Paper No. 02-1063

# Accuracy of Global Positioning System for Determining Driver Performance Parameters

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**Global Positioning System (GPS) technology can continuously monitor the time and location of vehicle usage. By recording and analyzing detailed vehicle activity data, researchers can analyze the safety and environmental implications of driver behavior and trip-making patterns. In 2000, NHTSA awarded the Georgia Institute of Technology a contract to equip 1,100 vehicles with a GPS-enhanced device to collect speed and location data. The objective was to acquire more accurate information on the role of excessive speed on crash frequency and severity. GPS technology allows the researcher to continuously measure driver speed, acceleration, and location. When merged with roadway characteristics within a geographic information system (GIS) environment, determinations of driver risk-taking behavior can be made. Second, continuous logging of GPS data allows researchers to capture high-resolution vehicle activity immediately before a crash event, reducing the potential error and bias introduced during determination of precrash speed estimates. Until May 1, 2000, the military degraded the position accuracy of GPS signals for commercial use, known as selective availability. For researchers, life without selective availability is a great improvement. Travel routes can clearly be discerned without the addition of differential correction units. The accuracy of speed, acceleration, and position data obtained from GPS signals for use in determining driver performance parameters without selective availability were tested. The test included four GPS packages, both corrected and uncorrected, simultaneously validated against a distance-measuring instrument. Equipment configuration, data collection methods, and sources of error are reported. The results suggested that noncorrected data can be used to obtain data within a reasonable range of the application requirements. Even without selective availability, GPS accuracy is still problematic in urban canyons and under heavy tree canopies. Although filtering for urban canyon outliers is labor intensive in a continuous monitoring situation, improvements in GIS hold promise for automation of this task.**

As early as 1983, transportation researchers and engineers were testing the Department of Defense's Global Positioning System (GPS) as a replacement for traditional survey technologies (*1*). The need for more labor-efficient and cost-effective means of locating facilities and constructing information systems initiated the spread of GPS applications to most areas of transportation. Whereas early applications of GPS were concentrated in high-precision, centimeter-level geodetic surveying, the general positioning utility of GPS made it a promising tool for less precise applications as well.

Automatic vehicle location and navigation (AVLN) systems make up a large portion of the meter-level accuracy applications currently implemented in the field. By using in-vehicle GPS receivers, the precise location of a vehicle can be determined within the roadway network. The position information can be used with an in-vehicle map display to determine route information, or the position information can be transmitted over wireless communications to a central control facility for use in dispatch operations or emergency response. Most commonly, AVLN systems give public and commercial operations the ability to continually monitor driver and vehicle resources to ensure efficiency. AVLN systems have become popular in the private vehicle sector for use as navigation aids and emergency response systems.

Because GPS technology can continuously monitor the time and location of vehicle usage, researchers can analyze the safety and environmental implications of driver behavior and trip-making patterns. In 2000, NHTSA awarded the Georgia Institute of Technology a contract to equip 1,100 vehicles with a GPS-enhanced device to collect speed and location data. Onboard computers will transmit location and vehicle activity data for a minimum of 2 years through a digital cellular link. The main objective of the NHTSA study is to acquire more accurate and objective information on the role of excessive speed on crash frequency and severity.

Previous studies of the role of speed in crashes have compared estimates of precrash speeds with estimates of prevailing travel speeds (*2–5*). Findings from these studies suggested that speed deviation from prevailing speeds is a contributor to crash risk. Unfortunately, the precrash speed estimations for these studies, determined from police reports, driver's reports, or third-party estimates, all have significant potential for error.

The advantages of using in-vehicle units for collecting driver performance parameters are twofold. First, GPS allows the researcher to continuously measure driver speed and acceleration and location. When GPS is merged with roadway characteristics within a geographic information system (GIS) environment, determinations of driver risk-taking behavior can be made. Second, continuous logging of GPS data allows researchers to capture detailed speed and acceleration data immediately before and during a crash event. During a crash event, the accelerometer records the detailed subsecond deceleration data for use in energy dissipation and biomechanics analyses. Given the monitored driver performance parame-

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ters, researchers will finally have a database that will facilitate analyses designed to answer several questions:

- How does the risk of crashing for drivers who exceed the speed limit differ from that of drivers who observe speed limits?
- What are the characteristics of drivers who are at a high risk of crashing, and how do they compare with drivers with a lower risk?
- What is the relationship of driver history with respect to crashes, citations, and driver profiles as determined from acquired data?
- How does the relationship between crash risk and speed change as other suspected risk-associated variables change?

As specified in the NHTSA request for proposals, "The equipment shall have the capability of recording the vehicle speed to an accuracy in the approximate range of ±2% and position that will enable the particular roadway being driven on to be identified correctly 95% of the time and the particular segment to be identified within approximately 10 feet 90% of the time" (*6*). This paper focuses on the accuracy of speed, acceleration, and position data obtained from GPS receivers for use in assessing driver performance parameters. The test included four GPS packages, both corrected and uncorrected, which were simultaneously validated against a distance-measuring instrument. Data collection, equipment configuration, and sources of error are reported in detail. Estimations of accuracy for all four packages are included.

## GPS: STATE OF THE PRACTICE

GPS is a satellite-based positional system conceived by the U.S. military in the 1970s. The system was implemented in phases during the 1980s and is now operational with a constellation of 24 satellites. The GPS computes ground position by measuring the signal travel times between a group of satellites and a ground-based receiver. Because radio signals travel at the speed of light, GPS receivers use signal travel times to estimate the distance to each satellite and to triangulate ground position.

GPS data are subject to a number of errors, including satellite orbit errors, satellite clock errors, receiver errors, atmospheric and ionospheric errors, multipath errors, and, until recently, selective availability. On May 1, 2000, President Clinton announced the immediate termination of selective availability, stating, "worldwide transportation safety, scientific, and commercial interests could best be served by discontinuation of selective availability" (*7*). Selective availability was the intentional introduction of satellite ephemeris errors by the U.S. Department of Defense. Selective availability degraded the precision of GPS accuracy up to 100 m for real-time, nonmilitary users. Selective availability was by far the largest source of error in GPS positioning (*8*). During the period of selective availability, differential corrections were required to achieve the level of spatial accuracy necessary for map matching in dense networks (*9*).

### Accuracy Levels

Selective availability is gone, but this does not necessarily mean that differential corrections no longer are needed. The government states that GPS accuracy without selective availability is within 20 m 2DRMS (the 95% confidence interval) or 10 m RMS (the 50% confidence interval), where RMS is root-mean-square and DRMS is distance-root-mean-square. These specified accuracy levels will not meet the NHTSA safety study requirement of matching a segment within 10 ft (3.3 m) 95% of the time.

Radio beacon differential corrections broadcast by the U.S. Coast Guard specify accuracy of 3 m to 10 m. However, the accuracy achieved with Differential Global Positioning System (DGPS) is more dependent on the performance specifications of the GPS receiver. With differential corrections, low-cost receivers typically reach accuracy levels between 5 and 10 m RMS, whereas high-end units achieve less than 1 m RMS (*10*). The GPS receivers used for the test reported in this paper are specified at 5 m RMS with differential corrections.

