is large enough to accommodate full survey page design, and can display graphics. The display has a backlight and screen contrast is adjustable by the user. The unit can provide an audible click for each key-press and will beep on command. The Workabout weighs 325 grams (11.5 ounces) including batteries. Prices for the Workabout as of January 1999 were $900 with 2MB RAM (standard), and an additional $300 for a 4 MB flash disk.

Power is provided through 2 internal AA batteries that can be recharged in a docking station (fast charge) or vehicle cradle (trickle charge). However, disposable batteries provide sufficient power for a week of travel data collection (trips only, no GPS data) without recharging. An RS232 port is available for communications. A Vehicle Interface Cradle (VIC) is available for the unit that provides a dashboard mount, one or three communications ports, and vehicle power conditioning. However, the current Georgia Tech project does not employ the in-vehicle cradle.

The Psion unit employs an object-oriented programming language (OVAL) which is similar to Visual Basic. The programming language is complex, but very powerful. The object-oriented program allows the provision of onscreen commands that allow users to turn from survey page to survey page at the push of a button. Hence, rather than scrolling through pages on the screen, larger pages can be broken into nested pages (where a button click takes the user from one page to another). The nested program capability also reduces the number of screens with which a user must interface. Screens that are not applicable, based upon previous data input, are never displayed.

The research team did not examine alternative handheld computers that employ touch screen technologies. As discussed in Wolf, Guensler, et al., 1999b, touch-screen units were outside the scope of the project, in part because a successful touch-screen unit was already in use on a FHWA project and alternatives needed to be evaluated. Unfortunately, Sony no longer sells the Magic Link, employed in the FHWA/Battelle travel diary project in Lexington, KY. Thus, the only touch-screen unit currently programmed for use as an electronic travel diary is unavailable for future studies (the replacement Sony technology requires new programming). Under a separate research project, Georgia Tech researchers are currently reviewing the specifications of several touch screen devices that came on the market in 1998. If any of these units appear promising for providing superior performance over the Psion unit, they will be procured and tested at Georgia Tech. GDOT and ARC will employ the Psion or an alternative unit in instrumented data collection activities associated with the year 2000 Atlanta household travel survey.

3.2 Global Positioning System (GPS)

To collect information about origin, destination, and route choice, a global positioning system (GPS) must capture actual x, y, and z coordinate data during each vehicle trip. Collection of spatially accurate route selection data is the overriding consideration in selecting a GPS system, data collection method, and data processing techniques. The research team stipulated that users should not have to interact with the GPS system and that a computer software interface shall trigger data collection.

3.2.1 GPS Original Specifications

To provide GPS capabilities from a moving platform (kinematic GPS), the selected GPS unit must be capable of simultaneously monitoring a minimum of eight satellite channels (four satellites need to be in view to achieve an acceptable position estimate). The GPS unit must provide second-by-second geocoded x-y coordinates for reconstructing routes. When position data collected during a trip are processed and imported into a Geographic Information System (GIS), the spatial detail must be of sufficient resolution that there is no confusion regarding which roads were traveled. The research team determined that the selected GPS receiver must be capable of providing spatial location of the vehicle to within 10 meters whenever a minimum of 4 satellites are in line-of-sight. This ensures that routes match to the correct roads when processed in a GIS system.

The unit should be capable of collecting and/or computing the following parameters: latitude, longitude, elevation, date, time, speed, heading, number of satellites used, PRNs (satellite identification numbers), PDOP (position dilution of precision, a measure of satellite geometry impacts on accuracy) and RMS (root mean square position error). Emissions are significant during the first few minutes of engine operation because the catalytic converter has not warmed up and emissions control systems are not functioning efficiently. To ensure data capture during this emissions-sensitive period, initial GPS positions should be determined within a maximum of 20 seconds after the unit is powered-up on a warm start and within 60 seconds after a cold start. Reacquisition time after loss of satellite lock should be no more than 3 seconds.

Because the travel diary will operate for at least one-week in field activities, the unit must provide the capability of collecting and storing 10 days of GPS data either on the controlling computer or on an independent data logger. A low profile antenna is desirable to discourage theft or loss. A dead reckoning capability is desirable for route reconstruction when satellite GPS signals are blocked (e.g., urban canyons, heavy tree canopies, and parking garages). Data transfer should be easy and efficient.

3.2.2 GPS Test Plans and Results

The research team procured and tested five different GPS receivers (manufacturers loaned two GLONASS receivers to the team). The research team tested the GPS receivers for positional accuracy and other performance measures. Table 3 describes each GPS receiver and Table 4 provides vendor specifications.

Table 3: GPS Equipment Description

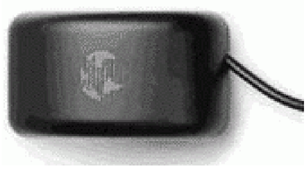
	GeoResearch Workhorse The Workhorse is an 8-channel GPS receiver manufactured by GeoResearch. It allows for differential correction, either real-time or post-processing, which yields a position accuracy of 2-5 cm. The unit has two serial data ports, which can provide interface capabilities with external devices, such as a PC.		Garmin GPS II Plus (handheld) The GPS II is a 12-channel GPS integrated antenna/receiver manufactured by Garmin. It allows for real-time differential correction, which yields a position accuracy of 5 meters. The unit has one serial data port, which can provide interface capabilities with external devices, such as a PC.
	3S GNSS-300 Sensor The GNSS-300 is a combined GPS-GLONASS receiver, with 12 channels that can be assigned to either GPS or GLONASS satellites. Using both satellite systems provides the receiver a position accuracy of 10 meters. The unit has two serial and one parallel data ports. An external PC can provide external control.		Garmin GPS35LP The GPS35LP is a 12-channel GPS integrated antenna/receiver manufactured by Garmin. It allows for real-time differential correction, which yields a position accuracy of 5 meters. The unit has one serial data port providing interface capabilities with external devices, such as a PC.
	Ashtech GG24 Sensor The GG24 is a combined GPS-GLONASS receiver with 12 L1 GPS and 12 L1 GLONASS channels. The use of both satellite systems allows the receiver to have a position accuracy of 16 meters in autonomous mode. The unit has three serial ports, through which external control can be provided.		PrecisionNav TCMVR-20 This low cost direction monitor has a 2-degree heading accuracy when level and 3 degrees when tilted. The selected unit is capable of operating between 0 and 20 degrees tilt. An RS232C serial interface facilitates external control. Heading information outputs in digital format at a programmable rate. This unit costs $345.

Table 4: Vendor Specifications for GPS Receivers

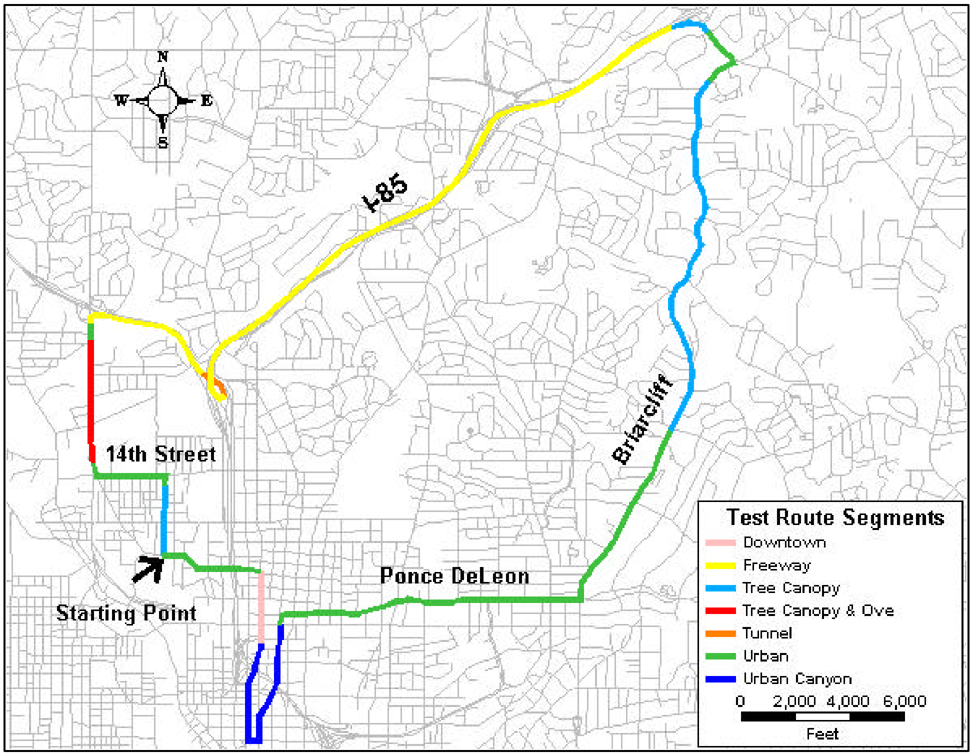
Manufacturer	**GeoResearch**	**Ashtech**	**3S Navigation**	**Garmin**	**Garmin**
Model:	Workhorse	GG24 Sensor	GNSS-300	GPS II Plus	GPS 35LP
Data Collection Activation / Deactivation	Can be controlled by external PC	Can be controlled by external PC	Can be controlled by external PC	Can be controlled by external PC	Can be controlled by external PC
Number of Channels	8 (GPS only)	24 (w/ GLONASS)	12 (GPS or GLONASS)	12 (GPS only)	12 (GPS only)
Antenna	Magnetic Mount	Magnetic Mount	Magnetic Mount Weight – 0.8 kg.	Detachable with standard connect	Embedded
Acquisition Times:					
Warm	22 sec	30 sec	30 sec	15 sec	15 sec
Cold	48 sec	40 sec	12.5 min	45 sec	45 sec
Re-acquire	2.5 sec	2 sec	10 sec	2 sec	2 sec
Update Rate	1 Hz	Up to 5Hz	1 Hz	1 Hz	1 Hz
Position Accuracy:					
Autonomous Mode:	100m with SA 25m w/o SA	16 meters GPS – 100m Glonass – 20m	10 meters	100m with SA 15m w/o SA	100m with SA 15m w/o SA
PP Differential Mode:	2-5 cm	75 cm GPS – 90 cm Glonass – 1m	NA	1 to 5 m with rtDGPS	5 m rtDGPS
PP DC Software	PostPoint ($350)	No	No	No	No
RT Differential (RTCM)	Yes	Yes	Yes	Yes	Yes
Velocity Accuracy	0.45--0.90 m/s A 0.05 m/s DC	0.15 m/s – Auto 0.05 m/s – DC	0.1 m/s	0.05 m/s	0.2 m/s
Data Storage Capacity	None	None	None	None	None
Size	83mm x 51mm x 15 mm	172mm x 58mm x 225mm	75mm x 178mm x 250mm	59mm x 13mm x 41 mm	56 mm x 96 mm x 26 mm
Weight	538 g	1545 g	2000g	255 g	124.5 g
Case	High impact, rugged	Water resistant	Receiver with environmental resistant enclosure	Receiver with integrated FTN display, detach antenna	Single construct integrated antenna/receiver water resistant
Temp Range (operating)	-30 to 85^{o}C w/o -20 to 60^{o}C with onboard battery	-30 to 55^{o}C	0 to 50^{o}C	NA	-30 to 85^{o}C
Power Source(s)	3 AH external 12vdc battery and charger	110/220 power supply and cables	110/220 power supply and cables	10-32 VDC, 4AA batteries or external	3.6 VDC to 6.0 VDC (LV$_{x}$ ver.) 6.0 VDC to 40 VDC (HV$_{x}$ ver.)
	Cigarette Adapter Lithium Battery	Cigarette Adapter	Cigarette Adapter	Cigarette Adapter	Cigarette Adapter
Interfaces:	NMEA0813 V2.00	NMEA0183 V2.01	NMEA0183 and RINEX	NMEA0183 V2.01	NMEA0183 V2.01
	2 serial ports	3 RS232 bidirectional serial ports to115,000 bps	2 serial ports 1 parallel port	1 RS232 serial ports	1 RS232 serial up to 19,200 bps
Cost (w/antenna)	$1795	$9250 / 5550	$8900 / 6675	$259	$350

A comparative evaluation of the GPS units required the development of a test route that includes a range of adverse conditions have the potential to affect GPS signal reception and/or data collection. Researchers developed a test protocol to assist in evaluation and selection of a GPS unit that would best meet the project goals and tested the accuracy of each GPS receiver along a standard route. The research team created a test route containing the following conditions expected to affect GPS operations:

- Open freeway segments where conditions are expected to be optimum for antenna reception
- Freeway and arterial overpasses, which are expected to block GPS signals for several seconds during data collection
- Urban arterials, which include electrical lines, telephone poles, and street signing, all of which may interfere with signal reception
- Tree canopies, made up of segments with dense overhead vegetation expected to interfere with signal reception
- Downtown segments, which are located in the central business district (CBD) with a significant number of buildings (especially those that are close to the roadway), but not as dense or tall as the urban canyon segment
- An urban street canyon, in the CBD, where dense development includes high-rise buildings close to the streets and overhead pedestrian walkways

The "tree canopy and overpass" segment differs from "tree canopy" sections due to the presence of several railroad overpasses along this area. Overpasses ensure intermittent loss of each satellite signals as the vehicle passes under the overpass, making loss of satellite lock more likely. The downtown segment refers to the area of the test route located in the central business district (CBD) but not in the urban canyon area where tall buildings surround the roadway. No GPS receivers could maintain satellite lock while in the urban canyon area. The test route was located near the Georgia Tech campus to facilitate frequent testing. Figure 1 provides a schematic of the test route (with color-coded test segments).

Figure 1: Test Route Segments



The research team compared field data captured along the test route with a corrected TIGER-based street network. This corrected street network is a proprietary, commercially available, street network residing in a GIS platform and made available to the university staff through a cooperative agreement. The proprietor started with the standard TIGER street network database manually geometrically corrected the database using such sources as aerial photos (typical), highly accurate GPS data, or other techniques.

Most GIS street databases use the roadway centerline as the reference line. A certain amount of accuracy error is inherent when the GPS data collected in a moving vehicle, which can change from lane to lane, are compared to roadway centerline data. On simple two-lane roads, this error may be 1.8 meters (i.e., half a lane width). Arterials with three lanes in each direction could have an initial position error of as much as 9 meters if the test vehicle is in the right-most lane (2.5 lane widths). Because the research team could not generate a separate validation data stream using a high-accuracy Ashtech Z-12 unit (see Guensler et al., 1999d) the roadway database centerline data were used for accuracy comparison. To provide consistent test conditions from unit to unit, the team drove the vehicle in the right-most lane whenever possible. Right-lane driving: 1) standardized the test run process across GPS units and thus the centerline error factor, 2) somewhat simulated the rules of the road by staying right except to pass, and 3) tested for worse-case tree canopy conditions. Accuracy measures were not ideal. Sub-meter accuracy would be impossible and reaching the initial goal of 10-meter position accuracy was difficult. Data were collected from each GPS receiver, processed, stored on a portable computer, uploaded to the GIS system, and analyzed for accuracy measures.

The percentage of data points falling within the specified distance for each segment type (freeway, tree canopy, overpass, urban, and downtown) are reported in a set of tables in Guensler, et al., 1999d. The tabulated results for the GPS systems is summarized as follows:

- The GeoResearch Workhorse outperformed every other GPS unit under every testing condition for providing high spatial resolution data at accuracy levels of 10m or better. At 30 meter resolution (percentage of data falling within 30 meters of the roadway centerline), the Garmin 35LP did outperform the Workhorse, but only on the combined tree canopy and overpass section.
- On most segments, GeoResearch Workhorse provided nearly twice the amount of data (60+%) at the 10-meter accuracy level compared to the lower-end Garmin units.
- All of the GPS units provided nearly 100% of the data at the 100-meter spatial accuracy threshold. At the 100-meter band, the Workhorse, Garmin II Plus, and the Garmin 35LP provided identical results.
- In tree canopy segments and areas where satellite signals are blocked more frequently, the Workhorse performed better than the lower-end Garmin units at high spatial resolution levels. However at 30, 50, and 100 meters, both low-end Garmin receivers give better results

The Russian satellite system, known as GLONASS, theoretically provides the same geographic coverage as the GPS satellites, only without selective availability. This means that if a complete GLONASS 24-satellite configuration is available for a GLONASS-capable receiver, differential correction would not be necessary for most applications. Although these receivers tend to cost more (approximately $9000 list price, $6000 with educational discounts), the benefit of highly accurate data without the overhead of differential correction is appealing. The research team borrowed GPS/GLONASS equipment from the two U.S. vendors offering combined receivers, which use both the GPS and GLONASS satellites in point calculations. The test results for these combined GLONASS devices clearly indicated they would not be useful for the electronic travel diary project. The GLONASS program has not yet achieved full satellite configuration and spatial accuracy was not acceptable (significant position scattering and absence of data for many route segments). The full analysis of the GLONASS systems and accompanying charts are contained in Guensler, et al., 1999d.

