IMPROVING AADT AND VDT ESTIMATION WITH HIGH-RESOLUTION SATELLITE IMAGERY

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ABSTRACT

State departments of transportation (DOTs), as well as national agencies in many countries, invest heavily in personnel and equipment to collect the data supporting the estimation of Average Annual Daily Traffic (AADT) and Vehicle Distance Traveled (VDT). Satellite- and air-based imagery can provide additional data for estimation and offers certain advantages over traditional ground-based sensors. Vehicles are evident in high-resolution satellite imagery, and we are developing algorithms that can automatically identify vehicles in 1-m resolution panchromatic imagery. However, the imagery only provides very short duration observation, whereas traditional estimation methods are based on traffic volumes measured over extended intervals of time. We review and present additional empirical comparisons between image-based AADT estimates and traditionally produced estimates that lead to an estimate of the error involved with expanding an image to an AADT estimate. The error appears unbiased with a relatively low standard deviation.

Real value would likely only be produced when using the image-based estimates on a large-scale, regular basis. We therefore developed software to simulate AADT and VDT estimation errors when using traditional ground-based samples only and when adding satellite-based data to the ground-based samples. We review and present additional simulation results indicating that DOTs could markedly decrease labor-intensive ground-based sampling efforts while improving AADT and VDT estimation.

THE APPEAL OF SATELLITE IMAGERY

Transportation agencies around the world are interested in estimating vehicular traffic over their highway networks and, in many cases, required to do so. Traffic estimates are used to document and forecast trends, identify problems, and serve as inputs to planning and design studies. Two of the most commonly used summary statistics of vehicular traffic are annual average daily traffic (AADT) and annual vehicle distance traveled (VDT) in Kilometers. Strict definitions can be found elsewhere (FHWA, 2000; McShane, *et al*., 1998). Loosely, AADT represents traffic on a highway segment on an average day, while annual VDT represents the distance traveled by all vehicles over a network of segments in a year.

Traditionally, AADT is first estimated for the segments of the highway system, then VDT is estimated by summing the product of the length of the segment and the AADT:

$$\text{VDT} = \Sigma_{\forall \text{segments } i} (\text{length}_i * \text{AADT}_i) \tag{1}$$

Lengths of segments are static and readily available. The AADTs are based on dynamic traffic conditions that are more difficult to obtain. Conceivably, AADT can be estimated in alternative ways (*e.g*., Zhao and Chung, 2001). Typically, however, in a given year three groups of homogeneous highway segments—segments with similar properties for estimation purposes—are considered, and the AADT is estimated differently for segments in the various groups. These groups are summarized as follows.

- Automatic traffic recorders collect extensive volume data on one group of segments. In principle, volumes are collected continuously—365 days per year, 24 hours per day—and AADT can be estimated by averaging daily volumes. However, in practice hardware and software difficulties lead to less than complete data, and some interpolation or more complicated estimation is necessary (FHWA, 2000). The extensive volume data are also used to develop seasonal adjustment factors used in estimating AADT for segments in the following group.
- "Coverage counts" are collected on another group of segments for periods of relatively short duration. Often, two consecutive 24-hour counts are collected, the seasonal factors developed from the first group of segments

are used to convert ("deseasonalize") each of the two 24-hour counts to estimated average annual conditions, and the two estimated average annual conditions are averaged to produce an AADT estimate.

- No samples are collected for the final group of segments. On these segments AADT is estimated from estimated AADT on segments in the previous two groups and from samples taken in previous years on the segment.

The data collection programs that support AADT and VDT estimation require large investments in equipment and labor expenses. Moreover, the limited sampling involved will lead to errors in the estimates of these summary statistics. Therefore, using high-resolution satellite imagery in AADT and VDT estimation programs could be beneficial. The imagery can provide an additional source of data. Vehicles are evident in the high-resolution commercial imagery that has recently become available to the civilian community, and image processing algorithms can be developed to identify these vehicles automatically. As an example, cars and trucks are evident in the portion of the IKONOS 1-m resolution panchromatic image presented in Figure 1a; in Figure 1b their shapes are distinguishable in the output of the software we have developed, and automatic counts match manual counts very well (McCord, *et al.*,2002b). Spatial coverage in satellite-based imagery is much greater than can be achieved from ground-based sensors. Satellites can also access remote highways more easily and, since they are off-the-road, collect data without disrupting traffic or jeopardizing the safety of ground-based data collection crews.

