

New and Existing Roadway Inventory Data Acquisition Methods

AEMAL J. KHATTAK

University of Nebraska—Lincoln

JOSEPH E. HUMMER

North Carolina State University

HASSAN A. KARIMI

University of Pittsburgh

ABSTRACT

A number of agencies collect roadway inventory data using the traditional manual method. Representing an advancement in roadway inventory data collection, mobile mapping systems use state-of-the-art imaging, georeference, and software technologies to collect data and are emerging as an alternative to the manual method. To gain an in-depth understanding of which method is more accurate and economical for an inventory job, this study compares the two data collection methods. Four experiments examine descriptive inventory data collected by the two methods, considering data accuracy in different roadway environments, type of inventory element, and data collection time. Because there are mobile mapping systems with different technological characteristics, the four experiments utilize four different mobile mapping systems to cover the spectrum of various systems available for data collection.

Statistical analysis shows that the accuracy of descriptive inventory data depends on the method of collection and that the manual method provides slightly more accurate data. Furthermore, the roadway environment and the type of inventory element measured affect data accuracy. Compared

Aemal J. Khattak, University of Nebraska—Lincoln, W348 Nebraska Hall, Lincoln, NE 68588-0531. Email: akhattak@unl.edu.

with the manual method, the mobile mapping systems required less time during field operations but more time during office processing. This research suggests that transportation agencies interested in adopting mobile mapping systems for data collection might not see significant improvements in descriptive inventory data accuracy. However, the use of mobile mapping systems for inventory data collection provides other benefits.

INTRODUCTION

Transportation agencies across the United States maintain and regularly update vast inventories of a variety of roadway elements. Information from these inventories serves as the basis for many transportation-related policy decisions. A roadway inventory may include elements such as lane width, traffic sign width, traffic sign height, and sign condition. For inventory purposes, an element must have two types of data: georeference and descriptive. The georeference data provide location of the element in space: latitude, longitude, and altitude. Descriptive data define the element: length, width, height, and condition. The accuracy of both georeference and descriptive data significantly determines the usefulness of an inventory element. Both georeference and descriptive data accuracy, is critical in a number of applications such as crash analysis, short term and long term transportation planning, maintenance operations, and lawsuits against a roadway agency.

Inventory Data Collection

The process of roadway inventory data collection requires a means for transportation, a means for measuring and recording georeference data, and a means for measuring and recording descriptive data. Roadway agencies in the United States have traditionally employed the manual method, typically involving data collectors, a vehicle (usually a van or a truck), a distance measuring instrument (DMI), and paper and pencil to collect inventory data. In this method, the collector locates an inventory element in the field and obtains its georeference data using a linear referencing method, such as a milepoint, a reference post, or an engineering station. The collector also records descriptive data,

usually personal estimates, pertinent to the inventory element. This method of inventory data collection is the most common among state departments of transportation (DOTs) in the United States (Karimi et al. 2000).

Representing a significant advancement in the roadway inventory data collection practice, the mobile mapping system (MMS) requires data collectors and a vehicle (usually a van or sport utility vehicle) equipped with such technologies as a Global Positioning System (GPS) receiver, a DMI, an inertial navigation system (INS), and digital cameras. After integration of data collected by the different sensors, collectors can obtain descriptive inventory data by making digital measurements on inventory elements captured in the camera images with the use of photogrammetric software packages. Digital measurements refer to geometric measurements in the three spatial dimensions (x , y , and z) on roadway elements captured in the images (see Agouris et al. 1997 for details). Wang (2000) provides information on the design of MMSs for pavement distress data collection. Obtaining inventory data with an MMS offers the possibility of reduced time spent in the field, reduced exposure to hazardous traffic conditions, and possible elimination of subsequent field visits.

Many roadway agencies using the manual method of data collection are considering adopting an MMS. Previous research has shown that the georeference accuracy of inventory elements collected by different MMSs is sufficiently high for roadway inventory purposes (Coetsee et al. 1994, Center for Mapping 1994, Vaidya et al. 1994, Whited and Kadolph 1995, Shaw and Guthrie 1997, Schwarz and El-Sheimy 1997, Novak and Nimz 1997). However, the literature lacks information on the accuracy of descriptive data collected by MMSs. This makes the MMS adoption decision difficult for agencies contemplating a change in their data collection practice.

This paper presents the results of four experiments comparing the accuracy of descriptive inventory data collected by the MMS method with data collected by the manual method. Because several systems with varying capabilities qualify as MMSs, the authors chose four different systems to cover the spectrum of available MMSs. Each experiment

used one of the chosen MMS's and compared data it collected with manually collected data. The conclusion uses these results to consider accuracy and other merits of data collection by the two methods.

LITERATURE REVIEW

Accuracy of Manually Acquired Descriptive Data

Several researchers have investigated human capability to visually estimate object dimensions and distances. Gibson (1950) presented the idea that the human brain represents space using the ground surface as a reference frame. A major aspect of Gibson's "ground theory" is that when the ground surface between the observer and the target object is disrupted, the visual system cannot establish a reliable reference frame and consequently fails to judge correctly object dimensions and distance to the target. Subsequently, Barlow (1961) and Sedgwick (1983) proposed that the human brain might use a quasi two-dimensional coordinate system with respect to the ground surface to judge distances rather than a three-dimensional spatial coordinate system.

