

Quantifying Position Accuracy of Multimodal Data from Global Positioning System-Enabled Cell Phones

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The emergence of cell phones with embedded Global Positioning System (GPS) chips provides opportunities to push personalized real-time travel information subject to an individual's current location. One such application, a travel assistant device, notifies cognitively disabled public transportation users when it is time to request a stop and exit the vehicle. GPS-enabled cell phones must provide highly accurate real-time location data for this type of service. The components used in the data-collection process are identified, and a quantitative analysis of real-time GPS data obtained with a cell phone while walking, driving a vehicle, and riding public transportation is provided. The expectation was that position accuracy would suffer when the GPS signal was obstructed by a vehicle or the user's clothing. The obtained data demonstrate the results of location fix attempts over different transportation modes in an urban environment. The highest percentage of GPS fixes (79.0%) was obtained by users walking with the cell phone open and unobstructed; walking also produced valid GPS data (i.e., location data estimated to be accurate within 30 m of the true position) 66.2% of the time. For bus trips, GPS and valid fix percentages were 71.7% and 66.1%, respectively, when the phone was held near the window; when the phone was placed in the traveler's lap, these numbers fell to 51.3% and 27.8%, respectively. Car trips provided higher numbers: 77.7% and 71.6%, respectively. Location-based transportation applications are feasible using current technology, but predictive algorithms may be required to deliver highly accurate and timely location-aware services to cell phone users in highly obstructed environments.

Cell phones are quickly becoming the world's most common computing device, outselling PCs by a ratio of 4 to 1 in 2004, with an ever-increasing market (1). With recent developments in communication technology, including satellite broadcasts and high-speed wireless data transmissions, numerous manufacturers have been incorporating high levels of functionality into cell devices that were recently found only on the desktop PC. With the recent incorporation of Global Positioning System (GPS) technology into cell phones, many location-based applications have become possible, including travel behavior tracking, region-specific weather and traffic reports,

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and emergency evacuation and position data (for 911 operators and fire departments). Of particular interest to the transportation industry are new opportunities to push real-time travel information subject to an individual's current location, which is determined by a GPS-enabled cell phone.

GPS-enabled cell phones offer new, sophisticated real-time applications made possible by embedded GPS technology, two-way communication, and the portable nature of the cell phone. The results of complicated processes or subsets of records from large databases [e.g., geographic information system (GIS) databases of public transportation routes and stops] can be relayed to the phone, which can further analyze these data or display them to the user. Such information may be used to facilitate the use of public transportation by cognitively disabled people or new transit riders.

As part of a research project to develop a travel assistant device (TAD) to aid transit riders with special needs, a software application that uses multimedia GPS-enabled cell phones was built to alert riders of events such as when to board and when their stop is approaching. It also would allow family members to track a rider's trip on the Internet and be notified should the rider deviate from the anticipated route (e.g., fail to get off the bus at the correct stop).

Although riders with cognitive disabilities are the initial target market for this application, TADs may be used by any travelers, such as tourists who are unfamiliar with a region and its transit system. Potential impacts of such personal TADs include increased transit ridership; decreased costs to the transit agency, by shifting some riders from paratransit to fixed-route transit; increased independence and improved quality of life for transit riders; and increased productivity of transit agencies' "travel trainers" (also called travel instructors), whose sole job is to provide one-on-one instruction (to new riders or to existing paratransit riders) on how to use fixed-route transit.

As with all next-generation location-based applications, a TAD relies heavily on reasonably accurate real-time position data. Because many applications that use real-time position information are beginning to emerge in the telecommunications market, the need for quantified position accuracy performance data of GPS-enabled cell phones is current and of greater importance than ever before.

GPS has been analyzed in many past transportation studies (2–8). Results have indicated that GPS is an objective technology that can be used to accurately record historical travel behavior data and potentially even replace the travel diary (4, 5, 8). However, many of these studies have used either personal digital assistants (PDAs) with supplemental equipment (2, 4) or vehicle-based GPS systems (3, 5, 6). Although other studies discuss the use of cell phones and GPS, many discuss their use hypothetically (9) or have used a regular cell phone in conjunction with a separate GPS device (10, 11).