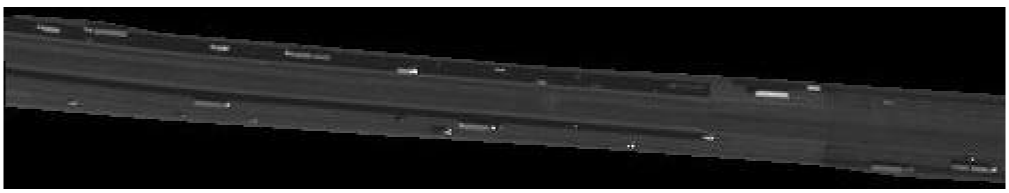

Figure 1a. IKONOS 1-m resolution panchromatic image of I-270 near Columbus. OH (from Space Imaging, Inc., through NASA Data Buy program)

Figure 1b. Binary image of highway in Figure 1a resulting from image processing software developed in McCord, *et al*., (2002b)

The difficulty is that high-resolution sensors are carried on satellites in near polar orbits that do not allow high-frequency temporal sampling of the links. Therefore, to be considered for use in AADT and VDT monitoring, it must be shown that the "noise" associated with inferring average traffic conditions from satellite imagery is small enough and the quantity of images is great enough that the information can be combined with ground-based data to improve estimation performance. In the following sections we summarize previous results and present new results indicating that high-resolution satellite imagery could decrease AADT and VDT estimation errors while reducing ground-based data collection efforts.

AADT ESTIMATION ERRORS FROM A SINGLE IMAGE

We are considering various ways of using satellite- and air-based imagery to improve the task of AADT and VDT estimation. However, in this paper we limit ourselves to using the imagery in a way that would parallel the approach presently used with ground-based data. In this approach a single traffic count obtained over an interval of time is converted to an estimate of average conditions for the year by using factors that estimate how a traffic pattern during the time period of observation deviates from annual average conditions. When more than one of these traffic counts is obtained, an estimate of annual conditions is produced for each observation period, and the estimates are averaged to produce an estimate of AADT.

Recently, for the first time to our knowledge we compared estimates of AADT produced from images to those produced from ground-based data. The details can be found in McCord, *et al*. (2002a). In short, we observed the numbers of cars and trucks and length of highway segment in the image, used these numbers of cars and trucks and an assumption on their velocities to estimate a space-mean speed, used the number of vehicles and length of the segment to determine density, and used the density and space-mean speed to determine a flow rate. This flow rate also corresponds to a vehicle count obtained during a short period of time, which we call an equivalent count interval, where the length of the interval t^{dur} is determined from the length of the segment and the space-mean speed. We then used available data on temporal distributions to convert the estimated flow rates to "image-based estimates of AADT," which we denote $AADT^{img}$.

In the study referenced above, we produced $AADT^{img}$ for eight 1-m resolution IKONOS satellite images and six sets of air photos covering 14 urban or rural interstate segments in Ohio. (Two of these 14 were the same segment imaged in two different years.) We used extensive ground-based data or published ODOT data to determine ground-based estimates of AADT, which we denote $AADT^{grd}$, and formed the relative difference *RD* between the image-based and ground-based estimates for the same segment in the same year:

$$RD = (AADT^{img} - AADT^{grd}) / AADT^{grd}. \qquad (2)$$

The distribution of the 14 RD values had sample mean 0.02 and sample standard deviation 0.14. Eight of the values were positive, and six were negative. These statistics led us to believe that the sample error distribution seemed relatively unbiased (mean close to zero). Given that the lengths of the equivalent count interval t^{dur} corresponding to the $AADT^{img}$ were so short—ranging from 0.6 to only 12.5 minutes—we found the magnitudes of the *RD* values surprisingly low. The relatively low magnitudes of the errors and the apparent unbiasedness indicate the potential to produce good estimates of ground-based AADTs by averaging several image-based estimates of the same segment.