Most off-the-shelf GPS receivers report a near-instantaneous speed reading in the default message set. Without making claims under selective availability, manufacturers report velocity accuracy levels in the range of 0.01 to 0.3 m/s for velocity without selective availability. Little has been reported on the accuracy of use of speed readings directly from the GPS receiver, and thus, this is the focus of this paper.

### Remaining Sources of Error

The March 1997 issue of *GPS World* provided a comprehensive table that allocates overall GPS error into definitive groups. The following are possible sources of error:

- Selective availability: 24 m RMS (46.6 m 2DRMS);
- Ionosphere: 7 m RMS (13.6 m 2DRMS);
- Clock and ephemeris: 3.6 m RMS (6.98 m 2DRMS);
- Average horizontal dilution of precision (HDOP): 2 m RMS (3.9 m 2DRMS);
- Receiver noise: 1.5 m RMS (2.9 m 2DRMS);
- Typical multipath: 1.2 m RMS (2.3 m 2DRMS);
- Troposphere: 0.7 m RMS (1.4 m 2DRMS);
- Total with SA: 40 m RMS (77.6 m 2DRMS); and
- Total without SA: 16 m RMS (31 m 2DRMS).

After selective availability, ionospheric error is the second greatest potential source of error for GPS. The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. Ionization varies greatly over time and tends to heighten with solar maximum as indicated by sunspot numbers. Solar maximums occur approximately every 11 years and are followed by a solar minimum. A solar maximum was predicted to occur in 2000. Preliminary data from the National Oceanic and Atmospheric Administration showed sunspot numbers reaching more than 400 in the month of July. Predicted solar maximum sunspot numbers range between 100 and 160. With this information, it could be assumed that data depicted a worst-case scenario.

## METHOD

To assess the accuracy of speed and acceleration data obtained from GPS receivers, four GPS equipment configurations logged data simultaneously in a kinematic field test. Data for this field test were collected on July 10, 2000, after selective availability was discontinued. Differential corrections were applied to one of the four GPS packages.

To evaluate the accuracy of vehicle speed from the GPS data steam, truck speed was measured by using a Nu-Metrics Nitestar NS-60 distance measuring instruments (DMI). DMI units are used in floating car, or probe vehicle, studies of highway and arterial speeds throughout the United States. DMI sensors are attached to the transmission of the probe vehicle. By monitoring the number of electronic pulses received, the DMI measures the number of drive shaft rotations. Each drive shaft rotation is converted into distance traveled as a function of the differential gear ratio and tire diameter. Each pulse typically represents less than 1 ft (30 cm) of travel. With a BASIC program, second-by-second speed and distance information was downloaded from the NS-60 to a laptop computer in the probe vehicle.

## Test Route

As with positional accuracy, velocity measurement is a function of satellite-user geometry and signal reception. An evaluation of the velocity readings from the GPS units required the development of a test route that included a range of adverse conditions that have the potential to affect GPS signal reception or data collection. During a recent study sponsored by FHWA (*9*), the Georgia Tech 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; and
- 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" segments because of the presence of several railroad overpasses in this area. Overpasses ensure intermittent loss of 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 CBD but not in the urban canyon area where tall buildings surround the roadway. 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).

## Equipment Configuration

Four GPS equipment configurations were used to log data simultaneously in a kinematic field test. Two packages consisted of an integrated Garmin 35LP integrated GPS receiver and antenna powered

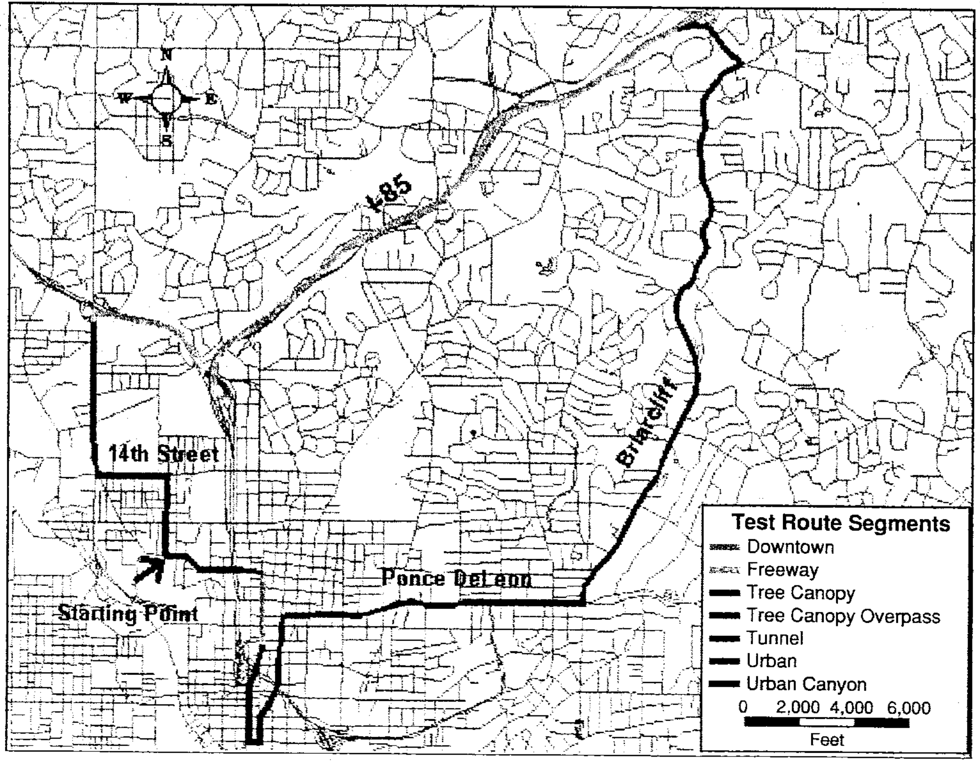


FIGURE 1 Test route segments.

TABLE 1 GPS Receiver Equipment Specifications

| Item | Specification | Package 1 | Package 2 | Package 3 | Package 4 |
|---|---|---|---|---|---|
| Data Logger | Palm IIIx | X | X | X | X |
| Differential Corrections Receiver | CSI MBX-3 DGPS (radio beacon DGPS signal) |  | X |  |  |
| GPS Receiver | Garmin 35 LP<br>• Velocity = .2 m/s A<br>• Position = 15 m no SA or 5 m w/rtDGPS<br>• 12 channels | X | X | X |  |
|  | Garmin II Plus<br>• Velocity = .05 m/s DC<br>• Position = 15 m no SA or 1-5 m w/rtDGPS<br>• 12 channels |  |  |  | X |
| GPS Antenna | SGM3900PC3 GPS antenna |  |  |  | X |
| Differential Corrections Antenna | MBL-3 Beacon loop antenna |  | X |  |  |

by the vehicle's battery and data logged to a Palm IIIx. A National DGPS radio beacon receiver, manufactured by CSI, provided differential correction to a third identical package. The fourth package consisted of a Garmin II Plus GPS receiver with a separate antenna, powered by the vehicle's battery and data logged to a Palm IIIx. Table 1 provides details of the four GPS packages.

