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Travel-Time Estimates Obtained from Intelligent Transportation Systems and Instrumented Test Vehicles

Statistical Comparison

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Accurate estimation of travel time is necessary for monitoring the performance of the transportation system. Often, travel times are estimated indirectly by using instantaneous speeds from inductance loop detectors and making a number of assumptions. Although these travel times may be acceptable estimates for uncongested conditions, they may have significant error during congested periods. Travel times also may be obtained directly from intelligent transportation systems (ITS) data sources such as automatic vehicle identification (AVI). In addition, mobile cellular telephones have been touted as a means for obtaining this information automatically. Data sources that collect travel-time estimates directly provide travel-time data for both real-time and off-line transportation system monitoring. Instrumented test vehicle runs are often performed to obtain travel-time estimates for system monitoring and other transportation applications. Distance measuring instruments (DMIs) are a common method of instrumentation for test vehicles. DMI travel-time estimates are compared with AVI travel-time estimates by using a variety of statistical approaches. The results indicate that the travel-time estimates from test vehicles instrumented with DMI are within 1% of travel-time estimates from AVI along the study corridor. These results reflect that DMI is an accurate instrumented test vehicle technology and, more important, AVI data sources can replace traditional system monitoring data collection methods when there is adequate tag penetration and infrastructure. A method for identifying instrumented test vehicle drivers who may require additional data collection training is provided. The described procedures are applicable to any instrumented vehicle technique (e.g., the Global Positioning System) in comparison to any ITS data source that directly estimates travel time (e.g., mobile cellular telephones).

A key performance measure for system monitoring is travel time, which may be estimated by using a variety of techniques (*1–3*). Historically, travel-time data have been measured from observations made by test vehicles driven along the corridors of interest. Usually, these test vehicles are outfitted with a distance measuring instrument (DMI), which is connected to the transmission of the vehicle to provide speed and distance measurement at regular intervals. The travel time can be estimated directly by using this data.

Intelligent transportation system (ITS) technology can be used to obtain travel-time estimates not only for system monitoring but also for a variety of transportation applications. Travel time may be estimated indirectly by using instantaneous speeds obtained from inductance loop detectors and some type of instantaneous speed → travel-time translation function (*4*). However, instantaneous speed variance estimates from loop detectors are not strongly correlated with travel-time variance (*4*). An alternative approach is to use automatic vehicle identification (AVI) technology to obtain travel time directly. These systems provide information on vehicles equipped with electronic toll tags at locations where AVI antennas have been deployed. The AVI systems have been used for real-time traffic monitoring by traffic management centers. Recently, the use of cellular telephones as traffic probes has been advocated as an inexpensive method for obtaining direct travel-time estimates (*5*).

Because ITS technology was developed for traffic operations, the data have not been used widely by transportation planning organizations. Consequently, even in cities with widespread ITS deployment, instrumented test vehicle runs are still being carried out on corridors with ITS equipment. The objective for this paper is to compare the travel-time estimates provided by an AVI system with those provided by DMI-equipped vehicles.

To perform the comparison, a chase car study using test vehicles equipped with DMI was conducted on a corridor in Houston, Texas, that is equipped with an AVI system. A comparison of the travel-time estimates by using standard analysis of variance (ANOVA) techniques was performed. Subsequently, a paired *t*-test was conducted to eliminate all extraneous variability sources. A method for identifying DMI drivers that need additional training was provided. Although the focus is on DMI and AVI collection systems, the methodology can be generalized to other data collection technologies. For example, the instrumented vehicle information could be obtained from a Global Positioning System (GPS) unit, or the AVI-type data could be obtained from mobile cellular telephones.

STUDY CORRIDOR AND DATA COLLECTION

Data were collected along an approximately 2-mi (3.2-km) eastbound segment of US-290 located northwest of downtown Houston, Texas, as shown in Figure 1. The corridor is a six-lane freeway with a reversible high-occupancy vehicle (HOV) lane down the center of the freeway. Five AVI reader stations along the corridor are located approximately every 0.5 mi (0.8 km). Figure 2 shows the location of the five AVI antennas. Note that Beltway 8 is the circumferential roadway inside FM 1960 shown in Figure 1. Figure 3 shows US-290 at the middle of the study corridor, and the barrier-separated HOV lane is also shown in the median of the highway. The corridor is