However, the $AADT^{grd}$s are only estimates of the true AADTs. In the study, the $AADT^{grd}$ for a given segment was produced in one of two general ways, depending on data availability. On three segments, $AADT^{grd}$ was estimated,either by the Ohio Department of Transportation or by us,with extensive ground-count data collected for the particular segment in the year the segment was imaged. On the other 11 segments, we estimated the $AADT^{grd}$ by using published growth factors and estimates of AADT obtained with much less ground-count data collected in previous years. Both the contemporary nature and the extensiveness of the data in the former group of 3 segments lead us to believe that the $AADT^{grd}$ would tend to be better estimates of the true AADT for these segments than for the other 11 segments. The three segments in that group had *RD* values very close to zero. Although the sample size is very small, the indication is that some of the error in the overall distribution may be attributable to errors in the ground-based AADT estimates, and not only to errors in the image-based estimates.

Estimating the $AADT^{grd}$ should not, therefore, be considered the absolute target of image-based AADT estimation, and we are investigating the error associated with these ground-based estimates so as to provide a better basis for interpreting the *RD* values. However, in the absence of results from such studies, $AADT^{grd}$ can be considered an intermediate target for image-based estimation, and the apparent unbiasedness and relatively low standard deviation of the sample *RD* distribution seem encouraging for image-based estimates.

We have recently produced four more *RD* values, all based on 1-m IKONOS satellite images on Ohio urban interstates—one segment of I-70 in the Dayton area and three segments of I-475 near Toledo. Information on these segments and the corresponding images is provided in the lines corresponding to numbers 15-18 in Table 1. The information for the first 14 segments was previously presented in McCord, *et al*. (2002c). The relative differences,*RD* between the image- and ground-based estimates, and the supporting data, for all 18 segments are provided in Table 2. Again, the information for segments 1-14 was previously presented in Table 2 of McCord, *et al*. (2002c).

This set of 18 *RD*s has sample mean of 0.03 and sample standard deviation of 0.15, compared to 0.02 and 0.14 for the previously analyzed set of 14 segments. Once again, one would not be able to reject a null hypothesis of a mean error equal to zero. Furthermore, the 12 positive and 6 negative *RD* values observed in Table 2 would not allow rejecting a null hypothesis that the median of the distribution is zero. Not rejecting these hypotheses is not the same thing as accepting them, but the indication is that averaging several image-based estimates could lead to good estimates of AADT. We also note that, as found in McCord, *et al.,* (2002c), the *RD*s corresponding to cases where the ground-based estimates of the AADT were produced from a large amount of contemporary data—what we call "based on PATR data" and denote by the double asterisk in Table 2—were generally lower than the other *RD*s. Of the four new *RD* values, the two corresponding to cases where the $AADT^{grd}$ was based on PATR data were smaller in magnitude than the two that were not—0.01 and 0.10, compared to 0.13 and 0.35. The sample mean and standard deviation of the 5 total *RD*s based on PATR data are 0.02 and 0.05, respectively, compared to 0.03 and 0.18 for the 13 *RD*s that were based on arguably poorer estimates of $AADT^{grd}$.