All four GPS antennas were placed in a single row on the top of a utility truck (front to back) so that the antennas were equally distant from roadway centerlines and each other. The Palm IIIx data loggers were securely attached to the dashboard of the truck with Velcro, for monitoring by research staff during data collection (Figure 2). Standard cigarette lighter power adapters and splitters provided battery power to all packages.

## Data Collection

GPS data from all four equipment packages were continuously collected during all field tests. The Garmin 35LP receivers log data once every second, and the Garmin II Plus logs at a rate of 2 s. GPS data were collected on Palm Pilot IIIx handheld personal organizers with proprietary software. GPS data elements included GPS time, latitude, longitude, velocity, HDOP, number of satellites, and GPS flag. Simultaneous speed data were collected by using a Nitestar distance-measuring instrument connected to a laptop. DMI data elements included cumulative distance measurement, delta distance, speed, and computer time stamp. A paper diary was kept to record any additional trip information that might be used in data postprocessing and analysis.

In the paper diary, the start and end times were recorded for each trip to verify an actual time of the trip with the GPS time. The start and end odometer readings were recorded. This information was used to estimate a total traveled distance and to compare it with the travel distance derived from the GPS data. Furthermore, a log of all roads traveled, with road and street names and the GPS time of entrance, was recorded. This information was necessary for com-

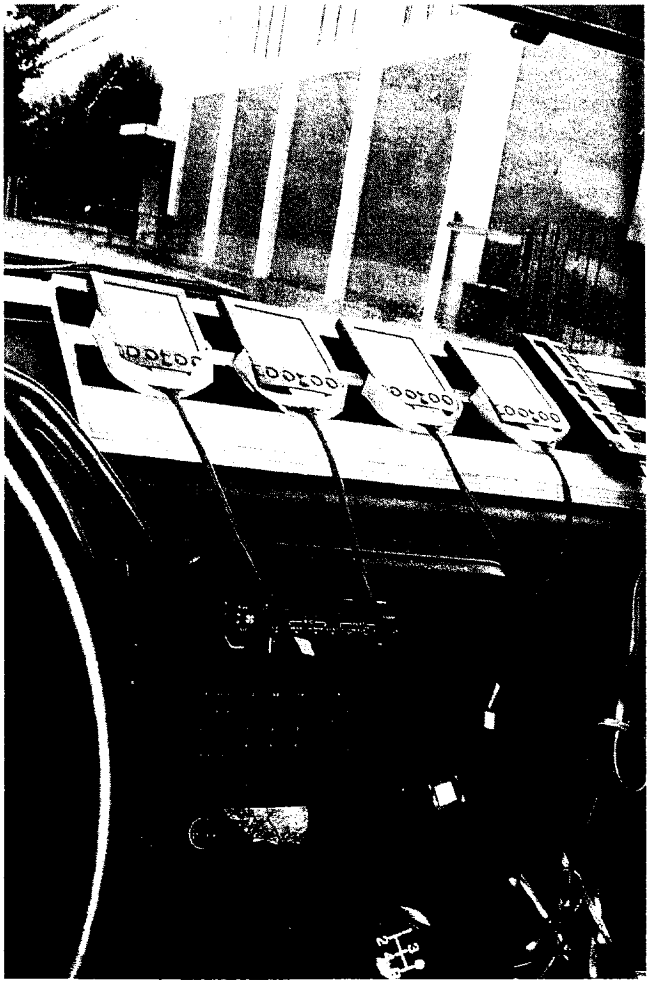


FIGURE 2 Placement of Palm Pilot data logging devices.

paring the actual roads traveled with the road network derived from the GPS data in the GIS map. All lane changes with the corresponding GPS time were logged on the paper diary. In addition to lane changes, possible signal interruptions were annotated on the form. This information was used to evaluate and compare the accuracy of the GPS and DGPS data.

Because the data logging software for the Palm Pilot is generally used for extended data collection activities, it has a built-in filter for vehicle nonmovement. If no vehicle movement is detected for more than 60 continuous seconds, data logging is suspended until vehicle movement is detected again. During data postprocessing, these missing cells are filled with zero speed values.

## ANALYSIS

### Time Alignment

The DMI records were time stamped based on the laptop computer time clock. Because GPS data were time stamped on the basis of the GPS clock, the two data sets were not synchronized in their raw format. The DMI time was recorded in the format hh:mm:ss. To match the DMI time with the GPS time, the DMI computer time was converted into a format consistent with the GPS time format. The conversion equation is time = (hour × 3600) + (minute × 60) + second. The speed versus time was plotted for the four GPS packages (see Figure 3) and for the DMI. From visual observation, 24 peaks of speed versus time were identified in the two plots. The absolute differences of the time for the corresponding peaks were then calculated. Finally, the mean time was used to shift the DMI computer time to synchronize it with the GPS time.

### Procedures to Replace Missing Values

As noted, data for intervals when the vehicle remained stationary for longer than 60 s were not logged. Other problems with satellite reception, such as the impact of line-of-sight obstacles, poor satellite geometry, and loss of satellite lock, also were associated with missing data. To facilitate a time series analysis among the four packages, the missing values in these cells were replaced through linear interpolation by using Statistical Package for the Social Sciences (SPSS) software. (SPSS did not provide a cubic fit capability.) The last valid reading before the missing value and the first valid value after the missing value were used in the interpolation. If the first or last case in the series had a missing value, the missing value was not replaced.

### Data Smoothing

Because the DMI unit records vehicle speed data in integer values, a standard smoothing technique (T4253H smoothing) was applied to the data to reestimate DMI speeds with SPSS statistical software. GPS speed estimates estimated to the first decimal digit could then