Sinai et al. (1998) tested Gibson's theory by placing a target on the far side of a 0.50-meter deep by 1.30-meter wide gap in the ground surface. The task of the observers in the experiment was to judge the distance from the point of observation to the target. The average estimated distance of 4.24 meters overestimated the actual distance of 3.66 meters by 0.68 meters. As a control, the examiners tested other observers over the same distance of 3.66 meters on a continuous surface. They found that the estimated distance for the continuous surface condition was 3.54 meters, much closer to the actual distance. Changes in the observer's placement, the gap depth, and the gap width produced similar results.

These researchers further tested the influence of surface texture discontinuity on distance judgment (Sinai et al. 1998). They found that, on average, observers underestimated the actual distance of 7.62 meters as 6.50 meters if the surface between the observer and the target was part concrete and part grass. Estimates by the observers were close to the actual distance when the surface was either only concrete or only grass. Overall, their results

indicated that distance judgment was affected by the presence of discontinuities either in the form of gaps in the surface (resulting in overestimation) or discontinuities in surface texture (resulting in underestimation). They concluded that their results supported Gibson's proposal that the human brain uses ground surface as a frame of reference for judging distances.

Accuracy of Descriptive Data Acquired by MMS

In a comparative study of data obtained by an MMS and ground truth observations, Lee et al. (1991) concluded that the data obtained by an MMS was of "reasonable" accuracy. The conclusion was not based on any statistical analysis, nor was a definition of "reasonable" accuracy provided. Mastandrea et al. (1995) reported an accuracy of 5 to 10 centimeters for various inventory elements collected by an MMS. They did not report on the evaluation methodology or data elements used in the evaluation or provide analysis details. El-Sheimy (1996) compared the accuracy of descriptive data obtained with an MMS to ground truth observations. His findings indicated that errors in digital measurements increased with increasing distance between the object and the camera. However, El-Sheimy does not provide information on the identity and size of the measured inventory elements or on the number of observations made on the elements.

In a test of crack identification and classification, Roadware Corporation (1994) compared the accuracy of its photogrammetric software package for crack identification with the long term pavement performance (LTPP) procedure and found them comparable. However, there was no similarity in crack classification (block, fatigue, transverse, longitudinal wheelpath, and edge) in the two methods. In another test, Roadware Corporation (1996) shows that its photogrammetric software package was able to automatically classify collected data on pavement cracks into the LTPP categories. However, there was no indication if the classification was correct.

In summary, the literature indicates that accuracy of the manual method depends on the surface composition and continuity between the point of

observation and the target object. Literature on the accuracy of descriptive data obtained by MMSs is insufficient to judge whether MMSs provide accuracy comparable to the manual method.

EXPERIMENT DESIGN

Because data collected by MMSs with different design and photogrammetric software characteristics all qualify as data collected by the MMS method, the authors used four different systems to cover the spectrum of MMS data collection methods. The four experiments, each utilizing one of the chosen MMSs and the manual method, took place at different locations.

A comparison of data collected by a collection method with ground truth values determined the accuracy of that method. The ground truth value represented the “true” dimension of an inventory element and required the measurement of an inventory element in the field as accurately as possible. For example, careful measurement of the width of a traffic sign in the field with a tape measure resulted in the ground truth observation for the width of that traffic sign. We termed the statistic representing the accuracy of measurement by a particular method as the percent measurement error (PME) and defined it for the manual method as

$$PME_{Manual} = \left[\frac{X_{Manual} - X_{GroundTruth}}{X_{GroundTruth}} \right] 100 \quad (1)$$

where:

X_{Manual} equals observation on an inventory element by the manual method, and

$X_{GroundTruth}$ equals ground truth observation for that inventory element.

The authors calculated the PME values for the MMSs (PME_{MMS}) by substituting the observation on an inventory element made by the particular MMS (X_{MMS}) used in the experiment for X_{Manual} in equation (1). The positive or negative sign of the PME indicates if a particular data collection method overestimates (positive sign) or underestimates (negative sign) the true dimension of the inventory element.

Each experiment was conducted in three different roadway environments: urban streets, two-lane rural, and interstate highway, the three environ-

ments in which most transportation agencies collect their inventory data. Termed experiments 1, 2, 3, and 4, each experiment includes data collected on equipment cost, field data collection time, and time spent in the office during data processing and computer inputting.

The main factors under investigation in each experiment were (1) the method of data collection, (2) the roadway environment, and (3) the inventory element type. The method of data collection had two levels: the particular MMS used in the experiment and the manual method. The roadway environment factor had three levels: urban streets, two-lane rural highway, and rural interstate highway. For the third main factor, type of inventory element, the authors chose lane width, traffic sign width, and lateral placement of traffic signs from lane edge, with all three representing the x -dimension; barrier height and traffic sign height, both representing the y -dimension; streetlight spacing and driveway width, both representing the z -dimension; and road sideslope, representing a combination of x - and y -dimensions. Several of these elements represent the same dimension. The authors included this redundancy because some inventory elements may not be present on a roadway test section and because different elements are at different distances from the MMS cameras. These elements are measurable by both collection methods under investigation and constitute typical elements in a road inventory.