No	Segment Descripton	FC*	Image	Date	Time	Segment Length (km)
1	I-71: @US62	11	Aerial	11/30/95	10:13 am	12.02
2	I-270: @I-70	11	Aerial	11/30/95	10:21 am	4.95
3	I-70: @SR142	1	Aerial	11/30/95	10:30 am	7.64
4	I-71: @US62	11	Aerial	10/29/96	10:20 am	20.93
5	I-270: @I-70	11	Aerial	10/29/96	N/A**	6.14
6	I-70: @SR142	1	Aerial	10/29/96	10:55 am	17.32
7	I-270: SR317 to US33	11	Satellite	5/29/01	12:20 pm	2.30
8	I-270: US33 to Alum Creek Dr.	11	Satellite	5/29/01	12:20 pm	4.59
9	I-270: Alum Creek Dr. to US23	11	Satellite	5/29/01	12:20 pm	6.02
10	I-75: US224 to TWP. RD. 99	1	Satellite	8/11/01	12:18 pm	3.38
11	I-75: TWP. RD. 99 to SR613	1	Satellite	8/11/01	12:18 pm	5.55
12	I-270: Morse Rd to Easton Way	11	Satellite	9/16/01	12:31 pm	1.02
13	I-270: Easton Way to US62	11	Satellite	9/16/01	12:31 pm	3.60
14	I-270: US62 to SR317	11	Satellite	9/16/01	12:31 pm	3.53
15	I-70: DAYTON AIRPORT ACCESS to I-75	11	Satellite	6/18/01	12:49 pm	2.90
16	I-475: US24 to SALISBURY RD.	11	Satellite	10/22/01	12:32 pm	3.01
17	I-475: SALISBURY RD. to SR2	11	Satellite	10/22/01	12:32 pm	3.49
18	I-475: SR2 to US20	11	Satellite	10/22/01	12:32 pm	6.97
*Functional Classification: 1=Rural Interstate, 11= Urban Interstate **Assumed 10-11am						

Table 1. Information on 18 segments and images used in study (Information on first 14 segments appears in McCord, *et al*., (2002c))

Segment Number	Segment Length, L (km)	Number of Cars Nc , Trucks Nt	Space-Mean Speed Us (kmph)	Duration of Simulated Count Interval t^{dur} (mins)	Image-based $AADT^{img}$ AADT	Ground-based $AADT^{grd}$ AADT	Relative Difference RD
1	12.02	98, 88	96.97	7.44	30248	30178**	0.0023
2	4.95	143, 33	101.57	2.92	78358	77497*	0.0111
3	7.64	72, 51	105.96	4.33	32778	45955*	-0.2867
4	20.93	233, 92	100.03	12.55	28881	30112**	-0.0409
5	6.14	219, 25	102.94	3.58	82566	78970*	0.0455
6	17.32	206, 130	106.40	9.77	42410	47931*	-0.1152
7	2.30	48, 10	101.81	1.36	43850	51604*	-0.1503
8	4.59	108, 26	101.46	2.71	50658	47852*	0.0586
9	6.02	137, 45	100.61	3.59	51989	45288*	0.1480
10	3.38	83, 8	111.22	1.82	38152	41920*	-0.0899
11	5.55	139, 8	111.75	2.98	37710	42210*	-0.1066
12	1.02	60,3	103.82	0.59	182430	139460*	0.3081
13	3.60	180,2	104.41	2.07	150401	145120**	0.0364
14	3.53	171,0	104.59	2.02	144406	134020*	0.0775
15	2.90	114,18	102.39	1.70	91176	67592*	0.3489
16	3.01	83,4	103.85	1.74	61818	60942**	0.0144
17	3.49	127,2	104.34	2.01	79610	70722*	0.1257
18	6.97	296,9	104.11	4.02	93943	84844**	0.1072
*: based on published AADT (and growth factors)							
**: based on PATR data							

Table 2. Relative differences and supporting data by segment (Information on first 14 segments appears in McCord, *et al*., (2002c))

In McCord, *et al*. (2002c), we also saw empirical evidence of an expected negative correlation between the magnitude of the error and the length of the equivalent count interval t^{dur}. Specifically, making the common assumption that vehicle arrivals on a lightly traveled segment follow a Poisson distribution, the variance of the error (approximated by *RD*) in image-based estimation—and, therefore, the mean size of the absolute value of the error—can be shown to increase with $1/t^{dur}$ (McCord, et al., 2002b). A linear regression of the absolute value of the 14 *RDs* against their corresponding $1/t^{dur}$ produced a significantly positive slope with an R^2 of 0.38. Since the value of t^{dur} can be obtained directly from the data, if a solid relationship can be established to indicate how the distribution of errors varies with this parameter, one could make more informed decisions on when and how to use an image-based estimate. For example, a newly acquired image would lead to an $AADT^{img}$ and a corresponding value of t^{dur}. The t^{dur} would lead to a distribution on the precision of the $AADT^{img}$. This distribution could be compared to the prior distribution of the AADT estimate to determine how much weight to give to the newly acquired $AADT^{img}$.