Because selective availability (scrambling of the satellite time codes by the military) introduces positional errors up to 100 meters, differential correction is a desirable feature. However, the GeoResearch Workhorse was the only GPS unit supporting post-processing differential correction that fell within the component's budget of $2000. (Real-time differential correction was not feasible at the time due to radio frequency limitations, however all units tested do support real-time correction, including the low-end Garmin units). Figure 2 below shows the difference between the absolute and differentially corrected data collected and analyzed for the Workhorse.

Figure 2: GeoResearch Workhorse Differentially Corrected Versus "Raw" Data

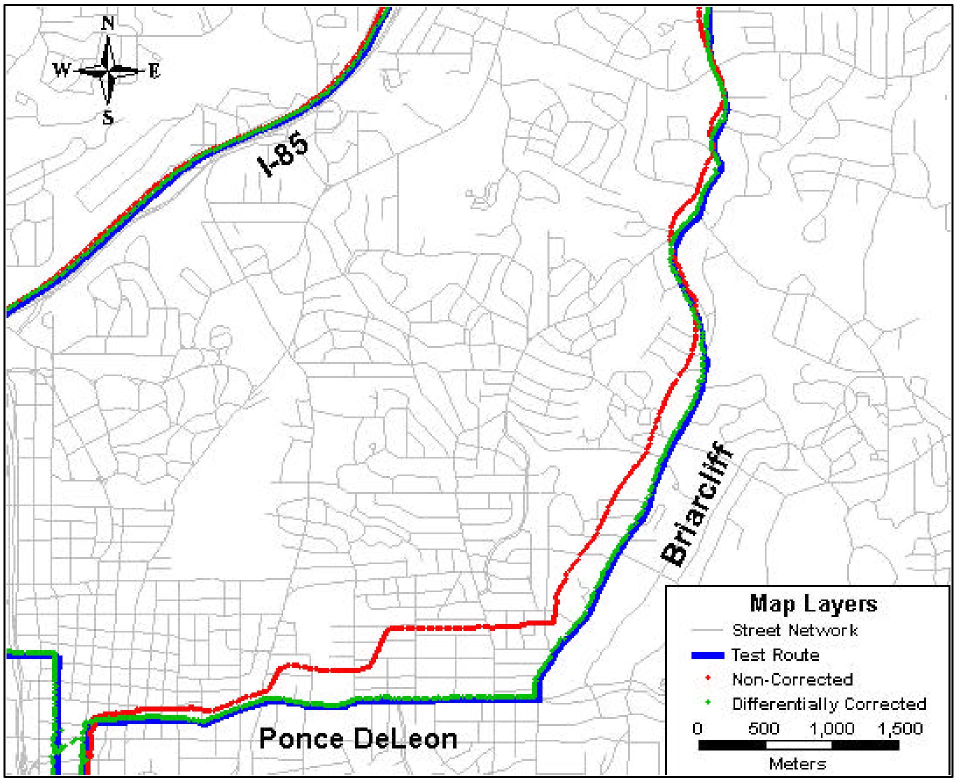


Table 5 compares the percentage of data points lying within specific distances from the actual test route between "raw" and differentially corrected data for three different test runs. Total number of points encompassed within each band width was calculated from the centerline of a geometrically-corrected TIGER-based street network. An average of 71% of GPS points for all three test runs were matched to within 10 meters of the street network while only 20% of uncorrected data were successfully matched to a 10-meter buffer. Even at a buffer distance of 50 meters from the street centerline, slightly more than half of the uncorrected points were located within the buffer distance. As illustrated, the use of uncorrected versus differentially corrected GPS data can have significant impact on the spatial accuracy of collected data points.

Table 5: GeoResearch Workhorse Corrected versus Uncorrected Data Accuracy

Percent GPS data points falling within specified distance of test route		**Total Points**	**Within 10 Meters**	**Within 30 Meters**	**Within 50 Meters**
16-Apr-98	**Corrected**	2859	72%	88%	88%
	Non-corrected	2859	19%	37%	53%
28-Apr-98	**Corrected**	2727	71%	100%	100%
	Non-corrected	2727	9%	34%	50%
7-May-98	**Corrected**	3979	70%	90%	92%
	Non-corrected	3979	31%	45%	55%

Complete route coverage is essential to route recovery; therefore, all missing portions of the route with no corresponding GPS data points were identified and a percentage of route covered was calculated for each receiver for each test run. Next, for all portions of the data stream in which there were no missing data, a points/second calculation was performed. This measure is critical since system requirements dictate one-second data capture intervals in order to adequately match GPS data with vehicle activity data spatially and temporally to the street network. Although each receiver was set up to capture data at this rate, not all GPS units actually achieve this rate.

Table 6 below shows both the route coverage and the number of data points captured per second for those portions of the route captured. Because all receivers were tested on the same fixed length route with the same environmental characteristics), the points per second ratio should be comparable across test dates. Receivers were tested separately. It should be noted that the capture rate was set at five second intervals rather than one second intervals for the first two runs with the GNSS-300.

Table 6: GPS Route Data Coverage (and Data Points/Second)

Date	Total Recorded Points	Route Coverage (% of route captured and points per second)					
		Workhorse		Garmin II +		Garmin 35LP	
		% route	Points/ sec	% route	Points/ sec	% route	Points/ sec
4/16/98	3511	100	1.0				
4/28/98	2918	99	1.0				
5/07/98	2445	100	1.0				
7/29/98	2782					93	0.8
8/06/98	2741	100	1.0	100	0.5		
8/28/98	2450	100	1.0	99	0.5	100	0.8
9/08/98	2500	99	1.0	100	0.5	100	1.0

Another performance measure of the GPS data is how well routes are mapped to street segments in a GIS using map-matching algorithms. Two factors that affect map-matching are missing data and data points that do not clearly follow the correct street segment. In Table 7 below, the percent of the route with missing data and the percent of data points across the entire route that would be incorrectly matched to the wrong street segment are shown. Overall, the Workhorse and Garmin 35LP have the lowest percentages of mismatched or missing data. The Garmin II Plus performed well, with no mismatches or missing data on one test run, only a 3% mismatch for the third run. However, 12% of the data would have been assigned to the wrong street segment.

Table 7: Map-Matching Results

Date	Workhorse	Garmin II Plus	Garmin 35LP
4/16/98	0% missing 3% mismatch		
4/28/98	1% missing 3% mismatch		
5/07/98	0% missing 2% mismatch		
7/29/98			7% missing 7% mismatch
8/06/98	0% missing 6% mismatch	0% missing 3% mismatch	
8/28/98	0% missing 5% mismatch	1% missing 13% mismatch	0% missing 4% mismatch
9/08/98	1% missing 2% mismatch	0% missing 6% mismatch	0% missing 6% mismatch

Because satellites employ highly accurate clocks, the research team initially assumed that the time stamps for all GPS data points would be accurate. While the different GPS receivers may not record the exact same positions at any given time, due to antenna placement and accuracy issues, the time stamps for proximal locations should be reasonably similar. As the study progressed, it became apparent that time stamps for each individual spatial data point may not be accurate. Detailed analyses of time shift issues are contained in Guensler et al., 1999d.

When comparing spatial data collected on different GPS units in a single test run, a clock shift appeared. At the start of testing, the two Garmin units provided identical time stamps for spatially proximal data points but 11-second clock shift was evident between the Garmin receivers and the GeoResearch receiver for spatially proximal data points. The initial lag between the two Garmin receivers and the Workhorse may be attributed to the difference between Greenwich Mean Time and the Satellite time used to establish the initial time stamp in the GPS unit at power on. Before combining GPS data with any other data stream (such as the onboard engine diagnostic data), researchers must identify the appropriate time shift for data handling. Alternatively, researchers can apply an independent time stamp is applied to all data as they are collected.

As the study progressed, the clock shift across all of the GPS units increased. The shift between one Garmin unit and the GeoResearch unit increased by 4 seconds. Even the two Garmin units that had started with identical time stamps had drifted by two seconds. The time drift across the units indicates that different algorithms are used to compute distance or interpolate time and position. Thus, each unit may be using different algorithms to assign a time stamp to recorded data after initialization. This finding further supports the need for developing an independent time stamp assigned in real-time to data from different data sources.

For the majority of GPS/GIS projects, this time variation is probably insignificant. It is not necessary to prove that each data point is temporally accurate, since a variation of even 20 or 30 seconds will have no effect on route choice recovery. However, for time-dependent applications, temporal accuracy is much more crucial. For the ETD project, temporal accuracy is important. Engine data link to GPS data points by time stamp, and then to a roadway position. Ideally, this information will allows vehicle activity to be related to physical characteristics of the road, such as grade or the vehicle's position on the roadway (such as when stopped at a traffic signal). A time drift of more than a few seconds could result in a false link between engine parameters and roadway characteristics such as grade or onramp acceleration. For example, a 20-second time drift could result in an enrichment event caused by a 9% roadway grade being mapped to a level segment downstream. Without the independent time stamp, researchers cannot accurately combine data from two different sources because it is impossible to address both time shift and time drift explicitly.

To obtain comparable measurement of start-up times, the research team defined warm and cold start-up times as follows:

- Cold Start Acquisition Time: The time between power-on and the time when the first position fix is obtained provided the ephemeris data in the receiver is at least 30 minutes old and that valid almanac, position, and time information are available.

- Warm Start Acquisition Time: The time between power-on and the time when the first position fix is obtained, provided the ephemeris data in the receiver is at least 15 minutes old and that valid almanac, position, and time information are available.

The mean values for start-up times obtained by the research team are listed in Table 8.

Table 8: Attributes Available for each Receiver

Receiver	**Cold Start (seconds)**	**Warm Start (seconds)**
Workhorse	69	57
Garmin II Plus	136	93
Garmin 35LP	38	18

The only receiver that came close to meeting the target value of 20 seconds for both the warm and cold starts was the Garmin 35LP. The other receivers require at least 47 seconds to start outputting usable data points. The differences between cold and warm start appear to be receiver-dependent.

3.2.3 Final Recommendations

After evaluating all measures of performance for each of the GPS units, the GeoResearch Workhorse appears to give the best overall performance. One important factor for the travel diary study is the unit's ability to consistently report data in one-second intervals. Another factor is that that unit provides good coverage of the street segment without missing large portions of data. It is also important that the reported data match correctly to the corresponding street segments since ultimately the data from individual vehicles will be matched to a street network. The Workhorse meets all of these requirements and in most cases outperformed the other units. For any GPS unit, the temporal accuracy issue must be addressed in combining data streams.

The Garmin 35LP and Garmin II Plus performed well, especially given the uncorrected data. Because they are available at a much lower cost than the Workhorse is, their use may be considered for studies in which the results are not as dependent on the unit's ability to consistently provide high positional or temporal accuracy. For example, the use of the lower cost receivers would be more suited to an application such as a travel time study, where the street segments traversed are known and runs with missing data may be discarded. In addition, the Garmin units will support real-time signal correction if a correction signal is available in the study region (either broadcast by the researchers or provided by a third party). If a correction signal is available for a study region, the Garmin units may be able to achieve accuracy comparable to the GeoResearch Workhorse.

Real-time differential correction may now a feasible alternative for use in electronic travel diary studies in Atlanta. Many GPS units can now be equipped to receive a radio signal broadcast directly from a base station by the research team or by a private company that operates a local base station. The correction signal compensates in real time for the selective availability introduced by the military. Because a correction signal arrives at the field GPS unit, there is no need to retain the copious satellite data required for laboratory post-processing. In essence, only the x, y, z, time, and a few precision measures need to be retained by the GPS. The reduced need for handling data can significantly reduce system memory requirements, power draw associated with recording data, and post-processing labor. The research team is currently field-testing two real-time differentially corrected GPS units in Atlanta as a component of a separate research project. These units are compatible with the Psion handheld diary. Researchers will use a Garmin 35LP GPS with real-time differential correction in Atlanta's year 2000 travel survey update, provided the real-time correction signal is viable throughout the region.

3.3 Onboard Diagnostic (OBD) System Monitors

OBDII is a standard engine diagnostic system and computer interface integrated into all new vehicles (as of model year 1996) sold in the US. The OBD system records a set of standard engine operating parameters and employs a standard data transfer protocol. The parameters available are dictated by SAE J1979, which gives the parameters required of Generic OBDII. The 29 parameters include emission related trouble codes, engine load, engine coolant temperature, intake manifold absolute pressure, engine RPM, vehicle speed, ignition timing advance, intake air temperature, mass airflow, throttle position, oxygen sensor output, and air:fuel ratio. Between 1981 and 1996, several manufacturers supported various OBD data streams, primarily for vehicle maintenance purposes.

Systems that can monitor an OBD data stream are known as "OBD scanners." Researchers can use these data, when combined with positional data (from GPS units) and driver demographic data, to separate the effects of aggregate travel behavior and individual driver behavior. The impacts that operating parameters such as congestion levels, grade, and other factors have on traffic flow can be discerned from those impacts that result from interaction of drivers with their vehicles (e.g. driver-throttle position interaction). When high-resolution operating data are available from a fleet of vehicles, traffic flow and motor vehicle emissions models can both benefit from the lessons learned about individual driver behavior.

3.3.1 Original Specifications

Issues of functionality were identified based on previous experience with OBD scanners. These issues served to identify the key features required of OBD scanners for use in this vehicle instrumentation package. These features include:

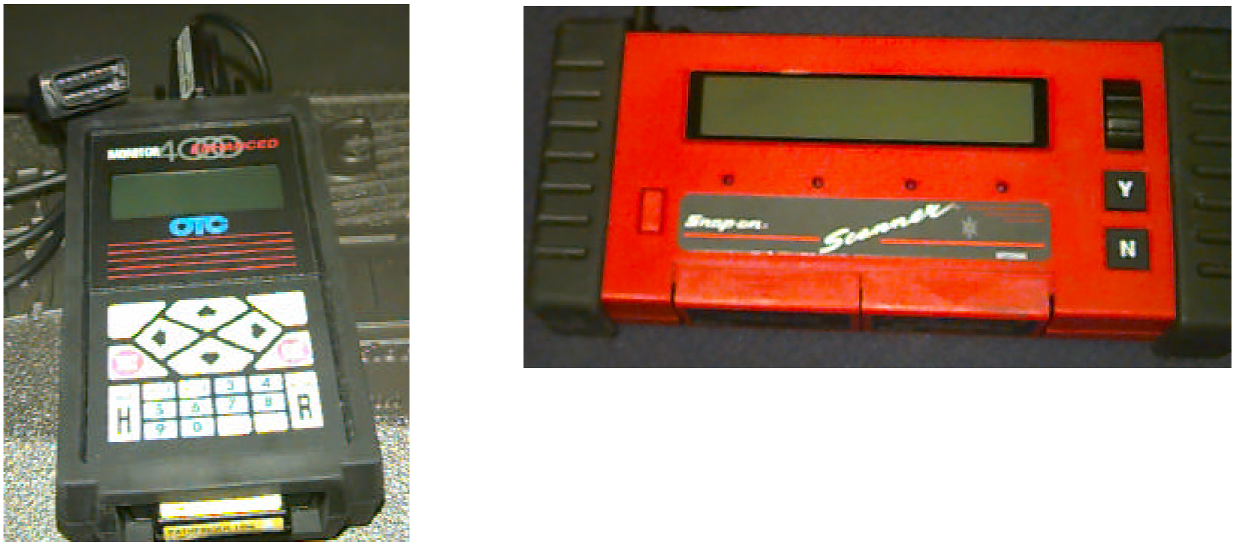
- The ability to provide engine and vehicle parameter values on a second-by-second basis for a minimum of 8 to 10 key parameters. This requirement is difficult to assess given that one second sampling rates do not necessary mean that the variables are updated each second.
- Parameter values should be precise. For example, integer values for speed may not be sufficient for use in calculations such as acceleration, especially if rounding or truncating has already occurred.
- A time and date stamp must be attached to each record from a central, synchronizing computer.
- Parameter values must be captured immediately upon vehicle start up. The first few minutes of vehicle operation are critical for monitoring variables which impact emissions.
- The OBD scanner must not require any manual intervention once the system is set up for a given vehicle. Each time the vehicle is powered on the OBD scanner must transmit parameter values immediately to the logging computer.