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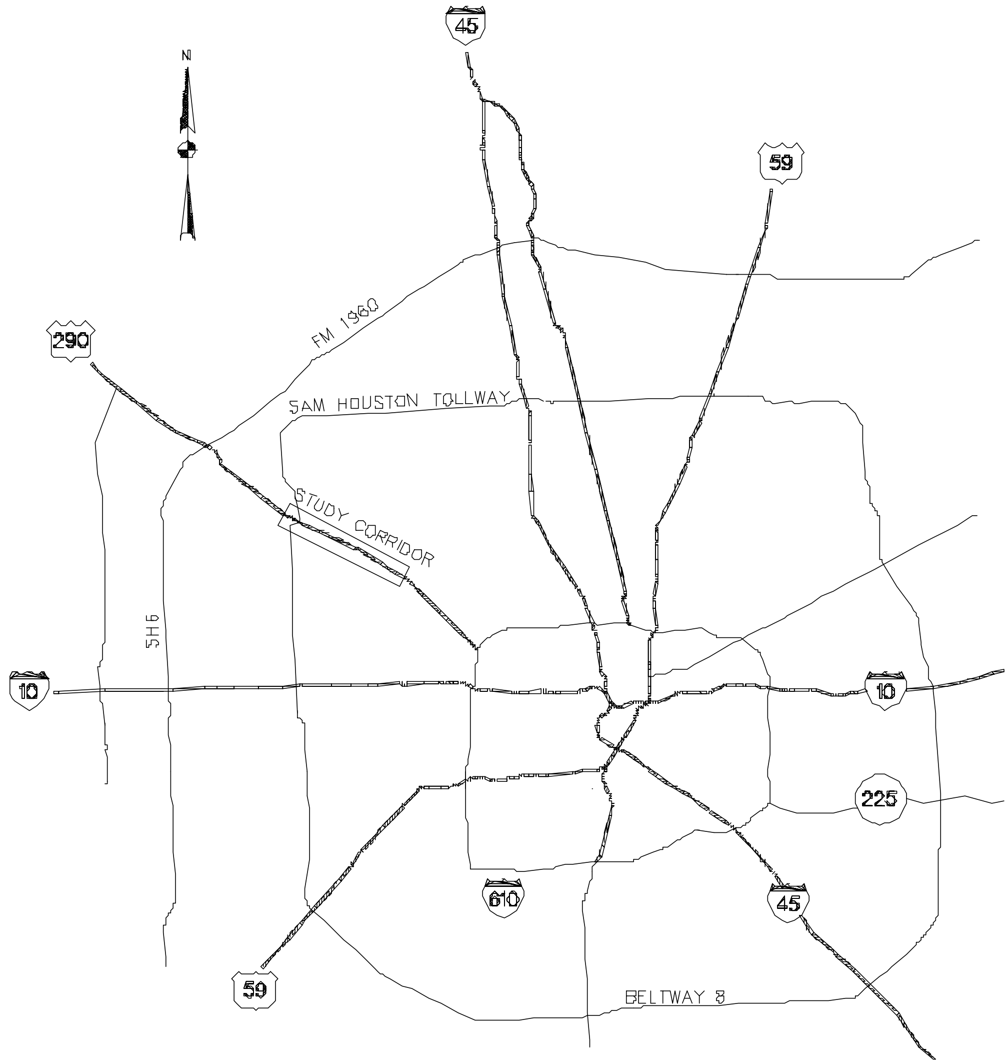

FIGURE 1 US-290 study corridor location in Houston, Texas.

