Probe Vehicle Sample Sizes for Real-Time Information: The Houston Experience

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Abstract—Probe vehicle travel time data is an important source of real-time travel information for a variety of intelligent transportation system applications. This paper investigates the required minimum number of probe vehicles that are necessary to report real-time travel speeds and times for a desired statistical accuracy. Empirical travel time data from the Houston traffic monitoring system were analyzed to calculate travel time variation and the corresponding minimum required probe vehicle sample sizes. A regression equation was developed to estimate travel time variation, which can then be used to calculate sample sizes. It was concluded that the current number of probe vehicles in Houston provide reliable peak period travel speed information (i.e., 95% confidence that displayed real-time speeds are ±10%).

I. Introduction

Real-time travel information is becoming increasingly important in many intelligent transportation system (ITS) applications, including congestion avoidance, route guidance, commercial vehicle routing, and pre-trip information. The real-time information allows travelers to make intelligent decisions about the time, route, and mode that most efficiently serves their trip. Real-time information allows commercial vehicles to bypass congested routes for just-in-time deliveries. It also allows commuters to take quicker alternate routes to home or work, or to leave or arrive at work during less congested times.

There are two basic approaches used to collect real-time travel information. One approach relies on collecting information at isolated but frequent locations. Inductance loop, infrared, video, and other vehicle detectors fall into this category, and are capable of collecting information like vehicle volumes, time mean speeds, headways, classifications, and lane occupancy. The other approach used to collect real-time information relies on instrumented vehicles traveling in the traffic stream. The instrumented vehicles, also known as probe vehicles, maintain frequent communications with a central computer that "tracks" the vehicle location and speed along the traveled route. The most common and useful information that probe vehicles collect is point-to-point travel time. The focus of this paper is probe vehicles and the collection of real-time travel times.

Probe vehicles can be instrumented with different types of electronic equipment, but a common feature is the periodic (and desirably, frequent) reporting of vehicle location. The different types of electronic equipment include, but are not limited to:

- Automatic Vehicle Identification (AVI)
- Automatic Vehicle Location (AVL)
  - Signpost-Based
  - Ground-Based Radio Navigation
  - Global Positioning Systems (GPS)
  - Cellular Phone Tracking

Several metropolitan areas are currently developing traffic management and monitoring systems that utilize real-time information on travel conditions. System planners and designers are being faced with many questions about the type of technology and the quantity of equipment necessary to monitor traffic conditions on a roadway network. An important issue when considering probe vehicle technology is the number of instrumented vehicles necessary to provide accurate, reliable travel information. A relatively small number of probe vehicles traveling in the traffic stream can potentially provide valuable information about current travel times. However, too few probe vehicles can provide erroneous or misleading data, weakening the credibility of the transportation agency and eroding public confidence in the traveler information or traffic management system. Limited research has been conducted to determine the probe vehicle sample sizes necessary for real-time traveler information systems.

This paper contains an examination of probe vehicle travel time data from the Houston AVI traffic monitoring system and provides recommendations about probe vehicle sample sizes for real-time traveler information. Section II, Background, contains information about sample size selection for other real-time information systems in the United States. Section III, Study Design, provides details about the statistical analyses used to calculate probe vehicle sample sizes. Section IV, Results, provides a summary of the statistical analysis results and the necessary probe vehicle sample sizes for different traffic conditions. Section V, Conclusions And Recommendations, contains general conclusions and recommendations of the study.

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II. BACKGROUND

Sample size requirements for probe vehicle data collection have been investigated in the development of several traffic monitoring systems. This section contains information about current or developing real-time traffic information systems in the United States that use probe vehicles. Sample size research for the ADVANCE project in the northwest suburbs of Chicago, Illinois is discussed. Studies of the AVI system being developed in the Puget Sound region are presented. Information about the AVI traffic monitoring system in Houston, Texas is also presented in this section.

