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Application of GIS and GPS for Collecting and Analyzing Travel Time, Speed and Delay

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The backbone of any successful Integrated Traffic Management System (ITMS) for a metropolis is the availability of 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. A global positioning system has recently become available for civil applications and, as it provides real-time spatial and time measurements, it has an increasing use in conducting different transportation studies. This paper presents the application of GPS in collecting travel time, speed and delay information on 64 major roads all over the State of Delaware. A comparative statistical analysis was performed between data collected by the GPS method and 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 was 50% more efficient in terms of manpower. Moreover, the sample-size requirement was determined to maintain a 95% confidence level throughout the controlled test. Benefiting from the Geographic Information System's Dynamic Segmentation tool, our travel time, delay and speed information was integrated with other relevant traffic data and presented graphically on the internet for public use. Statistical trend analysis for the data collected in 1997, 1998 and 1999 are also presented and applications in the overall ITMS are discussed.

INTRODUCTION

Traffic congestion is becoming a serious problem in the State of Delaware like any other state in the United States. Congestion, which occurs due to the inability of the current capacity of a transportation system to fulfill the need for auto travel demand, will continue to escalate in the foreseeable future, especially with the increasing limitations set on the needed resources to build new facilities. Therefore, there is a pressing and growing need to measure congestion levels in a consistent manner across places and time. Consequently, many states' departments of transportation, in the USA, as part of their integrated traffic management system, have established congestion management systems to monitor, control and alleviate congestion.

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Measuring congestion is a key step towards assisting transportation professionals, policy makers and the general public in effectively identifying the problem and developing necessary improvements.

Since the early 1990s, 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 the GPS technology to collect both the average running speed, travel time and delay on major routes all over the State. The technique has proven to be successful.

Travel time, speed and delay data are mainly used to evaluate different transportation projects by comparing estimated travel times with existing ones and, accordingly, refusing projects that do not reduce travel time. Another useful application for this data in transportation planning can be the usage of travel time data in traffic assignment models. More importantly, however, is 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 a "hot" segment that requires improvement. This information can also be provided to the public via the Internet. Nowadays, many web sites on the Internet 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 an origin and a destination. However, the actual shortest path, which should be based on the actual time spent traveling the road, has not been used.

Few researchers have written about using GPS technology to collect transportation data. These few include Taylor et al. who in their paper [1] presented the use of GPS in the measurement of vehicle speed and travel time. They discussed the accuracy of GPS speed observations under different driving conditions. That is, thay used a microscopic analysis to prove the accuracy of the GPS speed readings, compared to that measured by the actual car speedometer. In this paper, an aggregate approach is used to prove the accuracy of using GPS technology to perform travel time, speed and delay studies. In fact, in the method described in this paper, GPS speed readings were used only to identify the intervals of delay and were not used in computing any of the system performance measures. Therefore, in this paper a different approach is presented to compare the accuracy of the GPS method to the conventional one. In addition, the analysis to determine the sample size requirement will also be discussed. Moreover, in addition to other transportation systems information, the integration of travel time and delay data into the Geographic Information System (GIS) will also be presented. Finally, the paper will summarize and analyze the congestion trends in the State of Delaware over the last few years. A comparison between these congestion measures and traffic volume over the same road segments is proposed.

Travel Time and Delay Studies

There are several methods to conduct travel time and delay studies. These methods are [2]:

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

While the first two methods require driving a vehicle, the other two can be done remotely. Choosing a method depends mainly on the purpose, the type and length of the road being studied and the resources available to conduct the study.

The data that the average vehicle method provides include travel time, running time, distance traveled and delay. As far as delay data is concerned, the data gathered include the duration, cause and location of delay. An observer and a driver record the data as the test car travels along a section of an arterial road. In terms of equipment, a stopwatch, to measure travel and delay times and a distance measure (usually the vehicle's odometer), are necessary for this method. Once this data has been gathered, various analyses of the data can be implemented to obtain other information such as travel, space mean and running speed. In this study, the average range in running speed has been calculated to determine the sample size data, in terms of the number of runs. Because it is more stable, running speed is used instead of travel speed. The objective for finding the average range in running speed is to approximate the minimum number of runs with a statistical confidence level within a given permitted error.

OVERVIEW OF GPS

GPS is a space-based radio navigation system managed for the Government of the United States by the U.S. Air Force, which is the system operator. GPS was originally developed as a military force enhancement system in the 1970s. Because GPS has shown significant potential in benefiting the civilian community in an increasingly large number and variety of applications, civilians were allowed to make use of it in the 1990s [3].

The primary function of GPS is to provide the user with his/her three dimensional location (latitude, longitude and elevation) at any point on the land, sea and air. GPS also provides velocity and time, 24 hours a day, in all weather conditions. Making use of a traditional surveying topic, trilateration, GPS determines the position of the receiver by measuring the distance from a group of satellites. There are 24 operational NAVSTAR satellites orbiting the earth every twelve hours. The GPS receivers communicate directly with these satellites. To add the time dimension, all of the satellites in the network are constantly broadcasting signals that include the transmission time. Specially made ground receivers on, or near, the earth's surface are capable of picking up these signals and reading the time of broadcast from the satellite. If the receivers were equipped with clocks that ran at precisely the same rate as those on the satellite, then, the precise three dimensional location of a receiver could be determined by signals from three satellites, since, in general, three equations are required to solve a problem with three unknowns. However, in practice, the receivers are not equipped with clocks that are at an accuracy level comparable to the satellites. Therefore, time becomes a fourth unknown in the problem and a fourth satellite is needed to determine the accurate position of a receiver.