- Since OBD scanners do not support remote power on /off capabilities (which would introduce the need for key entry anyhow), the units will remain on throughout the duration of data collection. Therefore, scanner power consumption should be a key performance measure.

3.3.2 Test Plans and Results

Two units were initially identified for evaluation: the Snap-On Scanner and the OTC Enhanced Engine Monitor. A third monitor, a PCMCIA card offered by AED, was identified midway through the testing phase as a viable option for OBDII vehicles. The Snap-On unit has a proprietary architecture that requires manufacturer software modifications to meet specifications; consequently, this system was not included in the initial OBD engine monitoring tests. Details regarding the Snap-On scanner unit are available in Wolf, Guensler, et al., 1999d. Figure 3 below shows both the OTC scanner and the Snap-On Scanner. Test results to follow are for the OTC scanner and the AED PCMCIA card only.

Figure 3: The OTC Scanner (left) and Snap-On Scanner (right)



The on-board engine monitoring systems were evaluated across the following categories:
1) software interface to the engine monitoring system
2) power consumption of the unit
3) physical size and weight
4) operating limitations

<u>OTC Enhanced Engine Monitor</u>

The OTC unit has a serial terminal mode for monitor the data stream from the engine computer. All vehicles 1996 and newer are required to be OBDII compliant and will work with the OTC unit. Prior to 1996, there was no standardization and support varies across vehicles. Chrysler and GM vehicles from 1985 are supported with parameter selection. OTC also supports Ford vehicles from 1986 with at least selectable pages of parameters. Support within foreign vehicles is much more variable. Both Asian and European manufacturers have kept more of their engine interface protocols proprietary. The Europeans in particular have kept the diagnostic protocols and equipment proprietary, providing it only to their dealerships. Asian manufacturers have provided more information on the engine computer interface to the diagnostics companies. Additional OTC cartridges provide support for various vehicles. The unit provides methods to select the vehicle by description and VIN and stores the last six vehicle setups. The two primary cartridges used are Pathfinder 97, which supports domestic vehicles, and Import 96, which supports Asian cars. For newer cars, the generic OBDII mode will work as all outputs were standardized under Federal law. OTC was unwilling (or unable) to provide a list of vehicles (by manufacturer, model, and model year) that have data stream capabilities supported by their unit. Therefore, tables of supported vehicles were developed by paging through the software for each manufacturer, make, model, and model years and looking for a data stream option. The manufacturers supported by the OTC are presented in Wolf, Guensler et al., 1999d.

Normally the OTC unit is powered up when plugged in to the computer port on the vehicle. The power is transmitted through the connector, meaning that the OTC unit is running off the car battery. A special connector block was built to disconnect the power leads from the vehicle and provide external power for the unit so it does not drain the car battery when used in the ETD. Power down is done by disconnecting the power to the unit. After power down the unit must manually be put back into terminal mode. However, the OTC unit retains the last six vehicles setup in the unit.

Once the OTC unit is put into terminal mode it can be controlled from the PC. Control for different vehicles is complicated by the fact that there are different menu selections for different vehicles. The LabVIEW program controlling the OTC unit provides for variable keystroke patterns, but this requires that the researchers have a few hours with each vehicle to determine the format of the datastream and the keystrokes required to instigate and exit the datastream mode. Newer OBDII-equipped vehicles all work similarly, but many provide additional data items beyond those required by OBDII, still requiring an initial manual setup of the output screen.

The vehicle must be selected through its make, model, and year or VIN. A custom screen is selected and saved. The LabVIEW program starts and reads the name of the parameters from the output screen and then starts logging the parameters. The LabVIEW program sends the keystrokes to start the data stream mode. The unit takes 10-20 seconds to get into data stream mode. The data stream reacts differently to vehicle key-on and key-off depending on the vehicle. For OBDII vehicles, the data stream simply stops at key-off and resumes at key-on. This operation is used to advantage to detect engine-on and engine-off. This also allows only a 1-3 second delay in the start of logging of engine data when the engine is started, if the OTC unit is in data stream mode.

The OTC unit software controls data acquisition rate. Data are written to a tab delimited ASCII file every second. When data streams are provided less frequently than once per second, the parameter values are repeated. Because the data are in ASCII format, the size can vary, but the average size of the file for 11 parameters is approximately 200KB/hour. In OBDII mode, the unit monitors all the available parameters even if they are not displayed. This limits the update rate on engine data to about once every 3 seconds. However, this update rate limitation does not impact pre-OBDII vehicles. For example, if a subset of parameters is selected (e.g., 4 or 5 primary parameters) for older GM and Chrysler vehicles, one second data updates can be achieved. The output is provided in a tab-delimited column format keyed to GPS time. A new file is started for each trip (engine start). These data must be linked with the differential corrected vehicle position data and integrated within a GIS.

The OTC unit uses an RS-232 serial interface to a terminal or computer for display of output. The RS-232 interface must be enabled through manual keystrokes on the unit itself after power on. The initialization keystrokes are: "F2" (twice) to bring up the options menu, "2" to select display, and "2" to select terminal display. After this is completed, the unit can be controlled from a remote computer. The unit uses various connectors to the engine computer based on automobile make and model. The manual start-up of the unit requires that power be maintained continuously. A power failure will require manual activation of the unit before data collection can begin again.

When collecting engine data from various vehicles, the OTC unit writes engine and vehicle parameter values to disk for all available engine parameters. The parameters that are available for downloading from an engine are manufacture, make, model, and model year specific (Wolf, Guensler, et al., 1999d). Various engines report parameters in different units as well. Such differences are important to note in undertaking field studies. The inconsistencies across vehicles, in parameters reported and format, increased the associated labor with collecting engine parameter data.

VCS PCMCIA Card

An additional device used for engine monitoring, the VCS PCMCIA card manufactured by AED Inc., was obtained by the research team. The unit is a Type III PCMCIA card (taking up both card slots when inserted) that can be used to communicate with OBDII compliant vehicles. It has a LabVIEW library available for its programming. The major limitation is the fact that it is only usable with OBDII (1996 and newer) vehicles. The AED card allows low level communication conforming to SAE J1850 with the on-board vehicle computer. Each parameter is polled individually, allowing a much faster update rate than that available with the OTC unit. A single parameter can be updated at approximately 10 Hz. The AED card has been tested with a 1998 Ford and a 1997 Pontiac. Four parameters were logged at approximately 2 Hz. Apparently, AED has developed much of their equipment for GM and thus it appears that the AED card works better with GM vehicles. For GM vehicles, the requests could be sent as fast as the software could send without problems. However, the Ford controller was much more sensitive to timing issues; communications would lock up without a time delay between requests.

This card has the advantage of being fully computer-controlled and initialized and thus can be turned on and off with the computer if that becomes a power saving strategy. The card has only been used successfully with Generic OBDII. A method to gather the proprietary, vehicle-specific data that is reported by the OTC scanner is not available with this card.

Table 9: OBD Test Results - Summary

Manufacturer	OTC	Snap-On	Vetronix	AED
Product Name	4000 Enhanced	MT 2500	Mastertech	VCS PC Card
1. Software Interface Physical connection: Software Interface:	RS-232 Serial Controllable via LabVIEW	RS-232 Controllable via LabVIEW	RS-232 Serial Techview, bi-directional control	PCMCIA Type III LabVIEW library
2. Power consumption	300 mA, 12 V, (3.6 W)	? , 12 V	1000mA (12V via AC/DC converter)	200 mA (via computer)
3. Supported vehicles:	GM, Ford, Chrysler, Asian, and OBD II-equipped vehicles	GM, Ford, Chrysler, Asian, and OBD II-equipped vehicles	GM, Ford, Chrysler, Asian, and OBD II-equipped vehicles	Generic OBD II compliant vehicles
4. Power up/down	Cannot remotely power up/down the unit via software control.	Cannot remotely power up/down the unit via software control.	Cannot remotely power up/down the unit via software control.	Powered up and down with the computer
5. Initialization/Setup	Vehicle and parameter selections must be performed manually. Unit retains choices of selections through power cycles.	Vehicle and parameter selections must be performed manually.	Vehicle and parameter selections must be performed manually. Unit retains choices of selections through power cycles.	All initialization done in software, all communication is Generic OBDII
Parameter Selection	Selection limitations are varied based on vehicle models.*	Selection limitations vary based on vehicle models.*	Selection limitations are varied based on vehicle models.*	Selections limited to Generic OBDII
6. Data Acquisition				
Data Streaming Rate:	Varies based on # of parameters selected.* Once every 3 seconds 19,200 baud		High speed instrumentation interface	6-7 parameters at 1 Hz
Data Storage Rate:	Based on # of parameters selected. Maximum rate: 195KB/hour		Based on # of parameters selected and vehicle models	Same
Re-establishing data streaming after engine stall/ restart	Responses varied based on vehicle models.*	Manual reset is required	Manual reset is required	Data streaming continues at restart
7. Failure Recovery	Power off and on reset is required	Power off and on reset is required	Power off and on reset is required	Power off and on reset is required
8. Operation Condition	Not available	Not available	Not available	Not available
9. Physical Dimensions				
Size	5”x9.5”x2.5” (12.7x24.13x6.35cm)	5.3”x12”x2.25” (13.46x30.5x5.7cm)	4.5”x12”x3” (11.25x30x7.5cm)	Type III PCMCIA card
Weight	2.07 lbs.	3.06 lbs.	13 lbs.	na
10.Pricing				
Domestic	$1053 (with 10% discount)	$1595	$4146 (with 27% disc)	na
Asian	$738 (with 10% discount)	$800	$1278 (with 27% disc)	na
OBD II only	na	na	$2400	$1200
Accessories	$200	?	?	$350 (LabVIEW driver, 1 copy)

Comparative Results

The scanner evaluation summary is presented in Table 9. An additional scanner, manufactured by Vetronix, is also included in the summary. This scanner was identified during the final weeks of the project as another alternative to the Snap-On and OTC scanners. However, it is a high-end system with high-end prices to match. In addition, some customization would be needed to allow for capture beyond a 30-minute interval.

For all table entries tagged with an asterisk, the OTC initialization steps vary across vehicle models. At each setup, the selection of monitored engine parameters, the data streaming rate, and the steps required to re-establishing data streaming after a communication failure (including engine stall and restart) are vehicle-specific. This variation will require specific LabVIEW program modifications for some models during instrument installation.

3.3.3 Final Recommendations

The Snap-On MT2500 engine analyzer outputs a data stream of engine parameters. The interface is proprietary and logging of data is accomplished through an existing DOS-based program. This program is manually operated to start and stop the logging of the data stream. The program was also limited in the length of time it allowed logging. The research team worked with Snap-On software developers to determine the potential for modifying the Snap-On program to remove the time limit on logging the data stream and to allow control from a LabVIEW program. A quote was generated for the modifications and held until funding could be identified. In the intervening period, other customers began asking for Windows-based interfaces. Snap-On developed a PC translator program to communicate with the Snap-On Scanner through one serial port, translating the engine parameters to text and transmitted them out through a second serial port. This new program interfaces the Snap-On unit to other equipment in automobile test cells.

Snap-On is currently modifying the new program into what they are calling a dual-port RAM interface. The program will initialize the Snap-On unit, allow selection of engine parameters to report and then log these parameters into a dual-ported memory area that can be read by other programs. The interface reports the parameter names and units as well as the values. It also reports a special code to indicate engine-off. From the description given, it seems that this program could meet the qualifications to interface the current control program with the Snap-On scanner. This interface program is scheduled to be available in March 1999. The research team will continue to investigate the usefulness of the Snap-On scanner as new software becomes available.

Meanwhile, the OTC unit is the only viable onboard engine scanner available at this time. The reliability of the OTC to PC serial link was good during development testing. A few instances of OTC unit lockups occurred when initialization keystrokes were sent too quickly. In these instances, a power-off reset was required. One basic problem with the unit is that a manual keystroke is required to begin the data collection process. If the unit were to lose power during a testing period, the unit cannot restart without human interaction.

The OTC unit only provides second-by-second data when used in non-OBDII mode. Tests with new vehicles using the generic OBDII module resulted in 3-second data resolution. This resolution is insufficient for use in developing speed/acceleration profiles for use in engine load analyses. The lack of a viable standard OBDII mode for this unit increases setup labor during equipment installation. Parameters must be selected manually and, in some cases, adjustments to the LabVIEW code may be required. The research team believes that the same communication method is used for standard OBDII and proprietary data streams on newer vehicles, so there is currently no way around this limitation for newer vehicles. The team will continue to work with manufacturers of scanning equipment and urge them to improve their software such that 1Hz resolution will be achieved.

The AED VCS PCMCIA card provides acceptable data for OBDII-equipped vehicles. Six to seven engine parameters can be sent to the computer every second. The PCMICA unit also consumes 2/3 of the power that is consumed by the OTC. However, since completion of the analyses, the research team was informed that AED has gone out of business. The research team is currently searching for other PCMCIA-based scanning tools.

3.4 Computer

The computer will serve as the central data logging device for the various systems installed within the vehicle. Both the GPS receiver and the OBD scanner will transfer data to the computer for synchronization and storage. Other additional devices may also stream data into the computer, including devices which measure ambient temperature, relative humidity, catalyst temperature, or pollutant concentrations.

3.4.1 Original Specifications

The following features were identified as the minimum set of requirements necessary for the central computer within the instrumentation package:

- It must be portable and rugged, able to withstand temperature, humidity, and vibration extremes that can occur within a case located inside a trunk of a vehicle during a 10-day period at any time during the year.
- It must communicate over RS-232 serial links with the OBD engine monitor and the GPS receiver, requiring at least 2 serial ports.
- It must be able to log at least two independent data streams. These streams may be stored separately or in one integrated file, with each record tagged with the computer's date and time.
- To support PCMCIA-based applications or equipment, the computer must have PCMCIA slots – at least two Type I or II (which is equivalent to one Type III).
- A hard drive is required for storage of the operating system, programs, and logged data. The system must handle 750kB/hour for data logging for 14 hours (2 hrs/day for a week) of driving. Thus, 10.5MB of disk space is required for data storage. The Windows 95 operating system requires approximately 200MB of disk space and the compiled LabVIEW programs require 20MB of disk space. Allowing for hard drive swap space, a hard drive of 500MB capacity should be sufficient.
- A computer supporting a detachable keyboard and monitor is preferred. This will reduce the risk of screen damage and of respondent interference.

- The unit should support a deep suspend mode to lower power demand during non-use periods. In addition, the time for recovery from a suspend mode should be minimal (i.e., a few seconds) so that data is not lost when the vehicle is powered on. A triggering device / sensor may be implemented to assist with 'waking up' the computer prior to ignition on.

3.4.2 Test Plans and Results

The initial search of rugged laptops and portable computers revealed that only one product met most of the requirements mentioned above – the Datalux Databrick. Consequently, the research team purchased the Datalux Databrick 486, which has a detachable monitor and keyboard, a 486 processor and four RS-232 serial ports, and two PCMCIA expansion slots. It also contains an internal VGA video as well as a 1.5GB hard drive. The only disadvantage was a low operating temperature range – 50°C was the maximum temperature supported. The research decided that if this limitation were to become a problem, it would be addressed with air recirculation and/or cooling solutions.

Soon after the Databrick was purchased, Datalux discontinued the 486 and introduced the Databrick II, a Pentium-based unit. The Databrick II includes two RS-232 serial ports, two PCMCIA/CardBus expansion slots, an internal CD-ROM, and power management systems. Figure 4, the Databrick II, can be found on the following page. The research team purchased this computer and the Databrick II became the computer to test within the full instrumentation package configuration.

Figure 4: Datalux Databrick II

Windows 95 was selected as the computer operating system. It is currently the standard for Pentium computers and contains power management features. LabVIEW is the software used to develop the interface programs for the various components and the overall control program for the ETD system. The executables created in LabVIEW are then transferred to the Databrick II.