A. ADVANCE--Chicago, Illinois

A study for the ADVANCE project estimated that approximately 4,000 probe vehicles would be needed for a 200-square mile test area that primarily included a suburban arterial network [1]. This sample size was calculated by solving a static, user-optimal route choice model for the road network within the test area. The study was based on having at least one probe vehicle traverse a certain percentage of roadway links during different lengths of time (i.e., 5, 10, 15, and 20 minutes). This analysis consideration would then provide an updated travel time every 5, 10, 15, or 20 minutes. The sample sizes were based upon covering an acceptable percentage of the roadway links at frequent time intervals.

B. AVI Applications--Puget Sound Region, Washington State

A similar study conducted in Seattle examined the probe vehicle sample sizes that were necessary for incident detection purposes [2]. This study focused on providing a large enough sample to provide an acceptable incident detection time, and attempted to use trucks participating in the HELP/Crescent demonstration project as probe vehicles. The conclusions of the study indicated that sample sizes on the order of 20 to 120 vehicles per hour were required to provide a 1.5 to 6 minute detection time, respectively. The focus of this study was in providing an acceptable incident detection time, and the analysis techniques varied slightly from the ADVANCE study.

C. AVI Applications--Houston, Texas

The Texas Department of Transportation is currently developing a traffic monitoring system for the Houston area that uses AVI technology [3]. Reader units are being placed at 1.8- to 8.0 kilometer (1- to 5-mile) intervals along all the area's major freeways, eventually including over 483 kilometers (300 miles) of highway and 161 kilometers (100 miles) of HOV lanes. Several toll roads in the area have automated toll booths, encouraging the acquisition of thousands of AVI transponders by motorists in the Houston area. It has been estimated that approximately 40,000 AVI tags have been distributed in the Houston area. Transponders have also been distributed free of charge by TxDOT to motorists wishing to participate in the project as a probe vehicle. Two of three phases of the traffic monitoring system were completed by mid-1994.

III. STUDY DESIGN

This section provides details about the statistical analyses used to examine the travel time data and calculate probe vehicle sample sizes. The data source is described, and the time periods that were considered in the analysis are outlined. The basic sample size equation used in the statistical analysis is also presented. Two major inputs into the sample size equation, travel time variation and accuracy requirements, are also discussed in the context of real-time travel information.

A. Data Source

The source of empirical travel time data for this analysis was Phase One the Houston AVI traffic monitoring system. Phase One of the traffic monitoring system includes 3 corridors to the north and west of downtown Houston: Katy Freeway (I-10), Northwest Freeway (US 290), and North Freeway (I-45). Within each corridor, AVI tag reader sites are located at 1.8- to 8.2-kilometer (1.8- to 5.1-mile) spacings on both the freeway mainlanes and the high-occupancy vehicle (HOV) lanes located in the median of the freeway.

Based upon the AVI checkpoints, there are a total of 60 directional freeway and HOV segments for which travel time data was analyzed for this study. The 60 freeway and HOV segments represent a wide range of operating conditions, from free-flow on the HOV lanes to severely congested on some freeway segments.

Phase One of the Houston AVI system became operational in early 1994. The month of April was the first month in which complete travel time data for all 60 directional segments were available; consequently, travel time data from April 1994 was used in this analysis. Automatic traffic recorders (ATRs) in west Houston indicated that a seasonal adjustment factor was not necessary because April traffic volumes in west Houston are very near the annual average traffic volumes.

The primary objective of this analysis was to determine adequate probe vehicle sample sizes for providing real-time information. Real-time information is most critical during the peak congested periods, when speeds can change dramatically in a small amount of time. Peak periods on Houston freeways typically extend from 6:30 to 9:30 a.m. in the morning and 4:00 to 7:00 p.m. in the evening. These peak periods (i.e., 6:30 to 9:30 a.m., 4:00 to 7:00 p.m.) were used for the sample size analysis. Only weekdays (Monday through Friday) were considered in the analysis, with a total of 21 weekdays within April 1994. The data source and other input parameters are summarized in Table I.