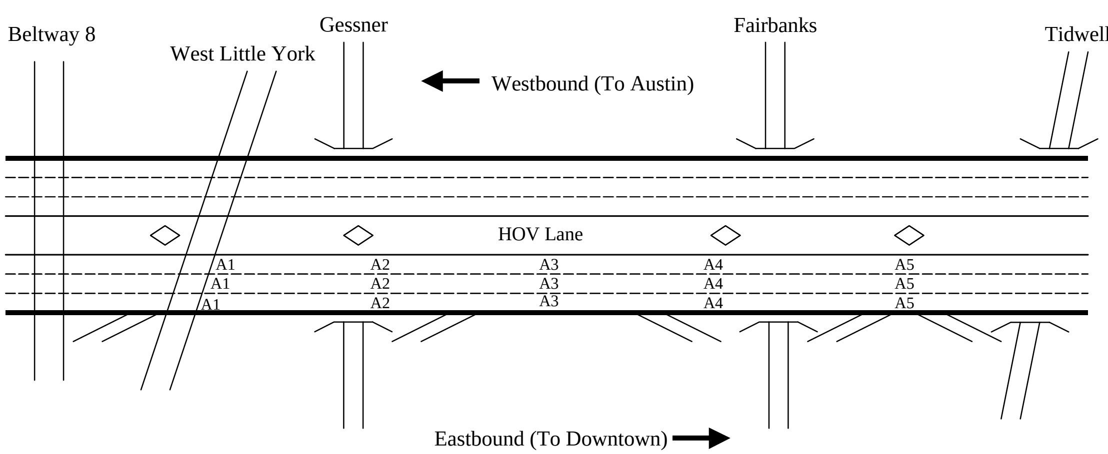

FIGURE 2 US-290 corridor in Houston, Texas (not to scale). A1–A5 are AVI reader sites.

FIGURE 3 Middle of US-290 study corridor.

approximately level except for a 3% to 4% grade at two overpasses. Figure 4 shows the AVI antenna configuration. Data were collected from Monday, October 25, 1999, through Friday, October 29, 1999. Congested conditions were of primary interest, and therefore the morning peak period, lasting from approximately 6:30 a.m. to 9:30 a.m., was targeted. The research described in this paper involved the separate, but simultaneous, data collection from instrumented (DMI) vehicles and AVI-equipped vehicles. The instrumented test vehicles also were equipped with synchronized AVI tags to allow for a direct comparison of the two techniques. The research project from which this paper originates also included the collection of travel-time estimates from commercial vehicles along the corridor, and the results of statistical and practical comparisons involving the commercial vehicle travel-time estimates are described in detail elsewhere (*4, 6*).

Instrumented Test Vehicles

The test vehicles used in the study were instrumented with a DMI that allows for the collection of speed information at half-second intervals. This technology was successfully demonstrated in previous studies (*3, 4, 6–8*). Electronic pulses are read from the vehicle's transmission into the DMI, and the subsequent output from the DMI is collected on an on-board laptop computer. The DMI instrumentation in the test vehicle is shown in Figure 5. The commercially available Computer Aided Transportation Software (CATS) was used for the DMI data collection and reduction, which reads flags that appear along the right side of the ASCII data file whenever a checkpoint is recorded. Speed, distance traveled every 0.5 s, cumulative distance, and a time stamp are collected at 0.5-s intervals.

The chase-car driving technique was used to obtain travel-time data for passenger cars in the traffic stream. Because the goal was to obtain travel-time distribution properties, in particular mean and variance, a chase car technique was used in the study. The drivers were given explicit directions for selecting random vehicles in the traffic stream. One individual served as a scheduler to keep the vehicles on a consistent 3-min headway schedule in the staging area. At a staging location upstream of the test corridor, the scheduler personally provided each subsequent test vehicle driver with the lane number in which they would find a vehicle to chase. The drivers were instructed to move to the given lane, count forward two vehicles, and follow that vehicle along the corridor. An adequate length of roadway preceding the study corridor allowed the drivers to identify and accelerate to the vehicles to be followed before entering the corridor.

After the test vehicle data were collected, the data files from each laptop computer were downloaded and collected on one central

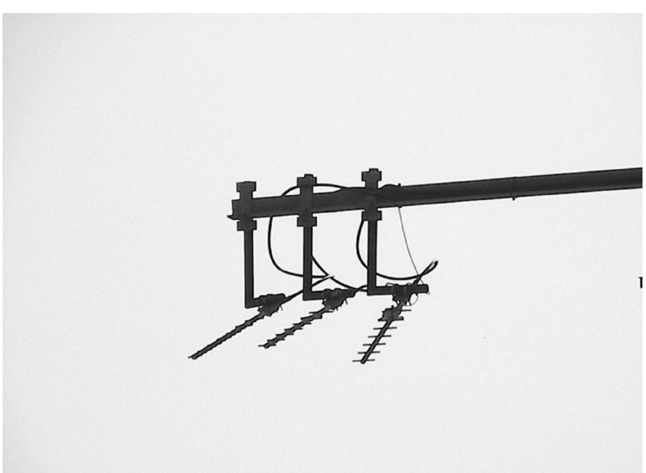

FIGURE 4 AVI antenna configuration.

FIGURE 5 DMI instrumentation in test vehicle.

office computer. CATS was used to analyze the data from each run and summarize it into executive summaries, gather statistics of interest, and write the speed profile graph by using the flagged checkpoints. The drivers missed the first checkpoint on 5 of the 407 travel-time runs over the week. This was corrected by measuring back from the first known accurate checkpoint and inserting the appropriate flag in the raw data file, then reprocessing the run through CATS. A correction of the DMI calibration number was necessary on 17 of the 407 travel-time runs. The calibration of the test vehicle travel-time runs is described in detail elsewhere (*4*).