To date, few quantified data exist regarding the accuracy of location data provided by GPS-enabled cell phones, assisted GPS (A-GPS) technology (12). A-GPS uses location information from the cellular network in addition to embedded GPS technology to quickly obtain more accurate location data for the mobile device (12). Because the E911 mandate by the U.S. Federal Communications Commission requires wireless carriers to provide location information within 50 to 300 m for emergency calls (9, 13), embedded location technology such as A-GPS is becoming more common in phones for many cellular networks (14–16). In the remainder of this paper, GPS refers to location data obtained with the use of A-GPS technology.

The performance of GPS-enabled systems relies heavily on how accurately each unit of location data, called a GPS fix, indicates the device's true position. GPS-enabled cell phones provide additional data, related to the estimated accuracy of each fix, that are not readily available from traditional GPS devices. The degree of certainty associated with fix accuracy depends on signal quality, geographic location, satellite position and accuracy, clock discrepancies, environmental obstructions, and numerous other variables (12, 17). This estimated accuracy can be used to evaluate whether the provided data meet certain accuracy criteria specified for each particular cell phone application.

To date, little quantitative information is available about the reliability of GPS data obtained from GPS-enabled cell phones in most real-world application settings, including those relevant to real-world transportation applications (18). Therefore, this paper presents a quantitative analysis of the accuracy of travel behavior data collected using GPS-enabled cell phones over various transportation modes, including walking, riding a bus, and traveling in a car among environmental obstructions in an urban setting.

The rest of this paper is organized as follows. First, the research methods used—including the data description and the software tools used in the collection process—are discussed. Next, study results and a discussion of their implications are provided. Finally, conclusions are presented.

METHODS

Data Representation and Collection

Accuracy Uncertainty

True accuracy in GPS applications is elusive; the actual position of a target must be known to evaluate properly the factual accuracy of the reported location. An estimated accuracy uncertainty is used to provide some idea of GPS fix reliability. As an uncertainty measure, this value is inversely proportional to the confidence that may be placed in the location data calculated by using signals from the GPS satellites and cellular network.

This concept is illustrated in Figure 1. An estimated accuracy uncertainty of 10 m for a GPS fix indicates a conceptual two-dimensional circle parallel to the ground with a radius of 10 m, centered on the reported geographic location in which the true location may be found. By specification, the cell phone must provide this circular area indicating the 1-sigma confidence level (19), which implies that the true location exists within the defined circle with a probability of about 68%, if a normal distribution is assumed (20). A smaller radius value reduces the size of the area around the reported location in which the actual location is believed to exist and therefore is considered more accurate.

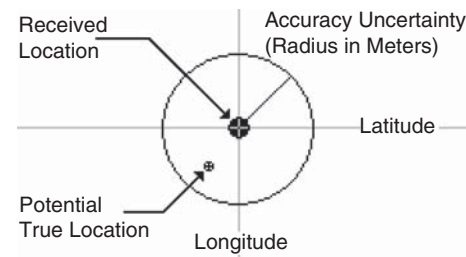


FIGURE 1 Estimated accuracy uncertainty.

For the purposes of this paper, an obtained GPS fix that is estimated to be accurate to within approximately 30 m of its true position is considered a valid fix (i.e., it meets the defined estimated accuracy uncertainty criteria of 30 m). Fixes returned from the test application are broken down per trip into three categories:

- Total fixes—all the location points returned from the application. If the cell phone fails to obtain a new GPS fix within a timeout limit set by the application developer (2 s for these tests), then the location data of a nearby cell tower are returned instead as a default (called a cellID fix). The number of total fixes includes all GPS fixes and cellID fixes that the application returned during a trip.
- GPS fixes—only those coordinates obtained by using GPS technology. This category excludes any cellID-type location data.
- Valid fixes—GPS fixes that are estimated to be accurate to within the 30-m accuracy criteria. A GPS fix is considered invalid for these tests if its accuracy uncertainty value is greater than 30 m.