Instantaneous velocity is another measurement that can be obtained by GPS, which can be achieved by

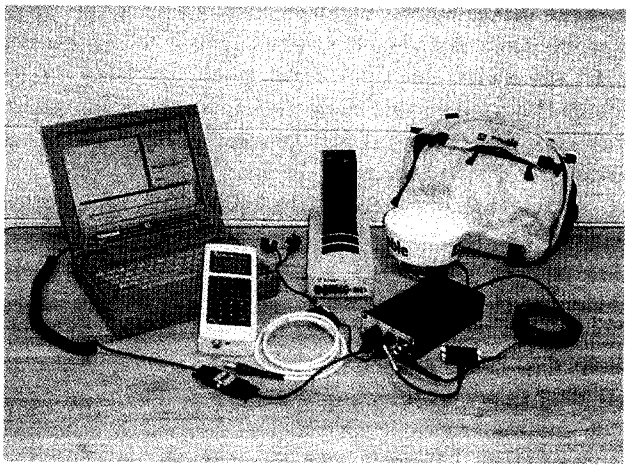

Figure 1. The GPS unit used.

using the Doppler principle of radio signals. Because of the relative motion of the GPS satellites with respect to a moving vehicle, the frequency of a signal broadcast by the satellites is shifted when sensed by the receiver. This measurable Doppler shift is proportional to the relative radial velocity. In this way, the velocity of the vehicle can be determined from the observed Doppler effects.

After much investigation on the different types of GPS receivers, Trimble's Mapping and GIS Systems© was used for this project. This unit consists of several components, including a GPS receiver, data collector and processing software. The data collector allows one to program the control points and various intersections before heading out on the road for data collection. By programming the data collector (which resembles a small calculator) before going out into the field, one is able to capture the location of interest by pressing a button. The GPS receiver can be placed in the rear or front window of a car (or on the optional magnet if available) for direct transmission communication with the satellites. When returning from the field, the processing software can download the position and feature information (that was pre-programmed and edited on the road), from the data collector to the PC Pathfinder Office©. The position and feature information include a map of the trip with the indicated control points, length of each segment, the time it took to travel the road, name of segment, date recorded and reason for delay (i.e. signal, construction, congestion, etc.). Figure 1 presents a picture of the equipment used.

Accuracy of the GPS Receiver

Due to the high complexity involved in its technology, data collected by the GPS receivers is subject to error, mostly due to inaccuracies in the coordinate positions of a point. Some other sources of error can be attributed to very small satellite and receiver clock errors or interference from buildings, trees, wires, atmospheric conditions, etc. during data collection.

The accuracy of GPS is dependent on the distance between the base and rover receivers, expressed by a fractional part called parts-per-million (ppm). The model used in this study, namely Trimble Pro XR, has an accuracy specification of 75 cm +1 ppm [4]. The 75 cm indicates how large the error is at zero distance from the base station and the 1 ppm indicates how much error to add with increasing distance from the base station. So, 1 ppm also means 1 mm/km or 0.1 cm/km or 1 cm/10 km. The subsequent equation is:

$$\text{Error} = 29.52 \text{ inches} + 0.0634^*(D) \text{ inches},$$

$$(= 75 \text{ cm} + 0.1^*(D)\text{cm}), \tag{1}$$

where D is the distance in miles (kilometers) from the nearest beacon station. From northern Delaware, the closest beacon station is at Cape Henlopen State Park. This is approximately 75 - 85 miles (121 - 138 kilometers) from most places in New Castle County, Delaware, 35 - 50 miles (56 - 81 kilometers) from Kent County and 20 - 30 miles (32 - 48 kilometers) from most roadways in Sussex County. The approximate errors for each of the three counties in Delaware are summarized in the first column in Table 1.

Although the GPS Control Segment intentionally induces some error, the vast majority of these errors can be removed from the data by "differential correction". So, how accurate is the differential correction of the Integrated GPS/Beacon Receiver (Pro XR)? In the presented model, positions are differentially corrected by MCORR400, which allows 50 cm + 1 ppm on a second-by-second basis (horizontal) and a sub-meter + 2 ppm on a second-by-second basis (vertical) [4]. Differential correction changes Equation 1 to:

$$\text{Error} = 19.69 \text{ inches} + 0.0634^*(D) \text{ inches},$$

$$(= 50 \text{ cm} + 0.1^*(D) \text{ cm}), \tag{2}$$

where D is the distance in miles (kilometers) from the nearest beacon station. The corrected values are summarized in the second column of Table 1. It was, thus, concluded that the acquired accuracy was allowable and within the acceptable range for the application in this project.

AUTOMATIC DATA COLLECTION

The early objective of this research was to use the GPS to determine speed, travel time and delay on the major roadways throughout the State of Delaware. The GPS method requires only one person to be in the vehicle

Table 1. Horizontal GPS receiver errors for Delaware counties.

County	Error Inches (cm)	Differential Correction Error Inches (cm)
New Castle	34-35 (86 - 89)	24-25 (61 - 64)
Kent	32-33 (81 - 84)	22-23 (56 - 58)
Sussex	31-32 (78 - 81)	21-22 (53 - 56)

(the driver) and needs a notebook that has the software necessary to save and retrieve data, in addition to the GPS unit. The method consists of three steps, as follows:

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

Before going to the field to collect data, some work has to be done in the office. The most important job is to establish a data dictionary, which is user-defined, to capture various attributes, such as control points and other features to be 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/she encounters them.

Once the GPS antenna and data logger are properly connected to the notebook and the battery, the driver can start to collect data directly. The only task the driver/the data collector needs to do is to make use of the aforementioned data dictionary to input the control and delay points. The control points are the starting and ending points of every roadway segment that the driver wants to collect data from. If and when it seems that the vehicle is slowing below 5 miles per hour, 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 is required to find the travel and delay time for each segment of the roadway traveled. With the help of the Pathfinder© software, this can be done quickly. This information will be then used in calculating mean travel and running speed and percent time in delay, in addition to travel time and total delay. The results are then summarized in a spreadsheet table indicating the name of the road, its segments, study period, direction of travel, length of the segment traveled, mean peak travel time and speed, total peak delay, delay source, mean peak running speed and percent of time in delay. A sample of this information is presented in Table 2.

