Application of GPS in Traffic Management Systems

ARDESHIR FAGHRI AND KHALED HAMAD *Department of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716*

Integrated Traffic Management Systems (ITMS) need reliable, accurate, and real-time data. Travel time, speed, and delay are three of the most important factors used in ITMS for monitoring, quantifying, and controlling congestion. GPS has recently become available for civil applications. Because it provides real-time spatial and time measurements, it has an increasing use in conducting different transportation studies. This article presents the application of GPS in collecting travel time, speed, and delay information on 64 major roads in the state of Delaware. A comparative statistical analysis was performed on data collected by GPS, with data collected simultaneously by the conventional method. The GPS data proved to be at least as accurate as the data collected by the conventional method, and it was 50% more efficient in terms of manpower. Moreover, the sample-size requirement was determined to maintain 95% confidence level throughout the controlled test. Benefiting from the Geographic Information System's dynamic segmentation tool, our travel time, delay, and speed information were integrated with other relevant traffic data. This was presented graphically on the Internet for public use. Statistical trend analysis for the data collected in 1997, 1998, 1999, and 2000 are also presented and applications in the overall ITMS are discussed.

INTRODUCTION

Traffic congestion is a serious problem in Delaware as it is in any other state. Congestion, due to the inability of the current transportation system to meet the need for travel demand, will continue to escalate in the foreseeable future, especially with the increasing limitations set on the resources to build new facilities. Therefore, there is a pressing need to measure congestion levels in a consistent manner across places and time. Consequently, many states' departments of transportation, as part of their Integrated Traffic Management System, have established congestion management systems to monitor, control, and alleviate congestion. For this purpose, measuring congestion provides a key step to assist transportation professionals, policy makers, and the general public to identify the problem and develop necessary improvements.

The evolution of GPS for civil applications has provided a powerful and cost-efficient tool for collecting travel data. Since 1996, the Delaware Department of Transportation (DelDOT), with the help of the Civil and Environmental Engineering Department at the University of Delaware, has been using GPS technology to collect the average running speed, travel time, and delay on all the major routes throughout the state.

Travel time, speed, and delay data are mainly used to evaluate various transportation projects by comparing the estimated travel times with the existing ones. This information is then used to refuse projects that do not take into account reducing travel time as well as other traffic management objectives such as increasing safety or reducing emissions. Another useful application for this data in transportation planning can be using travel time data in traffic assignment models. More importantly, however, is the fact that this data can be used to monitor congestion all over the state. Road segments with high travel time, compared to free flow travel time, indicate "hot" segments requiring improvement. This information can also be provided to the public via the Internet. Today, many websites provide door-to-door travel directions between two locations, based on the shortest path between them. Algorithms used to determine this path are based on the shortest distance between the origin and destination. Good examples are Yahoo and MapQuest. However, the actual shortest path, which should be based on the actual time spent traveling the road, has not been used.

GPS Solutions, Vol. 5, No. 3, pp. 52–60 (2002)

Taylor and colleagues (Taylor, D'Este, & Zito, 1999; Taylor, D'Este, Woolley, & Zito, 2000) and Quiroga and Bullock (1998, 1999) are among a few researchers who have written about using GPS technology to collect transportation data. In their papers, the authors use a microscopic approach to find travel time and speed for roadway segments. That is, segment speeds were obtained using the instantaneous GPS speeds. For this article, we first proved the accuracy of using GPS technology to perform travel time, speed, and delay studies. Then locational data and travel time for each segment were used to determine the average travel speed on each segment. This method can be described as a macroscopic approach to determining travel speed and delay information.

In the following sections of this article, we present the accuracy analysis, sample-size requirement, integration of data into Geographic Information System (GIS), and finally trend analysis for the collected data.