A total of 86 trip segments were undertaken, evenly split between walking and vehicular travel; the test application provided a data set of 9,547 location fixes transmitted in real time at 4-s intervals. Accuracy was expressed as the percentage of data points not obtained from the cell tower compared with all data points, taking into account the GPS-enabled cell phone's estimate of accuracy uncertainty for each individual fix.

Data Sets and Locations

Twenty-eight trip segments were recorded with the user walking outside with the cell phone open and unconcealed for a total of 2,389 data points. Five additional walking segments were recorded around the University of South Florida (USF) area with the cell phone closed and in the user's pocket (after obtaining a first GPS fix outdoors), providing an additional 115 data points. This method attempted to determine the ability of the phone to continue to receive a GPS signal after an obstruction was introduced. A third walking set began with the application being started indoors and the phone being immediately placed in a concealed location, inside a bag or a pocket; the user then walked outdoors and to another building. This method forced the cell phone to obtain a first GPS fix while faced with a constant obstruction of the GPS signal. Ten trips consisting of 676 fixes were recorded for this set. In total, 43 walking segments (3,180 fixes) were recorded.

A total of 13 trips (915 fixes total) were recorded on local USF bus shuttles; users held the cell phone near the shuttle window for 6 of these trips (483 fixes) and in their laps for the other 7 trips (432 fixes). These trips were recorded in and around the USF–Tampa campus.

The Hillsborough Area Regional Transit (HART) bus service of Tampa, Florida, also was used as a means of transportation while

the user recorded GPS fixes. A total of 12 segments (4,272 fixes) were recorded over 4 separate bus routes; users held the cell phone near the window for 6 of these trips (2,204 fixes) and in their laps for the other 6 trips (2,068 fixes).

Local trips around the Tampa area were recorded in a car with the cell phone placed in a plastic mount that fastens to the windshield above the dashboard with a built-in suction cup. This data set consisted of 18 trip segments (1,180 data fixes). Figure 2a shows a sample of one such trip with the GPS fixes displayed; Figure 2b illustrates the same trip with all data points (including those that indicate the position of the cell phone tower, returned as cellID fixes). Point U in Figure 2b shows the location of the cell phone tower with which the cell phone was in communication when these data points were recorded. The lines in the figures connect consecutive GPS points in the order in which they were recorded. However, because the CellID fixes are also displayed, whenever a cellID fix was recorded after a GPS fix, a blue line was drawn from the GPS fix location to the location of the cellID fix (as displayed in Figure 2b). This display can be used to identify locations where a GPS signal dropped out or could not be obtained (i.e., the location on Fowler Road, directly underneath the label for Temple Terrace).

Figure 3 illustrates a bus trip through downtown Tampa, where tall buildings provide more environmental obstructions. The cellID fixes giving the cell tower position (absent in Figure 3a but indicated by lines in Figure 3b) were obtained from the tower location at Point I.

Both sets of pictures exhibit noticeable gaps in the transmission of GPS position data, which may have significant negative impact on systems that intend to use real-time data to provide services for travelers in dense urban areas. These gaps are most likely due to highway overpasses (labeled Crossway Expy) and high-rise buildings that can block GPS signal reception from orbiting satellites.

Overall, 43 trips (6,367 location fixes) were recorded of users within vehicles and 43 (3,180 fixes) of users on foot. Data continue to be collected for all these travel modes.

Software Tools

The software tool used to collect GPS information with cell phones uses the Location API (application programming interface), found in the Java 2 Micro Edition (J2ME) programming environment and defined by Java Specification Request (JSR) 179 (19). This application was installed and run on a Motorola i870 cell phone using the Sprint-Nextel iDEN network. The data, obtained at 4-s intervals, include latitude, longitude, horizontal position accuracy, timestamps for both the receipt and subsequent transmission of the GPS data, altitude, speed, heading, location method (cell tower or satellite), location data validity (based on user-defined criteria such as horizontal accuracy limits), cellular signal strength, and battery level.