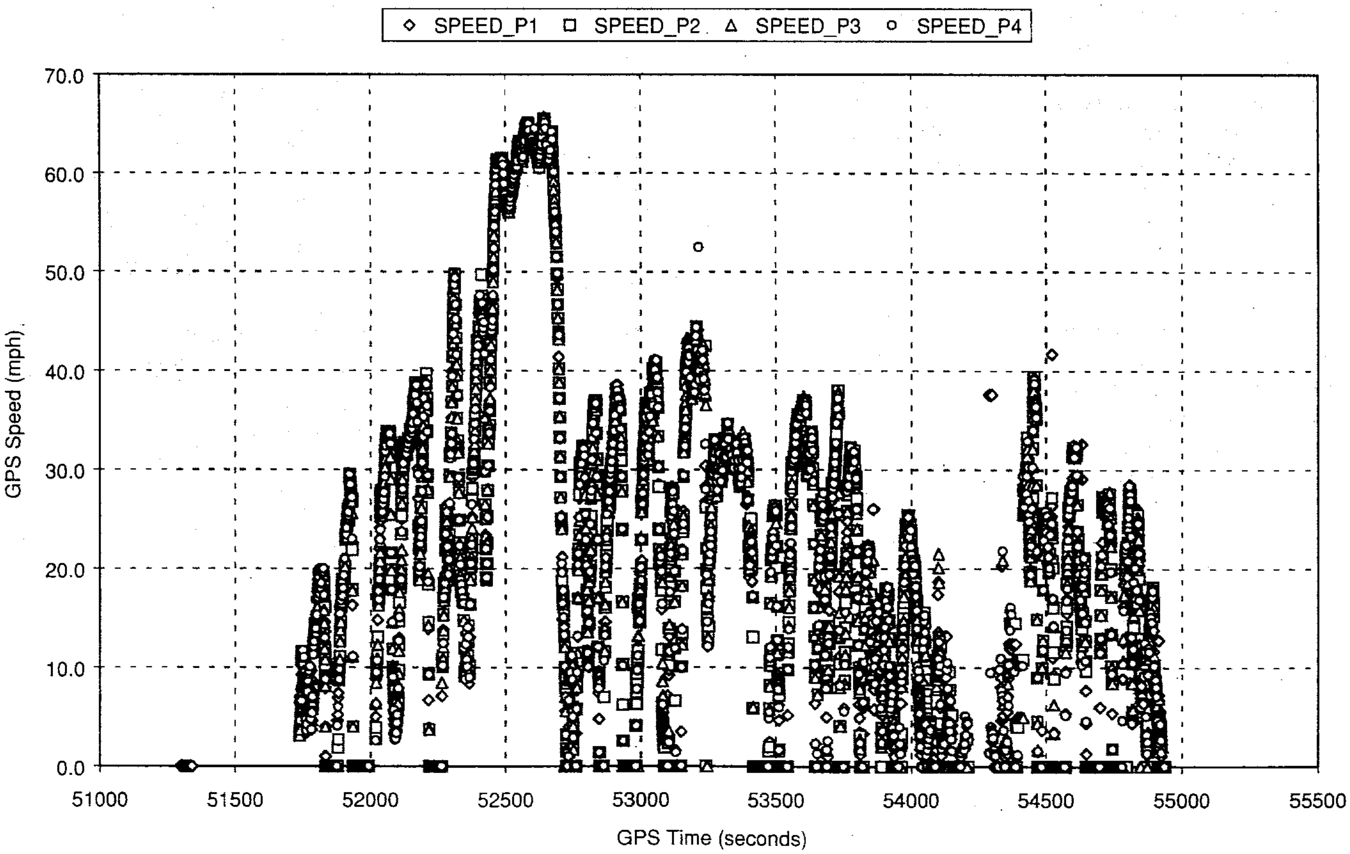


FIGURE 3 P1, P2, P3, and P4 speeds versus GPS time.

be compared with similar DMI values. Although it would have been preferable to collect DMI data to the same precision as that captured by GPS, it was not possible to do so by using this DMI unit. Researchers believed that use of DMI data without smoothing would result in an artificial inflation of error variance.

GPS speed data are noisy by nature. Individual 1-s readings at a constant vehicle speed vary significantly, although the average speed over a distance remains very accurate. The same SPSS statistical software smoothing routine (T4253H smoothing) was applied to the GPS data streams. Because this smoothing technique (or a similar technique to be developed later) would normally be applied to field-collected data before use in research, the reduction of data variance through smoothing was appropriate for this project.

### Statistical Analysis

Once the GPS speed data were filled and smoothed, acceleration values were created. The difference function provides a nonseasonal difference between successive values in the series. The order is the number of previous values used to calculate the difference. Because one observation is lost for each order of difference, system-missing values appear at the beginning of the series. For example, if the difference order is 2, the first two cases will have the system-missing value for the new variable. The difference in speed between the DMI data and each GPS package was then calculated for each second of vehicle operation. Differences in acceleration values between the DMI data and each GPS package were also calculated.

### Screening Criteria (Data Filters) and Statistical Analysis

Although GPS data generally are accurate overall, some manual postprocessing was necessary to verify the quality of the data and to identify outliers that should be discarded. Attributes of the GPS position calculation are available in the raw GPS data stream received from the satellites. These attributes include positional dilution of precision (PDOP), HDOP, vertical dilution of precision (VDOP), number of satellites, and differential corrections flags.

The PDOP attribute is the most commonly referenced positional accuracy attribute. PDOP is a function of both HDOP and VDOP and is calculated as $PDOP^2 = HDOP^2 + VDOP^2$. Generally, PDOP values greater than 4.0 indicate poor satellite geometry and should be discarded. PDOP and VDOP were not recorded in the current test. Because VDOP is half the equation when determining positional precision, many of the urban canyon data anomalies were not filtered with HDOP alone.

The number of satellites is also a good indicator of potentially bad data. To obtain an accurate three-dimensional position, four satellites must be simultaneously tracked. Three satellites provide an x, y position, but four or more are preferred. In combination, the detection of poor PDOP values and three or fewer satellites make a good screening duo. However, it is possible to have a bad data point with good PDOP values and four or more satellites. For detection of these points, it is best to examine the speed values and perform a visual inspection of the vehicle trace within the GIS environment (to see whether the vehicle position was predicted to have suddenly departed from the traveled way).

Filters were applied to the smoothed data sets to remove all points from the time series for each of the attributes and each of the packages:

- Urban canyon—visual editing of erratic positional data in the downtown urban canyon area;
- Number of satellites—discard of data points where number of tracked satellites is less than four; and
- HDOP—discard of data points where HDOP value is greater than or equal to 4.0.

If a point was discarded from P1, the corresponding point (denoted by time) was removed from the other three data streams. Once a point was discarded, if another point were to be discarded from the same package within the next 12 s, all 12 points were considered suspect and were removed.

### Visual Inspection for Spatial Accuracy

To identify operating environments experienced by the driver, it must be possible to link the raw GPS coordinates to other data containing important variables (i.e., road width, road classification, pavement condition, traffic congestion, surrounding land use, and average speed). The GPS points must be relatively accurate to other GIS databases to allow the inference. In many cases, the absolute GPS position will be more accurate than the other GIS data layers. The relative accuracy can be degraded by either poor GPS positional accuracy or poor GIS data positional accuracy. Regardless of which is more erroneous, the connectivity must be established. GIS layers usually are maintained by other agencies and are not easily updated. Furthermore, road databases generally attempt to follow the centerline, whereas the in-vehicle GPS units collect the vehicle path (usually not the road centerline). This systematic difference can be anywhere from 3 m to more than 15 m for multilane freeways.

## RESULTS

### Spatial Analysis Results: Horizontal Positional Accuracy

To assess the positional accuracy among the four unit types and the other data layers, the points were displayed with a 1993 digital orthophoto quarter quadrangle and a Georgia Department of Transportation (GaDOT) DLG-F road centerline (1:15,000) (see Figure 4). Three items were immediately evident. First, positional accuracy of all four units was as good as or better than the GaDOT centerline. Second, the horizontal positions of the units were all degraded around tall buildings in downtown Atlanta (see Figure 5), and the degradation of horizontal accuracy due to buildings was large enough to prevent path determination. Third, the path recorded by the unit with differential correction could not be discerned from the three noncorrected units. Any improvement that differential correction may have had was not enough to improve the ability to identify the traveled path. In fact, at least one segment of differentially corrected data was clearly poorer than the other units (see Figure 5). The reason for this occurrence has yet to be analyzed.