Travel Time and Delay Studies

There are several methods to conduct travel time and delay studies (Robertson, 1994):

1. Average vehicle method
2. Moving vehicle
3. License plate
4 Direct observation, or interview method

Although the first two methods require driving a vehicle, the other two can be done remotely. The major difference between the first and second methods is that the driver/recorder in the moving vehicle method has to record opposing traffic, overtaking traffic, and passed traffic, in addition to travel time. The choice of method among these depends mainly on the purpose, the type and length of the road being studied, as well as the resources available to conduct the study. The following paragraph describes the average vehicle method as it was used during the preparatory stage of this project.

An observer and a driver are needed to record the data as the test car travels along the roadway segment: one person records the total travel time it takes to travel the segment, while the other records the delay time. A stopwatch is used to record the duration of delay whenever the vehicle's speed drops below 5 mph (this was specified by DelDOT). Another stopwatch is also used to record the total travel time. Finally, the vehicle's odometer is used to read the trip length. The delay data can include the duration of delay, the cause of delay, and the location of delay. Once this data has been collected, various analyses of the data can be performed to obtain information such as travel speed, running speed, and percentage of time spent in delay.

AUTOMATIC DATA COLLECTION

The main objective of this research project was to use GPS to determine speed, travel time, and delay on all the major roadways throughout the state of Delaware. The GPS method requires only one person to be in the vehicle (the driver) who needs a notebook computer with the software necessary to save and retrieve data in addition to being connected to the GPS unit. After investigating several GPS receivers, Trimble's Mapping and GIS Systems® (Trimble Navigation, 1996) was chosen. This unit consists of several components, including a GPS receiver, data collectors, and processing software (see Figure 1). As can be observed from Figure 1, all the equipment necessary to automatically collect speed, travel time, and delay data by GPS can conveniently fit on one seat of a typical passenger car. The model used in this study, the Trimble Pro XR, has a differential correction capability, allowing less than 100 cm of error in any place in Delaware (Trimble Navigation, 1996). It was thus concluded that the acquired accuracy was allowable and within the acceptable range for the application in this project (Faghri, 1998).

The automatic data collection method consists of three steps:

1. Preparatory office work
2. Field data collection
3. Post-data-collection office work

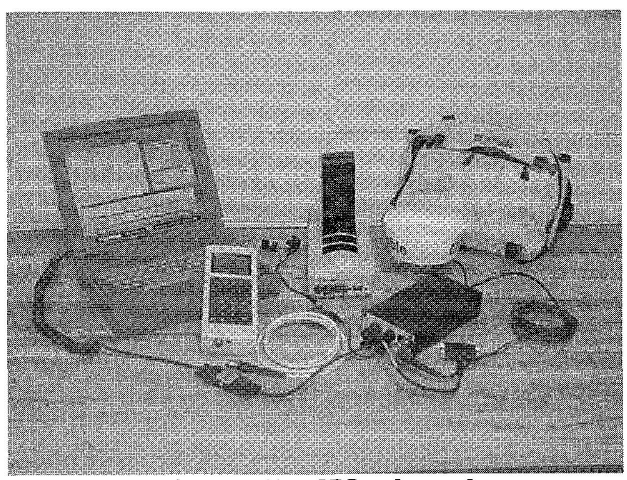


FIGURE 1. The GPS unit used.

Before going into the field to collect data, some work had to be done in the office. The most important was the establishment of a data dictionary, a user-defined dictionary that captures various attributes such as control points and other features expressed in the data collection. Establishing a dictionary saves time and allows the user to call upon the highlights already keyed into the dictionary once he or she encounters them. These highlights include the causes of congestion, weather conditions, and the control points, which are the starting and ending points of every roadway segment from which the driver wants to collect data.

Once the GPS antenna and data logger were properly connected to the notebook and the battery, the driver was able to collect data directly. He or she made use of the aforementioned data dictionary to input the control and delay points. If and when it seems that the vehicle is slowing below 5 mph, the driver can mark these points as delay points giving the appropriate code (for instance, "S" for signal and "C" for construction) and location of delay (which is automatically recorded).