The data thus obtained are transmitted to an active web service application by using the JAX-RPC API to invoke a remote procedure call (RPC). The JAX-RPC API is defined in the JSR 172 web services specification (21). The location data are packaged into an XML object by the API and sent to the web service by means of SOAP, which uses an HTTP connection for transmission (22, 23). Because HTTP uses a reliable transport-layer protocol, this method guarantees that no test data collected by the cell phone will be lost during transmission without notification. HTTP-based solutions are also compatible with any J2ME connected, limited device configuration (CLDC) specification version 1.1 phone with little modification effort required (24). On the server side, the web service application that receives the transmission retrieves the data elements from the XML object and inserts the values into their appropriate fields in an SQL database table for storage and analysis.

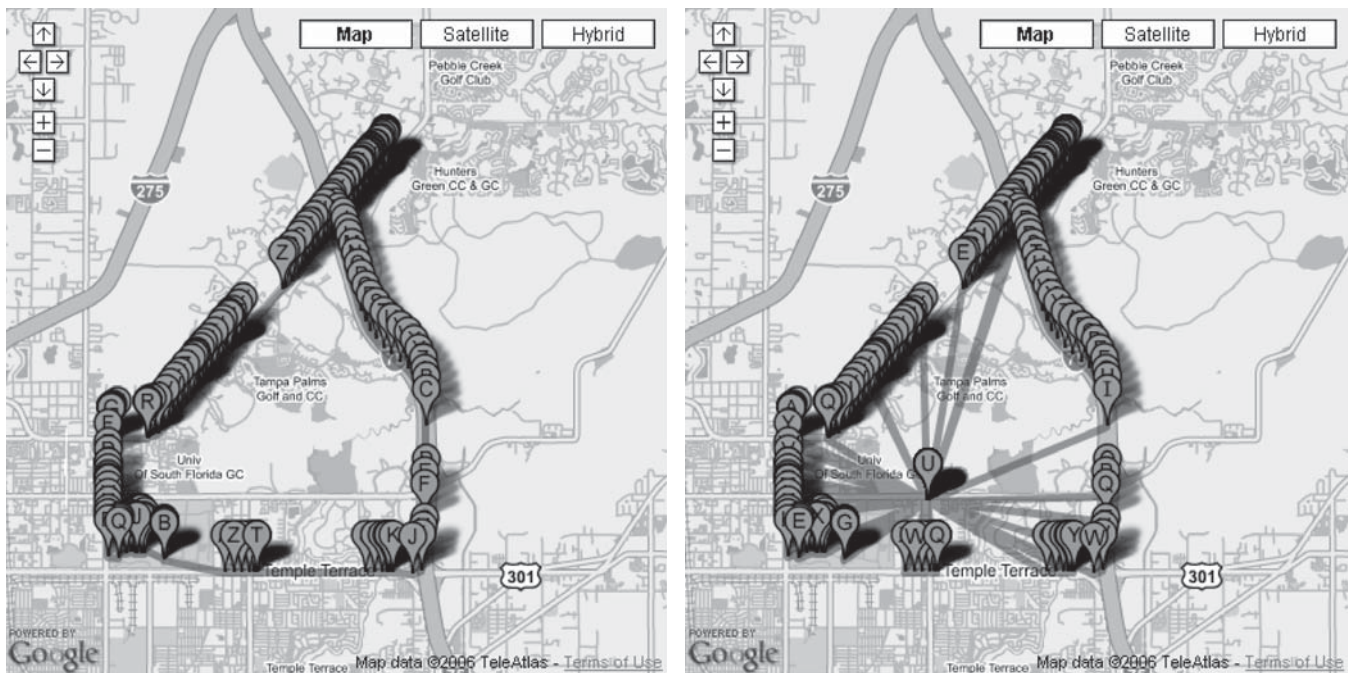


FIGURE 2 Car trip location fixes, showing (a) only GPS fixes and (b) all fixes, including location of cell phone tower (Data Point U).