To compare the GPS method for collecting travel time, speed and delay studies, it is necessary to collect these data by one of the above mentioned manual methods; then, the results are compared to those obtained by the GPS method. For this purpose, the average vehicle method was employed to collect the travel time, running time and the distance traveled. An observer and a driver recorded the data as the car was travelling along the roadway segment: One recorded the total travel time it took to travel the segment, while the other recorded the delay time. A stopwatch was used to record the duration of delay whenever the vehicle's speed dropped below 5 mph (this was specified

Table 2. Sample of a summary of travel time, speed and delay information.

Route	Segments	AM/PM	Dir.	Dis. (Miles)	Mean Peak Travel Time (Seconds)	Mean Peak Travel Speed (mph)	Total Peak Delay (Seconds)	Peak Delay Source	Mean Peak Running Speed (mph)	Percent Time Delay %
SR 4	SR 896 to Elkton	PM	WB	1.5	139	38.85	19	Signal	45.00	13.7%
Christiana	Elkton to SR 896	PM	EB	1.5	158	34.18	31	Signal	42.52	19.6%
	SR 72 to SR 896	PM	WB	0.9	170	19.06	65	Signal	30.86	38.2%
	SR 896 to SR 72	PM	EB	0.9	181	17.90	93	Signal	36.82	51.4%
	SR 273 to SR 72	PM	WB	2.5	271	33.21	67	Signal	44.12	24.7%
	Sr 72 to SR 273	PM	EB	2.5	312	28.85	102	Signal	42.86	32.7%
	Christiana H to SR 273	PM	WB	1.4	194	25.98	84	Signal	45.82	43.3%
	SR 273 to Christiana H	PM	EB	1.4	396	12.73	233	Signal	30.92	58.8%
	SR 7 to Christiana H	PM	WB	1.3	107	43.74	8	Signal	47.27	7.5%
	Christiana H to SR 7	PM	EB	1.3	140	33.43	13	Signal	36.85	9.3%
SR 4	SR 7 to Elkton Rd.	PM	WB	7.6	881	31.06	243	Signal	42.88	27.6%
Total	Elkton Rd. to SR 7	PM	EB	7.6	1187	23.05	472	Signal	38.27	39.8%

by the sponsoring agency). Another stopwatch was also used to record the total travel time. Finally, the vehicle's odometer was used to read the trip length. Once these data were collected, many variables, such as travel and running speeds and delay, were computed in the office.

A primary goal and a principal objective of the research that started in 1996, was to investigate the use of GPS as a tool for collecting speed, travel time and delay data for Delaware roadways. However, before the GPS technology was adopted to conduct travel time studies, it was necessary to discover and prove the following, respectively:

1. What sample size is required to acquire accurate data with a 95% confidence level,
2. Whether GPS is, at least, as accurate and precise as the manual methods.

Sample-Size Requirement

Prior to collecting any data from the field, by either the conventional method or the GPS method, it was necessary to know how many runs are required on every segment to maintain a significant level of 95%. In this study, the average range in running speed was computed to determine the sample-size (in terms of number of test runs) required, as shown in the following equation:

$$R = \frac{\sum A}{(N-1)}. \tag{3}$$

Because it is more stable, running speed is used instead of travel speed [2]. The objective for finding the average range in running speed was to approximate the minimum number of runs with a confidence level within a given permitted error.

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 roadway needed to be studied, which means four runs in each direction. The data collected during each run is trip length, trip time and stopped time. From these data, running speed was calculated as follows:

$$\text{Running Speed} = \frac{\text{Trip Length}}{(\text{Trip Time - Stopped Time})}. \tag{4}$$

Then, the running speed for each run was used to find the sample size, as described in the following procedure.

The initial step is to record the running speeds for each run, ensuring that each has the same dimensions (m/s, km/hr, ft/s, mph, etc.). Once these are noted, the next step is computation of the absolute difference between each of the running speeds in sequence (i.e., between the first and second, second and third, etc). This value will be the change in running speed, A. To find the running speed for the entire group of runs, A values were summed as in Equation 3. This summation was then divided by the number of runs minus one. The result obtained is the average range in running speed, R. The value of R was referenced with Table 3 to find the minimum number of runs needed for a certain degree of accuracy. A sample calculation spreadsheet is shown in Table 4.

To determine the sample size requirements throughout the data collection, four sample arterial roads were selected. The criteria for selection of these roadways was based solely, on their comprising a major arterial in the state of Delaware, thus representing the worst case scenarios in the study. According to Table 3, with a minimum confidence level of 95% and with errors of 1 to 5 miles per hour (1.6 to 8 kilometers per hour, kmph) in velocity, the minimum number of runs was computed. 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 kph) or less. Thus, the second row of Table 3 was used to find the required number of runs to collect the travel time, speed and delay data for the State of Delaware.

Comparative Analysis

Before the adaptation of the GPS method as the presented data collector, a statistical study was per-

Table 3. Sample-size requirements for travel time and delay studies with a confidence level of 95.0% [2].

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

Table 4. Sample spreadsheet for the calculation of average range in running speed.

Street Name: Kirkwood Highway.			Off-Peak Hour		West Bound	
	Running Speed (mph)	A (mph)	$\sum A$	R		Conclusion
Trial 1	41.76					Use minimum number of runs for an average range in running speed of: 5 mph
Trial 2	33.04	8.72	8.72	$\sum A/1 = 8.72$	for 2 runs	
Trial 3	36.84	3.80	12.5	$\sum A/2 = 6.25$	for 3 runs	
Trial 4	41.77	4.93	17.45	$\sum A/3 = 5.8$	for 4 runs	
Trial 5	40.17	1.60	19.05	$\sum A/4 = 4.8$	for 5 runs	

Table 5. Summary of travel and delay times collected by manual and GPS methods.