In each experiment, the dependent variable was PME and was quantitative, and the three main factors were categorical. The authors used analysis of variance (ANOVA) with fixed factor levels to explore the significance of the factors involved in the four experiments. The F -test is appropriate for testing the significance of the factors and the factor interactions (Neter et al. 1990, Devore 1991). The authors chose the customary significance level of $\alpha = 0.05$ for the tests.

Avoidance of Possible Biases

Most transportation agencies install standardized regulatory and warning signs. Bias in favor of the manual method may creep into observations if the data collector is familiar with the standard dimensions of those signs. To avoid such bias in the data,

this study limited the observations to guide signs only. Guide signs have non-standardized dimensions, ensuring unbiased data. With the manual method, bias can also appear in the data if two or more people collect them; therefore, only one person was designated to collect data by the manual method in all four experiments. That person also completed a pilot data collection effort to reduce any learning effects that could bias the data. The study controlled for other possibly biasing factors to the extent possible: collection of data on similar terrain (flat or rolling), under similar weather conditions (clear weather), and under similar natural light (adequate sunlight). Most roadway agencies typically collect their inventory data under these conditions. Because the study did not include data collection in mountainous terrain or low light conditions in the four experiments, these results cannot be applied to those situations.

MOBILE MAPPING SYSTEMS USED IN THE STUDY

Table 1 summarizes the hardware used in each of the four MMSs in this study. MMS1, for experiment 1, required two digital, full frame, progressive scan charged-couple device (CCD) cameras mounted on a van. These cameras captured 60 degrees of panoramic images of the targeted environment. One camera had black and white film because it provides better identification of certain objects. The system compressed the images into a Joint Photographic Experts Group (JPEG) format and stored data on removable computer hard drives. Environmental enclosures housed the cameras,

keeping the sensitive components free of dust. The enclosures also maintained optimal operating temperature and humidity levels for the cameras. The photogrammetric software package for data extraction was PC-based, and the identification of an object or a point of interest captured in image pairs provided the basis for the extraction of descriptive data.

MMS2, for experiment 2, required up to eight digital cameras housed in pressurized, temperature-controlled cases and mounted inside two towers attached to the vehicle. The PC-based photogrammetric software package allowed extraction of descriptive data from digital images by identifying conjugate points in image pairs.

MMS3, for experiment 3, employed a single, full-frame digital camera to capture digital imagery. Computer hard drives or CDs stored images in JPEG format (a 650 megabyte CD could store up to 110 miles of images). The photogrammetric Macintosh-based software package allowed extraction of descriptive data using a single image. The software package lacked the capability to make measurements in the z-dimension. This limited data to lane width, sign width, sign height, sign support height, and lateral placement of traffic signs.

MMS4, for experiment 4, was equipped with a single progressive scan digital camera that captured roadway imagery. Data extraction from the imagery involved the use of a calibrated grid with 0.5 by 0.5 meter gridlines overlaid on each captured digital image. Comparing inventory elements with the superimposed grid and judging their dimensions permitted data extraction. Because the

TABLE 1 Summary of Hardware Used in the MMSs

Collection method	GPS receiver	Digital camera (pixel resolution)	INS	DMI
MMS1	Trimble 7400	Pulnix (768×484)*	Litton*	Daytron*
MMS2	Ashtech Z-12	COHO 4980 RS-170 (640×480)	Honeywell Laser Ref III	Vehicle ABS
MMS3	Novatel*	Sony XC-007 (640×480)	INS with 3 gyros and 2 accelerometers	Vehicle ABS
MMS4	Leica MX 9212	Sony DXC 9000 (559×494)	Litton Laser Gyro	Hengstler R158-T/1800

* Exact make or model is proprietary information.
 INS = inertial navigation system
 DMI = distance measuring instrument

grid was calibrated on a flat surface at ground level, only measurements across and along the roadway (x - and z -dimensions) could be collected. This limited the data to lane width, driveway width, streetlight spacing, and traffic sign lateral placement.

DATA COLLECTION

Field data collection during each of the four experiments involved driving a particular MMS on a selected roadway section, collecting the data by the manual method and, lastly, collecting the ground truth data. Due to the absence of any prior information on sample sizes, as many observations as possible were collected. In-office processing of the MMS data involved application of differential corrections to the GPS data, merging data from the various sensors, and transferring them to the photogrammetric software package. Digital measurement capabilities of the software packages yielded descriptive data on selected inventory elements. For the manual method, in-office processing involved keying the data from the paper forms into a computer spreadsheet.