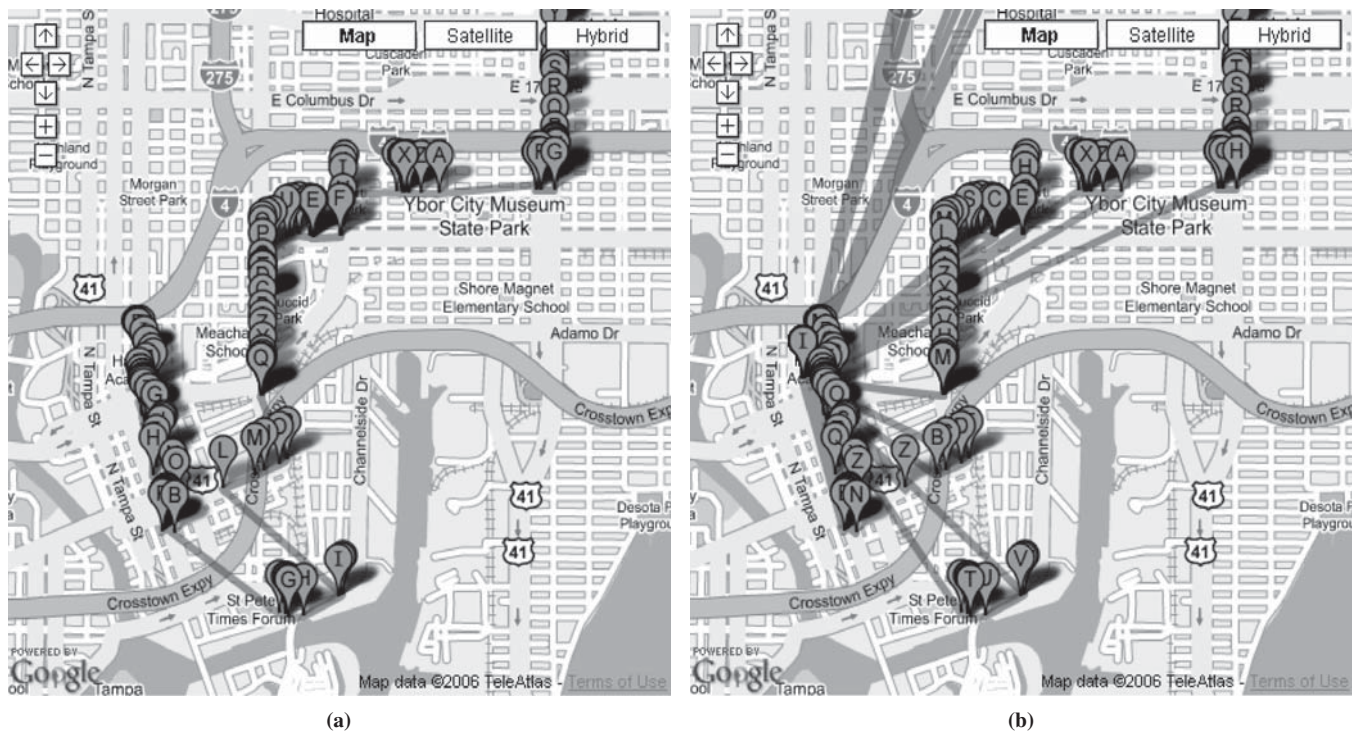


FIGURE 3 Bus trip location fixes, showing (a) only GPS fixes and (b) all fixes, including the location of cell phone tower (Data Point I).

RESULTS AND DISCUSSION

A summary of the results obtained from the GPS-enabled cell phones is listed in Table 1, broken down by transportation mode. The walking mode (which also includes standing still outside of a vehicle or building) is divided into three types. Walking (H) indicates that the phone is held open and in the hand of the user. Walk-

ing (P1) indicates that the phone is closed and placed in the pocket of the user after an initial GPS fix is obtained outdoors; this method tests the ability of the phone to continuously obtain GPS data when an obstruction is introduced after the first GPS fix is obtained. Walking (P2) indicates that the user began the trip with the phone in a concealed location (e.g., a building where the phone is unable to get an initial GPS fix), pocketed the phone, and then walked outdoors