In Figure 2, we plot the absolute value of the *RD* and the corresponding value of $1/t^{dur}$ with the regression line for the set of data that includes the four new observations. Again, there is a statistically significant relationship (t-statistic on the coefficient of the $1/t^{dur}$ term equal to 2.36). The R^2 is only 0.25, but it improves to 0.56 without the two outliers in the diagram. We are presently investigating explanatory factors other than t^{dur} to try to understand the performance of the outliers.

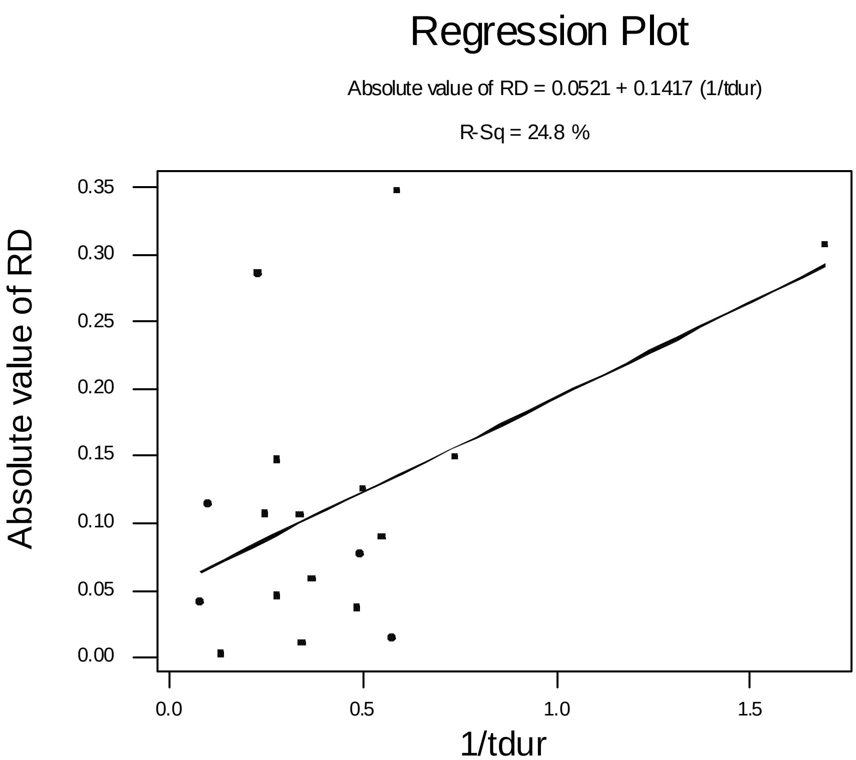

Figure 2. Plot of empirical data and least squares fit of *Absolute Value of Relative Difference (RD) vs. (1/t^{dur})*

The *RD*s of Table 2 came from AADT comparisons of segments of various lengths and, therefore, various lengths of equivalent count period t^{dur}. Assuming that traffic on these highways, which were lightly traveled at the time of imaging, follows a Poisson Process, we developed a method to standardize the errors to a given value of t^{dur} (McCord, *et al.*, 2002b). In Table 3, we present the *RD*s as they appear in Table 2 under the column entitled "Original t^{dur}." We also present the *RD*s standardized to t^{dur} values of 3.0 and 5.0 minutes. We see that the sample means for these standardized RDs are, respectively, –0.025 and –0.014, and the sample standard deviations are 0.17 and 0.10, respectively.