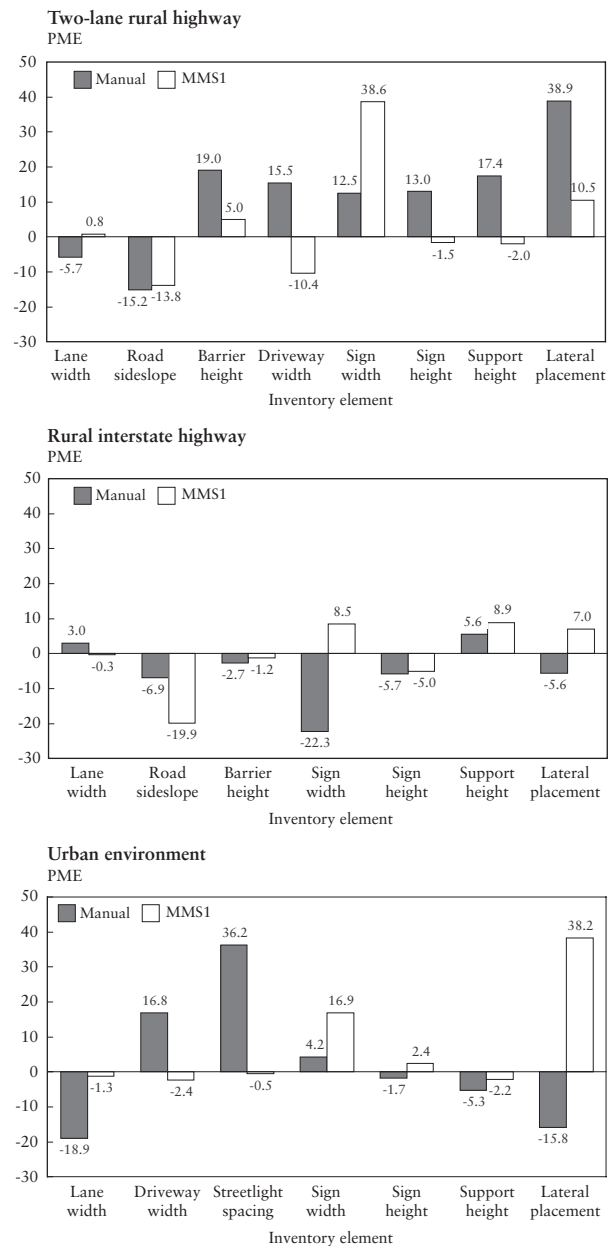
During experiment 1, MMS1 was driven on 8 miles of a two-lane rural highway, 31 miles of a rural interstate highway, and 7 miles of urban streets to collect data in the three environments. The MMS used in experiment 2 was driven on 17 miles of a two-lane rural highway, 25 miles of a rural interstate highway, and 8 miles of urban streets. MMS3 was driven on 13 miles of a two-lane rural highway, 16 miles of a rural interstate highway, and 13 miles of urban streets for collection of data by the MMS method. MMS4 was driven on 21 miles of a two-lane rural highway, 17 miles of a rural interstate highway and 5 miles of urban streets.

DATA ANALYSIS

Experiment 1

The descriptive inventory data collected by MMS1 and the manual method were compared with ground truth observations for accuracy assessment. Figure 1 graphically presents a summary of the mean PME values for the two methods. At the roadway environment level, MMS1 appears to be more accurate in the two-lane rural and the rural interstate environments. The manual method

FIGURE 1 Summary of PME Values, Experiment 1



appears to be more accurate in the urban environment. At the inventory element level, both methods significantly underestimated sideslope perhaps because it involves two dimensions, x and y . The manual method resulted in significant error in the measurement of driveway width and streetlight spacing, both involving the z -dimension. Inventory data pertaining to traffic signs were generally overestimated by both methods. MMS1 resulted in considerably high PME values for measurement of sign width and sign lateral placement.

Analysis of variance (ANOVA) was carried out on the collected data. ANOVA required that road

TABLE 2 Accuracy Differences at Different Experimental Levels

Experiment	Environment	Inventory Element									For all elements	Overall
		Lane width	Sign width	Sign lateral placement	Drive-way width	Street light spacing	Barrier height	Sign height	Sign support height	Side slope		
Experiment 1	Two-lane rural	V _{MMS1}	*	*	V _{MMS1}	-	*	*	V _{MMS1}	*	V _{MMS1}	M*
	Rural interstate	V _{MMS1}	V _{MMS1}	M	-	-	*	*	*	*	V _{MMS1} *	
	Urban	V _{MMS1}	M	M	V _{MMS1}	V _{MMS1}	-	*	*	*	M*	
Experiment 2	Two-lane rural	*	*	*	*	-	*	*	*	*	V _{MMS2} *	M*
	Rural interstate	*	*	*	-	-	*	*	*	*	V _{MMS2} *	
	Urban	*	*	*	*	*	-	*	*	*	M*	
Experiment 3	Two-lane rural	*	*	*	-	-	-	*	*	-	M	M*
	Rural interstate	*	*	*	-	-	-	*	*	-	V _{MMS3} *	
	Urban	*	*	*	-	-	-	*	*	-	M*	
Experiment 4	Two-lane rural	V _{MMS4}	-	M	M	-	-	-	-	-	M*	M*
	Rural interstate	*†	-	M	-	-	-	-	-	-	M*	
	Urban	V _{MMS4}	-	M	V _{MMS4}	V _{MMS4}	-	-	-	-	M*	