TABLE 1 Summary of Multimodal GPS Data

Transportation Mode	Total Trips	Total Fixes	GPS Fixes	% GPS of Total	Valid Fixes	% Valid of GPS	% Valid of Total
Walking (H)	28	2,389	1,888	79.029	1,582	83.792	66.220
Walking (P1)	5	115	54	46.957	41	75.926	35.652
Walking (P2)	10	676	255	37.722	210	82.353	31.065
All walking	43	3,180	2,197	69.088	1,833	83.432	57.642
Car	18	1,180	917	77.712	845	92.148	71.610
USF bus (W)	6	483	358	74.120	283	79.050	58.592
USF bus (L)	7	432	250	57.870	207	82.800	47.917
All USF buses	<i>13</i>	<i>915</i>	<i>608</i>	<i>66.448</i>	<i>490</i>	<i>80.592</i>	<i>53.552</i>
HART bus (W)	6	2,204	1,569	71.189	1,492	95.092	67.695
HART bus (L)	6	2,068	1,032	49.903	762	73.837	36.847
All HART buses	<i>12</i>	<i>4,272</i>	<i>2,601</i>	<i>60.885</i>	<i>2,254</i>	<i>86.659</i>	<i>52.762</i>
All buses (W)	12	2,687	1,927	71.716	1,775	92.112	66.059
All buses (L)	13	2,500	1,282	51.280	696	54.290	27.840
All buses	25	5,187	3,209	61.866	2,744	85.510	52.901
All vehicles	43	6,367	4,126	64.803	3,589	86.985	56.369
All modes	86	9,547	6,323	66.230	5,422	85.750	56.793

NOTE: Bold values signify summaries of cell tests on a specific mode; italic values signify summaries of a subset of tests within a mode.

to another building; this method tests the ability of the phone to obtain a first GPS fix when an obstruction is in place throughout the entire trip.

The USF bus mode indicates that the user was traveling on one of the local USF shuttles; if followed by a (W), the user held the cell phone near a bus window for that trip; if followed by an (L), the phone was placed on the user's lap. A similar system of notation (W and L) is used for the HART bus mode (i.e., trips taken on the local HART buses for the city of Tampa). The data for %GPS of Total are the percentage of total fixes obtained from GPS satellites, as opposed to nearby cell towers; %valid of GPS indicates the percentage of GPS fixes that were considered valid according to the 30-m accuracy constraint; %valid of Total provides the percentage of total fixes that are considered valid positions, for each type of trip.

Figure 4 is a graphical representation of the results by travel mode. Each mode is associated with two bars. The first represents the percentage of fixes for that type of trip that was GPS data, and the second is the percentage of total fixes that are both satellite fixes and accurate to within 30 m and thus considered valid.

The expectation of GPS performance was that the device would consistently provide accurate position information for the users in an outdoor environment but that the GPS signal would be partially obstructed by a vehicle. As Table 1 and Figure 4 show, the highest ratio of GPS fixes was obtained when the user was walking with an unobstructed cell phone. This number dropped only slightly when the cell phone was in a car or bus and near a windshield or a window, respectively. The modes car, USF bus (W), all buses (W), and HART bus (W) show the highest levels of GPS and Valid fixes, in some cases exceeding the level of accuracy obtained by a user traveling on foot. However, this level of accuracy diminished significantly when the cell phone was held in a more natural position, such as in a user's pocket or lap [see walking (P1), walking (P2), USF bus (L), HART (L), and all buses (L)].

Overall, data collected while walking (all walking) produced only 4.3% more GPS fixes than those obtained in a vehicle (all vehicles); valid fixes were 1.27% more common. Data were better from users in cars, who obtained GPS fixes 15.85% more frequently and valid fixes 18.71% more frequently than users in buses. The percentage of valid fixes in a car with the cell phone held near the windshield was higher than that obtained on average for walking trips (13.97%). The valid fix percentage in a bus with the cell phone near a window also is 8.42% higher than the average walking result.

These results generally were consistent with the initial hypothesis because of the expected impact of factors such as the signal

obstruction inherent in vehicular travel. One unexpected result from these tests was that the phone still occasionally received a GPS signal even after being placed in a bag or pocket. Initial expectations were that the ability of the phone to continuously calculate GPS fixes might be lost once it was obstructed. However, a GPS fix was obtained for 46.9% of location requests when the phone was placed in the user's pocket after calculating a first GPS fix. Because the first fix is the most difficult for the GPS technology in the phone to calculate (12), it also was expected that if the phone were placed into a bag or pocket indoors before it could obtain a first fix, then it would be unable to calculate any GPS fixes for the trip. However, the application was still able to obtain GPS data for 37.7% of location requests, including calculating a first fix while inside a pocket or bag.