Segment Number	Original t^{dur} (mins)	Original RD	Normalized RD $t^{dur} = 3$ mins	Normalized RD $t^{dur} = 5$ mins
1	7.44	0.0023	0.0058	0.0033
2	2.92	0.0111	0.0105	0.0061
3	4.33	-0.2867	-0.4294	-0.2487
4	12.55	-0.0409	-0.1961	-0.1133
5	3.58	0.0455	0.0540	0.0312
6	9.77	-0.1152	-0.4333	-0.2510
7	1.36	-0.1503	-0.0642	-0.0371
8	2.71	0.0586	0.0511	0.0295
9	3.59	0.1480	0.1717	0.0992
10	1.82	-0.0899	-0.0571	-0.0331
11	2.98	-0.1066	-0.1135	-0.0659
12	0.59	0.3081	0.0577	0.0334
13	2.07	0.0364	0.0246	0.0143
14	2.02	0.0775	0.0514	0.0298
15	1.70	0.3489	0.1890	0.1093
16	1.74	0.0144	0.0081	0.0047
17	2.01	0.1257	0.0824	0.0477
18	4.02	0.1072	0.1455	0.0842
Sample mean		0.0275	-0.0245	-0.0142
Sample st. dev		0.1543	0.1758	0.1018

Table 3. Original RDs and RDs standardized to t^{dur} values of 3 and 5 minutes

NETWORK-BASED ESTIMATION IMPLICATIONS

In McCord, *et al.* (2002a) we reported on our simulation-based analysis of AADT and VDT estimation errors within a set of homogeneous segments with and without the use of traffic data obtained with the sampling frequency of a 1-m satellite-based sensor. In that study, we presented the performance, as portrayed by the mean squared relative error (MSRE), for various levels of a simulation input parameter reflecting the error associated with estimating AADT from a single image. In McCord, *et al.* (2002b) we present the relationship between that parameter and the standard deviation of a relative error *RE* defined in the same way as *RD* in equation (2), but where the true value of the AADT is substituted for $AADT^{grd}$.

In Figure 3a we reproduce a figure from McCord, *et al.* (2002c) where we used the procedures described in McCord, *et al.* (2002a) but presented the results in terms of the standard deviation of the relative error *RE*. In this figure the MSRE in AADT estimates for a set of homogeneous segments is plotted as a function of the percentage of the segments sampled annually with two consecutive 24-hour ground-based traffic counts. In Figure 3b, we present a similar curve that corresponds to VDT estimation. –Note that the errors in Figures 3a and 3b are not plotted on the same scale. The errors are much smaller in VDT than in AADT estimation, since the over- and under-estimation errors in AADT can cancel out in the weighted average used to determine VDT.

As explained in McCord, *et al.* (2002a), in addition to the percentage of ground-based samples indicated on the abscissa, permanent automatic traffic recorders are assumed to be collecting ground-based data 24 hours per day, 365 days per year on approximately 3% of the segments (a number chosen to approximate practice). that would be available from a single 1-m satellite-based sensor for various values of the standard deviation of the relative error. For example, the ground-data-only MSRE is approximately 0.68 when 33% of the segments are sampled annually. This represents an AADT estimation error for a set of segments—as specified by the mean squared relative error, and averaged over hundreds of simulation runs, with each run representing one year—when 24-hour traffic counts are obtained for all 365 days in the year on 3% of the segments and for 2 consecutive days in the year on an additional 33% of the segments. (Sampling 33% of the segments per year would lead to "covering" all the segments every three years, the presently prescribed target for state DOTs to cover links in the USDOT's HPMS sample.) When estimating AADT using both data obtained from a single 1-m satellite-based sensor and the same ground-count data used to produce the ground-data-only curve, the MSREs is approximately 0.9 (worse than the 0.68

ground-data-only value) on the curve corresponding to a relative error standard deviation of 1.4, and it is 0.2 (better than the ground data only value) on the curve corresponding to a standard deviation of 0.1.