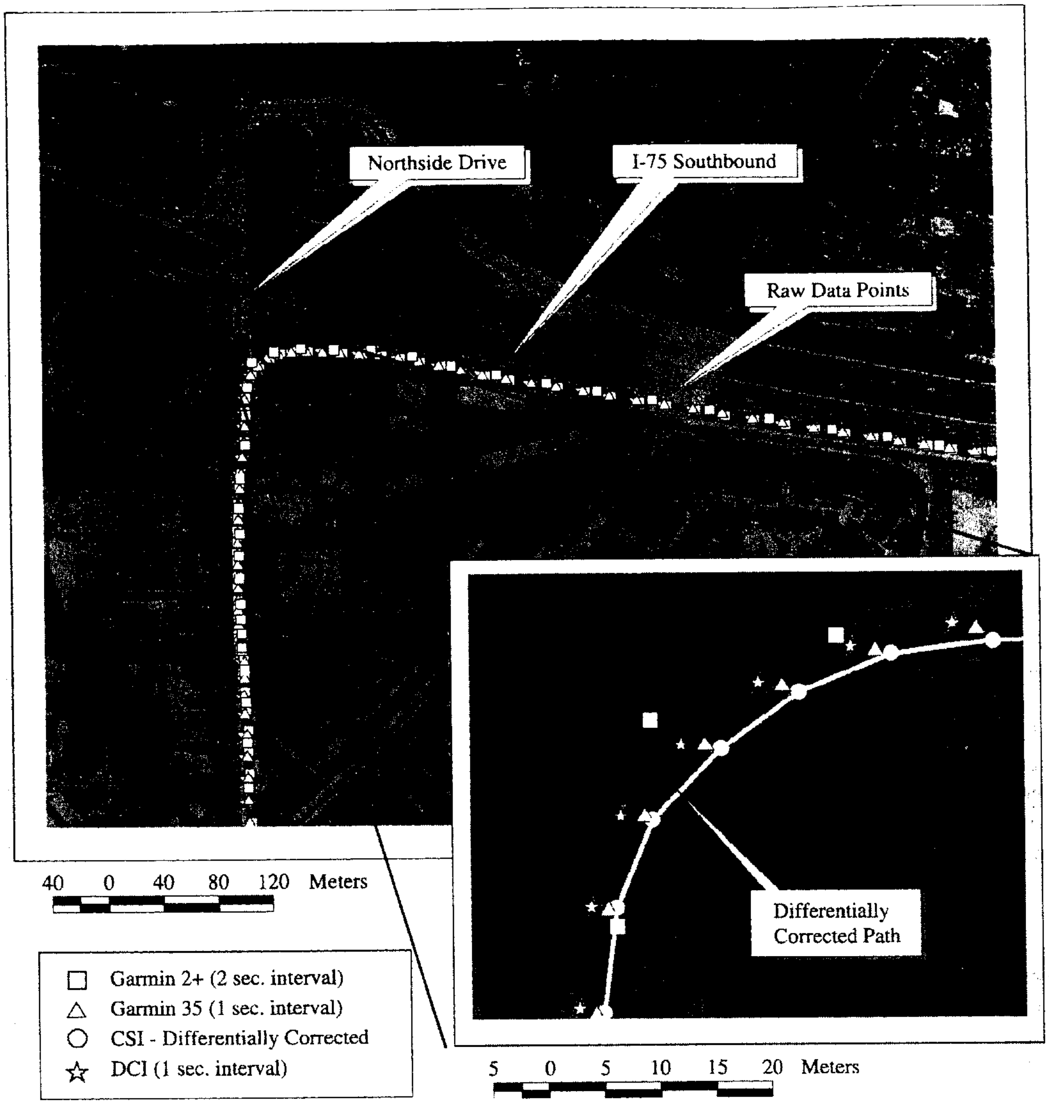


FIGURE 4 Horizontal positional accuracy.

The difference between the road centerline and the individual points was calculated for each unit. The data points collected in the urban canyons were removed to assess the relative accuracy of the remaining data. Of the remaining data points, 90% were less than 10 m from the GaDOT centerline for all four units (50% less than 5 m). Maximum errors were less than 50 m. All of the units were accurate enough that the actual traveled path along the GaDOT road centerline database could be immediately determined.

## Analytical Results for Speed Data

Descriptive statistics for the differences between DMI and GPS speed data are presented in Table 2. GPS speeds for all field units compared very favorably with the DMI speeds. The average speeds for all of the equipment are within 1.1 mph of the DMI average speed. Note that the DMI unit is calibrated to each individual vehicle (*11*). Because a relatively short distance (200 ft) was used to calibrate the unit, a slight bias in the DMI accuracy may exist. DMI accuracy can also fluctuate as a function of tire inflation (which changes the tire diameter and distance traveled per drive shaft rotation). Hence, the accuracy of the DMI unit for speed estimates ca change across days or even during the day as a function of tire temperature. The acceleration values (relative change in velocity) however, are not significantly affected by temperature. Thus, th mean difference of approximately 1 mph in average speeds for th GPS units is not a reason for concern. It is possible that the GP units provided a less biased estimate of average speed than did th DMI. The variability of speed estimates was the major concern fo this study.

During the tests, 3,080 s of data were collected. Minimum and maximum errors in 1-s speed measurements ranged from plus or minus 1 to 33 mph for each unit. The standard deviations of the differenc between GPS-predicted and DMI-derived data for all four units wa less than 2.6 mph. Note, however, that the standard deviation in spee errors reported for the P4 unit is artificially low because the P recorded unit data every other second (missing values were interpolated from surrounding values). The P2 unit employing differentia correction did not perform significantly better than the noncorrecte GPS units for any of the speed error metrics.

When the number-of-satellite and urban canyon filter algorithm were applied to the GPS data streams, the standard deviations c