TABLE I
SUMMARY OF DATA INPUT PARAMETERS

Data Source:	Phase One, Houston AVI Traffic Monitoring System
Three Freeway Corridors: (freeway mainlanes and HOV lanes)	Katy Freeway (I-10) Northwest Freeway (US 290) North Freeway (I-45)
34 Freeway Mainlanes Segments, 182 directional kilometers (113 miles) 26 HOV Lane Segments, 114 directional kilometers (71 miles)	
Time Periods:	21 Weekdays in April 1994 Morning Peak Period: 6:30 a.m. to 9:30 a.m. Evening Peak Period: 4:00 p.m. to 7:00 p.m.

B. Time Period Analysis

Summary and analysis of the travel time data considered two separate time periods: 5-minute and 15-minute periods. These analysis periods correspond to the sample sizes for which an accurate, real-time estimate of travel time or speed is desired. For example, a traffic information and control center may wish to update the travel speeds for a freeway segment every 5 minutes. In this case, estimates of travel speed are needed every 5 minutes. Ideally, the travel speed estimate would be based on average travel times recorded by probe vehicles over a 5-minute time period (fixed or rolling). The number of probe vehicles required for statistical accuracy during this 5-minute period is referred to as the required probe vehicle sample size.

Analysis periods longer than 15 minutes were not considered applicable because the study focus was on providing travel time estimates on a real-time basis. A 5-minute analysis period (update speeds based on 5-minute average) is comparable to information update frequencies being used in several real-time traffic information systems in the United States. A 15-minute analysis period is most likely the longest that would be considered for providing real-time information, and was considered in this study for other potential traffic operations analyses.

C. Calculation of Sample Sizes

For the purposes of this paper, probe vehicle sample sizes are the minimum number of instrumented vehicles that are required to estimate a travel time or speed for a given roadway segment and time period within a set statistical accuracy. Probe vehicle sample sizes are directly related to the variability of travel times, or the coefficient of variation (c.v.), as shown in (1). The input variables of this basic sample size equation are described in the following paragraphs.

The sample size, *n*, represents the number of instrumented vehicles necessary to accurately depict the true average travel time for a given roadway segment and time period. The *c.v.* is a relative measure of travel time variation, and is calculated as the mean travel time divided by the standard deviation of the travel time. For this study, the c.v. was calculated for both 5-minute analysis periods and 15-minute analysis periods. Using 5-minute analysis periods, there were a total of 1,512 c.v.'s for each roadway segment (12 5-minute periods per hour, 6 hours per weekday, 21 weekdays in April). The 85th percentile c.v. value (of the 1,512 total c.v. observations) was then used in the sample size equation for 5-minute analysis periods. An average c.v. value was not used because it was considered to be somewhat conservative for use in providing real-time information. Using the 15-minute analysis periods, there were a total of 504 c.v.'s for each roadway segment. Again, the 85th percentile c.v. value (of the 504 total c.v. observations) was used in the basic sample size equation.

$$n = \frac{z^2 \; c.v.^2}{e^2} \tag{1}$$

where n = number of instrumented vehicles for a given roadway segment and time period
z = standard normal variate based on desired confidence level in the travel time estimate
c.v. = travel time coefficient of variation,
= mean travel time/standard deviation
e = permitted relative error (%),

The statistical parameter, *z*, is based on the desired confidence level (typically between 80% and 95% for most statistical applications) and depends on the relative importance of an accurate travel time estimate. For example, z=1.96 for a 95% confidence level, z=1.845 for a 90% confidence level, etc. *Z*-values can be obtained from standard normal distributions tables. For this study, a 90% and 95% confidence level were chosen in calculating sample sizes because of the importance of real-time information in travel and route decisions..