AVI Data

The AVI system was developed to monitor travel times in the Houston area and to provide data for the speed map, available at traffic.tamu.edu/traffic.html. The system has more than 400,000 tags in circulation throughout the city and provides a very rich ITS data set. Tags are already distributed among the population for the area tool facilities. AVI tags were placed on the windshield of each DMI-instrumented test vehicle to provide a direct comparison of the DMI and AVI travel-time estimates. The time stamps on the laptop computers in each test vehicle were synchronized to the AVI system time. The AVI data used in this study were obtained from the advanced traffic management system in Houston.

STATISTICAL PROCEDURE

Both ANOVA and a paired *t*-test were performed to investigate the differences between the DMI and AVI travel-time estimates.

ANOVA

ANOVA was performed for the AVI and test vehicle data by using the fixed effects models shown in Equations 1 and 2. The travel-time estimates, including the mean, standard deviation, and coefficient of variation (COV), were aggregated to 5-min periods. The COV is defined as the ratio of the standard deviation to the mean. Although ANOVA is not the ideal test for such analysis to test the significance of the standard deviation and COV, there is no other more applicable standard test for two-way analysis. It was found that the results compared favorably to visual interpretation of the data. To obtain ANOVA results over time on the travel-time characteristics, the 5-min travel-time estimates were studied over 30-min periods. All statistical tests were performed at the $\alpha = 0.05$ level of significance. The fixed effects model shown in Equation 1 tests the significance of each day of the week and each period within each day. Because these effects are not mutually exclusive (i.e., the time variable is a component of the day variable), there is no interaction term. The fixed effects model shown in Equation 2 includes the added effect of the data source along with the related interaction effects of data source with day of the week and period.

$$y_{ij} = \mu + \beta_i + \tau_{j(i)} + \epsilon_{ij} \tag{1}$$

where

y_{ij} = value of jth observation at i,
μ = population mean,
β_i = effect due to day of week ($i = 1$ to 5),
$\tau_{j(i)}$ = effect due to period ($j = 1$ to 10 within i), and
ϵ_{ij} = random error term.

$$y_{ijk} = \mu + \theta_i + \beta_j + \tau_{k(j)} + (\theta\beta)_{ij} + (\theta\tau)_{ik(j)} + \epsilon_{ijk} \tag{2}$$

where

y_{ijk} = value of kth observation at jth location in i,
μ = population mean,
θ_i = effect due to data source ($i = 1$ to 2),
β_j = effect due to day of week ($j = 1$ to 5),
$\tau_{k(j)}$ = effect due to period ($k = 1$ to 10 within j),
$(\theta\beta)_{ij}$ = interaction effect of θ_i and β_j,
$(\theta\tau)_{ik(j)}$ = interaction effect of θ_i and $\tau_{k(j)}$, and
ϵ_{ijk} = random error term.

Paired *t*-Test

Because there was an AVI tag on each DMI vehicle, travel-time estimates were obtained from both DMI and AVI for each vehicle, and a paired *t*-test was performed to statistically compare the differences between the two travel-time estimates from each test vehicle. The paired *t*-test provides a powerful statistical test because it eliminates the vehicle-to-vehicle variability in the travel-time estimates. The null hypothesis (H_0) states that the mean travel-time difference between DMI and AVI equals zero (i.e., there is no difference between the two travel-time estimates). The *t*-test statistic is shown in Equation 3 (*9*).

$$t = \frac{\bar{d}}{s_d / \sqrt{n}} \tag{3}$$

where

t = *t*-test statistic,
$\bar{d}$ = differences sample mean,
s_d = differences sample standard deviation, and
n = number of observations.

The *t*-statistic shown in Equation 3 was used in the analyses that follow to investigate the statistical differences between AVI and DMI travel-time estimates for different links, days of the week, and drivers.

STATISTICAL COMPARISON OF DMI AND AVI TRAVEL-TIME ESTIMATES

ANOVA Differences

Table 1 shows the results of the ANOVA for day of week and period. Day of week was statistically significant for the mean of both the AVI ($p < 0.0001$) and the test vehicle ($p = 0.0033$) data. Period was also significant for each data source. The COV was not statistically different by day of week or period for either data source. This indicates that although the mean of each data source may differ statistically by day of week and period, the ratio of standard deviation to the mean (COV) does not have a statistical difference. This is valuable information in situations in which it may be difficult to obtain the variance of the travel-time estimate (i.e., inductance loop detectors) because an estimate of the variance can be obtained if the COV is known.