Some post-data-collection office work on the raw data was required to find the travel and delay time for each segment of the roadway. When returning from the field, the processing software transferred the position and feature information (which was programmed and edited on the road) from the data collector. The position and feature information include a map of the trip with indicated control points, length of each segment, time it took to travel the segment, name of the segment, date recorded, study period (AM or PM), direction of travel, length of the segment traveled and reason for delay (i.e., signal, construction, congestion, etc.) This information was then used in calculating mean travel speed, mean running speed, and percentage of time in delay, in addition to travel time and total delay.

Several runs were made on different selected roadways to test the functionality of the GPS hardware as well as the supporting software. The tests were all successful. However, before extensive statewide data collection could begin, we had to prove that the GPS method was at least as accurate as the traditional manual method. The following two sections describe (1) the sample-size requirements and (2) the statistical analysis that was performed to prove the accuracy of the GPS method.

Sample-Size Requirement

Prior to collecting any data from the field, either by the conventional method or by the GPS method, we had to know how many runs are required to maintain a confidence level of 95% on every segment. In our study, we computed the average range in running speed to determine the sample size (in terms of number of test runs) required. Running speed was used instead of the travel speed because it is more stable (Robertson, 1994).

The first step in calculating the required sample size of the data is to conduct an initial data collection of at least four runs on each of the roadways to be studied, which means four runs in each direction. The data collected during each run included trip length, trip time, and delay time. From these data, running speed was calculated as follows:

$$\text{Running Speed} = \frac{\text{Trip Length}}{(\text{Trip Time} - \text{Delay Time})} \qquad (1)$$

Once the running speeds for each run were recorded, the next step was to compute the difference between each of the running speeds in sequence between the first and second, second and third, etc. This value is the change in running speed, A. To find the running speed for the entire group of runs, we summed the A values. This summation was then used to obtain the average range in running speed, R, using the following equation:

$$R = \frac{\Sigma A}{(N-1)} \qquad (2)$$

where N is the number of runs. The value of R was then used in Table 1 to find the minimum number of runs needed for a certain degree of accuracy.

To determine the sample size requirements throughout our data collection, four sample arterial roads were selected: Route 202 (Concord Pike), Route 2 (Kirkwood Highway), Route 896, and Route 4. These roads were selected mainly because they are the four major and the most congested arterial roads in Delaware. Thus they represent the worst-case scenarios in the study. Based on the calculated values of the average range in running speed from all four-sample arterials, it was found that the average range in running speed was 5.0 mph (8 km/h) or less. Thus, using Table 1 with a minimum confidence level of 95% and with permitted errors of 1 to 5 miles per hour (1.6 to 8 km/h) in velocity, the minimum number of runs was computed.

GPS Method versus Conventional Method

To compare the accuracy of the GPS method for collecting travel time, speed, and delay data, we needed to col-

TABLE 1

Sample-size requirements for travel time and delay studies with a confidence level of 95.0%

Average Range in Running Speed (mph)	*Minimum Number of Runs for a Permitted Error of:* 1.0 mph	2.0 mph	3.0 mph	4.0 mph	5.0 mph
2.5	4	2	2	2	2
5	8	4	3	2	2
10	21	8	5	4	3
15	38	14	8	6	5
20	59	21	12	8	6

(Source: Manual of Transportation Engineering Studies, ITE, 1994)

lect these data by a conventional method and then compare the results to those obtained simultaneously by the GPS method. For this purpose, the average vehicle method (the most popular) was employed.

A statistical study was performed to see whether there are significant differences between the manual method and the GPS method. Analyses of means and variances were used to test if the difference between the two methods was due to a significant difference or due to chance. Evidently, when the variances and means have no significant difference, the two methods can be said to be statistically indifferent. Thus, they can be used interchangeably.