After receiving the Databrick II and building a working prototype system, the research team realized that the temperature limitation was a much greater issue with the Databrick than originally anticipated. First, temperatures with a trunk often exceed 50°C (122°F) in Atlanta during the summer months. In fact, temperatures measured during September revealed trunk temperatures approached 140°F when the outside air temperature was around 90°F for several hours (see Wolf, Guensler, et al., 1999d). In addition, the Databrick II does not support a deep suspend mode, meaning that it will consume power at high levels throughout the data collection process. These two issues, combined with the fact that Pentium processors typically generate heat at higher levels than a 486, indicated that there would be many times that the Databrick II would not be functional during the data collection period. A call to Datalux confirmed that at any time the processor temperature exceed 122^{o}F, the unit would simply shut down.

3.4.3 Final Recommendations

Although the prototype system incorporates the Databrick II, power draw issues and temperature concerns have prompted further research of rugged laptops possessing low power suspend modes and high temperature tolerances. Table 10 summarizes the results of this research. AED's Roadrunner was the best option found, with temperature tolerances ranging up to 70^{o}C and with a deep suspend mode having minimal power draw. Price discussions were conducted with AED during the December 1998. However, AED went out of business as of January 1, 1999 and thus the Roadrunner is not available for future use.

The next best solution is CyComm's PCMobile, which has a 586 processor, a monochrome monitor with a detachable keyboard, temperature tolerances up to 60^{o}C (140^{o}F), and a deep suspend /low power draw mode. Discussions on functionality and price have been completed with CyComm and the research team is currently waiting for the allocation of funds to purchase and evaluate this laptop within the instrumentation package. As a result of this change in the computer component, new casing will also be acquired to allow for the necessary clearance of a laptop monitor and for cooling and venting options.

3.5 Power Supply

One of the primary requirements of the vehicle instrumentation package has been that it is powered independently from the vehicle. This constraint arose from several concerns, including the need to minimize intrusion of the package within the vehicle, the need to reduce liability introduced by tapping into the vehicle's power system, and the need to eliminate the assistance of a mechanic. This requirement of independence has made the selection of a power supply very challenging given other constraints, such as those to minimize size and weight.

3.5.1 Original Specifications

Original requirements of the power supply include:

- Power supply should be sufficient to last for a 7 day period without failure
- Power system should not tap into the vehicle's power supply or electrical system
- Power supply should be easy to install (i.e., should not require a mechanic)
- Power system should not affect vehicle operation (from excessive weight of batteries)
- Power system should be small enough for implementation in all vehicle types, including those with limited trunk space such as in sport cars, sport utility vehicles, and trucks
- Power system should be safe (with no possibility of fluid leakage) and should be capable of withstanding both high and low temperatures in vehicles
- Power system should have minimal cabling to reduce intrusiveness of package and susceptibility for disconnected power during operation.

Table 10: Rugged Laptop Evaluation

Manufacturer	Datalux	Datalux	CYCOMM	AED	Stealth Computer Corp
Model	Databrick 486	Databrick II	PCMOBILE 586/133	RoadRunner	Stealth Notebook Warrior II
CPU Speed Standard (optional)	33 MHz (66 MHz)	120 MHz (166 MHz)	133 MHz	100 MHz	200 MHz (233 MHz)
Memory (RAM) Standard Optional	4MB 16MB	16MB up to 64MB	16MB 32MB	8MB 32MB	16MB up to 128MB
Hard Disk Space Standards Optional	840MB	1.4GB	4GB 520MB or 1GB PCMCIA	1GB	2.1GB up to 5GB
Ports Number of Serial Number of Parallel	2 Bi-Directional, ECP, or EPP (IEEE 1284)	2 1	1 1	1 1	2 (D-type) 1 (25-pin parallel port, EPP/ECP)
PCMCIA Slots	2	2	4 Type I/II or 2 Type III	2	2
Docking Station Expansion Options	No Mounting Bracket	No Mounting bracket	Yes 4 serial ports	No	No
Disk Drive (S/O, I/E) CD Drive (S/O, I/E)	Optional, int. or ext.	Optional, External Optional, Internal	Optional, External Optional, External	Optional, External Optional External	Optional, External Optional, External
Power Source	AC-DC, Switching IEC input, 100-260 VAC	Universal AC, 12 VDC Optional 12 V DC-DC	9-20 VDC input, universal AC adapter	7-32 VDC, no conversion required	10-20VDC direct input car 20-32VDC car adapter
Power Demand (spec) Active Suspend	12.4 V at 1.92 A 12.4 V at 1.76 A	12.4V at 2.19 A 12 4V at 1.29 A	12V at 2.08 A 12V at 0.28 A	12V at 1.75A 12V at 10 mA	
Temperature Range Operating Storage	+5 C to +50 C (+41 F to 122 F) -5 C to +85 C (23 F to 185 F)	5 C to +50 C (+41 F to 122 F) 0 C to +85 C (32 F to 185 F)	-30 C to +60 C (-22 F to 140 F) -40 C to +85 C (-40 F to 185 F)	-20 C to +70 C (-4 F to 158 F) -40 C to +85 C (-40 F to 185 F)	-20 C to +50 C (-4 F to 122 F) -40 C to +70 C (-40 F to 158 F)
Operating Vibration Range			Can withstand 3-ft drop on concrete		0.075mm 55-500Hz
Detachable Monitor	Yes	Yes	No	No	No (has external monitor port)
Detachable Keyboard	Yes	Yes	Yes	Yes	No
Size in Inches (cm)	2.16”x11.32”x9.46” (5.49x28.75x24)	2”x10.25”x6.5” (5.08x26.03x16.51)	3 ¼”x11 3/8”x10 5/8” (8.26x28.89x26.99)	2.3”x11”x8” (5.64x27.94x20.32)	2.6”x12.2”x10.0” (6.6x31x25.4)
Weight in Pounds (kg)	3.3 lbs. (1.5 kg.)	4.4-5.28 lbs. (2.0-2.4 kg.)	9.6 lbs. (4.32 kg.)	6.3 lbs. (2.84 kg.)	10.78 lbs. (4.9kg.)
Standard Price With desired options	No longer available	$2385	$5,422	$5,500	$4,895

Table 10: Rugged Laptop Evaluation (Continued)

Manufacturer	Stealth Computer Corp	Dolch	Dolch	ADMAX	Omnidata / GeoResearch
Model	Notebook Warrior ER	DuraPAK	FieldPAK		RDT 3000
	ER-4024 (486)				
CPU Speed					
Standard	66MHz	166 MHz	166 MHz	166 MHz	25 MHz
Options		233 MHz	233 MHz	200 MHz	
Memory (RAM)					
Standard	4MB	16MB	32MB	16MB	1MB
Options	up to 16MB	up to 64MB	up to 128MB	128MB	up to 8MB
Hard Disk Space					
Standards	1.2GB	2GB	2.0GB	2.2GB	
Options	up to 5.0GB	4GB	4.0GB		
Ports					
Number of Serial	2 Standard -D Type	4 RS-232	2 RS-232	2	2
Number of Parallel	1 Standard - D Type	Bi-directional	Bi-directional	1	1
PCMCIA Slots	2	2	2	2	1
Docking Station	No	No	No	Yes	
Expansion Options					
Disk Drive (S/O, I/E)	Optional, External	Optional, External	Internal	Optional, Removable	
CD Drive (S/O, I/E)	Optional, External	Optional, External	Internal	Optional, Removable	
Power Source	90-264 VAC/12-16 VDC	90-265 VAC, external 12 VDC adapter	90-265 VAC, 12 VDC via external adapter	Ni-MH battery, AC adapter	
Power Demand					
Active					0.75 A
Suspend					
Temperature Range					
Operating	-20 C to +50 C	0 C to +50 C	0 C to +50 C	-10 C to +60 C	-20 C to +50 C
	(-4 F to 122 F)	(32 F to 122 F)	(32 F to 122 F)	(14 F to 140 C)	(-4 F to 122 F)
Storage	-40 C to +70 C			-20 C to +65 C	-30 C to +60 C
	(-40 F to 158 F)			(-4 F to 149 F)	(-22 F to 140 F)
Operating Vibration Range		10-55 Hz, 0.3mm, 55-500 Hz, 2.0 G		5-5.5 Hz 1.0 in 5.5-200 Hz 1.5 G	13 Hz-1500 Hz 4 G 1500 Hz-2000 Hz 2 G
Detachable Monitor	No	no	No		No
Detachable Keyboard	No	removable	Yes		No
Size (inches and cm)	2.75"x13.4'x10.4" (6.99x34x26.4)	4.0"x15.0"x11.0" (10.16x38.1x27.94)	3.0"x18"x13 (7.62x45.7x33.0)	2.5"x12.3"x9.7" (8.25x31.2x24.8)	1.6"x11.5"x9.0" (4.1x29.2x22.9)
Weight (lbs. and kg)	14.3 lbs. (6.4 kg)	12.5 lbs. (5.63 kg)	15 lbs. (6.8 kg)	9.5 lbs. (4.3 kg)	3 lbs. (1.6kg)
Standard Price	$5,295	$9,495	$7,995	$5,900	
With discount		$6,296	$5,393		

3.5.2 Test Plans

As stated above, power system specifications call for the vehicle data logging system to run on its own independent power supply for a one-week test period. To determine the necessary battery capacity for this task, the power draw for each of the system components was determined. Worst-case total operating time over a week was estimated and the total power demand calculated. The basic system consists of three primary components: the computer, the GPS unit, and the engine monitor. It is assumed that a stand-alone driver trip entry device will be used and not require power from the instrumentation package batteries.

Power Draw Assessment

To determine actual power draw, each component of the final prototype was connected to a 12-volt battery and operated in a normal mode. Voltage and current were measured over the typical operating ranges of the unit. If a power saving mode was available, it was initiated and the power was measured again. Table 11 provides the results of component power draw analyses.

Table 11: Measured Power Consumption

Unit/Activity	Voltage	Current Draw (amps)
OTC Engine monitor	12.33	0.28
GeoResearch Workhorse	12.48	0.21
Databrick II (Pentium) idle	12.4	2.03
Databrick II HD active	12.4	2.20
Databrick II doze (slowed CPU)	12.4	1.46
Databrick II standby (video off)	12.4	1.33
Databrick II suspend (drive off)	12.4	1.24

The next task was to estimate the worst-case operating time for each component and to calculate total power required for the week. The computer will have to be on the entire time, at least in a power saving mode. Although it may be possible to power down the GPS receiver and the OBD scanner, there are considerations regarding start up time for these components as well as operational limitations, such as manual key press requirements, that are not fully resolved. Therefore, the worst case analysis assumes that both components will be powered on for the full week. The power system must provide continuous operation of the equipment package for a full week (168 hours). The total power required, based upon measured power draw, and the total operating time, determine the capacity and thus size of batteries required for a week of unattended operation. The total power draw for the prototype unit is estimated to be 452 amp-hours (168 hrs * (2.2 amp (Databrick II) + 0.28 amp (OTC) + 0.21 amp (GPS)). However, this estimate does not include any safety factor or adjustment for battery capacity reduction with use.

The majority of the power draw is due to the computer. The Pentium-based Databrick II has fairly high power draw when active, but does support a range of power saving modes. If no activity is occurring, the computer goes into doze mode, which slows the CPU speed and reduces power consumption. The Databrick II also supports standby and suspend modes, with even lower power demands. However, the Databrick II does not support the deep suspend modes that other laptop PC's offer (typically below 1.0 amp). There is also a downside to power saving modes -- the time it takes to recover and start collecting data once commanded. The Databrick II takes from 5 to 15 seconds to "wake-up" from the suspend mode.

After the instrumentation package was assembled, system power draw was tested. Both the Workhorse and OTC unit were powered on constantly. The Databrick II was set in power saving mode, providing the only variable power draw. Activity on the keyboard or serial ports awakens the Databrick from low power modes. Thus, while the system is logging data, constant activity on the serial ports keeps the Databrick operating in high power mode. When the key is turned off, the OTC stops sending data. The lack of an OTC signal triggers the Workhorse to stop sending data, allowing the Databrick to enter low power mode. Measured power draws of the system while operating and idle are:

- Power consumption during logging: 2.68 amps
- Power consumption during suspend: 1.78 amps

Table 12 shows the power system capacity requirements (in amp-hours) under various vehicle usage scenarios. Because some batteries (e.g., lead-acid, absorbed glass mat, nickel cadmium) do not recharge well after discharging to less than 20% of the remaining capacity, the seven-day power demand has been adjusted upward 20% to accommodate the recommended reserve level.

Table 12: Power Demand: Databrick II, GeoResearch Workhorse, and OTC Scanner

Power Demand Scenarios	15 min/day (infrequent use)	2 hours/day (average use)	5 hours/day (maximum use)	24 hours /day (worst case)
1 day	42.9	44.5	47.2	64.3
3 days	128.7	133.5	141.6	192.9
3 days + 20%	154.4	160.2	169.9	231.5
7 days	300.6	311.6	330.5	450.2
7 days + 20%	360.7	374.0	396.6	540.2

Battery Research

A summary of the battery alternatives considered and their associated parameter values can be found in Table 13. The estimates are based on the requirement of providing power for 168 hours (7 days), where two hours of vehicle operation are considered for each day. The alternatives are sorted in order of lowest total weight to highest total weight. In cases where the battery voltage is less than 12 volts (which is required by the instrumentation system), the batteries will be connected in series, so that the capacity of the connected batteries remains constant, while the voltage is combined. Conversely, in cases where the battery voltage is 12 volts, batteries will be connected in parallel so that the total capacity will be the summation of the individual capacities.

Analysis of the table reveals that the lowest weight solution, which is the zinc-air batteries at 42 pounds, comes at an unacceptably high cost ($5187). The silver zinc battery solution weighs only 53.6 pounds, but is also too expensive ($6000). To reduce battery costs, other technologies such as absorbed glass mat, lead acid, gel, nickel cadmium, and nickel metal hydride were considered. However, these more traditional technologies come with greatly increased weights. The best (i.e., lowest weight and cost combined) of the 13 alternatives in these categories was the Trojan SCS 225 lead acid battery. This solution requires three batteries connected in parallel

(13.5 x 20.7 x 9.9 inches) at a total cost of $291 and a total weight of 211 pounds. Although the cost is reasonable, the size and weight are such that vehicle operations and emissions may be affected for smaller vehicles. Given that the other alternatives all have even greater weights (with the exception of the nickel cadmium, which is too expensive), independent battery alternatives may not be feasible for a full week of data collection. Using one or two batteries would reduce weight and size of the battery pack, but would reduce power capacity accordingly.

Solar panels were also considered as an independent power source to provide power for two hours of vehicle operation each day over one week. “Micro EX” solar panel technology, developed by ICP Canada (which specializes in compact solar panels to recharge the battery of the vehicle) is a representative technology. The solar panel alternative, however, would require 78 panels connected in parallel (each panel is 36"x12"x1", 1.17 pounds, and $170.00). The low power generated by the panels (four AH average per day for seven days) and the relatively large dimensions of the solar panels do not provide a feasible solution for this project.

As a result of this research, and to support three-day system tests of the equipment package, a Trojan 5SHP lead acid battery (183A, 86 pounds) and a Trojan SCS225 (144A, 66 pounds) lead acid battery were obtained. Results of the system tests, including a full power demand analysis, can be found in the system evaluation section.