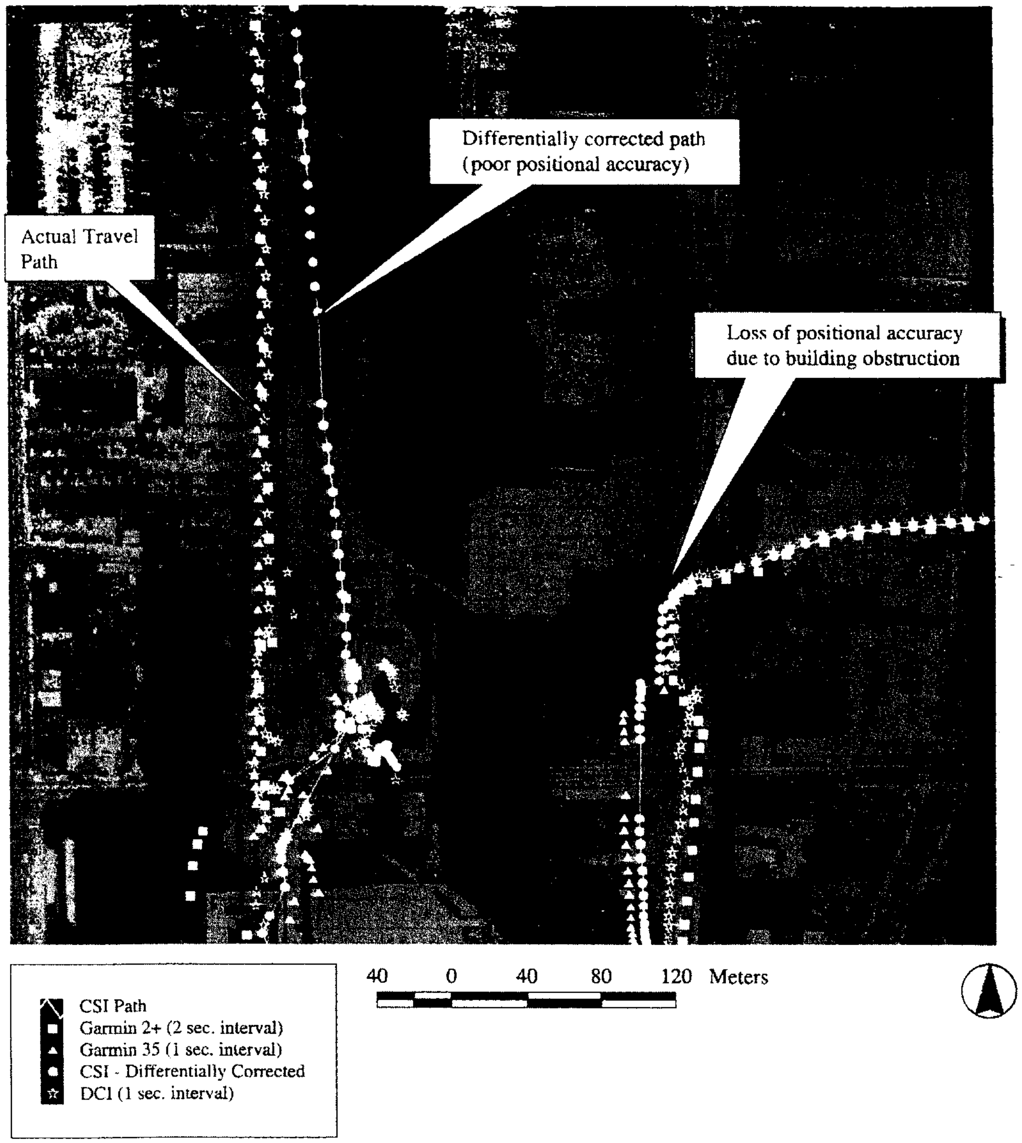


FIGURE 5 Urban canyon degradation.

speed errors dropped significantly. The HDOP and uncorrected P2 filters did not improve estimates and are not reported here. The standard error of speed errors dropped by approximately 30% for all units when the number-of-satellites filter was applied. However, the satellite filter screened approximately 50% of the data from the analysis because the data from all four units were screened from the comparative analysis whenever any one of the units dropped below the filtering criteria. Because, in any given second, one of the four units may drop to three satellites for a brief period, a large fraction of the total data points were screened. When the urban canyon filter was applied to the data, the standard error of speed differences dropped by approximately 40% for the uncorrected GPS data streams. This large improvement resulted from the filtering of only 20% of the data from the analysis. The significant improvement of speed results from screening all urban canyon data may result from an impact of both satellite number and satellite orientation (reflected in PDOP metrics) in the urban center on speed estimation. Although the units receive data from four or more satellites in the urban center, these satellites are much more likely to be clustered overhead, and this may affect speed predictions. Unfortunately, because PDOP data were not collected by the data logging software, statistical analyses to test this hypothesis cannot be performed with these data. It is also interesting to note that the P2 unit with differential correction improved more under the satellite screening than under the urban canyon screening. This appears to be due to the screening of data for the period outside of the urban center when the P2 spatial data deviated significantly from the actual road route (also due to a loss of satellite data). Box plots of the experimental results are presented in Figure 6.

### Analytical Results for Acceleration Data

Descriptive statistics for the differences between DMI and GPS acceleration data (change in speed over 1 s) are presented in Table 3. The mean values for GPS acceleration differences collected by all GPS field units was approximately zero, which compares

**TABLE 2 Delta Speed Statistics**

All Data Points

| | | DSPD1 | DSPD2 | DSPD3 | DSPD4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 3080 | 3080 | 3080 | 3080 | 3080 |
| Minimum | Statistic | -33.50 | -14.08 | -14.57 | -28.76 | |
| Maximum | Statistic | 14.74 | 24.07 | 20.19 | 13.46 | |
| Mean | Statistic | .8471 | 1.0789 | 1.1013 | .8841 | |
| | Std. Error | 4.669E-02 | 4.443E-02 | 4.564E-02 | 3.202E-02 | |
| Std. | Statistic | 2.5913 | 2.4657 | 2.5329 | 1.7771 | |
| Skewness | Statistic | -5.274 | 2.567 | .718 | -2.981 | |
| | Std. Error | .044 | .044 | .044 | .044 | |
| Kurtosis | Statistic | 66.940 | 24.724 | 15.260 | 55.378 | |
| | Std. Error | .088 | .088 | .088 | .088 | |

Filter = # Satellites < 4

| | | DSPD1 | DSPD2 | DSPD3 | DSPD4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 1468 | 1468 | 1468 | 1468 | 1468 |
| Minimum | Statistic | -11.27 | -5.84 | -6.44 | -28.76 | |
| Maximum | Statistic | 10.31 | 10.24 | 12.08 | 8.30 | |
| Mean | Statistic | .7471 | .8728 | .8830 | .6850 | |
| | Std. Error | 4.459E-02 | 4.425E-02 | 4.447E-02 | 4.975E-02 | |
| Std. | Statistic | 1.7084 | 1.6953 | 1.7038 | 1.9062 | |
| Skewness | Statistic | -.614 | .889 | .806 | -5.763 | |
| | Std. Error | .064 | .064 | .064 | .064 | |
| Kurtosis | Statistic | 8.320 | 4.762 | 5.887 | 79.468 | |
| | Std. Error | .128 | .128 | .128 | .128 | |

Filter = Urban Canyon

| | | DSPD1 | DSPD2 | DSPD3 | DSPD4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 2421 | 2421 | 2421 | 2421 | 2421 |
| Minimum | Statistic | -11.27 | -5.84 | -5.78 | -5.68 | |
| Maximum | Statistic | 11.09 | 24.07 | 15.17 | 8.30 | |
| Mean | Statistic | 1.0316 | 1.2041 | 1.1501 | 1.0139 | |
| | Std. Error | 3.121E-02 | 4.418E-02 | 3.219E-02 | 2.723E-02 | |
| Std. | Statistic | 1.5355 | 2.1737 | 1.5836 | 1.3400 | |
| Skewness | Statistic | .077 | 4.917 | 1.610 | .273 | |
| | Std. Error | .050 | .050 | .050 | .050 | |
| Kurtosis | Statistic | 8.202 | 44.034 | 10.370 | 2.912 | |
| | Std. Error | .099 | .099 | .099 | .099 | |