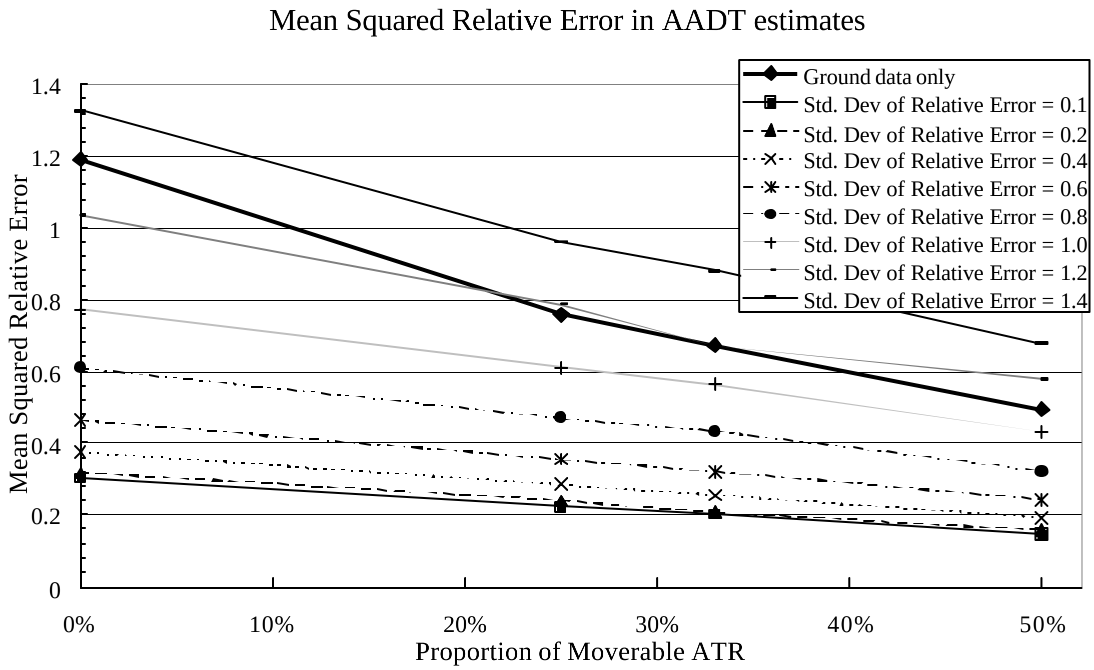

Figure 3a. Simulated mean-squared relative error in estimated AADT vs. percentage of highway segments sampled annually for different standard deviations of relative error of *AADT*^{img} (appears as Figure 2 in McCord, *et al*., (2002c))