Road	Date	Time	Direction	Travel Time (sec) GPS	Travel Time (sec) Manual	Delay Time (sec) GPS	Delay Time (sec) 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

formed to see whether there were significant differences between the manual method of travel time and delay data collection and the GPS method. Analysis of mean and variance were used to test if the difference between these two methods was due to a significant difference or was just due to chance alone. Evidently, when the variances and means have no significant difference, the two methods can be proven to be identical and, thus, be used interchangeably.

For this purpose, the travel time and delay study was performed twice on Kirkwood Highway, from Newark, DE, to Wilmington, DE, a stretch of about 9 miles (14.4 Km): One study using the conventional manual method and the other, simultaneously, with the GPS method. Driving the same van, two teams worked independently, in collecting the data; one using a manual system of data collection and the other using the GPS method. Table 5 summarizes the trials performed for each method. As can be observed, the travel time over Kirkwood Highway was measured 12 times, manually, by the average vehicle method and 12 times using the GPS method. Trials were performed during morning and afternoon peak hours for both directions (east and west) of the road, to account for any traffic variations during the day.

The two-sample t statistic test was used to compare the means of the samples collected. Prior to using the t-test, the F-test was used to test whether equal variances should be assumed or not. As shown in Table 6, equal variances can be used (for example; $F = 0.007, P > 0.05$) for both directions. Thus, the

Table 6. 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)	0.007	0.932	Not significant equal variances used	0.056	22	0.956	Not significant
Travel Time (East Directions)	0.271	0.611	Not significant equal variances used	0.229	14	0.822	Not significant
Travel Time (West Directions)	0.002	0.964	Not significant equal variances used	0.000	6	1.000	Not significant

pooled two-sample t-test was applied using [5]:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \tag{5}$$

where:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}. \tag{6}$$

If there were a significant difference in the variances of the two samples, the following equation could be used to find the t-statistic:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}. \tag{7}$$

The test was performed three times: Once for the East direction, once for the West direction and the third was for both directions combined. Table 6 shows a summary of the results. It is obvious that there is no statistically significant difference between the means and variances of travel time collected using the manual method and that using the GPS method (for example $t = 0.000, df = 6, P > 0.05$ for travel time in both directions).

INTEGRATING GPS DATA WITH GIS

One of the primary objectives of this project was to develop a systematic method to transfer the travel data collected by GPS into a GIS environment where they can be mapped, analyzed and, most importantly, combined with other transportation data from different resources. 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). This was done with the travel time and delay data, illustrating such themes as running speed, travel speed, percent time in delay and a measurement of congestion index. The GIS software used for this purpose was ARCVIEW©, a powerful and popular GIS software for conducting different studies.

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 [6]. Dynamic segmentation allows one to:

1. Define a linear feature within a line coverage,
2. Work with data in a route-measure format,
3. Associate attributes in route-measure format to any part of a route without modifying underlying xy coordinates. Then, these attributes can be stored, displayed, queried and analyzed.

This is a key issue in transportation, since most transportation data are located using a Linear (one-dimensional) Referencing System (LRS) instead of using xy (or latitude-longitude) measurements. For example, Milepost 2 on route US202 is a route-measure recording method. Moreover, various transportation databases can store information to a common network using this route-measure method.

The procedure to integrate the travel time and delay data into GIS involves three steps:

1. Building a route - system: In order to linearly reference GPS data efficiently, it is essential to use a good base vector map to link the data records to their database. A directional centerline network map for the New Castle, Kent and Sussex counties was obtained from DelDOT. In this Arcview© file, a roadway id and beginning and ending mileposts for each area that constitutes each of the major roads, were defined. To make the dynamic segmentation method possible, a route - system was built in Arc/Info using the ARCSECTION command;
2. Editing travel data: Before adding travel data (or route events) to GIS, the original files containing the

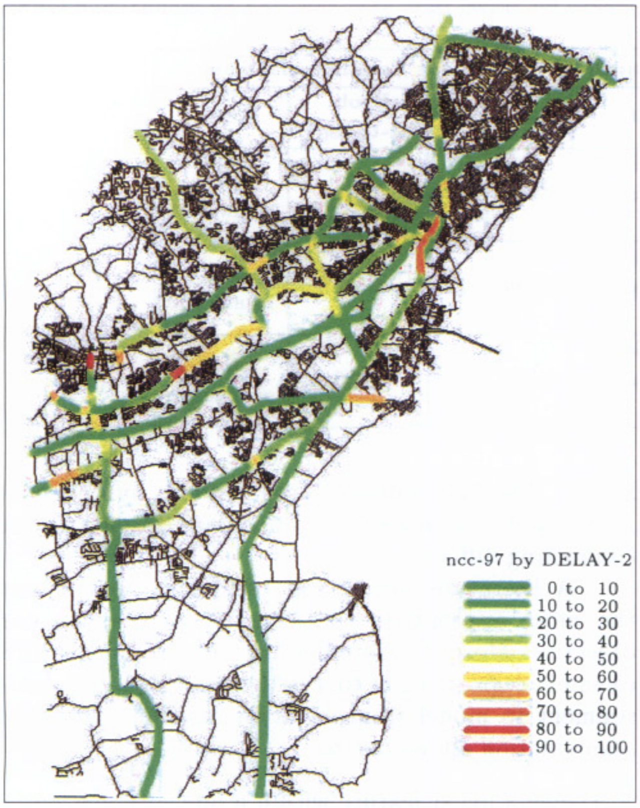

Figure 2. Percent time in delay for New Castle County, Delaware 1997.

data need to be edited. Three columns (roadway id, beginning and ending milepost) were added to each segment of the sample roads used in this project. Then, the files were saved in dbase format to be used in Arcview©;

3. Adding the route events: The first step in adding the route event data is to open a theme that contains the route system created by ArcInfo©. To add the event data, which can be a point, line or continuous events, an "Adding Route Events" command was chosen in Arcview©. The event field could be any of the data available, such as average running speed, percentage of delay, etc.