Table 13: Alternative Battery Characteristics

Technology	Manufacturer/ Model	Nominal voltage (V)	Rated capacity (AH)	Weight (lbs.)	Cost Per unit	Qty.	Total weight (lbs.)	TOTAL COST	Dimensions L (in)	W (in)	H (in)
Zinc-air	AER Energy Resources Model – 12015	1.4	23	0.36	$399 per 10 cell	126	42.12	$5,187	5.12	2.88	0.55
Silver-zinc	Yardney LR 360	1.5	360	6.7	$750	8	53.6	$6,000	5.83	2.73	7.36
Lead acid	Trojan 5SHP	12	183	86	$166	2	172	$332	13.6	6.9	11.4
Lead acid	Trojan SCS 225	12	144	66	$91	3	198	$273	13.5	6.9	9.9
Nickel metal Hydride	Ovonic	13.2	85	40.04	$2,500	5	200.2	$12,500	16.36	4.08	7.04
Nickel cadmium	SAFT STM5.180	6	180	51.04	$1,023	4	204.16	$4,092	10.4	7.6	10.4
Lead acid	Yuasa DM80/12	12	80	47.0	$167	5	235	$835	12	6.3	8.0
Lead acid	Power Sonic PS-121000	12	100	65	$168	4	260	$672	12	6.6	8.2
Lead acid	Energystore 12RP570	12	570	294.8	$320	1	294.8	$320	20.4	11.9	22.8
Lead acid	Power Sonic PS-12800	12	80	62.4	$161	5	312	$805	12.0	6.6	8.2
Absorbed glass mat	Lifeline 8D	12	255	158	$334	2	316	$668	20.6	11.0	10.2
Gel	SEC 12-260G	12	260	161	$339	2	322	$678	20.8	11.0	10.0
Absorbed glass mat	Optima D750	12	52	46.1	$180	8	368.8	$1440	9.94	6.88	7.81
Nickel cadmium	SAFT STH 1900	1.2	190	20.46	$331	20	409.2	$6,620	4.68	6.64	13.6
Lead acid	Rolls 6CS-25P	6	820	318	$815	2	636	$1630	22.0	11.3	18.3

Source: Trojan Battery Company

Battery Recharging

The research team also identified the need for battery chargers. There are fast and regular speed battery chargers available on the market with recharge rates of 20 and 10 Amp/hr, respectively. Associated Model 9411 is the one recommended by Voltex, the company through which the researchers purchased the Trojan batteries ($145). Another option is to buy a regular charger with a 10 Amp/h rate ($40 to $60). Table 14 summarizes the time required to recharge the two batteries acquired on each of the chargers. The team tested one battery of each type.

Table 14: Time Required for Battery Recharge

Battery capacity Amp	Associated Model 9411 20 Amp/h rate	Regular 10 Amp/h rate
144 (Trojan SCS 225)	7.2 hrs	14.4 hrs
183 (Trojan 5SHP)	9.15 hrs	18.3 hrs

3.5.3 Final Recommendations

Since preliminary research found no feasible independent power solutions for a seven-day data collection period, the research team did perform a thorough review of alternative power configurations in which the power supply was recharged and/or supplemented by the vehicle's power and electrical system. This analysis is contained in the power analysis section of Wolf, Guensler, et al., 1999d. However, this dependency is still not preferred and therefore not presented here. The research team decided instead to re-examine the power demand side of the equation and to replace the power-draining Databrick II with a more efficient rugged laptop.

When a low-power-draw alternative to the Databrick II is obtained, such as a rugged laptop with a deep suspend mode, the Trojan 5SHP battery may provide the power needed for an entire week. The tradeoff in this case is that most rugged laptops range in price from $5000 to $10,000. As an example, the AED Roadrunner has an active power demand of 1.75A and a suspend-mode power demand of 0.1A and costs $5500 (note: this company is no longer in business). Cycomm's PCMobile is the next best alternative, with an active power draw of 2.08A and a suspend draw of .28A ($5400 fully loaded).

Various power demand scenarios for a system that includes the PCMobile rugged laptop, the OTC scanner, and the GeoResearch Workhorse can be found in Table 15. With this configuration, an active mode consumes 2.57 amps (2.08 amp (PCMobile) + 0.28 amp (OBD) + 0.21 amp (GPS)) and a suspend mode draws 0.77 amps (0.28 amp (PCMobile) + 0.28 amp (OBD) + 0.21 amp (GPS)). Using a maximum use scenario of 5 hours per day of vehicle operation, the total power demand for one week would be 7* (5*2.57 + 19*.77) → 192AH needed for the period. Once this is adjusted for the minimum capacity reserve of 20%, a single battery with 231 AH would suffice for the entire week. With an average of 2 hours per day of vehicle operation, the one-week power demand, adjusted for the minimum capacity reserve, decreases to 185AH. For this scenario, the Trojan 5SHP would work; the only disadvantage would be the weight of 86 pounds.

There is one additional scenario necessary for future power demand analyses. The total length of installation as proposed in the deployment plan calls for a nine-day cycle, which means that the system needs to operate for at least nine days. When the total demand is calculated for the various use patterns, the final capacity needed is in the range of 200 to 300AH. The system power demand does dictate a need for further battery research (or identification of new components with lower power demand). The research team plans to continue to evaluate new battery systems with improved power-to-weight ratios as they become available.

Table 15: Power Demand: PCMobile, GeoResearch Workhorse, and OTC Scanner

Power Demand Scenarios	15 min/day (infrequent use)	2 hours/day (average use)	5 hours/day (maximum use)	24 hours /day (worst case)
1 day	18.9	22.1	27.5	61.7
4 days	75.7	88.3	109.9	246.7
4 days + 20%	90.9	106.0	131.9	296.1
7 days	132.5	154.6	192.4	431.8
7 days + 20%	159.0	185.5	230.9	518.2
9 days	170.4	198.7	247.3	555.1
9 days + 20%	204.4	238.5	296.8	666.1

The following component configuration alternatives will also be considered in the next round of equipment testing. Accordingly, power assessments should be updated for these equipment options:

- GeoResearch Workhorse GPS Receiver (.21A) with a DCI3000 Radio Receiver (for real-time corrections at .12A)
- Garmin 35LP GPS Receiver (.12A to .14A) with a DCI3000 Radio Receiver (for real-time corrections at .12A)
- Any additional sensors which require external power, such as an electronic compass

4. SYSTEM EVALUATION

The prototype instrumentation package developed and tested under this research project consists of an onboard GPS receiver with a low-profile magnetic-mount antenna (the GeoResearch Workhorse GPS receiver and antenna), an OBD-II onboard engine computer monitoring system (the OTC enhanced scanner), and an onboard portable computer (the Datalux Databrick II). In addition to the equipment package installed in the vehicle, the driver is given a handheld electronic travel diary (the Psion Workabout) on which they are asked to record basic travel diary information, such as trip origin, destination, and purpose.

The integrated equipment package is battery powered and self-contained in a single suitcase-sized box. For the prototype system, a case produced by Cadence Manufacturing was purchased. This heavy, rugged case (27 pounds, 9”x12”x24”) is standard for music equipment storage (see Figure 5). The configuration of the unit is such that that the system can be placed in the trunk of a vehicle with connecting cables to the low-profile GPS antenna and to the OBD diagnostic system interface.

Figure 5: Integrated Equipment Package

Table 16 lists the integrated system components and their specifications. Components are configured to remain dormant when the vehicle is not in operation and to use the auto ignition signal to trigger data collection. The system can be placed in the trunk of a vehicle with connecting cables to the low-profile GPS antenna, located on top of vehicle or trunk, and to the OBD diagnostics system interface, which is typically located inside the passenger compartment under the steering wheel or passenger-side dashboard.

Table 16: Prototype System Components and Specifications

Components	Databrick II (computer)	Workhorse (GPS)	OTC 4000 (OBD scanner)	Trojan SCS225 (battery)
Temp. Range:				
Operating	5 C to +50 C (+41 F to 122 F)	-30 C to +85 C	Not Specified	-18 C to +52 C (0 F to 125 F)
Storage	0 C to +85 C (32 F to 185 F)	-30 C to +85 C	Not Specified	
Power Demand	2.19A (active)	0.21A	0.28A	
Supply	1.29A (passive)			144 AH (12V)
Size (inches)	2”x10.25”x6.5”	2”x3.25”x0.64”	5” x 9.5” x 2.5”	13.5”x6.9"x9.9"
(cm)	(5.08x26.0x16.5)	(5.08x8.26x1.6)	(12.7x24.1x6.35)	(33.8x17.3x24.8)
Weight (lbs.)	4.4-5.28 lbs.	1.17 lbs.	2.07 lbs.	66 lbs.
(kg)	(2.0-2.4 kg.)	(0.532 kg)	(1.390 kg)	(29.7kg)
Cost	$2250	$1795	$1989	$91

4.1.1 Operation

A LabVIEW program running on the rugged computer serves as the controller of the integrated instrumentation system. This program coordinates the collection and storage of the data streams generated by the engine monitor and the GPS unit. The engine monitor data stream, which is automatically triggered each time the vehicle is powered on, is used to trigger the logging of both engine and position data. Each time the engine monitor data stream ceases, LabVIEW then closes the log files for the current trip. The engine and GPS data streams are stored in separate files due to the need for differential post-correction of the GPS data. The GPS time stamp is used to tag the engine parameter data to facilitate the matching of the engine and position data in the post-processing phase.

As mentioned above, the system generates a new set of log files for each engine start, assuming each engine start is a new trip. Consequently, the system will miss some trips embedded in trip chaining when the engine is not turned off between trips, such as what occurs while stopping at a drive-through fast-food window. These cases will need to be detected during post-processing. Each file is named based on the computer date and time to facilitate matching the captured data with the travel diary data entered on the driver device. The raw GPS data file requires 550 kilobytes of storage space per hour and the engine parameter data requires 200 kilobytes of storage space per hour.

4.1.2 Installation

The instrumentation package was designed to have minimal connection with the vehicle so that a mechanic would not be required for installation. Therefore, the prototype system requires only a connection to the engine computer. The package (33 pounds) and its power supply (a 66 pound, 12V deep cycle battery) are placed in the trunk of an automobile or inside the passenger compartment of a truck or sports utility vehicle. Then, a cable is routed to the engine computer port and the GPS antenna is placed on the trunk lid or vehicle roof. The OTC engine analyzer is initialized for the given vehicle and is placed in terminal mode to enable communication with the computer. The LabVIEW logging program is then started and the instrumentation case closed. The instrumentation package then logs trip data each time the engine is started. In addition, the driver records basic trip information for each trip using the handheld device.

4.1.3 Evaluation

Due to several equipment problems (a faulty Datalux monitor, servicing of the Ashtech Z12 base station, and Databrick power and temperature issues), system tests were delayed until January 1999. In addition, the high power demand of the Databrick II reduced the test period from seven to three days. The first test occurred on the weekend starting on January 8 in a 1997 Pontiac Grand Prix. The instrumentation was installed in the vehicle trunk with one 12V Trojan battery (144AH) provided for power. The engine computer in the passenger compartment was connected to the equipment package with a cable and the GPS magnetic mount antenna was placed on the trunk lid. The handheld device was given to the driver after usage instructions were reviewed.

The system started logging trips at 4:37 p.m. on Friday and the last trip was logged at approximately 9:30 p.m. on Saturday, January 9. The battery was fully discharged sometime between 9:30 p.m., January 9, and 9:30 a.m., January 10, effectively ending all further data collection. During this weekend, the GPS base station at Georgia Tech also logged correction data for post correction of the GPS information. All data were transferred from the instrumentation package and handheld device for analysis.

During the period of equipment operation, nine trips were entered on the driver device, the first of which was a fictitious 'home to home' trip entered while initializing the system. Four additional trips were logged by the instrumentation package, which are explained by four engine starts and tests conducted during an oil change service of the vehicle that were not logged on the driver device. Finally, the handheld device also has two additional trips recorded after the system failed; these were entered before the driver realized the system had shut down.

The trips recorded on the driver device are listed in Table 17 and trips found on the computer with GPS and OBD data are listed in Tables 18 and 19, respectively. A few notes follow each table.

Table 17: Trip Log as Entered into Handheld Device

Trip #	Diary Date	Diary Time	Trip Origin	Trip Destination	Comments about the diary data
1	1/8/99	17:51	test	Test	Time was off by one hour,
2	1/8/99	17:58	home	GT	handheld was on standard time,
3	1/8/99	17:58	GT	GA Valve	test was during daylight savings
4	1/8/99	18:33	GA Valve	home	
5	1/9/99	11:25	home	CarServe	the time is now correct
6	na	na	na	na	Service station was testing vehicle
7	na	na	na	na	Service station was testing vehicle
8	na	na	na	na	Service station was testing vehicle
9	na	na	na	na	Service station was testing vehicle
10	1/9/99	11:25	CarServe	gas	Note that trips 5, 10, & 11 were entered
11	1/9/99	11:25	gas	home	after returning home (same time stamp)
12	1/9/99	18:55	home	movie	
13	1/9/99	21:29	movie	home	
14	1/10/99	10:48	home	church	Equipment package no longer working
15	1/10/99	12:39	church	home	Equipment package no longer working

Trip 1 was created during the initial set up of the equipment package. Trips 6 through 9 were trips logged by the equipment package but were not real trips made by the driver; these trips were created by the garage mechanic who turned the engine on and off four times. Trips 14 and 15 were recorded on the handheld device after the equipment package shut down due to the lack of power.

Table 18: GPS Trips as Recorded on the Databrick II

Trip #	Date	GPS Start Time (gmt)	GPS Finish Time (gmt)	Comments on Processed GPS Data
1	1/8/99	21:37:18	21:38:27	Bad data
2	1/8/99	21:40:03	21:42:16	Just 3 groups of points - no clear route
3	1/8/99	21:55:23	22:29:26	Complete route (strange route, perhaps missed trip?)
4	1/8/99	22:32:05	23:34:18	Complete route
5	1/9/99	14:23:50	14:48:21	First 55 sec. bad data (cold start), remainder is good
6	1/9/99	14:51:57	15:35:21	vehicle in garage -- bad data (no sky view)
7	1/9/99	15:43:19	15:43:53	vehicle in garage – bad data (3 groups of points)
8	1/9/99	15:50:31	15:50:40	vehicle in garage – bad data (just 9 points)
9	1/9/99	15:50:57	15:51:22	vehicle in garage – bad data
10	1/9/99	15:52:21	16:09:18	Complete route
11	1/9/99	16:12:40	16:20:41	Complete route
12	1/9/99	23:53:51	0:00:09	Complete route
13	1/9/99	2:27:30	2:33:08	First point is distinct, otherwise complete route
14	1/10/99	missing	missing	no power
15	1/10/99	missing	missing	no power

The results above reveal a 55 second delay in obtaining position information during a cold start, which occurred at the beginning of trip 5 after the vehicle had been inside a garage overnight. Trip data for trips 6 through 9 show what happens when the vehicle is running inside a closed environment where there is no sky view. The trip start and finish times are not completely synchronized between the GPS and OBD files, especially the start of Trip 6.

Table 19: OBD Trips as Recorded on the Databrick II

Trip #	File Date	File Time	Start Time (gmt)	Finish Time (gmt)	Comments about the OBD Data
1	1/8/99	4:44 PM	21:37:17	21:39:34	Header Time 4:40:59 PM, bad times first 90
2	1/8/99	4:46 PM	21:39:36	21:42:17	Header Time 4:44:29 PM, bad times first 3
3	1/8/99	5:33 PM	21:42:19	22:29:27	Header Time 4:59:51 PM, bad times first 2
4	1/8/99	6:38 PM	22:34:10	23:34:19	Header Time 5:36:21 PM, bad times first 5
5	1/9/99	9:52 AM	14:23:51	14:48:22	Header time 9:28:18 AM, bad time first 6
6	1/9/99	10:39 AM	15:35:11	15:35:22	Header time 9:56:10 AM, bad time first 4
7	1/9/99	10:48 AM	15:43:18	15:43:55	Header time 10:47:46 AM, bad time first 4
8	1/9/99	10:55 AM	15:50:32	15:50:43	Header time 10:54:59 AM, bad time first 5
9	1/9/99	10:55 AM	15:50:58	15:51:23	Header time 10:55:24 AM, bad time first 6
10	1/9/99	11:13 AM	15:52:26	16:09:19	Header time 10:56:48 AM, bad time first 2
11	1/9/99	11:25 AM	16:12:45	16:20:43	Header time 11:17:07 AM, bad time first 2
12	1/9/99	7:04 PM	23:53:50	0:00:10	Header time 6:58:19 PM, bad time first 6
13	1/9/99	9:37 PM	2:27:30	2:33:09	Header time 9:31:59 PM, bad time first 6
14	na	na	na	na	no power
15	na	na	na	na	no power

Notice that the GPS timestamps contained within the GPS and OBD files are in Greenwich Mean Time, which is five hours ahead of the U.S.'s Eastern Standard Time.

The GPS data was post corrected using the base station files and then the engine data were linked with the position data using the GPS time as the common field. This enables the examination of trips via thematic maps created in a GIS . Figures 6 through 8 are thematic maps that illustrate the distributions of speed, engine load, and throttle position, respectively for trip #10.