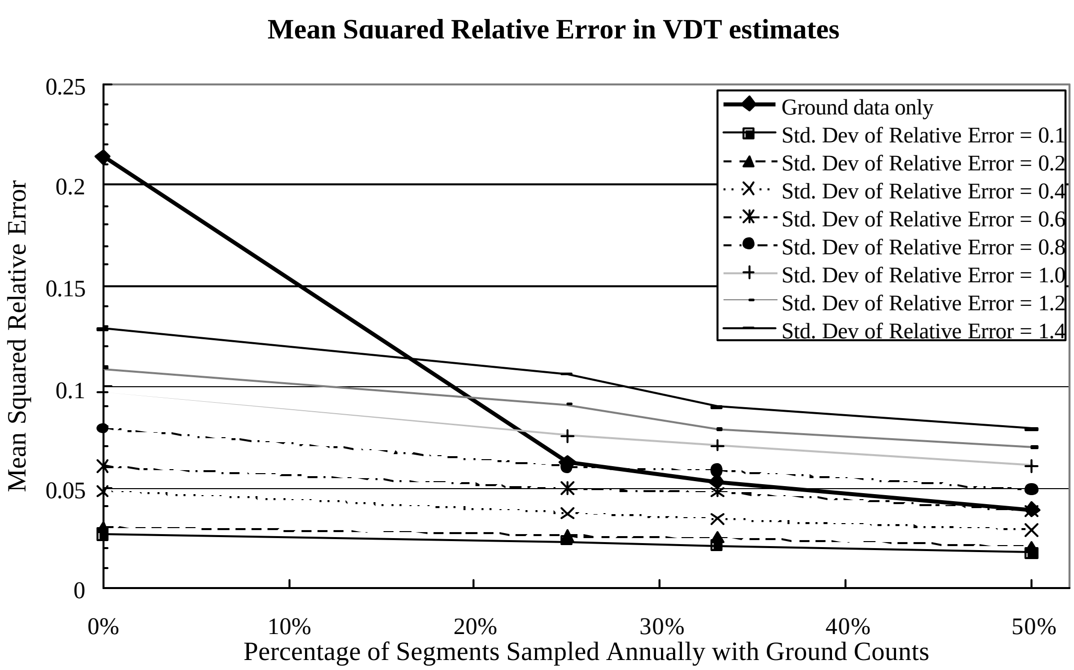

Figure 3b. Simulated mean-squared relative error in estimated VDT vs. percentage of highway segments sampled annually for different standard deviations of relative error of *AADT*^{img}

The solid ground-data-only curves in Figures 3a and 3b portray the performance when not incorporating any satellite data, that is, when only using ground counts. The other curves represent the performance when adding data

In producing the simulated data that led to these curves, the standard deviations correspond to standard deviations assuming a zero mean error. The standard deviation of the empirical *RDs* in Table 2, assuming zero mean, is 0.15. (This is identical, to two decimal places, to the sample standard deviation because the sample mean is so close to zero.) If we use our relative difference *RD* as a proxy for the relative error *RE* considered in Figure 3, the 0.15 standard deviation would lead to curves of markedly lower estimation errors than the ground-data-only curves for all ground count sampling percentages shown in the figures. We also note that on a 0.15 standard deviation curve—and even on curves with standard deviations over four times as large in the case of AADT estimation, and three times as large in the case of VDT estimation—the error at 0% ground count sampling (when only permanent automatic traffic recorders are collecting data) would be less than that on the ground-data-only curve at 33% sampling. That is, if satellite data were used in AADT and VDT estimation, the ground count sampling programs and corresponding expenses associated with the "coverage counts" could be eliminated and better estimates would be produced than when adhering to the targeted 3-year (33% per year) coverage cycle with ground data only. The same conclusion is reached even when using the higher standard deviation obtained when errors are all standardized to the 3-minute value of t^{dur}. We are investigating the use of this parameter in more detail, but the preliminary conclusion is that even with segments corresponding to such short interval durations, satellite based information can be helpful.

CONCLUSION

Coverage counts would be valuable for other reasons, and other assumptions in the simulation-based analysis would need to be investigated. For example, much of the error reduction in our network-based results seems to come from improved estimates on the segments that are not sampled in the year of analysis, that is, in the third group of segments identified above. We have not yet investigated the ability to estimate the AADT on some of these segments from samples obtained in previous years, opting instead to use the average estimated AADTs of segments in the other groups.

Our results, therefore, should not be used to advocate elimination of ground-based sampling programs. However, they do illustrate the *potential* for sizable benefits when incorporating satellite-based data in AADT and VDT estimation, if the monetary costs of obtaining and processing these data and the associated institutional costs were low enough. Although we have not conducted an economic analysis, we are fairly sure that the costs are presently too high to advocate that state DOTs, or other transportation agencies, begin purchasing satellite data from commercial providers for AADT and VDT estimation. On the other hand, the large potential benefits should motivate further investigation into lowering these costs and refining methods that could exploit the use of satellite data for these purposes.

We also note that aerial photographs would be an additional source of added data. The use of these data could offer similar benefits and be confronted with similar issues. Like satellite imagery, the air photos offer "snapshots" of the traffic that would need to be converted to more representative conditions. The cost of flying special photography surveys for AADT and VDT estimation would likely not be cost-effective. However, the marginal costs of converting air photos obtained for other purposes to traffic data that could be used in AADT and VDT estimation could be low, and our empirical results indicate that snapshots of traffic conditions may indeed be valuable in this effort.

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