Table legend

- = Not tested

* = Not statistically different at the 95% confidence level

M = Data collected by the manual method are statistically more accurate at the 95% confidence level

V_{MMS1}, V_{MMS2}, V_{MMS3}, V_{MMS4} = Data collected by the particular method are statistically more accurate at the 95% confidence level

† = Shoulder width measured in place of lane width

sideslope, barrier height, driveway width, and streetlight spacing be excluded from the analysis because these factors are not common across all levels. The *F*-value for the model was statistically significant at the 95% confidence level, indicating model viability. The 3 main factors were statistically significant at the 95% level in the ANOVA.¹ However, a conclusion regarding significant differences in the means could not be reached due to the significance of interaction effects. All interactions among the main factors were statistically significant. The significance of the three-way interaction among method of data collection, roadway environment, and inventory element type indicated that it is necessary to look at the combinations of individual levels of each of the three main effects for differences in the means. The individual comparisons, excluded from the ANOVA (road sideslope, barrier height, driveway width, and streetlight spacing), included the levels of the inventory element type factor.

Paired *t*-tests between the manual and the MMS1 PME values for the inventory elements in the two-lane environment indicated that the

MMS1 method of data collection provided data that were more accurate for lane width, sign support height, and driveway width (see table 2). The differences in the measurement of other inventory elements were not statistically significant. Paired *t*-tests among PME values in the rural interstate environment indicated that in comparison with the manual method of data collection, the MMS1 method provided data that were more accurate for lane width and sign width while the manual method provided data that were more accurate for lateral placement of traffic signs. Paired *t*-tests among PME values in the urban environment showed that the MMS1 method outperformed the manual method in the measurement of lane width, streetlight spacing, and driveway width, while the manual method performed better for sign width and sign support height.

Findings from Experiment 1

Analysis of data collected in experiment 1 indicated no clear-cut trend in terms of overestimation or underestimation by either of the two methods. ANOVA confirmed that 1) there is a difference in the accuracy of descriptive data collected by the MMS1 and the manual method, 2) the accuracy of descrip-

¹ Detailed ANOVA model diagnostics are reported in Khattak (1999).

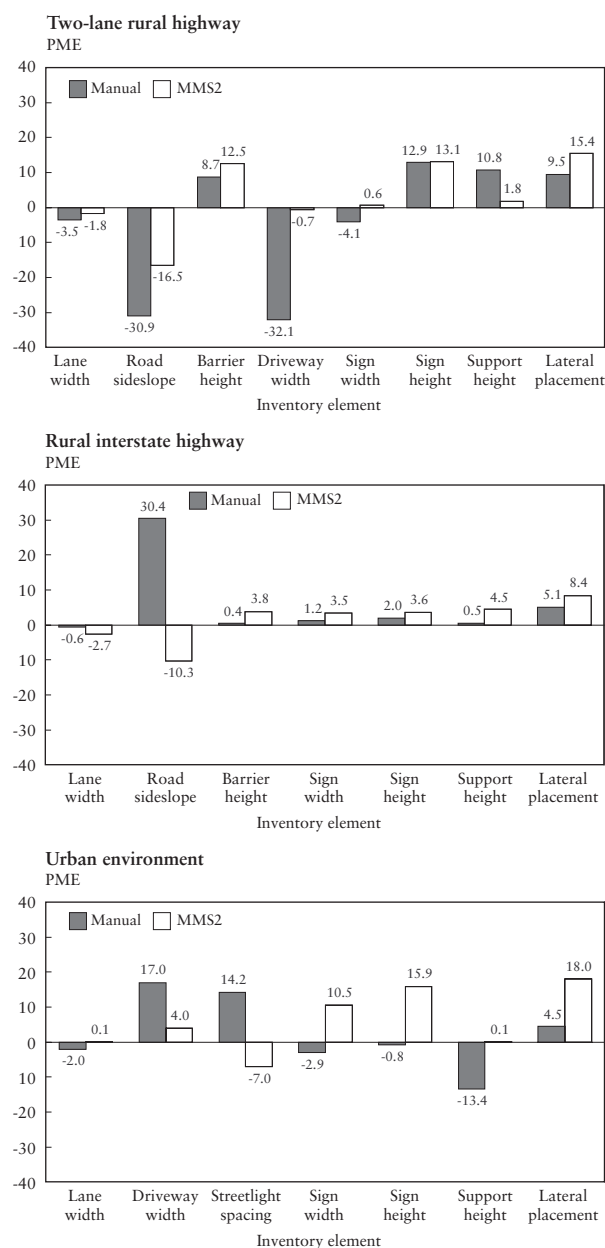
tive data varies across different roadway environments, and 3) the accuracy of descriptive data varies across different inventory elements. However, ANOVA also indicated that the accuracy of data collection by the two methods depends on the roadway environment and type of inventory element.