Once these three steps were performed, many outputs were produced from the information, such as:

- Color coded maps corresponding to the average running speed and percentages of delay for the collected data (see Figure 2),
- Chart figures showing the variations of data over the different segments of the transportation network,
- Some statistical measures such as maximum and minimum values.

TREND ANALYSIS

Since a primary objective of the travel, speed and delay data collection was to monitor traffic congestion, the next step was to compare the information gathered over the three years of data collection (1997 - 1999). When viewing the data for different years, one can identify the roads (or segments of roads) that had either an increase or a decrease in any of the traffic measures utilized, i.e. travel time, peak speed and percentage of time in delay. For the purpose of this analysis, samples of the major roads in Delaware were chosen. These roads were I - 95, SR - 2, SR - 7, SR - 4 and US 13.

The first step was to summarize the collected data for the three years into a spreadsheet, as shown in Table 7. Once this data was ready, analysis of the data started by plotting it into graphs as shown in the sample charts in Figure 3. For example, there is a gradual increase in travel time in the West Bound, while there is a decrease in travel speed. On the other hand, these changes are not consistent in the East Bound. 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 professionals to monitor and control congestion on an annual basis, thus, evaluating the impact of improvement projects, accordingly. The Paired Samples t - test was chosen to keep the comparison to be performed on a segment to segment basis. For example, the travel speed of road segment 1 on the Kirkwood Highway in 1997 was compared to its equivalent in 1998. A sample result is shown in Table 8. As one can see, although there was a decrease in speed in both directions, this decrease was not statistically significant.

Another application that could be helpful is not only to compare travel time and speed from year to year, but, also, to compare it with traffic volume over the same segments of road. The importance of such a comparison is as follows. As a higher demand is expected from year to year, it is important to know the consequent increase in travel time (and decrease in travel speed) by looking at the trends of the traffic volume and travel measures from year to year. For example, suppose the capacity of a road segment was increased in 1997. By looking at the resulting travel measures and traffic volume in the following year, one can measure the impacts of such an improvement. More importantly, however, is that having traffic volume besides travel measures can be helpful in prioritizing the congestion alleviating management projects. For instance, segments with a high traffic volume and highly increasing travel time should have first priority, compared to segments with

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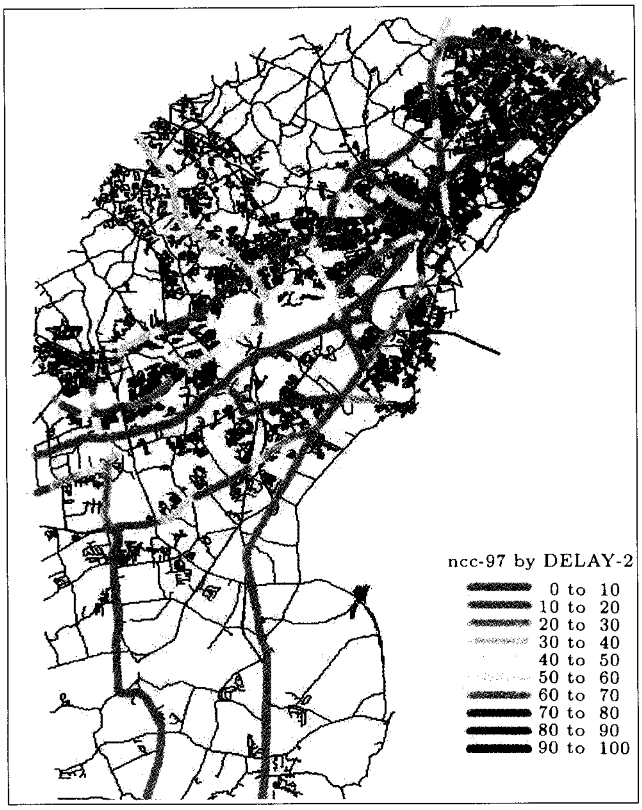

Figure 2. Percent time in delay for New Castle County, Delaware 1997.

data need to be edited. Three columns (roadway id, beginning and ending milepost) were added to each segment of the sample roads used in this project. Then, the files were saved in dbase format to be used in Arcview©;

3. Adding the route events: The first step in adding the route event data is to open a theme that contains the route system created by ArcInfo©. To add the event data, which can be a point, line or continuous events, an "Adding Route Events" command was chosen in Arcview©. The event field could be any of the data available, such as average running speed, percentage of delay, etc.

Once these three steps were performed, many outputs were produced from the information, such as:

- Color coded maps corresponding to the average running speed and percentages of delay for the collected data (see Figure 2),
- Chart figures showing the variations of data over the different segments of the transportation network,
- Some statistical measures such as maximum and minimum values.

TREND ANALYSIS

Since a primary objective of the travel, speed and delay data collection was to monitor traffic congestion, the next step was to compare the information gathered over the three years of data collection (1997 - 1999). When viewing the data for different years, one can identify the roads (or segments of roads) that had either an increase or a decrease in any of the traffic measures utilized, i.e. travel time, peak speed and percentage of time in delay. For the purpose of this analysis, samples of the major roads in Delaware were chosen. These roads were I - 95, SR - 2, SR - 7, SR - 4 and US 13.