Table 2 shows ANOVA results for the travel-time characteristics of interest by comparing the AVI and test vehicle data sources as

TABLE 1 ANOVA Results on Travel-Time Characteristics from AVI and Test Vehicle Data Sources

Data Source	Travel Time Variable Tested	Factor	Degrees of Freedom	Mean Square	F	Pr > F
AVI	Average	Day of Week	4	4.79	12.14	<0.0001*
		Time Period	45	23.80	60.58	<0.0001*
		Error	238	0.39	–	–
	Standard Deviation	Day of Week	4	0.10	5.18	<0.0005*
		Time Period	45	0.19	9.49	<0.0001*
		Error	222	0.02	–	–
	Coefficient of Variation	Day of Week	4	9.59	1.24	0.2947
		Time Period	45	11.17	1.45	0.0442
		Error	222	7.73	–	–
Test Vehicle	Average	Day of Week	4	1.86	4.07	0.0033*
		Time Period	43	22.05	48.26	<0.0001*
		Error	214	0.46	–	–
	Standard Deviation	Day of Week	4	0.14	1.22	0.3077
		Time Period	42	0.27	2.29	0.0004*
		Error	95	0.12	–	–
	Coefficient of Variation	Day of Week	4	65.37	1.43	0.2301
		Time Period	42	46.65	1.02	0.4559
		Error	95	45.72	–	–

*Indicates a statistical difference at the $\alpha = 0.05$ level of significance.

shown in Equation 2. The null hypothesis (H_0) is that the AVI and test vehicle travel-time characteristic value are the same. The data source was not found to be significant ($p = 0.5563$) when the AVI and test vehicle mean and standard deviation data were compared. The travel-time mean and standard deviation were found to be statistically different by day of week and period. Interaction effects between the data source and date were found for the COV ANOVA ($p = 0.0209$). After plotting the interaction effects, it was found that the average COV ranged from 0.08 to 0.09 for the AVI data and 0.07 to 0.10 for the DMI data. This translates to a 200% larger range in variability (COV) within the DMI data source as compared to the AVI. This larger range results in the significant interaction effects. These results indicate that the average travel-time estimate from the test vehicles and AVI are not statistically different. The ANOVA results explained here are discussed in more detail elsewhere (*4*).

Paired *t*-Test Differences by Link

A total of 136 observations of the DMI travel-time runs along the entire AVI system corridor (i.e., from AVI Reader 1 to AVI Reader 5) were collected for comparison to the test vehicles for the entire week. As indicated previously, the statistically more powerful *t*-test was used for these analyses.

Table 3 presents the mean travel-time difference, percentage difference, and statistical significance for the paired *t*-test comparing the AVI and test vehicles between the AVI antennas indicated along the corridor. The difference between the AVI and the test vehicles was, at most, 1.2 s, equivalent to a maximum 2.4% difference. A significant difference at the $\alpha = 0.05$ level was found for each link comparison except between the third and fifth AVI antennas ($p = 0.3984$). Although a statistical difference was found for most links, the average difference between the two data sources for link travel time was only 0.2 s. Because the paired *t*-test removes the effect of other variables, it is, in fact, a stronger statistical test for comparing the two systems. The remaining statistical differences found here are likely due to a variety of conditions. Variation between the test vehicle drivers (discussed in a later section) can cause the differences. Differences may also occur because the AVI system sometimes reads tags when the vehicle is upstream of the antenna, especially during congested periods [i.e., speeds below 30 mph (48 km/h)], and the test vehicle drivers were instructed to hit each checkpoint below the AVI antenna. The angle and orientation of the AVI antenna, along with its sensitivity setting, also may be causes of differences between the two estimates. Therefore, although statistically there are differences, for system monitoring of the test corridor studied in this paper, the differences would not make a practical difference. It should be pointed out, however, that in some situations the differences could be greater, and it is not clear a priori which corridors would be affected. Therefore, before ITS can be used for system monitoring, a similar test should be performed across a variety of congested conditions.