There are three possible reasons why the MMS1 method performed better in the two-lane rural and the rural interstate environments while the manual method performed better in the urban environment. First, inventory elements are typically located farther from the vehicle on two-lane and interstate roadways than on urban roadways. Although the accuracy of measurements by both the MMS1 and the manual method decreases with increasing distance from the point of observation, this rate of decrease may be higher in the case of the manual method. The manual method was superior to the MMS1 method at close range (in the urban environment), but due to the higher accuracy deterioration rate, it underperformed in the two-lane and interstate environments. Second, the reduced accuracy of data collected by the manual method in the rural environments may be due to gaps and surface discontinuities between the observer and the target object as Sinai et al. (1998) describe. Gaps such as drainage ditches and surface discontinuities such as guardrails exist more often on two-lane rural and rural interstate highways than on urban streets. Third, the underperformance of the MMS1 method in the urban environment may be due to possible loss of the GPS signal, more likely in an urban environment where large buildings may interfere with the satellite signal. In the case of GPS signal loss, the system accuracy degrades over the next few minutes until the signal is recovered by the GPS receiver. This accuracy degradation is then reflected in the descriptive data obtained by the photogrammetric software package. However, a check of the raw data did not reveal loss of the GPS signal during data collection in the urban environment. Therefore, the first reason, higher rate of accuracy deterioration in the manual method, is more likely to have contributed to this accuracy pattern.

Experiment 2

Figure 2 is a graphical representation of the mean PME values for data collected during experiment 2.

FIGURE 2 Summary of PME Values, Experiment 2



At the inventory element level, the manual method underestimated inventory elements in the two-lane rural environment, while the MMS2 method overestimated them. In the other two environments, both methods overestimated nearly all inventory elements. At the inventory element level, both methods resulted in substantial errors in the measurement of sideslope, again perhaps due to the involvement of x - and y -dimensions in sideslope measurement. The manual method resulted in significant error in the measurement of streetlight spacing, while the MMS2 method resulted in sizeable error in the measurement of lateral placement of traffic signs.

The authors analyzed the data using ANOVA after excluding road sideslope, barrier height, driveway width, and streetlight spacing because these elements were not common across all factors. The *F*-value for the overall model was statistically significant at the 95% confidence level (details reported in Khattak 1999). The type of inventory element proved statistically significant, indicating that the accuracy of measurement depends on the type of inventory element collected. The method of data collection was also statistically significant, but the roadway environment factor was not. Due to the significance of the interaction between the method of collection and the environment (the only significant interaction), nothing could be conclusively said about the effect of the collection method alone on PME.

Data collected by the MMS2 method in the two-lane rural and the rural interstate environments were more accurate whereas data collected by the manual method in the urban environment were more accurate (see table 2). However, none of the differences between the MMS2 and manual methods were statistically significant for individual elements.

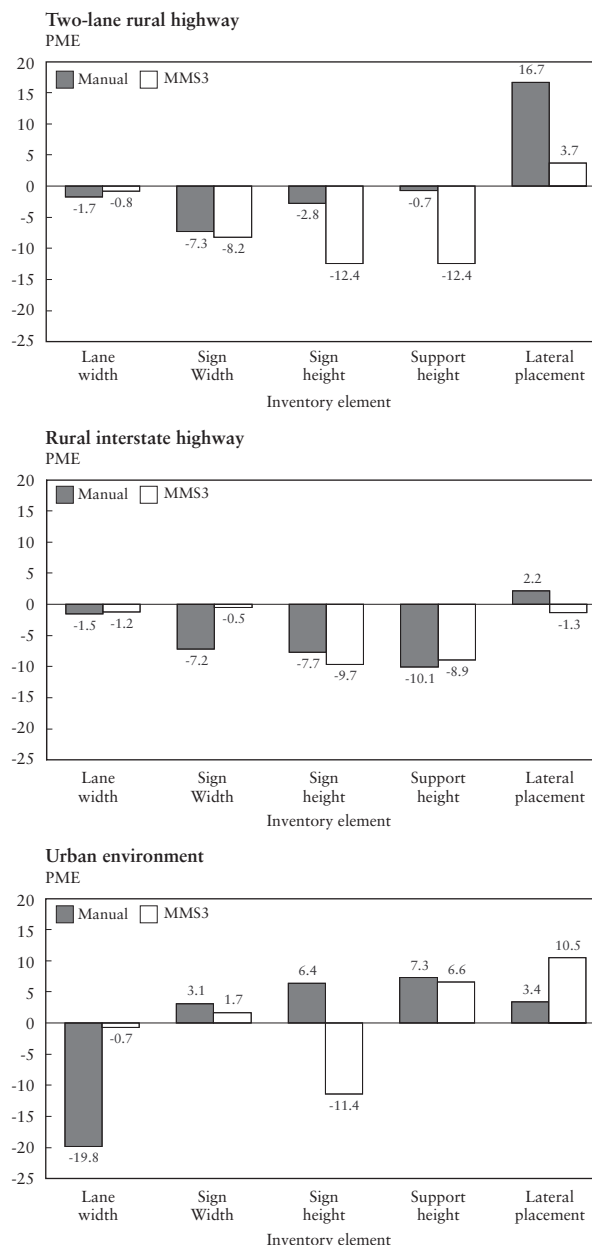
Findings from Experiment 2

Data collected in experiment 2 indicated overestimation by the MMS2 method in all three roadway environments. ANOVA also indicated that the accuracy of inventory data depended on the type of data element measured. The significance of the interaction between the other two main effects showed that the accuracy of inventory data depended on the method of data collection in different roadway environments. Data collected by the MMS2 method in the two-lane rural and the rural interstate environments were more accurate compared with the data collected by the manual method. However, data collected by the manual method in the urban environment were more accurate than that collected by the MMS2 method. This pattern was similar to the accuracy pattern in experiment 1, probably for the same reasons.