For this purpose, the travel time and delay study was performed twice on Kirkwood Highway, from Newark to Wilmington, DE, a stretch of about 9 miles (14.4 km): the first by using the conventional manual method and the second, simultaneously, with the GPS method. Two teams worked independently, one for manual and the other for the GPS data collection. Table 2 summarizes the trials performed for each method. As can be observed, the travel time over Kirkwood Highway was measured 12 times manually using the average vehicle method and 12 times using the GPS method. These trials were performed during morning and afternoon peak hours for both directions (east and west) to account for any traffic variations during the day.

The two-sample t test was used to compare the means of the samples collected. Prior to using the t test, the F test was used to determine whether we had to assume equal variances or not (Moore & McCabe, 1999). As shown in Table 3, equal variances can be used (for

TABLE 2

Summary of travel and delay times collected by manual and GPS methods

ROAD	*Date*	*Time*	*Direction*	*Travel Time (s)* GPS	*Manual*	*Delay Time (s)* GPS	*Manual*
Route 2 (Kirkwood Highway)	06/15/1998	PM	East	1482	1399.66	310	455.62
	06/15/1998	PM	West	1939	1943.57	640	973.97
	06/15/1998	PM	East	1392	1392.98	370	479.59
	06/15/1998	AM	East	1258	1251.41	170	337.26
	06/15/1998	AM	West	1202	1205.88	310	357.49
	06/15/1998	AM	East	1348	1354.19	252	444.59
	06/15/1998	AM	West	1061	1061.62	180	236.13
	06/15/1998	AM	East	1284	1288.78	240	366.66
	06/17/1998	AM	East	1337	1337.83	415	431.01
	06/17/1998	PM	East	1466	1470.52	295	527.47
	06/17/1998	PM	West	1871	1862.08	434	879.62
	06/17/1998	PM	East	1420	1421.46	402	487.68
		Mean		1421.67	1415.83	334.83	498.09
		Standard Deviation		254.54	252.99	129.67	216.17

TABLE 3

Test of equality of variances and *t* test for equality of means for travel time data collected by manual and GPS methods

	Test for Equality of Variance			t test for Equality of Mean			
	F	*Prob.*	*Result*	*t*	*df*	*Prob. (2-tailed)*	*Result*
Travel Time (both directions)	.007	.932	Not Significant Equal variances used	.056	22	.956	Not Significant
Travel Time (east direction)	.271	.611	Not Significant Equal variances used	.229	14	.822	Not Significant
Travel Time (west direction)	.002	.964	Not Significant Equal variances used	.000	6	1.000	Not Significant

example, $F = 0.007$, $p > 0.05$ for both directions). Thus, the pooled two-sample t test was applied using:

$$t\text{-}statistic = \frac{\bar{x}_1 - \bar{x}_2}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad (3)$$

where s_p is the pooled estimator of the population variance σ^2, which can be calculated as:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \qquad (4)$$

where $\bar{x}_1$ and $\bar{x}_2$ are the means of sample 1 and sample 2, respectively; s_1^2 and s_2^2 are the variances of sample 1 and sample 2, respectively; and n_1 and n_2 are the sizes of sample 1 and sample 2, respectively.

In the case where there was a significant difference in the variances of the two samples, the following equation would have been used to find the t-statistic:

$$t\text{-}statistic = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad (5)$$

The test was performed three times: for the east, for the west, and for both directions combined. As shown in Table 3, it is obvious that there is no statistically significant difference between the means and variances of travel time collected by the manual method and the GPS method (for example, $t = 0.000$, $df = 6$, $p > 0.05$ for travel time in both directions). As a result, we can conclude that the GPS method is at least as accurate as the conventional manual method.