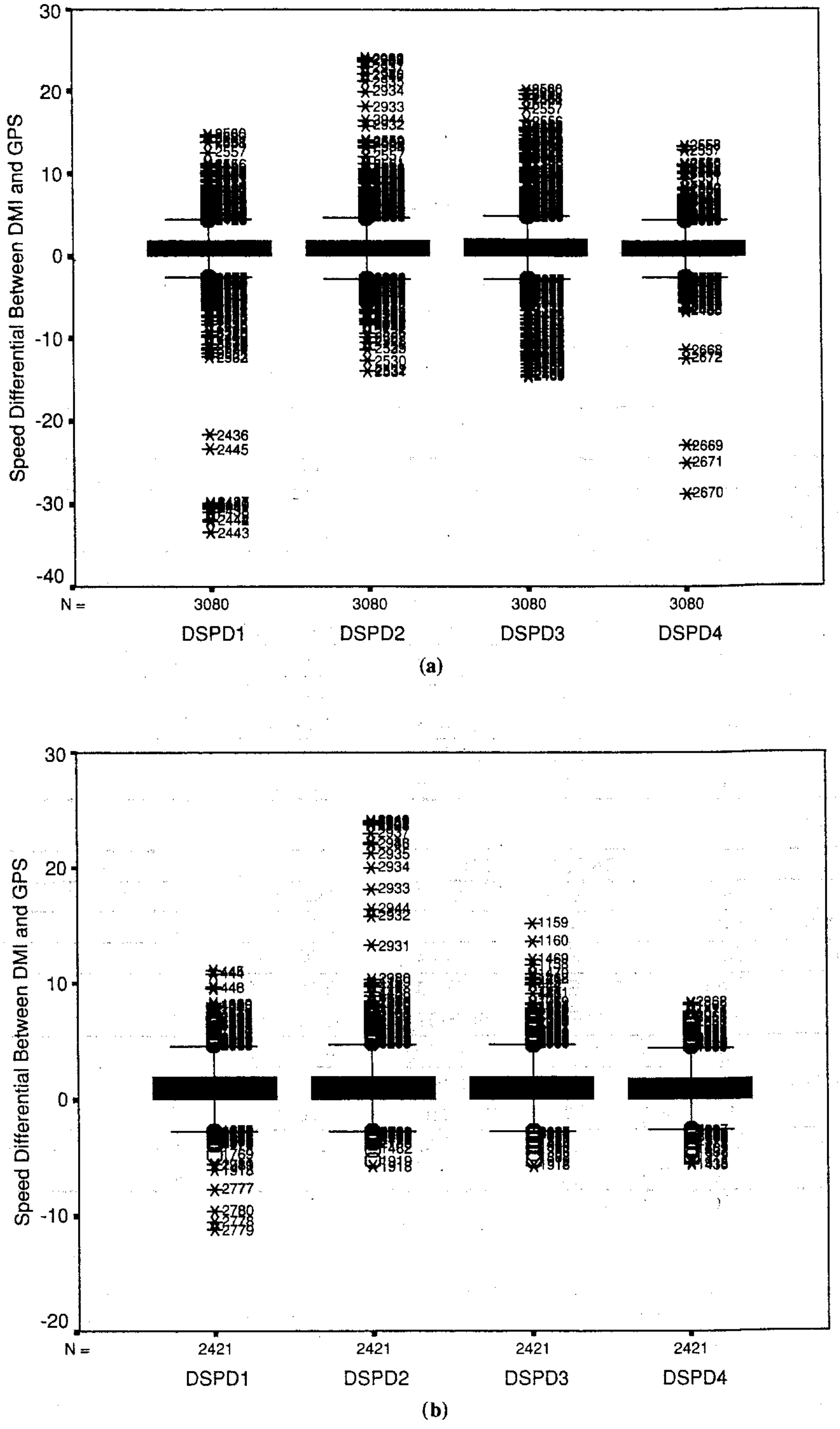
favorably with accelerations based on DMI speeds. Because acceleration is calculated from consecutive speed readings, the potential bias in speed from the DMI does not affect the acceleration calculations.

Minimum and maximum errors in 1-s acceleration measurements ranged from plus or minus 4 to 12 mph/s for each unit. The standard deviations of the difference between GPS-predicted and DMI data for all four units was less than 0.8 mph/s. The P2 unit employing differential correction did not perform significantly better than the noncorrected GPS units for any of the acceleration error metrics. For the purposes of the NHTSA study and future vehicle emissions studies, additional acceleration validation studies must be conducted to ascertain the potential impact of the noted acceleration variability on potential research findings.

The satellite screening criteria did not improve acceleration errors significantly. The HDOP and uncorrected P2 filters did not improve estimates and are not reported here. When the urban canyon filter algorithms were applied to the GPS data streams the standard deviations of acceleration errors dropped slightl The standard error of acceleration errors dropped by approx mately 10% to 30% for the corrected and uncorrected units whe the urban canyon filter was applied. Again, this improvemen may result from an impact of both satellite number and satellit orientation (reflected in PDOP metrics) in the urban center o speed estimation. Figure 7 presents the box plots of experiment results.

## CONCLUSIONS

For researchers and practitioners, life without selective availabi ity is a great improvement. Travel routes can clearly be discerne without the addition of differential correction units (saving tim money, and headaches). Although these tests were not rigorous



(a)

(b)

**FIGURE 6 Difference between DMI and GPS speed values: (*a*) all data and (*b*) urban canyon data filter.**

their ability to determine whether differential corrections can be eliminated from the NHTSA in-vehicle equipment configuration, they do suggest that noncorrected data can be used to obtain data within a reasonable range of the requirements. Further testing will examine multiple sources of DGPS against noncorrected sources. The researchers had planned to test an FM subcarrier DGPS broadcast as one of the four packages, but the service was no longer in operation. This type of problem is one of several that can be quite disruptive to data collection activities. The in-vehicle equipment design will be able to accept differential correction signals. The specified GPS receiver is a more high-end version than the ones tested in this effort, so results with the new equipment are expected to be even better (especially if signals are differentially corrected).

**TABLE 3 Delta Acceleration Statistics**

All Data Points

| | | DACC1 | DACC2 | DACC3 | DACC4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 3079 | 3079 | 3079 | 3079 | 3079 |
| Minimum | Statistic | -13.36 | -8.08 | -7.83 | -11.57 | |
| Maximum | Statistic | 13.47 | 4.44 | 4.95 | 12.69 | |
| Mean | Statistic | -2.79E-04 | -8.44E-04 | -9.09E-04 | -4.56E-04 | |
| | Std. Error | 1.417E-02 | 1.244E-02 | 1.277E-02 | 1.245E-02 | |
| Std. | Statistic | .7864 | .6901 | .7084 | .6910 | |
| Skewness | Statistic | -.126 | -1.107 | -.919 | -.077 | |
| | Std. Error | .044 | .044 | .044 | .044 | |
| Kurtosis | Statistic | 77.645 | 15.420 | 16.272 | 94.089 | |
| | Std. Error | .088 | .088 | .088 | .088 | |