Experiment 3

Because there is no measurement capability in the *z*-dimension, the photogrammetric software package used in experiment 3 only provided data on

FIGURE 3 Summary of PME Values, Experiment 3



lane width, sign width, sign height, sign support height, and lateral placement of traffic signs. PME values for the collected data are graphically shown in figure 3. At the roadway environment level, the manual method appears to provide more accurate data in the urban environment. At the inventory element level, the two methods present mixed results regarding underestimation or overestimation. The MMS3 method resulted in relatively more accurate measurements for lane width, sign width, and lateral placement, all in the *x*-dimension, as opposed to sign height and sign support height, in the *y*-dimension. This may be due to GPS

characteristics since the altitude component (i.e., the y -dimension) in the GPS is the weakest (El-Sheimy et al. 1995).

Experiment 3 data did not present the empty cell problem, and the ANOVA results indicated a statistically significant model at the 95% confidence level (detailed model-specific statistics are reported in Khattak 1999). The method of data collection and the environment factors were not statistically significant. The inventory element type factor was statistically significant, indicating that the type of inventory element affected the descriptive data accuracy. None of the two- or three-way interactions among the main factors were statistically significant.

Findings from Experiment 3

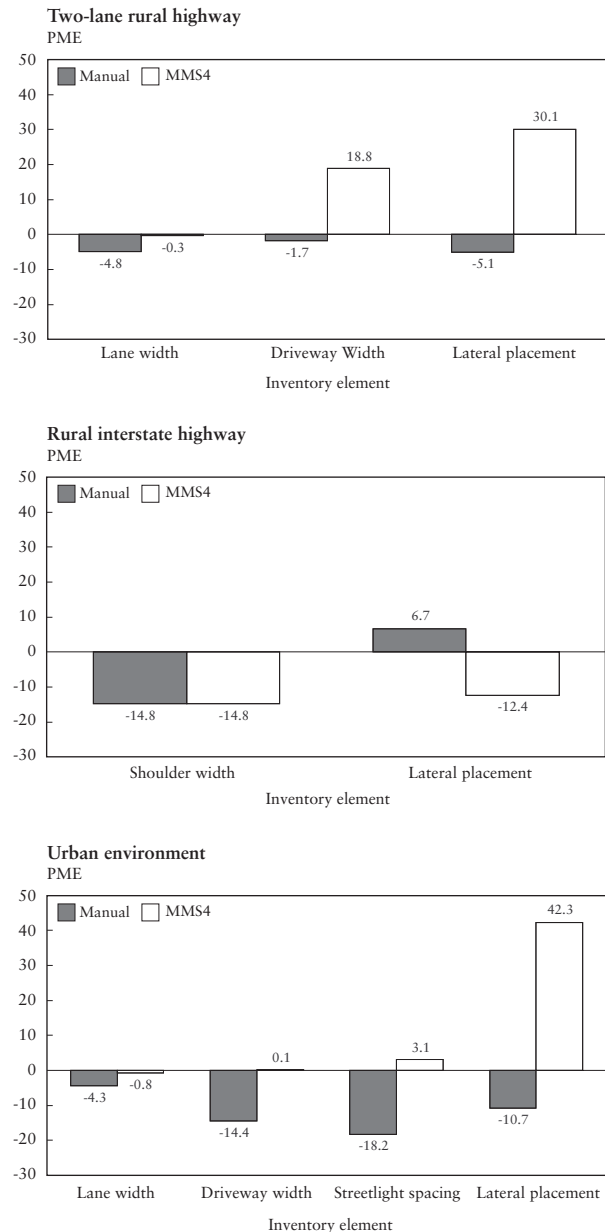
Experiment 3 provided no consistent pattern regarding the accuracy of the MMS3 and manual methods. However, it appears that the relatively inconsistent GPS altitude data resulted in greater inaccuracy in the measurement of inventory elements in the y -dimension as compared with the x -dimension.

Experiment 4

Data collection was limited to lane width, driveway width, streetlight spacing, and lateral placement of traffic signs in experiment 4 because superimposing a grid, calibrated at the ground level in front of the vehicle, restricted measurements to the x - and z -dimensions. In addition, the width of the shoulder substituted for lane width measurements due to unsafe conditions on the interstate highway. Figure 4 presents a graphical summary of mean PME values. There was no consistent pattern regarding underestimation or overestimation of measurements at the roadway environment and inventory element levels by the two methods. However, the accuracy of the MMS4 method at the inventory element level tended to decrease with increasing distance between the camera and the inventory element.