Figure 6: Thematic Map of Vehicle Speed

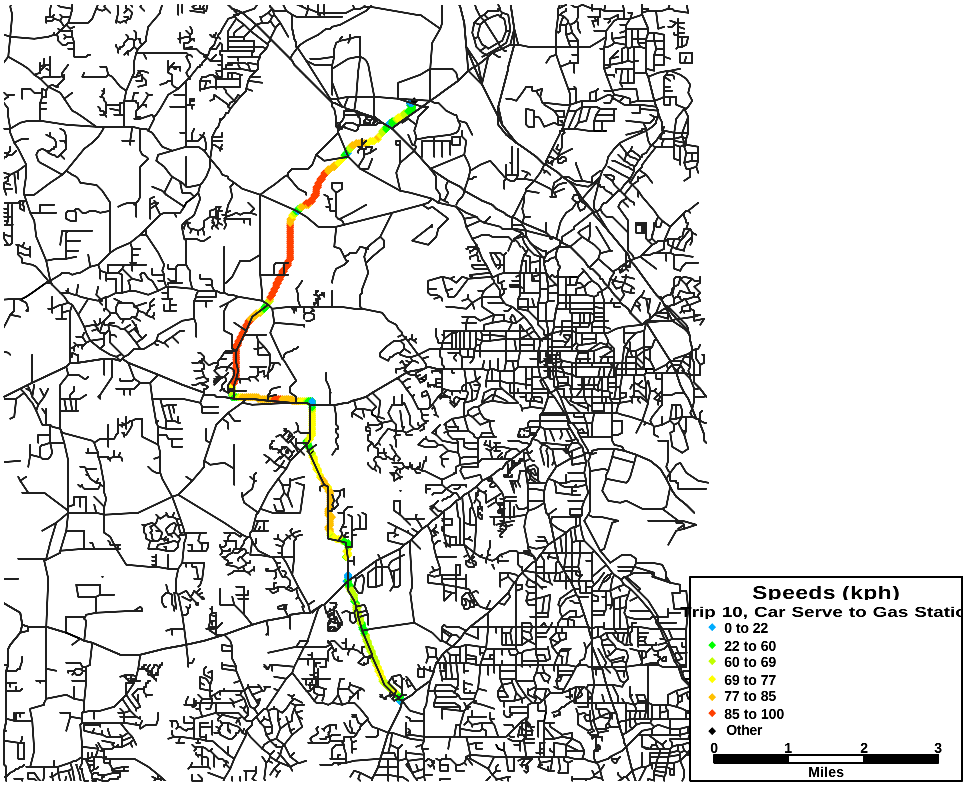


Figure 7: Thematic Map of Engine Load

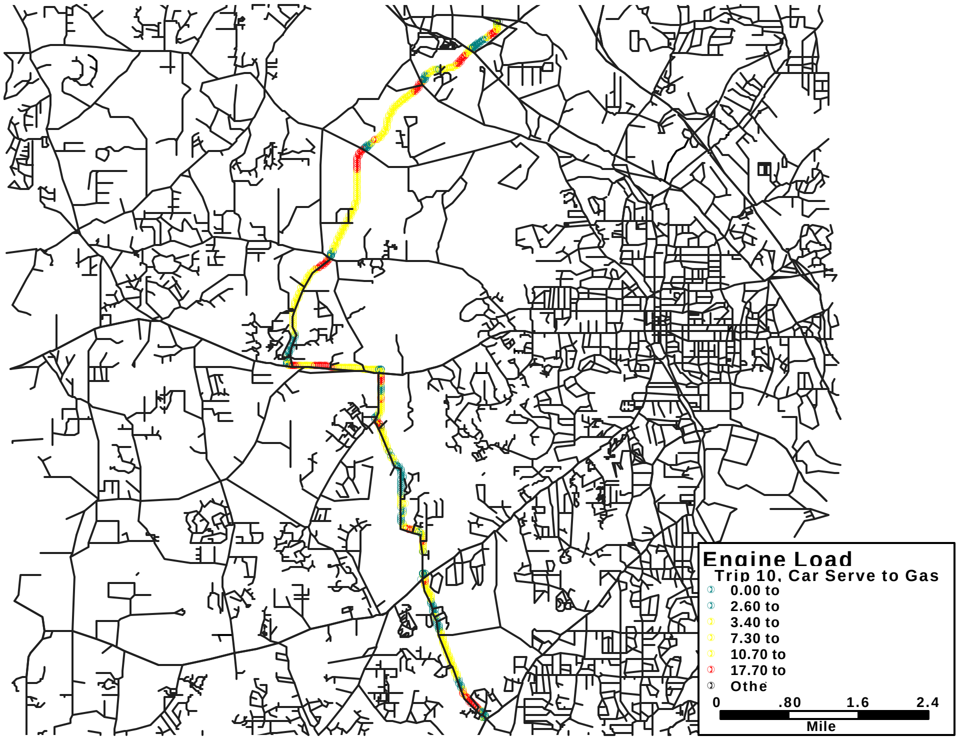
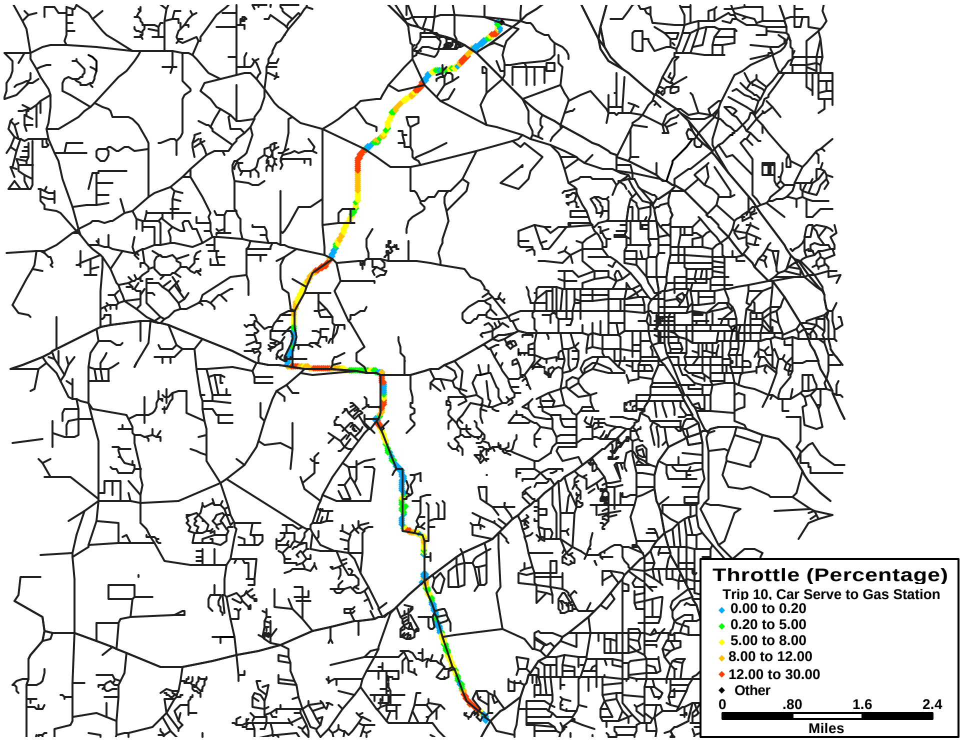


Figure 8: Thematic Map of Throttle Position



4.1.4 Test Results

The system test provided great insight to the overall operation of the instrumentation package and into the post processing work required after data collection. Power demand and supply were the most significant operating problems encountered. The equipment package itself operated as designed when provided sufficient power. The tasks of post-processing the GPS files and of matching the GPS files to the OBD files proved to be overwhelmingly labor and time intensive.

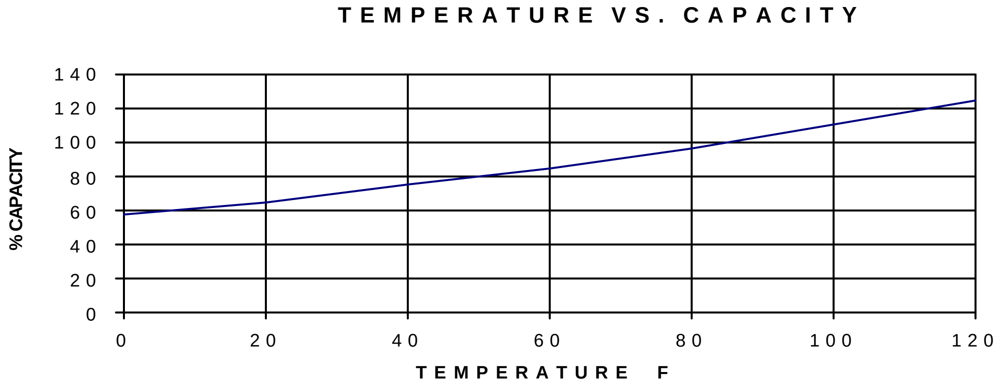
Power Demand / Supply

The primary issue with the instrumentation hardware was power consumption. The battery did not last as long as anticipated. As mentioned previously, the Trojan lead acid 12V battery used with the prototype system has a rated capacity of 144AH. The prototype system power consumption rate is 2.68 amps per hour (2.19 amp (Databrick) + 0.28 amp (OBD) + 0.21 amp (GPS)) during data logging (active mode) and 1.78 amps per hour (1.29 amp (Databrick) + 0.28 amp (OBD) + 0.21 amp (GPS)) during suspend mode. At worst case, assuming the computer is always active, a fully charged battery should operate for 53.7 hours (144/2.68). However, the battery was fully discharged sometime between the 29th and 41st hour.

Further research into battery capacity revealed that a new battery has only 70% to 80% of the capacity of a fully charged battery. Our battery vendor recently confirmed that 30 charge-discharge cycles are needed to charge the battery to its full capacity. Since this was not known in advance, the batteries were not primed for full capacity. The worst case expectancy can be recalculated starting at 70% of full capacity (144*.70)/2.68, which is 37.6 hours before full discharge. This is consistent with the actual results. Of course, the Databrick II was not active during the entire period. Examination of active versus inactive status of the first 29 hours indicates that the system was active for approximate 2 hours and inactive for 27 hours, yielding a total power draw of 53.4 amps (2*2.68 + 27*1.78) by 9:30 p.m. on January 9.

Another key variable affecting actual battery capacity is air temperature. As showed in the chart below, the 100% rated capacity is based on a temperature of approximately 80°F. Temperatures above 80°F increase capacity, whereas temperatures below 80°F decrease actual capacity. On Friday, January 8, the air temperature was 63°F at 4 p.m., decreased steadily to 26°F by midnight, January 9, and dropped as low as 20°F by 8 a.m. on Sunday. According to the chart, the initial capacity was only 86% of the rated capacity on Friday afternoon (144*.70*.86 = 87A) and continued to drop to 65% of capacity by Sunday morning. (Of course, data collection during the months of April through June in Atlanta should not encounter this type of deterioration of capacity, and, in fact, should benefit from temperatures exceeding 80°F.) So, the combination of decreased initial capacity (144*.7 = 101A) and diminishing residual capacity caused by low temperatures (from 86% down to 65% of existing capacity) fully explains why the system experienced complete power failure sometime between the 29th and 41st hour of operation.

Figure 9: Temperature versus Battery Capacity Tradeoff



Data Processing Requirements

As mentioned earlier in this report, the research team decided that differentially corrected GPS data was a requirement given the need for route choice (position) accuracy levels within 10 meters. At the time of the research effort, real-time differential correction (RTK) options were not considered due to previous experiences with a correction signal provider in the Atlanta region and to major delays in obtaining a licensed radio frequency to be used by the research team. Consequently, the GeoResearch Workhorse GPS receiver was selected as the best receiver available which supported post-processing differential correction.

The following analysis provides estimates of the time required and data storage requirements that are needed for the collection and analysis of the GPS and OBD data for trips under the present configuration of equipment and processes. The estimates of time and disk space requirements are forecast for a 10-day collection period based on the data handling experiences incurred during the 3-day test presented in this section. The actual collection of GPS and OBD data on the equipment package itself is not included.

1) Setting Up The Base Station and Collecting Base Station GPS Data

a) Setting up the base station requires clearing space on the base station hard drive, clearing all previous memory on the base station receiver, and getting the base station receiver initialized to receive GPS data. This start up process takes 10 minutes.

b) The collection of base station data for each day of data collection requires a person to periodically transfer the base station data to a separate processing workstation (through the network) and to restart logging base station data to a new file. Base station data files typically occupy approximately 70 to 80 MB of disk space after one day of data logging. Since the base station computer has limited space, the file needs be carefully transferred to another computer and deleted to make space for a new file. This transfer-delete-log new file process generally takes about 30 minutes per day

Total estimates for a 10-day data collection period:

Time estimates: 10 minutes day 1, 30 minutes per day for days 2 through 10; total: 280 minutes

Disk space needed: Base station must have at least 100 MB free space; processing workstation must have at least 700MB of disk space for a 10 day period.

2) Post Processing the GPS Rover Data

The post processing of the GPS data takes a lot of time. Moreover, it is fraught with ambiguities that are impossible to rectify. First of all, the base station data is in the form of distinct files for approximately each day of data collection as described above. This is advantageous given that each trip file must be processed against a base file, and smaller base files will result in quicker processing. However, splitting the base files into 10 different data files for each of the 10 days leads to other problems. The following points describe processes and issues related to post processing the rover data files:

a) **Creating the Output Correction Files (OCF) :**

Post processing first requires that an output correction file be generated from the base station data. Creating an output correction file in turn requires converting the base station data into RINEX format. Thus, both operations need to be carried out for each of the 10 base files for a typical 10-day data collection period. Converting the base data of one day to RINEX format takes about 10-15 minutes. Creating the output correction file from the RINEX files takes another 10 minutes. The output correction files and the RINEX files for one day of base station data further require approximately 90 MB of disk space.

Total estimates for a 10-day data collection period:
Time estimates for conversion of base files to OCFs: approximately 300 minutes
Space required for the RINEX and OCFs: approximately 900 MB

b) **Post Processing :**

Next, the output correction files have to be used to process the rover files for each trip. The problem associated with this is that for each trip, an appropriate output correction file needs to selected from the set of OCFs created in step a. This involves the following problems:

- There is risk of manual error in selecting the correct OCF.
- When a trip occurs across the time periods represented by two OCFs, only one section of the trip is processed. (Note: this will be a common occurrence with multiple participants.)

Moreover, the effort involved in processing each file against an appropriate rover file is overwhelming. Typically, for a 10 day survey there would be around 100-150 trips per survey participant. Then, for 10 survey participants there would be around 1000-1500 rover files to post process. Post processing of each rover file takes about 10 minutes.

Total estimates for a 10-day data collection period:
Total time estimated: 167 to 250 hours, or 7 to 10.4 days
Space required for the post-processed GPS files: about 50 KB for a 5-minute trip – assuming an average trip length of 20 minutes, total space required is 200MB.

c) **Converting the processed GPS data (one file per trip) into GIS files.**

Once each trip file is post-processed (i.e., differentially corrected), then a macro is run which converts each GPS file into a TRANCAD (GIS) file; this takes about 5 minutes per file.

Total estimates for a 10-day data collection period:
Total time estimated: Assuming the required automation is achived – about 1000 to 1500 minutes assuming a processing time of 1 minute per trip. (17 to 26 hours)
Space required for the GIS files: about 350K per trip. Total: 350MB to 525MB.

d) **Joining the GPS data to the corresponding OBD data in GIS:**
The final step in processing the GPS and OBD data streams is to join the files within a GIS. This currently involves a lot of data foramt manipulations before the two files for each trip can be joined. Given the existing file structures and format, it is estimated that the joining process for a single trip will take about 10 minutes.
Total estimates for a 10-day data collection period:
Total time estimated: 10,000 to 15,000 minutes. (7 to 10.5 days)
Space required for the post-processed GPS files: about 350K per trip – 350to 525MB.

4.1.5 Final Recommendations

The limited system tests conducted revealed and/or confirmed several project limitations that should be addressed before the next round of testing is initiated. These include:

1) The Databrick II does not support a deep suspend mode or high temperature tolerances. Consequently, CyComm's PCMobile will be the laptop for use in the next round of system tests.

2) Alternate casing is needed, given the current lack of venting options and clearance (necessary to open a rugged laptop). The existing case is also too heavy and bulky.

3) All batteries to be used for future testing and deployment will be discharged and recharged the prerequisite number of cycles to ensure the full capacity rating is reached. In addition, expected air temperatures will be assessed with respect to their impact on in-use battery capacity.