INTEGRATING GPS DATA WITH GIS

Another major objective of this project was to develop a systematic method to transfer the travel data collected by GPS into GIS environment where they can be mapped, analyzed and, most importantly, combined with other transportation data from different sources. GIS allows for maps to be created with color-coded values similar to that of Doppler radar, categorizing rainfall intensity in an array of colors from red (high intensity) to green (low intensity). A literature survey was conducted to find out the most appropriate technique to accomplish our objective. Most of the studies have proven that the GIS dynamic segmentation tool is the most powerful environment to model transportation data (Quiroga, 1998). With the help of ARCVIEW®, a powerful and popular GIS software, we successfully integrated the travel time and delay information into the GIS environment. The procedure can be summarized as follows:

1. Build a route-system using directional centerline network in order to linearly reference the data in GIS
2. Prepare a database file that contains the travel data, in addition to roadway ID, beginning milepost, and ending milepost for each segment of each road in the network.
3. Link the database file that contains the data to theme that contains the route system created in the first step. This can be achieved using the dynamic segmentation capabilities of any available GIS software.

Once these three steps were performed, many different outputs were produced from the information collected by the GPS. This information included color-coded maps corresponding to the average speed, chart figures showing the variations of data over the different segments of the transportation network, some statistical measures, and simple or complex queries such as determination of the top ten most improved, as well as most degraded, roadways over the study period. Figure 2 presents a sample of different mean peak travel speed profiles.

TREND ANALYSIS

Since the primary objective of our travel-data collection was to monitor traffic congestion, the next step was to compare the information over the four years of data collection (1997–2000). When viewing the data for different years, we can identify the roads (or segments of the roads) that had either an increase or a decrease in any of our traffic measures, i.e., travel time, peak speed, and percentage of time in delay. For the purpose of this analysis, a sample of the major roads in Delaware was chosen: I-95, Route 2, Route 7, Route 4, and US Route 13.