These results have separate implications for the collection of historical travel behavior data and real-time location-based applications. Passive tracking applications that require no user input can be used to gather historical trip data, but most data may be assumed to be gathered with the phone in a position that reflects normal cell phone use (i.e., on lap or in pocket). Even if there are gaps in collected data, a reasonable assumption of the travel path could be reconstructed by using the knowledge of the street network. However, travel behavior studies should provide a means to place the GPS-enabled cell phone in a position with a view of the open sky to maximize the quality of data collected. User effort to place the phone in a better position could increase the number of GPS and Valid fixes collected and therefore provide more accurate data.

Real-time location-based applications require more complete data to reach optimal performance. Although GPS data gaps can be reconstructed for historical trips, real-time applications must have current, accurate position data to convey the proper information to the user. If the transit rider is traveling on a bus and a GPS signal is obstructed as the bus nears the correct stop, then the passenger may not be properly alerted. Therefore, the accuracy of the data in the application's particular environment must be considered when designing a location-based application. One property of real-time applications that may increase the level of accuracy of position data is that because users may focus attention on the phone when expecting a notification, they may be more likely to position the phone to receive a better GPS signal. On the basis of the results shown in this paper, it is recommended that the phone application give feedback to the user regarding the current level of GPS accuracy to allow them to discover conditions in their local environments that influence GPS signal reception.

One possible solution for providing precise real-time location notifications in areas that are prone to blocked GPS signals is to sup-

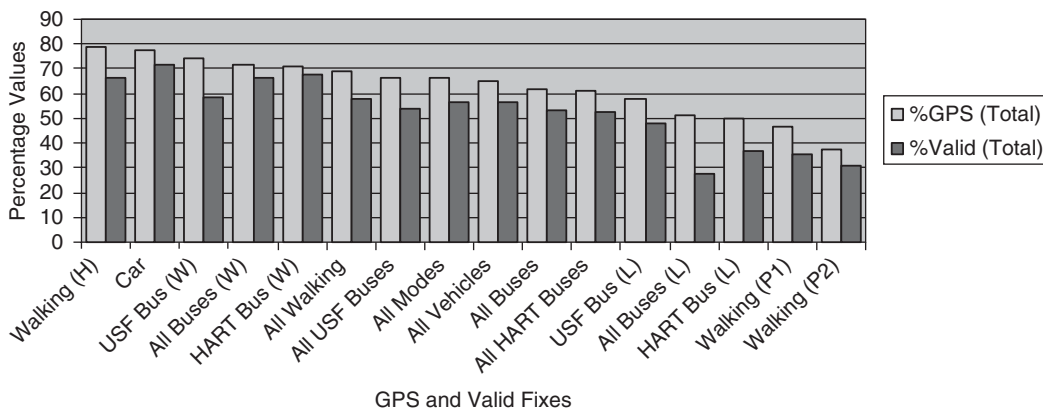


FIGURE 4 Percentages of GPS and valid fixes, by mode.

plement simple radius detection of the goal stop with predictive algorithms that rely on path recognition from the user's travel history and other route-prediction algorithms (25). Additionally, information from transit GIS databases can be used to keep track of a rider's relationship to bus stops previous to the goal stop. After a rider passes the stop preceding the goal, the reminder can be delivered. GIS databases also can provide bus route and timing information to further supplement these methods. Additional tests are planned to evaluate these types of notifications.

Several notable observations were made during the design and testing of the application used to collect the data for this paper. One issue is that although JAX-RPC is reliable for data collection, it is not optimal for real-time location-based systems. JAX-RPC was initially selected because it is a rapid-development solution for distributed systems using cell phones and web services; provides reliability so that data collected in controlled tests are not lost; and is highly compatible with all J2ME-compliant phones, with little modification effort required. However, because of the additional overhead involved not only in encapsulating the location data in XML but also in the handshake and retransmission of lost or corrupted data by TCP—the underlying transport-layer protocol—using JAX-RPC to send real-time location information is neither timely nor efficient. The average total transmission time measured for 7,589 transmissions from when a location fix was sent from the phone to when the server application received it was 5.531 s; the average total elapsed time from when a GPS location was actually calculated by the phone and the server received it was 6.291 s.