The permitted relative error, *e*, is set according to the desired accuracy of the travel time estimate. The application of the travel time estimate should help determine the desired accuracy. The Institute of Transportation Engineer's (ITE) *Manual of Transportation Engineering Studies* lists the following ranges of permitted absolute error for various study applications [4]:

- Transportation planning and highway needs studies: ± 4.8 to ± 8.0 kph (± 3 to ± 5 mph).
- Traffic operation, trend analysis, and economic evaluations: ± 3.2 to ± 6.4 kph (± 2 to ± 4 mph).
- Before-and-after studies: ± 1.6 to ± 4.8 kph (±1 to ± 3 mph).

Most existing real-time travel information systems display travel speeds to the nearest ±10%. For example, the real-time speeds from the Houston AVI system are displayed on a color-coded network map that show speeds to the nearest 10 mph (e.g., 0 to 19 mph, 20 to 29 mph, 30 to 39 mph, 40 to 49 mph, greater than 50 mph). Real-time travel information displays from the California Department of Transportation (Caltrans) show speeds to the nearest 15 mph (e.g., 20 mph and below, 20 to 35 mph, 35 mph and above). The Washington Department of Transportation does not use speed ranges for their real-time travel information, only color-coded qualitative descriptions of traffic flow (e.g., pink=stop and go, red=heavy, yellow=moderate, green=wide open). To date, no market research has been conducted to survey commuters and travelers as to the desired accuracy of travel information.

Based on the traveler information systems already in place and anecdotal experience, a permitted relative error of ±10% appears most appropriate for real-time information. A relative error of 10% translates to ± 7 mph at 70 kph, ± 6 kph at 60 kph, etc. Two separate statistical scenarios were examined for this study:

- 95% confidence level, 10% relative error
- 90% confidence level, 10% relative error

IV. Results

A. Minimum Sample Sizes--Houston AVI System

The analysis results are shown in Table II for 5-minute analysis periods and in Table III for 15-minute analysis periods. Each of the tables contain summary statistics for the 60 freeway mainlane or HOV lane segments. The following paragraphs describe the results summarized in the tables.

The average number of runs represents the average number of probe vehicles providing a travel time during the analysis period. For example, the first line of Table II shows that Section 1 of Katy Freeway (I-10) Eastbound had an average of 5 probe vehicles during each 5-minute period within the analysis (6:30 to 9:30 a.m., 4:00 to 7:00 p.m.), or approximately 1 vehicle probe every minute. The average number of runs range from 1 to 7 probe vehicles every 5 minutes (Table II), or 2 to 20 probe vehicles every 15 minutes (Table III). The highest average number of probe vehicles are located on the freeway mainlanes close to major activity centers and the two toll facilities, Hardy Toll Road and the Sam Houston Tollway (Beltway 8). The HOV lanes have a lower average number of probe vehicles than the freeway mainlanes because of the low HOV lane volume (compared to 3 or 4 freeway lanes) and the restrictive nature of the barrier-separated HOV lanes.

The 85th percentile c.v. represents the 85th percentile value of all 5-minute or 15-minute c.v. values. For 5-minute analysis periods, a total of 1,512 c.v. values were computed (one c.v. value for each 5-minute period). For 15-minute analysis periods, a total of 504 c.v. values were computed (one c.v. value for each 15 minute period). The c.v. values for 5-minute periods range from 5% to 15%, whereas the c.v. values for 15-minute periods are slightly higher and range from 5% to 19%.

The 85th percentile c.v. values were used in Eq. 1 to calculate the minimum required sample sizes shown in Tables II and III. For 5-minute periods, a 95% confidence level and a 10% relative error, the sample sizes range from 1 probe vehicle every 5 minutes for free-flow conditions (HOV lane segment) to 6 probe vehicles every 5 minutes for severely congested conditions on the Katy Freeway Eastbound. Sample sizes are slightly lower for a 90% confidence level and 10% relative error. The sample sizes confirm the intuitive notion that congested freeways require a greater number of probe vehicles than uncongested freeways.

The average number of probe vehicles currently providing travel times for the Houston AVI system equal or exceed minimum sample sizes in almost all cases. For the 15-minute analysis periods, the average number of probe vehicles exceed the minimum sample sizes for 90% and 95% confidence levels. For 5-minute analysis periods, only 4 severely congested segments have fewer average probe vehicles than the minimum required sample size for a 95% confidence level and 10% relative error.