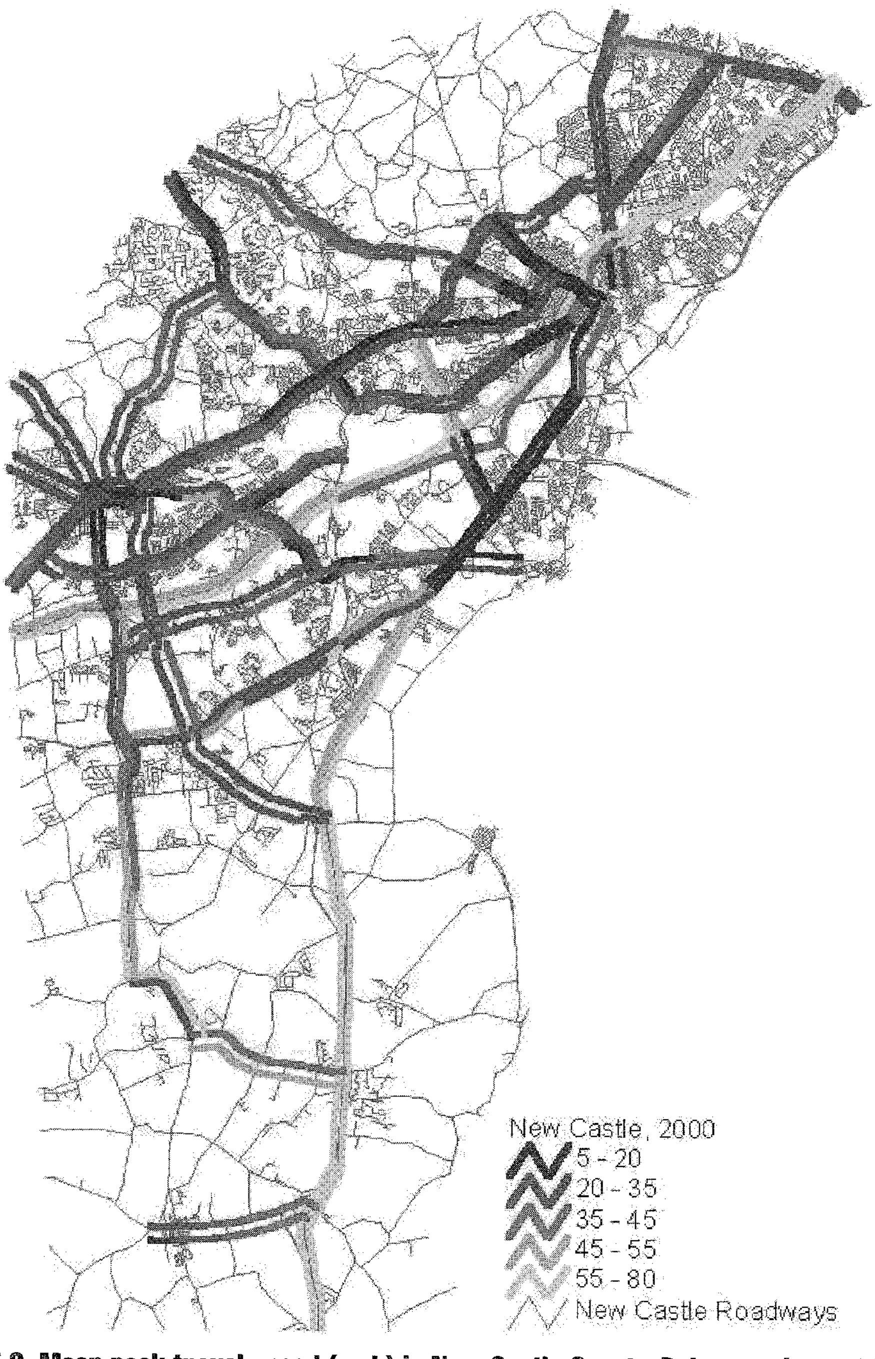
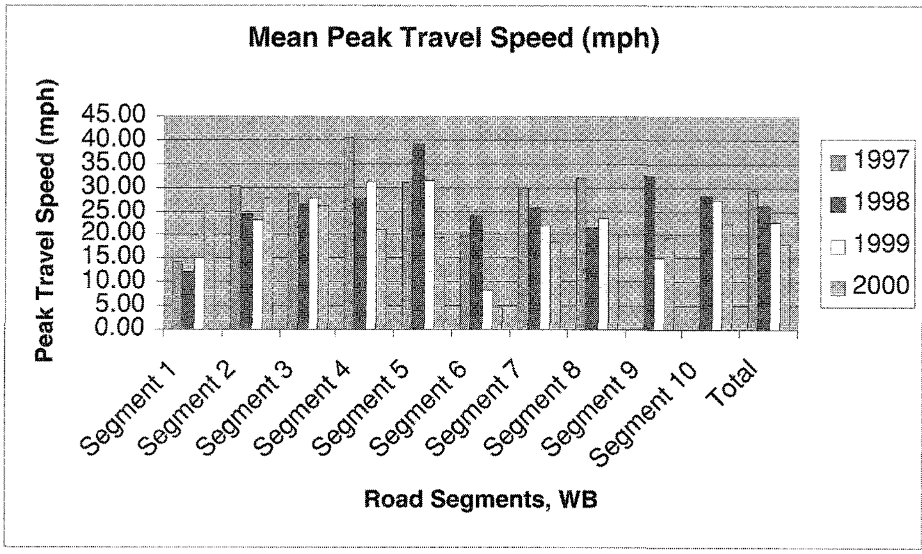


FIGURE 2. Mean peak travel speed (mph) in New Castle County, Delaware (year 2000).