Paired *t*-Test Differences by Day

Table 4 presents the results for the entire corridor from AVI Antenna 1 to Antenna 5 by day of the week. The largest difference is 0.5% on Tuesday, which equates to a 1-s difference between AVI and test vehicles. For this corridor, these differences are small, and the added cost of performing system monitoring with an instrumented test vehicle (DMI) even in locations with adequate ITS infrastructure probably would not be justified. However, this decision ultimately would be up to the agency or individual performing the data collection. Only

TABLE 2 ANOVA Results on Travel-Time Characteristics Comparing AVI and Test Vehicle Data Sources

Data Source	Travel Time Variable Tested	Factor	Degrees of Freedom	Mean Square	F	Pr > F
Test Vehicle and AVI	Average	Data Source	1	0.15	0.35	0.5563
		Day of Week	4	6.76	15.97	<0.0001*
		Time Period	45	44.28	104.63	<0.0001*
		Interaction of Data Source and Day of Week	4	0.13	0.32	0.8674
		Interaction of Data Source and Time Period	43	0.16	0.39	0.9999
		Error	452	0.42	–	–
	Standard Deviation	Data Source	1	0.03	0.57	0.4521
		Day of Week	4	0.16	3.32	<0.0111*
		Time Period	45	0.39	7.94	<0.0001*
		Interaction of Data Source and Day of Week	4	0.09	1.76	0.1367
		Interaction of Data Source and Time Period	42	0.06	1.22	0.1786
		Error	317	0.05	–	–
	Coefficient of Variation	Data Source	1	26.50	1.39	–
		Day of Week	4	37.37	1.96	–
		Time Period	45	37.22	2.94	0.0209*
		Interaction of Data Source and Day of Week	4	56.11	1.35	0.0793
		Interaction of Data Source and Time Period	42	25.86	–	–
		Error	317	19.11		

*Indicates a statistical difference at the $\alpha = 0.05$ level of significance.

TABLE 3 *p*-Values for Each Link for Paired *t*-Test Comparing AVI and Test Vehicle Data

Link Defined by AVI Antennas	Number of Observations	Mean Difference (AVI-DMI) (seconds)	Percent Difference	P-Value
1 to 2	173	-0.5	-0.9	<0.0008*
2 to 3	48	1.2	2.4	<0.0001*
3 to 4	39	-0.5	-1.9	0.0050*
4 to 5	126	0.6	0.8	0.0006*
1 to 3	46	0.8	1.0	0.0042*
3 to 5	39	0.1	0.0	0.3984*
1 to 5 (corridor)	136	0.8	0.3	<0.0001*

*Indicates a statistical difference at the $\alpha = 0.05$ level of significance.

TABLE 4 *p*-Values for Entire Corridor by Day Comparing AVI and Test Vehicle Data

Day	Number of Observations	Mean Difference (AVI-DMI) (seconds)	Percent Difference	P-Value
Monday	26	1.4	0.4	0.0284
Tuesday	28	1.0	0.5	0.0012*
Wednesday	35	0.8	0.2	0.0265
Thursday	27	0.2	0.1	0.5750
Friday	20	1.8	0.1	0.4924

* Indicates a statistical difference at the $\alpha = 0.05$ level of significance.

Tuesday was statistically different at the $\alpha = 0.05$ level of significance. It is interesting to note that when all the days of the week in Table 4 are combined, a statistically significant result was found, as shown in the final row of Table 3. On further investigation, it was found that the larger percent differences occurred on Monday and Tuesday with 0.4% and 0.5%, respectively. When these days are removed from the analysis, the results for the remaining days indicate there is no statistical difference ($p = 0.0278$). The larger percent differences on Monday and Tuesday are likely attributable to the fact that the drivers were in a learning mode during the early part of the week. This is a potential problem affecting travel-time estimates conducted in this manner. Analyses were conducted for all the links for each day, and statistical differences were not found in 70% of the 30 tests performed across days and links.

Paired *t*-Test Differences by Test Vehicle Driver

Further analyses were performed to investigate the differences between the AVI and test vehicle mean travel-time estimates by driver. Figure 6 presents the difference in seconds between the AVI and test vehicle (DMI) corridor travel-time estimates plotted against the time of arrival to the corridor. This figure visually displays that Drivers 2 and 4 are often on the outer edges of the data. The average differences in travel time for Drivers 2 and 4 are occasionally greater than 5 s, whereas the average difference for all drivers is approximately 1 s.