B. Minimum Sample Sizes--Other Real-Time Systems

The sample size information in Tables II and III apply to the real-time information system in Houston; however, it would be useful to have similar sample size information for planning real-time information systems in other metropolitan areas. The required sample sizes calculated for the Houston AVI system are directly related to the travel time variation (i.e., 85th percentile c.v. value). If travel time variation can be estimated for roadway segments, then probe vehicle sample sizes can be estimated for planning purposes.

Previous research has indicated that travel time or travel speed variation has a direct correlation to the level of congestion. This study attempted to correlate two congestion-related variables to travel time variation:

- Average daily traffic volume (ADT) per lane.
- Average travel speed.

ADT per lane has been used as a surrogate measure of the level of congestion in many analyses at the Texas Transportation Institute (TTI). Travel speed is a direct measure of congestion level, and should be available through travel time studies.

Preliminary analyses indicated that travel speed was a better predictor of travel time variation than ADT per lane. A regression equation, shown as (2), was then obtained that predicted travel time variation (85th percentile c.v.) based on average speed. Using this technique, only average segment speeds would be required to estimate probe vehicle sample sizes and coverage for a particular roadway network.

TABLE II
TRAVEL TIME VARIATION AND SAMPLE SIZES FOR 5-MINUTE ANALYSIS PERIODS

Facility	Section Number	Section Length (km)	Average Number of Runs	85th percentile c.v. (%)	Minimum Required Sample Size	
					95%, 10%	90%, 10%
Katy Freeway (I-10) Eastbound	1	6.36	5	8.7	2	1
	2	5.88	3	10.7	3	2
	3	3.62	4	14.7	6	4
	4	6.52	6	7.8	2	1
	5	3.94	4	8.2	2	1
Katy Freeway (I-10) Westbound	1	3.86	3	9.8	3	2
	2	5.88	5	10.1	3	2
	3	4.67	3	10.4	3	2
	4	4.67	3	9.9	3	2
	5	7.25	4	8.5	2	1
Katy (I-10) HOV Eastbound	1	7.08	1	7.3	1	1
	2	2.50	n.a.	n.a.	n.a.	n.a.
	3	6.60	n.a.	n.a.	n.a.	n.a.
	4	2.25	1	8.0	2	1
Katy (I-10) HOV Westbound	1	2.25	1	8.0	2	1
	2	6.60	n.a.	n.a.	n.a.	n.a.
	3	2.50	n.a.	n.a.	n.a.	n.a.
	4	7.08	1	6.1	1	1
Northwest Freeway (US 290) Eastbound	1	6.52	3	9.8	3	2
	2	8.21	2	9.1	2	1
	3	2.50	5	12.2	4	2
	4	4.59	6	9.5	2	1
	5	3.94	7	9.8	3	2
	6	1.77	6	12.7	4	3
Northwest Freeway (US 290) Westbound	1	1.77	5	13.5	5	3
	2	3.94	7	10.1	3	2
	3	4.67	6	10.1	3	2
	4	2.50	5	9.7	3	2
	5	6.84	1	8.5	2	1
	6	7.89	2	9.4	2	1
Northwest (US 290) HOV Eastbound	1	4.75	1	11.4	4	2
	2	2.50	1	9.1	2	1
	3	4.59	1	6.6	1	1
	4	3.94	1	5.8	1	1
	5	1.61	2	6.4	1	1
	6	2.50	2	7.4	2	1
Northwest (US 290) HOV Westbound	1	2.50	1	11.3	4	2
	2	1.61	2	8.5	2	1
	3	3.94	1	5.9	1	1
	4	4.59	1	6.0	1	1
	5	2.50	1	7.5	2	1
	6	4.75	1	6.5	1	1
North Freeway (I-45) Southbound	1	5.96	5	8.3	2	1
	2	6.12	5	7.6	2	1
	3	7.81	3	8.0	2	1
	4	5.80	4	8.5	2	1
	5	6.92	5	9.2	2	1
	6	4.67	4	9.4	2	1
North Freeway (I-45) Northbound	1	4.59	3	10.2	3	2
	2	6.92	6	8.9	2	1
	3	5.80	5	9.0	2	1
	4	7.81	3	9.2	2	1
	5	6.12	4	9.7	3	2
	6	5.96	5	8.3	2	1
North (I-45) HOV Southbound	1	5.80	1	6.6	1	1
	2	6.92	2	5.7	1	1
	3	6.04	2	5.5	1	1
North (I-45) HOV Northbound	1	6.04	2	7.1	1	1
	2	6.92	2	5.8	1	1
	3	5.80	1	4.7	1	0