The first step was to summarize the collected data into spreadsheets. Once this data was ready, the analysis was started by plotting it into graphs as shown in the sample chart in Figure 3. For example, there is a gradual decrease in travel speed in the west-bound direction of Kirkwood Highway, while there is an increase in percentage time in delay. On the other hand, these changes are not consistent in the east-bound direction. Therefore, the next step, before making any conclusions, was to test whether this increase (or decrease) is statistically significant. The paired samples t test was used to make a year-to-year comparison, i.e., comparing 1997 to 1998, 1998 to 1999, etc. The year-to-year comparison assists transportation planners to monitor and control congestion on an annual basis, thereby evaluating the impacts of the improvement projects accordingly. The paired samples t test was chosen to ensure that comparison was performed on a segment-to-segment basis. For example, travel speed of road segment 1 in Kirkwood Highway in 1997 was compared to its equivalent in 1998. A sample result is shown in Table 4. As we can see, though there was a decrease in speed in both directions, this decrease was not statistically significant.



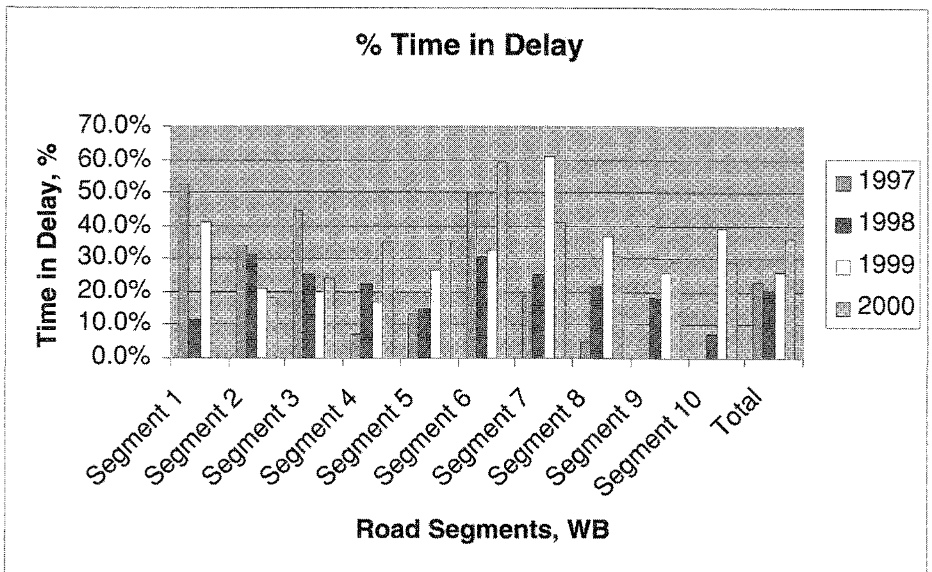


FIGURE 3. Comparison of mean peak travel speed and percentage time in delay for west-bound direction of Kirkwood Highway, Delaware (1997–2000).

TABLE 4

Paired *t* test for equality of means for speed data pairs between 1997 and 2000

Paired Samples t Test–West Bound

		Paired Differences Mean	Std. Deviation	t	df	Prob. (2-tailed)	Result
Pair 1	SPEED97–SPEED98	3.2175	6.8977	1.319	7	.229	Not Significant
Pair 2	SPEED98–SPEED99	3.6260	7.5778	1.513	9	.165	Not Significant
Pair 3	SPEED99–SPEED00	1.9319	7.1589	.853	9	.416	Not Significant

Paired Samples t Test–East Bound

		Paired Differences Mean	Std. Deviation	t	df	Prob. (2-tailed)	Result
Pair 1	SPEED97–SPEED98	5.3462	9.1320	1.656	7	.142	Not Significant
Pair 2	SPEED98–SPEED99	−2.3470	5.7188	−1.298	9	.227	Not Significant
Pair 3	SPEED99 – SPEED00	−1.0720	9.3926	−.361	9	.726	Not Significant

SUMMARY AND CONCLUSIONS

For the past five years, the Delaware Department of Transportation, with the help of the Civil and Environmental Engineering Department at the University of Delaware, has used GPS technology to perform travel time and delay studies on all the major routes in Delaware. The technique has proven to be successful, and the project is expected to continue for the next five years. The main purposes of collecting these data are to monitor the performance of individual routes and the overall network, to identify potential problem sites in the transportation network, and to ascertain the degree to which specific planning objectives are being met.