Filter = # Satellites < 4

| | | DACC1 | DACC2 | DACC3 | DACC4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 1467 | 1467 | 1467 | 1467 | 1467 |
| Minimum | Statistic | -9.02 | -8.08 | -4.88 | -11.57 | |
| Maximum | Statistic | 3.96 | 3.83 | 4.62 | 12.69 | |
| Mean | Statistic | -1.61E-02 | -4.79E-03 | 2.884E-03 | -7.12E-03 | |
| | Std. Error | 1.822E-02 | 1.837E-02 | 1.797E-02 | 2.165E-02 | |
| Std. | Statistic | .6977 | .7036 | .6881 | .8294 | |
| Skewness | Statistic | -1.625 | -1.551 | -.011 | .584 | |
| | Std. Error | .064 | .064 | .064 | .064 | |
| Kurtosis | Statistic | 23.432 | 18.350 | 9.039 | 90.154 | |
| | Std. Error | .128 | .128 | .128 | .128 | |

Filter = Urban Canyon

| | | DACC1 | DACC2 | DACC3 | DACC4 | Valid N (listwise) |
|---|---|---|---|---|---|---|
| N | Statistic | 2420 | 2420 | 2420 | 2420 | 2420 |
| Minimum | Statistic | -4.11 | -8.08 | -5.53 | -3.92 | |
| Maximum | Statistic | 3.96 | 4.44 | 4.95 | 3.01 | |
| Mean | Statistic | -8.31E-04 | -1.27E-03 | -1.54E-03 | -1.08E-03 | |
| | Std. Error | 1.111E-02 | 1.297E-02 | 1.303E-02 | 1.003E-02 | |
| Std. | Statistic | .5466 | .6379 | .6411 | .4936 | |
| Skewness | Statistic | -.648 | -1.542 | -.763 | -.458 | |
| | Std. Error | .050 | .050 | .050 | .050 | |
| Kurtosis | Statistic | 9.044 | 21.788 | 15.375 | 7.194 | |
| | Std. Error | .099 | .099 | .099 | .099 | |

Data collection activities will continue throughout the year to determine if there are any significant effects of ionospheric error on variations in positional accuracy. Extremely high sunspot numbers might indicate that the GPS world is experiencing worst-case interference. It will be interesting to track the variation in positional accuracy to determine if there are any trends that follow the solar maximum and minimums.

GPS without selective availability is still problematic in urban canyon environments as shown in Figure 5. Researchers at Georgia Tech will examine ways to minimize outlier data from these situations over the next year. Current visual inspections will be too labor intensive to complete for continuous tracking of the 1,100 vehicles in the NHTSA study. The research plans to use information contained in the land use database to develop and implement automatic filters for these types of error.

The results of these statistical analyses indicate that a GPS receiver without differential correction can also provide a successful alternative to DMI units in urban speed studies. Floatin car and car-following studies designed to obtain travel route an speed data may be more accurate when data are collected wit GPS systems. However, the usefulness of the GPS-derived acce eration data remains uncertain. If the goal of a study is to develo histograms of acceleration data for the purposes of improving th performance of traffic signal models, the GPS units may provic sufficiently accurate acceleration data. However, in cases whe accurate joint acceleration and speed distributions are require (such as in the case of modal emission rate modeling), it is impo tant to determine whether the acceleration errors are correlate with speed or acceleration values. Cross-tabulation analyses a under way to determine whether the acceleration errors are rando and have uniform variance across all speed and acceleratic groups. If so, then the joint probability distributions for the GPS units can be used for an even wider variety of purposes th reported here.

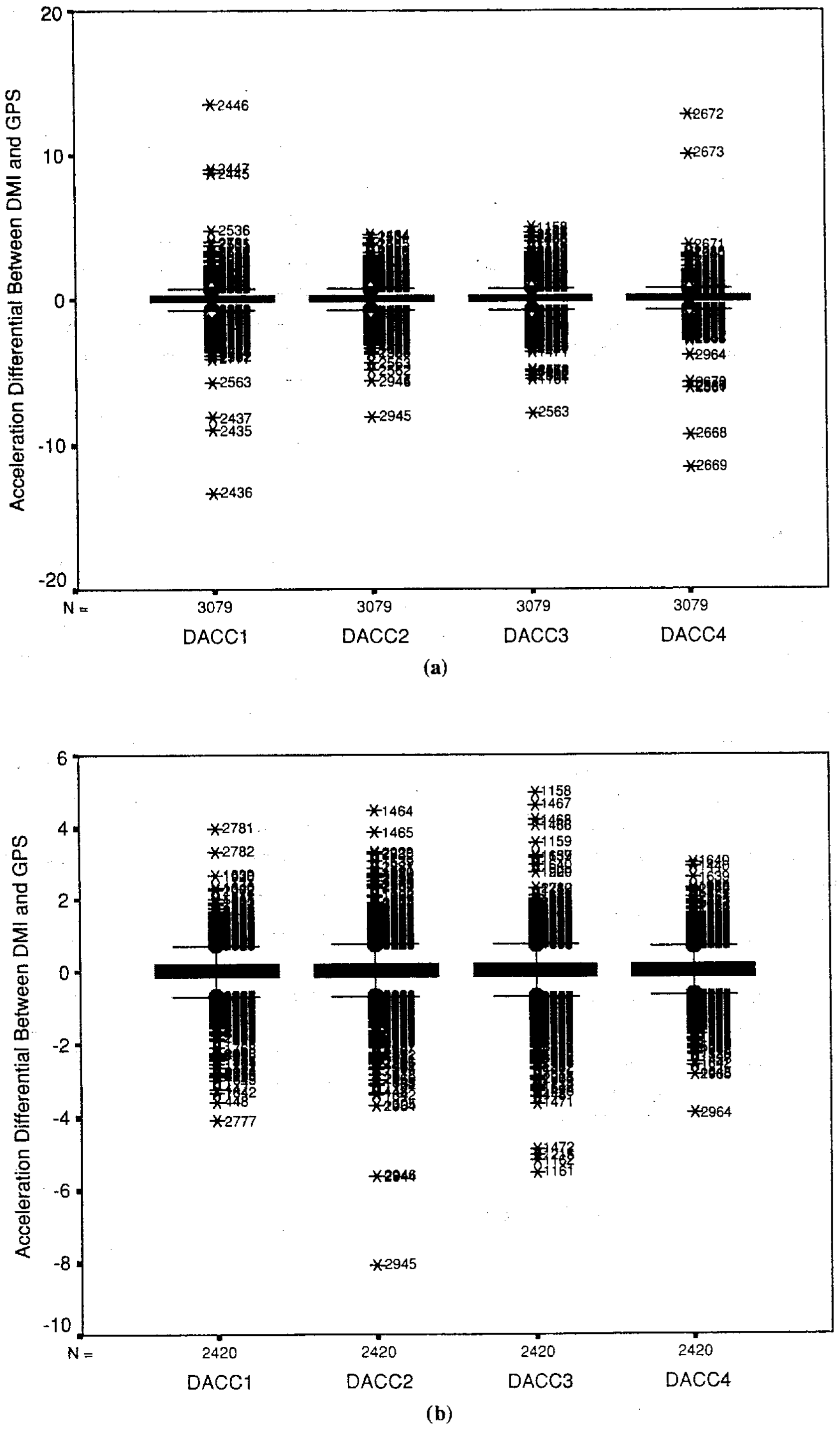


FIGURE 7 Difference between DMI and GPS acceleration values: (*a*) all data, (*b*) urban canyon data filter.

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*Publication of this paper sponsored by Committee on Traffic Law Enforcement.*