4) The post-processing of GPS files is time consuming and labor intensive. GPS receivers supporting real-time differential correction will be tested in the spring of 1999. If successful, this functionality will eliminate the need to post process the GPS data, thus reducing real-time GPS data storage requirements and post-processing labor requirements (steps 1a, 1B, 2a, and 2b above). In addition, real-time correction will allow for real-time synchronization and logging of both position and engine data streams to the same data file, thus eliminating step 2d above. In fact, with RTK technology, the only post-processing step remaining is to convert the GPS-OBD file into the GIS file format.

5) Further examination and refinement of time stamps used on, within, and between files is needed. The time stamps present in the collected files are not 100% complete and synchronized. It is also noteworthy that many travelers may decide to enter diary data after the fact, and may even enter all trips at the end of the day. Although this can easily be detected by examining the time stamps found in each record of the diary / trip log file, it will make the process of matching trips and detecting missed trips with the GPS and OBD data more difficult.

5. OVERALL FINDINGS

During the development of the comprehensive vehicle instrumentation package, there were several issues that emerged early in the research process. These issues include vendor stability, equipment specifications and accuracy, equipment durability, system power demands, and data post-processing requirements. These issues remained problematic throughout the research effort and therefore recommendations are provided which focus on potential remedies for each issue.

5.1 Vendor Stability / Reliability

Manufacturer support for various equipment is highly variable. As with many high technology companies, numerous firms contacted were unable to answer the most basic questions regarding product functionality. Members of the research team were often transferred around within a company in an attempt to locate someone who understood the equipment specifications. Other times the research team was given a simple 'don't know' answer (e.g., operating temperature ranges for OBD scanners are not available or known).

It was also common for product lines to be discontinued soon after purchasing a product and for vendors to go out of business while in the midst of negotiating – in both cases there was no advanced warning. Many of the candidate components identified for testing, and some of those actually procured for testing, were no longer being manufactured one year later. The replacement models (if any are available) do not always meet system specifications. For example, the Datalux Databrick 486 was identified initially as the computer to evaluate, but soon after this model was purchased the research team learned that the model was discontinued and that the Pentium-based Databrick II would replace it – as soon as the manufacturing lines were retooled. The Pentium version runs hotter and consumes more power than the original 486 model.

Another example is the company AED, Inc., which served was a proving grounds for GM. This company produced two products of great interest to the research team. The first product was the VCS PCMCIA card, which eliminated the need for a separate OBD scanner for all OBDII compliant vehicles. The second product was the AED Roadrunner, the best rugged laptop of those inventoried, with the highest operating temperature range (up to 70oC) and the deepest suspend mode (.10A). The research team purchased and evaluated the PCMCIA card and was in the process of negotiating a price for the Roadrunner when AED dropped from sight. No one answered their phones and emails bounced back after a few days. Another vendor in Phoenix confirmed that AED had gone out of business.

A final example is that of Engine Control and Monitoring (ECM), a firm which provides a proprietary software interface for Snap-On OBD Scanners. Researchers at Georgia Tech had purchased several Snap-On Scanners and customized software from ECM several years ago for another research project. Once requirements were defined for this instrumentation package and reviewed with ECM representatives, the research team learned that ECM wanted more than $40,000 to further customize their DOS-based software for Georgia Tech use. This cost was simply not reasonable given the limited expansion of functionality requested. It appeared that ECM did not want to take on the customization of a somewhat ancient application and that the cost would actually be used to overhaul the generic software. Once Georgia Tech stated that the price was unacceptable, ECM came back with a very reasonable offer ($5000) for the four or five key modifications requested. By that point in the research, the research team decided to evaluate the OTC scanner before contracting with ECM. After a few months, the research team went back to ECM to reopen the discussions. It was then revealed that ECM was in the process of overhauling their software and that a Windows-based system could be ready in March 1999 with much of requested functionality included. The research team remains skeptical at this point in time.

5.2 Equipment Accuracy

Even when equipment specifications on accuracy were available, these specifications are often based on optimal test conditions. For this project, route and time accuracy are critical, and route choice accuracy is a function of the GPS receiver accuracy. Field tests dramatically demonstrated the importance of using GPS units that provide accurate latitude and logitude position under conditions of Selective Availability (purposeful degradation of the satellite signals by the military to reduce position accuracy). The research team determined that a unit capable of post-processing differential correction (which corrects the signal to compensate for military signal degradation) is required for future systems. An alternative to post-processing the GPS data, which is time and resource intensive, would be to use equipment that can receive position corrections in real time via radio signal. For use in metropolitan area studies, these units would need to be capable of receiving the correction signal throughout the region. The research team is currently testing two units in Atlanta under a separate research effort. A complete analysis of route choice accuracy issues was conducted and can be found in Wolf, et al., 1999.

Accurate time stamps must be recorded for each data stream captured to ensure correct matching occurs between GPS location data and OBD engine activity data. The research team found that GPS units do not all initialize with the same time stamp when they are powered on, resulting in a potential clock offset between two separate units. Clock drift was also noted across the variety of GPS units tested, indicating that the units may employ different internal algorithms for tracking the passage of time. The computer clock may also drift, as well as the clock within the driver device. Any research effort aimed at integrating data on a time basis (matching the location of an event and the environmental conditions associated with that event) must consider clock drift. An independent single time stamp needs to be applied to all recorded data streams if exact synchronization of data is required.

The onboard engine diagnostics units currently available on the market do not yet provide an optimal solution. The OTC scanner provides the best capabilities for vehicles today. However, the OTC has to be specifically configured for each vehicle. When operated in a default onboard diagnostics (OBDII) mode, the data are only updated on three-second intervals, which is insufficient to provide accurate acceleration data. New systems are entering the market this year and should be considered for future studies.

5.3 Equipment Durability

Onboard computers and other components must be capable of performing under very high temperature conditions if they are to be located in a vehicle trunk. Few computers can perform at temperatures exceeding 140°F. Performance at the lower end of the temperature range may also be an issue in locations where temperatures fall below freezing (many components list 0^oC

as the minimum operating temperature.) General equipment durability is also a critical issue. Component failure during data collection efforts will result in data loss for the duration of the equipment outage. Warning systems to notify the driver of component failure should be built into future systems.

5.4 Post-Processing Differential Correction Requirements

As reviewed in the system test results section, the data processing requirements involved with storing and processing the GPS base station and rover files is quite time consuming and labor intensive. It also requires much storage space, both on the equipment package itself, on a base station computer, and on another processing workstation. With all the steps involved, it is also quite susceptible to data handling errors. In the example provided for 10 respondents traveling for 10 days and averaging 15 trips per day, the total data processing time estimates were 336 hours and data storage estimates were 2.95GB . One can easily imagine the daunting time, labor, and storage requirements associated with collecting and processing differential correction data for three continuous months for 600 respondents making 60,000 to 90,000 trips.

Real-time differential correction, if feasible, would eliminate all data handling steps detailed in the test results section with the exception of the simple conversion of the GPS-OBD file from its original ASCII format into a GIS file format. Time and storage estimates are reduced to only those detailed in step 2c (26 hours, 525MB for 10 respondents averaging 15 trips for 10 days). In addition, the potential for storing the GPS and OBD files as one integrated file introduces great efficiencies in data handling and greatly reduces the risk of data matching errors.

5.5 Power Demand

The power demand of the current prototype system is such that a single deep cycle 12-volt battery will only power the unit for three days. Adding a second battery will extend the duration of tests, but will also add significant weight to the vehicle (and may influence the response of the engine to various driving conditions by adding to vehicle load). Hence, future system research should continue to focus on reducing the power demand of the various components as well as on continuing technology advances in the battery / power field.

Off-the-shelf batteries are not capable of storing their rated charge. Batteries must be fully discharged and recharged 30 times before their rated charge can be met. Field studies need to purchase and "season" batteries well in advance undertaking any studies.

6. WHAT'S NEXT: SMARTRAQ

In September 1998, a new research program, SMARTRAQ, was undertaken at Georgia Tech by the City Planning group within the College of Architecture and the Transportation Engineering group with the School of Civil and Environmental Engineering. The overall goal of this research effort is to provide an analytical framework for assessing the impacts of urban form, transportation accessibility, household socio-economics, and transportation investments on household travel behavior, vehicle emissions, and household physical activity levels (Frank, Washington, 1998). To accomplish this goal, an activity based survey instrument will be designed and implemented within the Year 2000 Atlanta Metropolitan Region Travel Survey , resulting in a detailed database for the Atlanta metropolitan region. This database will enable planners to model the implications of various land use and transportation investment combinations on transportation facility performance, vehicle emissions, and the amount of physical activity per household for the Atlanta region.

The scope of the travel survey will include the development and implementation of an electronic travel survey with vehicle instrumentation to be used with a sub-sample of households to provide greater detail and insight into the relationships between land-use, travel behavior, and on-road vehicle activity parameters that affect emissions. Consequently, the prototype vehicle instrumentation package presented in this report will be enhanced and used in the year 2000 Atlanta metropolitan region travel survey. In addition, two other instrumentation packages will also be developed and implemented – a handheld electronic travel diary (ETD) with GPS capabilities to capture all modes of travel and a passive GPS receiver with a data logger to capture all vehicle trips. The handheld diary with GPS will allow for more thorough evaluation of non-motorized trips and the passive in-vehicle GPS receiver will allow for actual versus reported trip and trip detail comparisons.

6.1 Research Objectives of Instrumentation

The primary research objectives of vehicle and person instrumentation include:

1) to estimate the difference between actual and reported travel for starts, hot soaks, total trips, departure times, travel times, soak times, and trip chaining frequencies
2) to evaluate the suitability of route choice models and algorithms
3) to estimate the effect of household socio-demographics, life-cycle stage, and land-use measures on walk and bike distances, motorized trip substitutions, and vehicle selection

Secondary research objectives include estimating the effects of socio-demographics, life-cycle stage, and vehicle technology on driving behavior and emissions, on air conditioning use and emissions, and on technology deterioration.

6.2 SMARTRAQ Equipment Deployment Plan

The total sample size for the year 2000 Atlanta Metropolitan Region Travel Survey will most likely fall between 4000 and 5000 households. Households will be surveyed using traditional paper diary methods with data collected via telephone interviews. However, a subset of 10-15% of the households will be provided one of three separate equipment packages:

- Passive In-Vehicle GPS – used in tandem with paper diaries for later analysis of reported versus actual trip rates.
- Electronic Travel Diary (ETD) with Portable GPS (to survey all travel modes) – used instead of paper diaries to fully automate travel diary data collection and to gain additional temporal and spatial trip elements provided by GPS technology.
- Electronic Travel Diary (ETD) with GPS and Engine Monitor (to survey all travel modes) – used instead of paper diaries to fully automate travel diary data collection to gain additional temporal and spatial trip elements, and to gain temporal and spatial vehicle and engine activity data for all vehicle trips.

Initial goals for the number of households to be instrumented or automated are:

- 250 households with passive GPS (vehicle only)
- 250 households with ETD and GPS (all modes)
- 50 households with ETD, GPS, and OBD (all modes)

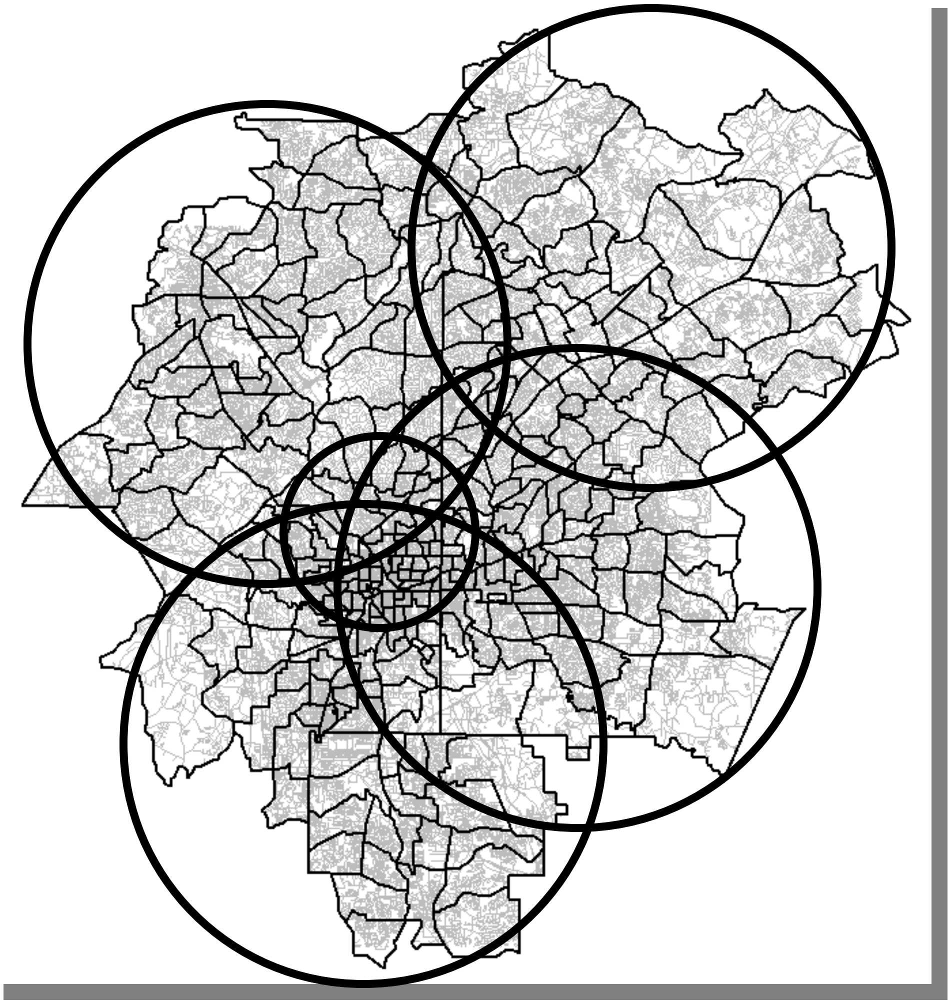
The duration of the instrumented samples will be one week per household. Given the burden introduced by this length of time, respondents will be provided monetary incentives for their participation. This incentive will be set somewhere in the range of $100 dollars per household.

6.2.1 Deployment Centers

Four regional deployment centers will be established to provide centrally located operations within each quadrant of the Atlanta metropolitan region. In addition, a fifth deployment center will be operated at Georgia Tech to provide service for those who work or live in the downtown / midtown area. Participants will be given the option to choose any location or to have the installation performed at their home. The deployment team will rotate from center to center according to the schedule presented later in this section.

The four regional centers will be centrally located in a strip or rural shopping mall, located at test-only inspection and maintenance facilities. It is possible that the state DNR could provide free I/M tests as an additional incentive for participants. Figure 9 below represents likely coverage areas for each deployment center.

Figure 10: Potential Service Areas for the Five Deployment Centers



6.2.2 Deployment Team / Equipment Rotation

Each equipment package will be deployed on a 9-day cycle:

Day 1:	Equipment is installed in the afternoon by deployment team
Day 2:	Respondent becomes familiar with using the handheld device
Days 3-9:	Respondent enters data that are saved as travel diary information
Day 10:	Equipment is returned to the study team in the morning and re-deployed in new studies during the afternoon

In this deployment plan, Monday deployments return the next Wednesday. The deployment team will attempt to schedule equipment returns in the a.m. hours and equipment installations in the p.m. hours. Of course, the deployment team must work within the respondents scheduling limitations.

The deployment team will devote one day at each of the four regional deployment centers, and then one half day at the Georgia Tech center. Consequently, the team will work 4.5 days and then have 4.5 days off, while deploying at respondent homes as required. A single pass through this 9-day schedule is equivalent to one cycle.

The plan calls for the team to receive and install 13 equipment sets per day, which includes 6 passive GPS systems, 6 electronic travel diaries with GPS, and 1 full instrumentation package (with ETD, GPS, and OBD components). The day at Georgia Tech will entail the turnaround of 3 passive GPS systems, 3 electronic travel diaries with GPS, and 1 full instrumentation package. The deployment rotation schedule for the passive GPS equipment package is illustrated in Table 20, where the numbers indicate the sample number from 1 to 270, for up to 270 participating households (this will ensure that at least 250 households with valid data will be captured). The gray diagonal lines represent individual waves of deployment. This same deployment schedule applies to the ETD with GPS group.