The first step was to summarize the collected data for the three years into a spreadsheet, as shown in Table 7. Once this data was ready, analysis of the data started by plotting it into graphs as shown in the sample charts in Figure 3. For example, there is a gradual increase in travel time in the West Bound, while there is a decrease in travel speed. On the other hand, these changes are not consistent in the East Bound. 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 professionals to monitor and control congestion on an annual basis, thus, evaluating the impact of improvement projects, accordingly. The Paired Samples t - test was chosen to keep the comparison to be performed on a segment to segment basis. For example, the travel speed of road segment 1 on the Kirkwood Highway in 1997 was compared to its equivalent in 1998. A sample result is shown in Table 8. As one can see, although there was a decrease in speed in both directions, this decrease was not statistically significant.

Another application that could be helpful is not only to compare travel time and speed from year to year, but, also, to compare it with traffic volume over the same segments of road. The importance of such a comparison is as follows. As a higher demand is expected from year to year, it is important to know the consequent increase in travel time (and decrease in travel speed) by looking at the trends of the traffic volume and travel measures from year to year. For example, suppose the capacity of a road segment was increased in 1997. By looking at the resulting travel measures and traffic volume in the following year, one can measure the impacts of such an improvement. More importantly, however, is that having traffic volume besides travel measures can be helpful in prioritizing the congestion alleviating management projects. For instance, segments with a high traffic volume and highly increasing travel time should have first priority, compared to segments with

Table 7. Summary of travel time, speed and delay information for Kirkwood Highway, Delaware 1997 - 1999

			1997			1998			1999		
			Dist.	Mean Peak Travel Time	Mean Peak Travel Speed	Dist.	Mean Peak Travel Time	Mean Peak Travel Speed	Dist.	Mean Peak Travel Time	Mean Peak Travel Speed
Route	Segments	Dir.	(Miles)	(Sec.)	(mph)	(Miles)	(Sec.)	(mph)	(Miles)	(Sec.)	(mph)
SR - 2	Segment 1	WB	0.4	99.25	14.51	0.4	119	12.10	0.4	95	15.16
		EB	0.4	128.75	11.18	0.4	111	12.97	0.4	122	11.80
	Segment 2	WB	1.0	119	30.25	1	147	24.49	1.0	155	23.23
		EB	1.0	148.5	24.24	1	117	30.77	1.0	94	38.30
	Segment 3	WB	0.7	88	28.64	0.7	95	26.53	0.7	91	27.69
		EB	0.7	59.2	42.57	0.7	110	22.91	0.7	66	38.18
	Segment 4	WB	1.5	134	40.30	1.5	195	27.69	1.5	173	31.21
		EB	1.5	142.25	37.96	1.5	189	28.57	1.5	198	27.27
	Segment 5	WB	1.9	218.75	31.27	1.9	175	39.09	1.9	216	31.67
		EB	1.9	174	39.31	1.9	290	23.59	1.9	287	23.83
	Segment 6	WB	0.5	91	19.78	0.5	75	24.00	0.5	219	8.22
		EB	0.5	103	17.48	0.5	93	19.35	0.5	71	25.35
	Segment 7	WB	1.8	217.25	29.83	1.8	251	25.82	1.8	294	22.04
		EB	1.8	202	32.08	1.8	249	26.02	1.8	229	28.30
	Segment 8	WB	1.6	179.25	32.13	1.60	271.00	21.25	1.6	245	23.51
		EB	1.6	239.75	24.03	1.60	263.00	21.90	1.6	276	20.87
	Segment 9	WB	NA	NA	NA	0.70	78.00	32.31	0.7	168	15.00
		EB	NA	NA	NA	0.70	107.00	23.55	0.7	127	19.84
	Segment 10	WB	NA	NA	NA	1.50	193.00	27.98	1.5	198	27.27
		EB	NA	NA	NA	1.50	299.00	18.06	1.5	310	17.42
	Total	WB	9.4	1146.5	29.52	11.60	1599.00	26.12	11.6	1854.0	22.52
		EB	9.4	1197.5	28.26	11.60	1828.00	22.84	11.6	1780.0	23.46

			1997			1998			1999		
			Total Peak Delay	Mean Peak Runing Speed	Percent Time in Delay	Total Peak Delay	Mean Peak Runing Speed	Percent Time in Delay	Total Peak Delay	Mean Peak Runing Speed	Percent Time in Delay
Route	Segments	Dir.	(Sec.)	(mph)	%	(Sec.)	(mph)	%	(Sec.)	(mph)	%
SR - 2	Segment 1	WB	52.25	30.64	52.6%	14	13.71	11.8%	39	25.71	41.1%
		EB	78.09	28.42	60.7%	37	19.46	33.3%	71	28.24	58.2%
	Segment 2	WB	40.00	45.57	33.6%	46	35.64	31.3%	33	29.51	21.3%
		EB	55.83	38.85	37.6%	12	34.29	10.3%	10	42.86	10.6%
	Segment 3	WB	39.27	51.71	44.6%	24	35.49	25.3%	18	34.52	19.8%
		EB	25.9	75.68	43.8%	28	30.73	25.5%	4	40.65	6.1%
	Segment 4	WB	9.93	43.52	7.4%	44	35.76	22.6%	29	37.50	16.8%
		EB	30.18	48.18	21.2%	17	31.40	9.0%	72	42.86	36.4%
	Segment 5	WB	28.56	35.96	13.1%	26	45.91	14.9%	58	43.29	26.9%
		EB	0	39.31	0.0%	103	36.58	35.5%	84	33.69	29.3%
	Segment 6	WB	45.67	39.71	50.2%	23	34.62	30.7%	133	20.93	60.7%
		EB	56.07	38.35	54.4%	36	31.58	38.7%	27	40.91	38.0%
	Segment 7	WB	40.05	36.57	18.4%	64	34.65	25.5%	108	34.84	36.7%
		EB	32.28	38.18	16.0%	62	34.65	24.9%	77	42.63	33.6%
	Segment 8	WB	8.34	33.70	4.7%	59	27.17	21.8%	64	31.82	26.1%
		EB	110.42	44.54	46.1%	177	66.98	67.3%	51	25.60	18.5%
	Segment 9	WB	NA	NA	NA	14	39.38	17.9%	66	24.71	39.3%
		EB	NA	NA	NA	9	25.71	8.4%	33	26.81	26.0%
	Segment 10	WB	NA	NA	NA	14	30.17	7.3%	51	36.73	25.8%
		EB	NA	NA	NA	43	21.09	14.4%	164	36.99	52.9%
	Total	WB	264.07	38.35	23.0%	328.00	32.86	20.5%	599.0	33.27	32.3%
		EB	388.77	41.85	32.5%	524.00	32.02	28.7%	593.0	35.18	33.3%