Figure 7 shows the percent difference of the travel-time estimates between AVI and test vehicles (DMI) by arrival time for the corridor. Again, Drivers 2 and 4 are along the outside of the data plot. The maximum difference is 2% and is often the result of a travel-time run by either Driver 2 or Driver 4. The average difference is 0.3%. It is interesting to note that the difference remains within approximately 2% through congested and uncongested conditions. Similar analyses were performed for all links along the corridor, and the average percent differences remain below 3% for all links. Although these percent differences are small, they indicate that if DMI is being used, it is important to train the drivers thoroughly, because even trained drivers will make errors.

Statistical differences were also analyzed by driver with the paired *t*-test to further investigate the variability by driver at the $\alpha = 0.05$ level of significance. Table 5 presents the *p*-values and degrees of freedom on each link for each driver. Drivers 2 and 4 have statistically different results for Links 2 to 3, 4 to 5, and 1 to 5. Drivers 6 and 7 have statistically different results for Links 1 to 2. These results validate statistically the visual differences shown for Drivers 2 and 4 in Figure 6 and Figure 7. Although the test vehicle drivers for this study were trained and they used the DMI extensively before the data collection, these results indicate that human error in measurement still can occur. However, for longer corridors, or corridors in other locations, these results may not apply. As before, it would be useful

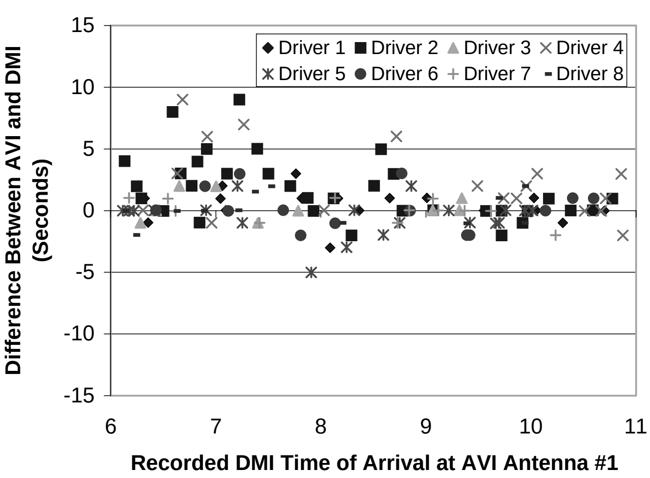

FIGURE 6 Difference between AVI and test vehicle (DMI) travel-time estimates by driver for entire corridor.

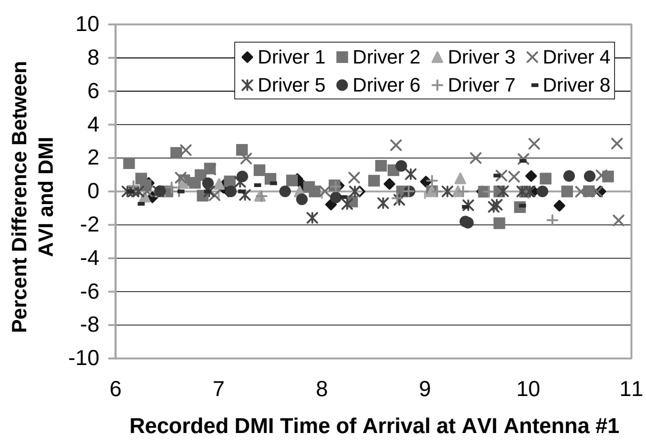

FIGURE 7 Percent difference between AVI and test vehicle (DMI) travel-time estimates by driver for entire corridor.

TABLE 5 ***p*-Values and Degrees of Freedom for Each Driver for Paired *t*-Test Comparing AVI and Test Vehicle Data**

Link Defined by AVI Antennas	Instrumented Test Vehicle Driver							
	#1	#2	#3	#4	#5	#6	#7	#8
1 to 2	0.1232 (29)	0.5497 (29)	0.1682 (8)	0.1176 (29)	0.0370 (18)	0.0018* (22)	0.0012* (21)	0.0266 (10)
2 to 3	0.1089 (8)	0.0021* (7)	–	0.0103* (10)	0.0304 (6)	0.4759 (2)	0.0797 (8)	–
3 to 4	0.6759 (6)	0.0645 (6)	–	0.4612 (9)	0.2172 (2)	0.0888 (3)	0.4831 (4)	0.4875 (1)
4 to 5	0.0588 (16)	0.0003* (23)	0.5312 (5)	0.0103* (23)	0.3592 (18)	0.3130 (15)	0.3147 (9)	0.7715 (9)
1 to 3	0.4293 (8)	0.1541 (6)	–	0.0910 (6)	0.2853 (6)	0.2491 (5)	0.98 99 (6)	1.0000 (2)
3 to 5	0.9873 (3)	0.2120 (5)	–	0.3491 (6)	0.2966 (5)	0.4021 (3)	0.0437 (6)	0.3850 (4)
1 to 5 (corridor)	0.2159 (16)	0.0004* (32)	0.3916 (8)	0.0032* (18)	0.1286 (19)	0.6445 (13)	0.9953 (11)	0.7354 (11)