TABLE III
TRAVEL TIME VARIATION AND SAMPLE SIZES FOR 15-MINUTE ANALYSIS PERIODS

Facility	Section Number	Section Length (km)	Average Number of Runs	85th percentile c.v. (%)	Minimum Required Sample Size	
					95%, 10%	90%, 10%
Katy Freeway (I-10) Eastbound	1	6.36	14	9.0	2	1
	2	5.88	8	13.2	5	3
	3	3.62	11	18.7	10	6
	4	6.52	17	9.1	2	1
	5	3.94	13	7.5	2	1
Katy Freeway (I-10) Westbound	1	3.86	9	13.4	5	3
	2	5.88	14	12.5	4	3
	3	4.67	10	12.4	4	3
	4	4.67	9	10.8	3	2
	5	7.25	13	8.4	2	1
Katy (I-10) HOV Eastbound	1	7.08	3	8.2	2	1
	2	2.50	n.a.	n.a.	n.a.	n.a.
	3	6.60	n.a.	n.a.	n.a.	n.a.
	4	2.25	3	7.2	1	1
Katy (I-10) HOV Westbound	1	2.25	3	7.6	2	1
	2	6.60	n.a.	n.a.	n.a.	n.a.
	3	2.50	n.a.	n.a.	n.a.	n.a.
	4	7.08	3	6.6	1	1
Northwest Freeway (US 290) Eastbound	1	6.52	8	10.0	3	2
	2	8.21	5	10.1	3	2
	3	2.50	14	14.6	6	4
	4	4.59	18	10.4	3	2
	5	3.94	20	11.0	3	2
	6	1.77	18	16.1	7	4
Northwest Freeway (US 290) Westbound	1	1.77	16	16.8	8	5
	2	3.94	20	12.3	4	2
	3	4.67	17	11.8	4	2
	4	2.50	15	10.0	3	2
	5	6.84	4	9.2	2	1
	6	7.89	6	9.3	2	1
Northwest (US 290) HOV Eastbound	1	4.75	4	10.8	3	2
	2	2.50	3	10.9	3	2
	3	4.59	4	8.5	2	1
	4	3.94	4	8.1	2	1
	5	1.61	6	7.4	2	1
	6	2.50	6	8.2	2	1
Northwest (US 290) HOV Westbound	1	2.50	2	9.6	3	2
	2	1.61	5	8.7	2	1
	3	3.94	3	6.7	1	1
	4	4.59	3	6.7	1	1
	5	2.50	2	7.7	2	1
	6	4.75	4	7.4	2	1
North Freeway (I-45) Southbound	1	5.96	16	9.1	2	1
	2	6.12	16	8.2	2	1
	3	7.81	9	8.7	2	1
	4	5.80	13	9.0	2	1
	5	6.92	14	11.3	4	2
	6	4.67	11	11.3	3	2
North Freeway (I-45) Northbound	1	4.59	10	10.8	3	2
	2	6.92	18	8.8	2	1
	3	5.80	16	8.8	2	1
	4	7.81	8	10.3	3	2
	5	6.12	13	11.9	4	2
	6	5.96	14	9.2	2	1
North (I-45) HOV Southbound	1	5.80	3	6.6	1	1
	2	6.92	6	6.7	1	1
	3	6.04	7	6.2	1	1
North (I-45) HOV Northbound	1	6.04	7	6.9	1	1
	2	6.92	6	6.6	1	1
	3	5.80	2	5.0	1	0

$$85th\ percentile\ c.v. = 33.9 - 0.27 \times Avg.\ Speed(kph) \quad (2)$$
$$r^2 = 0.60$$