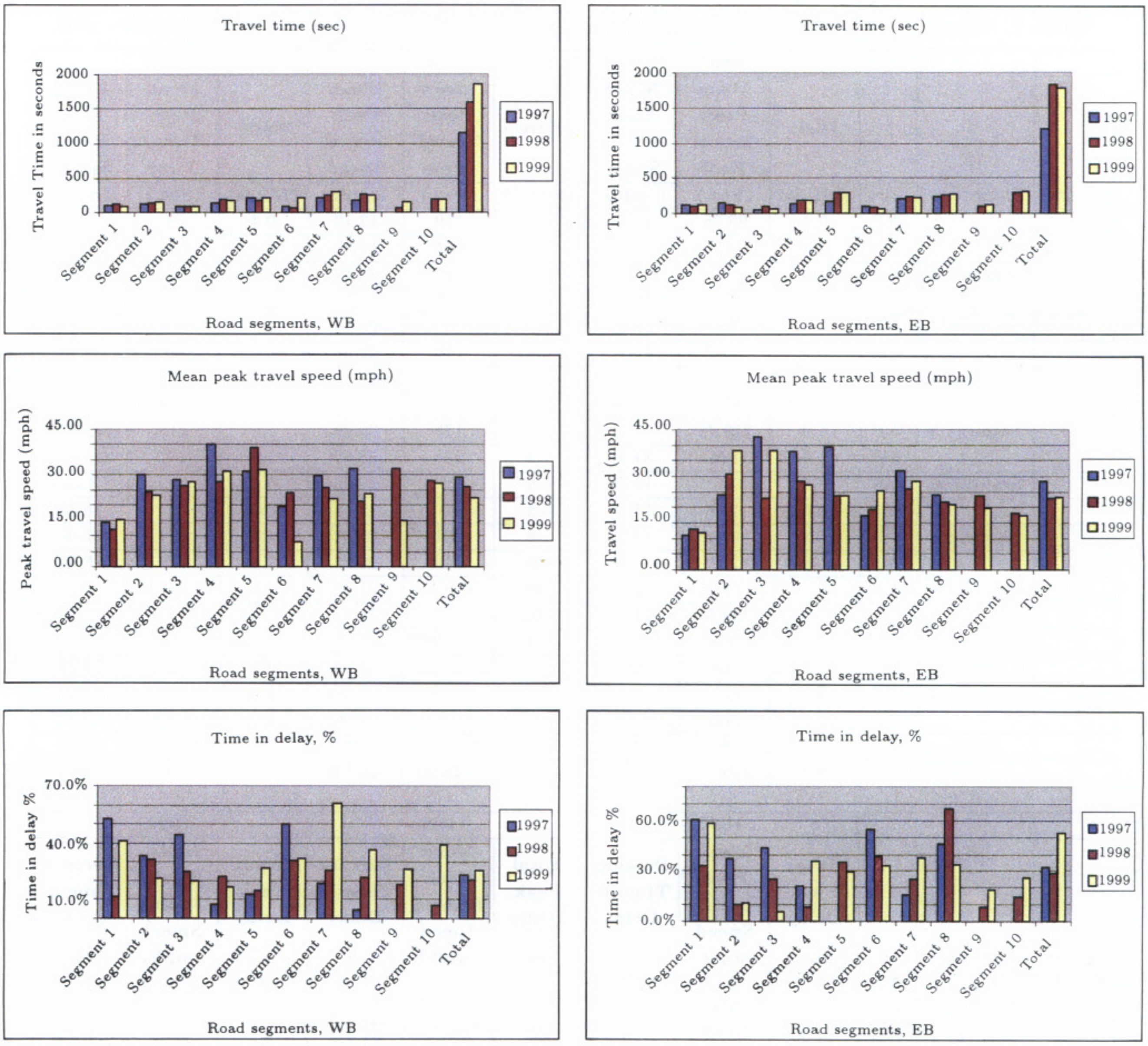

Figure 3. Comparison of peak travel time, mean peak travel speed and time in delay information for Kirkwood highway, Delaware 1997 - 1999.

Table 8. Paired t - test for equality of means for speed data pairs between 1997 and 1999.

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	0.229	Not significant
Pair 2	Speed98 - Speed99	3.6260	7.5778	1.513	9	0.165	Not significant
Pair 3	Speed97 - Speed99	5.4975	4.7844	3.250	7	0.014	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	0.142	Not significant
Pair 2	Speed98 - Speed99	- 2.3470	5.7188	- 1.298	9	0.227	Not significant
Pair 3	Speed97 - Speed99	1.8687	9.4832	0.557	7	0.595	Not significant