Finally, the deployment schedule for the full instrumentation package calls for one uninstall and install per deployment date given five instrumentation packages. Given five installs per cycle and a ten cycle data collection period, this yields a total sample size of 50. If more complete instrumentation packages are purchased, the sample size will increase accordingly.

The following text describes how the passive GPS deployment could work at a given center on a given day. First, respondents from the previous cycle will be scheduled to stop by the center to have the equipment removed and to discuss any participation issues. The data will then be off-loaded from the data logger and the equipment reinitialized for the next installation. The turnaround time for the equipment package could range from 1/2 hour to 1-1/2 hours, depending on the data storage and battery technologies used. As new participants arrive, the processed equipment packages collected for that day will be installed and the participants will receive any relevant training information before departing. This complete process will occur for 6 passive GPS systems, 6 ETD with GPS systems, and 1 full instrumentation system per day.

6.2.3 Instrumentation Study Duration

The sampling plan goal is to automate some portion of the travel diary study for 550 households; 250 households for passive GPS only, 250 for ETD with GPS, and 50 with the full instrumentation package. There will be 59 households processed every 9 nine days, in 10 waves or cycles, yielding a total sample of 590 households. The larger sample allows for 40 occurrences of household withdrawal or catastrophic equipment failure (7.4% for the passive GPS and ETD with GPS groups). The total data collection period will last for 95 days and will occur during May, June, and July, 2000.

To fulfill this deployment plan, 27 passive GPS packages, 27 active ETD/GPS units, and 5 active ETD with GPS and OBD full instrumentation packages must be purchased and assembled. One wave's worth of extra batteries and power systems will also be purchased. As a result, power supplies can be swapped out during equipment turnover, reducing equipment turnaround time. Data storage devices such as PCMCIA cards and flash cards are also under consideration to reduce real-time downloading requirements during equipment rotation.

Table 20: Deployment Schedule for Passive GPS Equipment Package

Week	Day	Site 1	Site 2	Site 3	Site 4	GT
1	Mon	1-6				
	Tues	1-6	7-12			
	Wed	1-6	7-12	13-18		
	Thu	1-6	7-12	13-18	19-24	
	Fri	1-6	7-12	13-18	19-24	25-27
	Sat	1-6	7-12	13-18	19-24	25-27
	Sun	1-6	7-12	13-18	19-24	25-27
2	Mon	1-6	7-12	13-18	19-24	25-27
	Tues	1-6	7-12	13-18	19-24	25-27
	Wed	1-6 / 28-33	7-12	13-18	19-24	25-27
	Thu	28-33	7-12 / 34-39	13-18	19-24	25-27
	Fri	28-33	34-39	13-18 / 40-45	19-24	25-27
	Sat	28-33	34-39	40-45	19-24 / 46-51	25-27
	Sun	28-33	34-39	40-45	46-51	25-27 / 52-54
3	Mon	28-33	34-39	40-45	46-51	52-54
	Tues	28-33	34-39	40-45	46-51	52-54
	Wed	28-33	34-39	40-45	46-51	52-54
	Thu	28-33	34-39	40-45	46-51	52-54
	Fri	28-33 / 55-60	34-39	40-45	46-51	52-54
	Sat	55-60	34-39 / 61-66	40-45	46-51	52-54
	Sun	55-60	61-66	40-45 / 67-72	46-51	52-54
4	Mon	55-60	61-66	67-72	46-51 / 73-78	52-54
	Tues	55-60	61-66	67-72	73-78	52-54 / 79-81
	Wed	55-60	61-66	67-72	73-78	79-81
	Thu	55-60	61-66	67-72	73-78	79-81
	Fri	55-60	61-66	67-72	73-78	79-81
	Sat	55-60	61-66	67-72	73-78	79-81
	Sun	55-60 / 82-87	61-66	67-72	73-78	79-81
5	Mon	82-87	61-66 / 88-93	67-72	73-78	79-81
	Tues	82-87	88-93	67-72 / 94-99	73-78	79-81
	Wed	82-87	88-93	94-99	73-78 / 100-105	79-81
	Thu	82-87	88-93	94-99	100-105	79-81/ 106-108
	Fri	82-87	88-93	94-99	100-105	106-108
	Sat	82-87	88-93	94-99	100-105	106-108
	Sun	82-87	88-93	94-99	100-105	106-108
6	Mon	82-87	88-93	94-99	100-105	106-108
	Tues	82-87 / 109-114	88-93	94-99	100-105	106-108
	Wed	109-114	88-93 / 115-120	94-99	100-105	106-108
	Thu	109-114	115-120	94-99 / 121-126	100-105	106-108
	Fri	109-114	115-120	121-126	100-105 / 127-132	106-108
	Sat	109-114	115-120	121-126	127-132	106-108 / 133-135
	Sun	109-114	115-120	121-126	127-132	133-135

Table 20 (Continued): Deployment Schedule for Passive GPS Equipment Package

Week	Day	Site 1	Site 2	Site 3	Site 4	GT
7	Mon	109-114	115-120	121-126	127-132	133-135
	Tues	109-114	115-120	121-126	127-132	133-135
	Wed	109-114	115-120	121-126	127-132	133-135
	Thu	109-114 / 136-141	115-120	121-126	127-132	133-135
	Fri	136-141	115-120 / 142-147	121-126	127-132	133-135
	Sat	136-141	142-147	121-126 / 148-153	127-132	133-135
	Sun	136-141	142-147	148-153	127-132 / 154-159	133-135
8	Mon	136-141	142-147	148-153	154-159	133-135 / 160-162
	Tues	136-141	142-147	148-153	154-159	160-162
	Wed	136-141	142-147	148-153	154-159	160-162
	Thu	136-141	142-147	148-153	154-159	160-162
	Fri	136-141	142-147	148-153	154-159	160-162
	Sat	136-141 / 163-168	142-147	148-153	154-159	160-162
	Sun	163-168	142-147 / 169-174	148-153	154-159	160-162
9	Mon	163-168	169-174	148-153 / 175-180	154-159	160-162
	Tues	163-168	169-174	175-180	154-159 / 181-186	160-162
	Wed	163-168	169-174	175-180	181-186	160-162 / 187-189
	Thu	163-168	169-174	175-180	181-186	187-189
	Fri	163-168	169-174	175-180	181-186	187-189
	Sat	163-168	169-174	175-180	181-186	187-189
	Sun	163-168	169-174	175-180	181-186	187-189
10	Mon	163-168 / 190-195	169-174	175-180	181-186	187-189
	Tues	190-195	169-174 / 196-201	175-180	181-186	187-189
	Wed	190-195	196-201	175-180 / 202-207	181-186	187-189
	Thu	190-195	196-201	202-207	181-186 / 208-213	187-189
	Fri	190-195	196-201	202-207	208-213	187-189 / 214-216
	Sat	190-195	196-201	202-207	208-213	214-216
	Sun	190-195	196-201	202-207	208-213	214-216
11	Mon	190-195	196-201	202-207	208-213	214-216
	Tues	190-195	196-201	202-207	208-213	214-216
	Wed	190-195 / 217-222	196-201	202-207	208-213	214-216
	Thu	217-222	196-201 / 223-228	202-207	208-213	214-216
	Fri	217-222	223-228	202-207 / 229-234	208-213	214-216
	Sat	217-222	223-228	229-234	208-213 / 235-240	214-216
	Sun	217-222	223-228	229-234	235-240	214-216 / 241-243
12	Mon	217-222	223-228	229-234	235-240	241-243
	Tues	217-222	223-228	229-234	235-240	241-243
	Wed	217-222	223-228	229-234	235-240	241-243
	Thu	217-222	223-228	229-234	235-240	241-243
	Fri	217-222 / 244-249	223-228	229-234	235-240	241-243
	Sat	244-249	223-228 / 250-255	229-234	235-240	241-243
	Sun	244-249	250-255	229-234 / 256-261	235-240	241-243

Table 20 (Continued): Deployment Schedule for Passive GPS Equipment Package

Week	Day	Site 1	Site 2	Site 3	Site 4	GT
13	Mon	244-249	250-255	256-261	235-240 / 262-267	241-243
	Tues	244-249	250-255	256-261	262-267	241-243 / 268-270
	Wed	244-249	250-255	256-261	262-267	268-270
	Thu	244-249	250-255	256-261	262-267	268-270
	Fri	244-249	250-255	256-261	262-267	268-270
	Sat	244-249	250-255	256-261	262-267	268-270
	Sun	244-249	250-255	256-261	262-267	268-270
14	Mon		250-255	256-261	262-267	268-270
	Tues			256-261	262-267	268-270
	Wed				262-267	268-270
	Thu					268-270

7. REFERENCES

Abdel-Aty, M., R. Kitamura, P. Jovanis, R. Reddy, and K. Vaughn. New Approach to Route Choice Data Collection: Multiphase, Computer-Aided Telephone Interview Panel Surveys Using Geographic Information Systems Data Base. Transportation Research Record 1493, TRB, National Research Council, Washington, D.C., 1995, pp. 159-169.

André, Michel. Vehicle Uses and Operating Conditions: On-Board Measurements; Understanding Travel Behaviour in an Era of Change, Pergamon-Elsevier, Oxford, 1995, pp. 469-481.

Bachman, William, Wayne Sarasua, and Randall Guensler. GIS Framework for Mobile Source Emissions Modeling; Transportation Research Record; Number 1551; pp. 123-132; Transportation Research Board; Washington, DC; 1996.

Benjamin, Michael; CARB. Using GPS/GIS for the Collection of Motor Vehicle Activity Data; Presented at the Environmental Management and Technology Conference, November 1997.

Casas, Jesse and Carlos Arce; NuStats International. Trip Reporting in Household Travel Diaries: A Comparison to GPS-Collected Data; Presented at the 78th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1999.

Czerniak, R. and J. Reilly. Applications of GPS for Surveying and Other Positioning Needs in Departments of Transportation. A Synthesis of Highway Practice, NCHRP Synthesis 258, TRB, National Research Council, 1998.

DeFries, T. and S. Kishan; Radian Corporation. Light-Duty Vehicle Driving Behavior: Private Vehicle Instrumentation; Final Report; Presented to US EPA, Office of Mobile Sources; August, 1992.

Draijer, G., N. Kalfs, and J. Perdok. Possible Application of Global Positioning System (GPS) for Collecting Travel Data, Project Report; Transport Research Centre of the Ministry of Transport, Public Works, and Water Management; The Netherlands, 1998.

Frank, Larry and Simon Washington. Objectives and Operating Procedures of the SMARTRAQ Research Program, Project Document, Georgia Institute of Technology, December 1998.

Greaves, S. Applications of GIS Technology in Recent Household Travel Surveys. Conference Proceedings: GIS-T Symposium, March 1997, pp. 95-133.

Guensler, R. (1993). "Data Needs for Evolving Motor Vehicle Emission Modeling Approaches"; In: Transportation Planning and Air Quality II; Paul Benson, Ed.; American Society of Civil Engineers; New York, NY.

Guensler, Randall, Michael O. Rodgers, Simon Washington, William Bachman; An Overview of the MEASURE GIS-Based Modal Emissions Model; In: Transportation Planning and Air Quality III; Tom Wholley, Ed.; American Society of Civil Engineers; New York, NY; July 1998.

Haubold, Ines and Kay Axhausen. Handheld PC based travel data collection by self administered interviewing. Presented at the Association of Survey Computing Conference on New Methods for Survey Research, Southampton, England, August 1998.

Kalfs, N. and W.E. Saris. Eds D.F. Ettema and H.J.P. Timmermans. New Data Collection Methods in Travel Surveys. *Activity-based Approaches to Travel Analysis*, Pergamon Press, 1997.

Kelly, Nelson A., and Peter J. Groblicki (1993); Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles; Journal of the Air and Waste Management Association; Volume 43; pp. 1351-1357; Pittsburgh, PA; October 1993.

LeBlanc, D., F. M. Saunders, M. D. Meyer, and R. Guensler (1995). “Driving Pattern Variability and Potential Impacts on Vehicle CO Emissions”, Transportation Research Record; Number 1472; pp. 45-52; Transportation Research Board; Washington, DC.

Plaxton, John, Paul Jackson, John Polak, and Diana Wofinden; Centre for Transport Studies, Imperial College, London. Using the Internet to Collect Data on Travel Behaviour; Presented at the 78th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1999.

Ochieng, Washington. ATT Positioning Requirements: GPS Performance in the city of London; Project Report, Centre for Transport Studies, Imperial College, London; December 1998.

Flavigny, Pierre-Olivier, Jean-Paul Hubert and Jean-Loup Madre; INRETS. Analysis of Road Traffic Data Observed by GPS and Comparison with Other Sources. Presented at ADEME-INRETS Conference, Number 9815, September, 1998.

Richardson, A.J. and E.S. Ampt. Nonresponse Issues in Household Travel Surveys; Conference Proceedings 10: Conference on Household Travel Surveys: New Concepts and Research Needs; Irvine CA 1995; National Academy Press; Washington, D.C., 1996; pp. 79-114.

Ross,Catherine, Michael Meyer, Scott Barker, and Yared Zemere. Analysis of Travel Behavior using Three-Parameter Dataloggers; Journal of Transportation Engineering, Vol 121, No. 4, 1994, pp. 338-344.

Sarasua, W. and M. Meyer. New Technologies for Household Travel Surveys. Conference Proceedings 10: Conference on Household Travel Surveys: New Concepts and Research Needs, Irvine CA 1995; National Academy Press; Washington, D.C., 1996; pp. 170-182.

Stecher, Cheryl, Stacey Bricka, and Leslie Goldenberg. Travel Behavior Survey Data Collection Instruments; Conference Proceedings 10: Conference on Household Travel Surveys: New

Concepts and Research Needs; Irvine CA 1995; National Academy Press; Washington, D.C., 1996; pp. 154-169.

Taylor, Gordon. AUTOLOGGER: A Long Duration Vehicle Use Data Collection System Conference Proceedings: Sixth International Conference on Travel Behaviour, May 1991, Vol 2, pp. 432-443.

Wagner, David; Battelle Memorial Institute. Report: Lexington Area Travel Data Collection Test; GPS for Personal Travel Surveys. Final Report for OHIM, OTA, and FHWA, September 1997.

Wagner, David, John Seymour, Norman Malcosky, John Kinateder, and John Nguyen; Battelle Memorial Institute. Determining Heavy Duty Truck activity Using Global Positioning System (GPS) Technology; Presented at the 8th CRC On-Road Vehicle Emissions Workshop, San Diego, CA; April 1998.

Wolf, Jean, Randall Guensler, Simon Washington, Wayne Sarasua, Chris Grant, Shauna Hallmark, Marcelo Oliveira, Maxim Koutsak, Ranganathan Thittai, Robert Funk, Jeffrey Hsu. (1999a) Development of a Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior - Literature Review (GTI - R - 99001); Georgia Transportation Institute; Georgia Institute of Technology; Atlanta, GA; February 1999.

Wolf, Jean, Randall Guensler, Simon Washington, Wayne Sarasua, Chris Grant, Shauna Hallmark, Marcelo Oliveira, Maxim Koutsak, Ranganathan Thittai, Robert Funk, Jeffrey Hsu. (1999b); Development of a Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior - Project Overview and Functional Specifications (GTI - R - 99002); Georgia Transportation Institute; Georgia Institute of Technology; Atlanta, GA; February 1999.

Wolf, Jean, Randall Guensler, Simon Washington, Wayne Sarasua, Chris Grant, Shauna Hallmark, Marcelo Oliveira, Maxim Koutsak, Ranganathan Thittai, Robert Funk, Jeffrey Hsu. (1999c); Development of a Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior - Technical Specifications and Analysis (GTI - R - 99003); Georgia Transportation Institute; Georgia Institute of Technology; Atlanta, GA; February 1999.

Wolf, Jean, Randall Guensler, Simon Washington, Wayne Sarasua, Chris Grant, Shauna Hallmark, Marcelo Oliveira, Maxim Koutsak, Ranganathan Thittai, Robert Funk, Jeffrey Hsu. (1999d); Development of a Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior - Test Plans and Results (GTI - R - 99004); Georgia Transportation Institute; Georgia Institute of Technology; Atlanta, GA; February 1999.

Wolf, Jean, Shauna Hallmark, Marcelo Oliveira, Randall Guensler, Wayne Sarasua; Accuracy Issues with Route Choice Data Collection Using GPS; TRB Paper #991310 (to be published), Presented at the 78th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1999.