The coefficient of determination, r^2, for this relationship between travel time variation and average speed was 0.60, which means that 60% of the variability in this relationship can be described with the equation shown as (2). This equation was developed using 15-minute time periods because of the greater stability of c.v. values at this time period. The equation is based on speeds between 45 and 105 kph (28 to 68 mph); consequently, the regression equation will only provide reasonable sample size results for speeds in this range. This equation is probably adequate for early planning stages of probe vehicle applications.

V. Conclusions

This paper reported on a study that developed minimum required sample sizes for probe vehicles based on empirical data from Houston's AVI traffic monitoring system. The study examined the travel time variation for 5- and 15-minute periods during peak congested times, and used the 85th percentile coefficient of variation (c.v.) value of all such time periods during the month of April, 1994. The c.v. value is a relative measure of travel time variation, and use of the 85th percentile c.v. value instead of an average c.v. value was deemed necessary for the provision of reliable real-time information. The c.v. values were consistently greater for congested freeway segments, indicating a direct relationship between average speeds and travel time variation.

Sample sizes were calculated for two separate statistical scenarios: 1) 95% confidence level, 10% permitted error, and 2) 90% confidence level, 10% permitted error. A 10% permitted error was chosen because of a typical commuter's insensitivity to small changes in speed or travel time. The sample sizes calculated for these two statistical scenarios were then compared to actual sample sizes that were collected during April 1994 with Houston's AVI traffic monitoring system. The current sample sizes were in almost all cases greater than the calculated minimum required sample sizes. From this comparison, it was concluded that the current number of AVI tags in Houston provide reliable peak period travel speed information (i.e., 95% confidence that displayed real-time speeds are ±10%).

Additional AVI tags could be distributed to HOV lane users, but generally the HOV lane speeds are very stable and should require extensive coverage. Additional tag distribution would also increase the reliability of the travel time data, increasing its usefulness for before-and-after or other operational evaluation studies.

A regression equation was developed (r^2=0.60) that predicted the 85th percentile c.v. using only average speeds as an input. The 85th percentile c.v. can then be used to estimate require sample sizes for the desired statistical accuracy. This equation is considered to be useful in early planning stages of probe vehicle deployment.

V. Recommendations

The study reported in this paper found that the existing number of probe vehicles equipped with AVI tags in Houston provide reliable real-time information for the study corridors during peak periods. However, implementation of several recommendations would improve the accuracy and reliability of the travel time data being collected by the probe vehicles. These recommendations for improving the current collection of data include:

- Install additional AVI tag readers where current segment lengths exceed 5 to 6 kilometers (3 to 4 miles). Current AVI reader sites are based on travel patterns and available overhead mounting structures. Providing reader sites every 3 to 4 kilometers (2 to 3 miles) on congested segments and every 5 to 6 kilometers (3 to 4 miles) on uncongested segments provides more accurate, up-to-data travel times.
- Distribute additional AVI tags to HOV lane users. The current average frequency of probe vehicles on the HOV lanes are one probe vehicle every 5 to 15 minutes.

There are several areas of additional research that would assist planners and designers in developing traveler information systems:

- Determine the tradeoffs and desirable applications of probe vehicle traffic monitoring versus spot location (loop, camera, vehicle detector) traffic monitoring.
- Examine the cost-effectiveness and reliability of various probe vehicle techniques for collecting travel time data. These include AVI (signpost-based) and several different AVL techniques like ground-based radio navigation, GPS, and cellular phone tracking.

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