*Indicates a statistical difference at the $\alpha = 0.05$ level of significance.
Cells with no data present are indicated with "–."

to test the assumptions empirically. More important, the paired *t*-test analysis applied here could be used to check the quality of data obtained from different drivers to help identify drivers in need of more training.

CONCLUDING REMARKS

This paper presented ANOVA and paired *t*-test statistical tests to compare travel-time estimates from DMI and AVI. A method for using the statistical paired *t*-test to compare instrumented test vehicle mean travel-time run estimates with those obtained from an ITS data source was also presented. Although DMI is used for test vehicle data collection in the application demonstrated in this paper, the procedure would apply to any instrumented test vehicle technique (e.g., GPS). Similarly, any ITS travel-time estimate may be used, provided the estimation technique measures travel time directly along the corridor. Therefore, the methods can be applied to emerging techniques, such as anonymous mobile cellular telephones, that have been shown to be promising travel-time data sources for travel-time estimation (*5*).

It was found that the DMI technology provided an average 0.3% difference with travel-time estimates from AVI along the 2-mi segment of US-290 in Houston, Texas. This result indicates the successful use of the DMI technology for test vehicle instrumentation. Further, it demonstrates that if there is adequate tag penetration and ITS infrastructure (in this case AVI), these technologies can replace the need for system monitoring and travel-time runs using individual travel-time runs. In addition, larger amounts of data can be collected throughout the entire year as AVI systems continuously provide good variability information (unlike inductance loop detectors). This better information can be used to improve performance monitoring and other real-time and off-line transportation applications.

Finally, it was demonstrated how the *t*-test may be used to identify which drivers may require additional training on the instrumented test vehicle travel-time data collection method by directly comparing the AVI and instrumented test vehicle (DMI) travel-time estimates from the same vehicle. The *t*-test analysis provided further statistical evidence that the DMI is a proven technology for performing travel-time runs and that these travel-time estimates can be compared to a direct ITS travel-time data collection source (AVI in this paper). This suggests that the DMI technology and a *t*-test could be used by practitioners to statistically compare direct ITS travel-time estimates from any technology (e.g., AVI, mobile cellular telephone) at regular intervals and over varying traffic conditions to identify the effectiveness of their automated ITS travel-time data collection.

The study was controlled for several factors that could have resulted in differences in the travel-time estimates. Several factors, however, could not be controlled. One of these is the drivers themselves. Table 5 indicates that there are statistical differences between drivers. Although the drivers were trained on the method of test vehicle data collection for this study, human error in the marking of checkpoints is present. Another factor is the time at which the AVI system receives a tag read. During congested conditions (i.e., speeds below 30 mph) it was observed that at times the AVI system would read a tag when the vehicle was upstream of the actual AVI antenna location. The drivers, however, were instructed to hit the checkpoints below the AVI antennas. In addition, the sensitivity on a particular AVI antenna can be adjusted. If an AVI antenna's sensitivity is turned up, the antenna will read tags earlier than it will at low sensitivity settings. Finally, the physical directional setting of the AVI antenna can affect when a particular antenna reads a tag. It is anticipated that for most applications the differences found along the study corridor used in this paper would be acceptable given the relative expense of performing a DMI travel-time run. Future work is recommended that will control and isolate the effects of these additional factors and investigate longer corridors.

There is also a need for further work that identifies individual driver behaviors. Test vehicle driver behaviors were investigated in the research presented here, but the driver behavior of individual drivers in the traffic stream was not monitored from day to day. Previous work investigated the travel-time variability of individuals from aggregate- and disaggregate-based travel-time estimates, and it was found that aggregation of travel-time data can lead to considerable error when compared to individual motorist travel-time information (*10*). Future research is needed that will identify a driver behavior element in comparison with other transportation system performance measures.

Future work is also needed that directly compares DMI-instrumented test vehicles with test vehicles instrumented with GPS. Both methods have their advantages and disadvantages, yet these trade-offs have not been fully quantified.

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