10-2

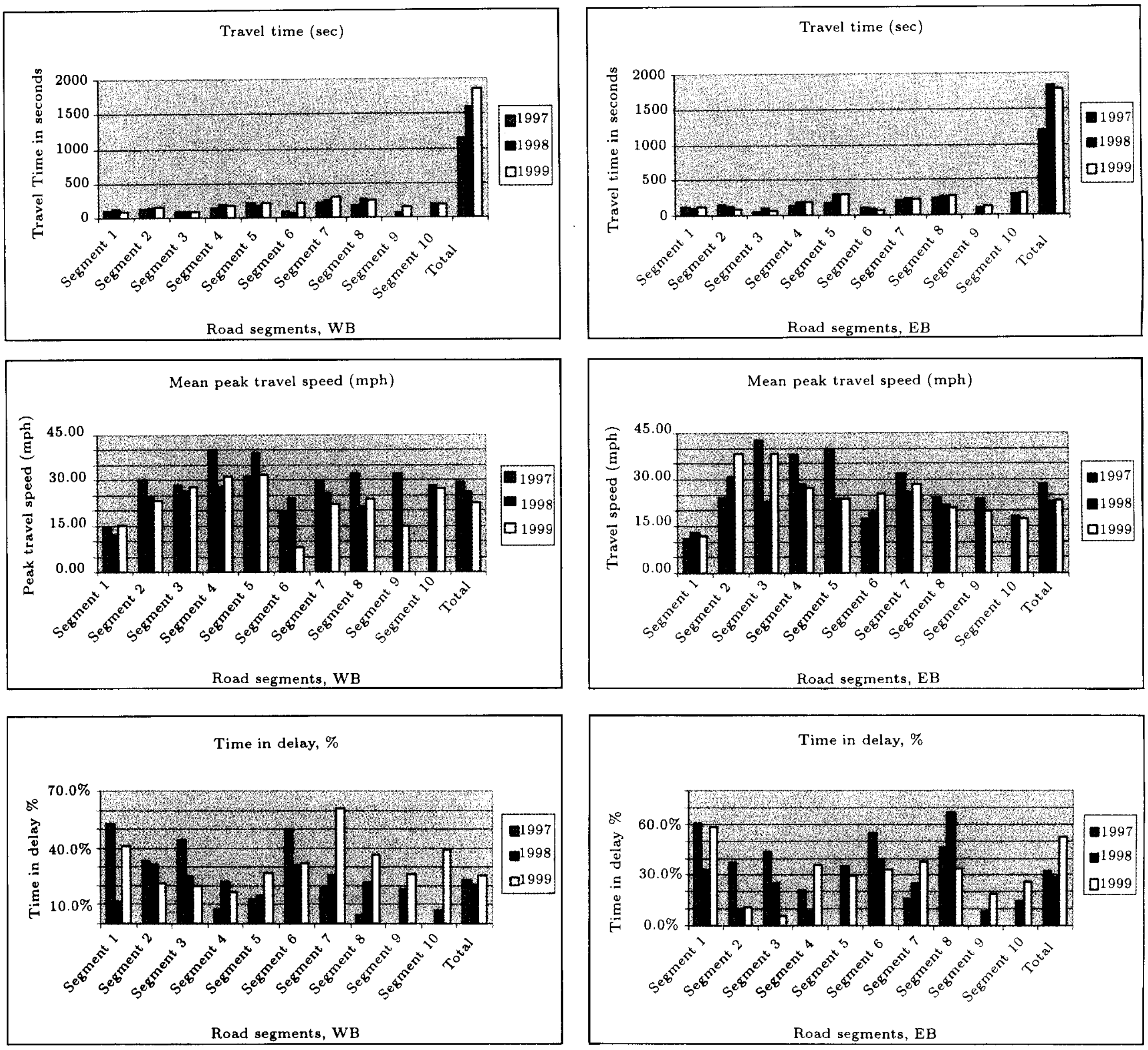

Figure 3. Comparison of peak travel time, mean peak travel speed and time in delay information for Kirkwood highway, Delaware 1997 - 1999.

Table 8. Paired t - test for equality of means for speed data pairs between 1997 and 1999.

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	0.229	Not significant
Pair 2	Speed98 - Speed99	3.6260	7.5778	1.513	9	0.165	Not significant
Pair 3	Speed97 - Speed99	5.4975	4.7844	3.250	7	0.014	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	0.142	Not significant
Pair 2	Speed98 - Speed99	- 2.3470	5.7188	- 1.298	9	0.227	Not significant
Pair 3	Speed97 - Speed99	1.8687	9.4832	0.557	7	0.595	Not significant

less volume, even with a higher increase in travel time. In fact, studying the relationship between traffic volume and travel measures from year to year could be crucial to the development of a congestion index. Here, the benefits of GPS as an efficient travel data collector, combined with GIS capabilities are obvious as a congestion index can be developed once the relationship between traffic volume and travel measures has been established.

SUMMARY AND CONCLUSIONS

The Delaware Department of Transportation (DelDOT), 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 all over the major routes of the State of Delaware. The technique was proved to be successful in 1997, 1998 and 1999 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 travel time and delay study performed in the state of Delaware was accomplished in three steps. After brief preparatory office work, the GPS was used to collect data on specific routes in the New Castle, Kent and Sussex Counties. For this purpose, each route was divided into two or more segments to perform the data collection. Moreover, each segment was traversed on an average of four times to maintain a 95% confidence level in the data collected. The third step involved office work to compute the mean travel time, average running speed and delay percentages for both directions of every segment under study. Also, for certain roads of heavy traffic volume, the travel characteristics were computed for both peak and off - peak hours. The results were then summarized in a table indicating the name of the road, its segments, study period, direction of travel, length of the segment traveled, mean peak travel time and speed, total peak delay, delay source, mean peak running speed and percent of time in delay. This information was then integrated into GIS to map the data in a more representative manner.

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 quick 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 the GPS data collector and processing information is easy to use, but it is also more accurate, less tedious, involves less human error and has a built - in differential correction for interference while in the field. Moreover, there are more possible sources of error using manual methods, due to inconsistencies between the observer and the stop watch and misjudging when the car is actually travelling less than 5 miles per hour. When using GPS, the distance and time traveled on a segment can be determined when the data is transferred from the data collector to the Pathfinder Office program. Therefore, the exact speed can be determined for each data point.

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