These measurements indicate that for real-time location applications using JAX-RPC and high-frequency GPS polling intervals, the amount of time required to calculate and transmit the location data may on average exceed the period of time between GPS fixes. Real-time applications that use JAX-RPC may inadvertently begin queuing location data to be transmitted and therefore jeopardize the timeliness of the data for real-time server calculations.

Additional testing was performed on Sprint–Nextel's iDEN network by directly using the user datagram protocol (UDP), which is more appropriate for real-time applications where timeliness is more important than reliability (24, 26). As expected, UDP exhibited a shorter total transmission time of less than 2 s per fix. This shorter transmission time also allowed more fixes to be transferred to the server, which occasionally helped to provide more information near gap areas like those shown in Figure 2. However, because J2ME CLDC 1.1 does not require that UDP be supported by Java-compliant phones (27), a mobile application that directly uses UDP may not be supported on all devices or cell phone networks. Also, high-speed data networks such as EDGE and EV-DO exhibit much faster data rates than iDEN, but the same relationship between JAX-RPC and UDP is expected. As a result of these issues, application developers will have to carefully weigh application portability and reliability versus performance when selecting the appropriate protocols for location data transfer.

Another related issue surrounds the length of battery life for the cell phone when GPS fixes are requested at a frequency of 4 s. In several tests, the phone battery lasted only 3 to 4 hours when JAX-RPC was used as a transmission protocol. Tests using UDP exhibited a significant increase in battery life, to around 11 to 12 h. This result also was expected because UDP does not require the phone to spend as much time transmitting overhead information, which costs additional time and energy.

One final issue for real-time applications is that the Sprint–Nextel iDEN network supports voice and data transmissions independently

but not simultaneously (18). Therefore, if a call to the phone is attempted while an application is transmitting data, the call will be sent to voicemail. Therefore, data communication for current real-time applications on iDEN phones will have to be highly managed to keep the transmission frequency as low as possible. This property is network-dependent, so it may not be applicable to all current cellular networks, and also is expected to change in the future. The use of UDP instead of JAX-RPC did not appear to have any effect on this observation when a 4-s transmission interval was used.

CONCLUSIONS

Recent advances in mobile technology now support location-aware software applications on GPS-enabled cell phones. The position accuracy of geographic data that the cell phone provides is critical to most location-based applications and defines whether certain real-time applications are feasible for use with current technology. The results of data analysis in this paper indicate little significant difference in the number of valid GPS fixes (i.e., fixes estimated to be accurate within 30 m of their true position) obtained from users traveling on foot and in a vehicle.

Differences in performance can be potentially significant if the GPS-enabled cell phone is not held near the windshield or window of the vehicle in which a user is traveling. This difference may affect the functionality of current real-time location-based applications, because even under the best circumstances, noticeable gaps appear on the routes.

Services that attempt to transmit data to travelers on the basis of precise real-time locations may be challenged in heavily obstructed areas such as urbanized sections of cities. However, GPS data gaps may be alleviated by means of route-prediction algorithms based on previous GPS fixes and information obtained from GIS databases. As GPS-enabled cell phones become available on cellular networks that also support network-based positioning technologies, network positioning information will help to fill these gaps in the absence of GPS reception (12).

Also, since the tests reported in this paper were performed, new cell phones that incorporate highly sensitive GPS chips have been released (28). Initial tests using these phones have yielded results better than those presented in this paper, including the regular calculation of valid GPS fixes in the middle interior of a bus. As these new phones penetrate the market, next-generation location-aware services probably will flourish on accurate position information, even in highly obstructed environments.

This paper also illustrates the importance of choosing an appropriate communication protocol when designing a real-time location-based application. JAX-RPC, the reliable protocol used to gather GPS data in these tests, has not been optimal for real-time applications because of the size of the data packet, the time required to transfer each location fix to the server, and significant power consumption. The preferred protocol for real-time applications that rapidly transmit location data is UDP, which may not be supported by all cell phones and networks.

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