The main advantage of monitoring congestion using GPS is that real-time information on travel time and speeds can be obtained in an accurate, economical, and timely manner. This technology can be used for annual congestion monitoring with periodic data collection during a particular season or infrequently throughout the year. It can also be used for daily congestion measurement with data being collected on a daily basis. In addition to recording data, the receivers can be used to precisely locate any incidents that occur on the freeway.

Not only is the GPS data collector and processing information easy to use, it is also more accurate, less tedious, involves less human error, and has a built-in differential correction. Moreover, there are more possible sources of error using manual methods due to inconsistencies between the observer and the stop watch and misjudging of when the car is actually traveling less than 5 mph.

Detailed trend analysis will be performed during the next five years on a segment-by-segment basis using the GPS data. The results will continue to be used in conjunction with the state-wide traffic management systems, congestion monitoring, planning, administration, and resource allocation.

ACKNOWLEDGMENT

The study reported herein was financially supported by the State of Delaware Department of Transportation. The authors particularly appreciate all the support received from the staff at DelDOT's Planning Division.

REFERENCES

Faghri, A. 1998. Application of global positioning system (GPS) for monitoring congestion. Masters Thesis. University of Delaware, Newark, DE.

Moore, D.S., & McCabe, G.P. (1999). Introduction to the practice of statistics (3rd ed.). New York: W.H. Freeman.

Quiroga, C.A., & Bullock, D. (1998). Travel time studies with GPS and GIS: An integrated methodology, transportation research. Part C: Emerging Technologies, Vol. 6, Issue 1. (Quiroga 1998) Oxford, England: Elsevier Science Ltd.

Quiroga, C.A., & Bullock, D. (1999). Travel time information using GPS and dynamic segmentation techniques. In Transportation Research Record, No. 1660 (pp. 48–57). Washington, DC: National Academy Press.

Robertson, H.D. (1994). The ITE manual of traffic engineering studies. Prentice Hall.

Taylor, A.P., D'Este, G.M., Woolley, J.E., & Zito, R. (2000). Integration of the GPS and GIS for traffic congestion studies. Transportation Research. Part C: Emerging Technologies, 6(1).

Taylor, A.P., D'Este, G.M., & Zito, R. (1999). Using GPS to measure traffic system performance. Computer-aided civil and infrastructure engineering. Malden, MA: Blackwell Publishers.

Trimble Navigation. (1996). Mapping systems: General reference. Suunyvale, CA: Trimble Navigation Limited.

Trimble Navigation. (1996, 2 October). Characterizing accuracy of Trimble Pathfinder mapping receivers. [On-line]. Available: http://guest.epoch@www.trimble.com/support/kbase/pdf/acc_sum.pdf

BIOGRAPHIES

Ardeshir Faghri, Ph.D., is associate professor in the Civil Engineering Department at the University of Delaware since 1990. His primary areas of teaching and research are transportation systems engineering, computer methods in traffic engineering, intelligent transportation systems, GIS, GPS, and transportation in developing countries. He graduated from the University of Virginia in 1987.

Khaled Hamad obtained his Bachelor's degree in Civil Engineering from An-Najah National University in Palestine in1996 and his Master's degree in Civil Engineering, with concentration in Transportation Engineering, from the University of Delaware in 2000. He served as an instructor in the Department of Civil Engineering at the Islamic University of Gaza from 1996 to1998. He also worked as a part-time consulting engineer for two years in the Middle East. Khaled is currently a Ph.D. degree candidate in the Civil Engineering Department at the University of Delaware. His primary research interests are transportation engineering systems, GPS, GIS, and intelligent transportation systems.

Peer Review: This paper has been peer-reviewed and accepted for publication according to the guidelines provided in the Information for Contributors.