Because they were not available across all environments, data on driveway width and streetlight spacing from the ANOVA were dropped. The F -value for the overall model was statistically significant at the 95% level (model details reported in Khattak 1999). ANOVA results showed that the three main effects under investigation were all sta-

FIGURE 4 Summary of PME Values, Experiment 4



tistically significant. However, the significance of the interaction terms made reaching a conclusion regarding their effect on data accuracy difficult.

Both two-way interactions involving the inventory method factor and the three-way interaction among the three main effects were all statistically significant. This indicated the need for a separate examination of the mean PME values for each inventory element in each roadway environment and across each data collection method. A comparison of mean values of PME for the MMS4 and manual methods for the two-lane rural environ-

ment (table 2) indicated that lane width was more accurately measured by the MMS4 method, whereas lateral placement of signs and driveway width were more accurately measured by the manual method. All differences were statistically significant.

A comparison of mean values of PME for the MMS4 and the manual methods for the rural interstate environment indicated that the lateral placement of signs was measured more accurately by the manual method, and the difference between the two methods for this inventory element was statistically significant. Lane width was also measured with higher accuracy by the manual method, but the difference between the manual and MMS4 methods was not statistically significant.

A comparison of data collected in the urban environment indicated that the MMS4 method outperformed the manual method in measuring lane width, driveway width, and streetlight spacing. The manual method produced more accurate results for the lateral placement of traffic signs. All differences were statistically significant.

Findings from Experiment 4

Analysis of the data collected in experiment 4 indicated a mixed pattern regarding underestimation or overestimation of inventory elements. For later-

al and longitudinal measurements in urban environment, the MMS4 method performed better than the manual method. The manual method produced better results in the two-lane rural and the rural interstate environments. The analysis confirmed that there is a difference in the accuracy of the data collected by the MMS4 and the manual methods and that the accuracy of descriptive data varies across different roadway environments. Furthermore, the experiment showed that the descriptive data accuracy varied across different types of inventory elements.

Overall, the manual method appeared more accurate than the MMS4 method. This may be because the MMS4 method requires the data collector to use a 0.50 by 0.50 meter grid overlay on the computer monitor. As such, the MMS4 method is not as automated as the other three MMSs investigated and likely more prone to human error.

DATA COLLECTION TIME AND COST

Table 3 summarizes information on data collection time (including data storage and presentation) and equipment costs for the collection methods under investigation. Overall, data collection by the manual method was more time-consuming in the field in all three roadway environments because the

TABLE 3 Summary of Time and Cost of Data Collection by Different Methods

Item	Manual method			MMS1-4		
	Two-lane rural	Rural interstate	Urban	Two-lane rural	Rural interstate	Urban
Mean collection time for 100 inventory elements in the field, including equipment setup and driving the roadway (person-minutes)	38	40	36	7	9	9
				8	7	10
				8	8	9
				6	7	8
Mean in-office processing time for 100 inventory elements (person-minutes)	-	-	-	5*	5*	5*
Mean inventory data extraction time for 100 inventory elements, inputting to computer, and creation of inventory database including transfer to GIS (person-minutes)	45	45	45	76	80	78
				82	77	80
				72	76	77
				84	82	75
Sum of mean collection, processing, and extraction times	83	85	81	87	92	92
One-time purchase of equipment (hardware, software, and peripherals, in dollars)	30,000 †			250,000 and above ‡		

- = Not applicable

* = Approximately the same time for all four methods using vehicle systems

† = Manual method cost includes purchase of vehicle and a computer workstation

‡ = The cost of the methods employing vehicle systems depend on the number and type of sensors installed onboard and varies significantly

observer had to make frequent stops during data collection to achieve any reasonable degree of accuracy for the elements of interest. Note that for safe operations, the MMSs required two operators: a vehicle driver and a technician who monitored the various data collection sensors, while manual collection required just one person. The four MMSs required data processing time in the office, consisting of downloading the data from the vehicle, Differential Global Positioning System (DGPS) processing, and aggregation of the data from the different collection sensors (DGPS, INS, DMI, digital cameras, and so forth). This time was not required for the manual method.

Inventory data extraction and the creation of a database in the case of the manual method included coding the data from paper forms into a computer spreadsheet and then transferring the data to a geographic information system (GIS). In the cases of MMS1, MMS2, and MMS3, inventory data extraction and database creation involved making digital measurements with photogrammetric software packages and then transferring the data to a GIS. Overall, these methods were more time-consuming as compared with the manual method because the data collector carefully executed multiple point-and-clicks with the computer mouse on inventory elements captured in the digital images. Because the MMS4 method did not involve the use of any photogrammetric software package, obtaining data from the digital images was less time-consuming than for MMS1, MMS2, and MMS3.

Table 3 provides general information on one-time purchasing costs of equipment for inventory data collection and processing. The cost of the manual method is based on the purchase of a vehicle and a computer workstation. There is significant variation in the cost of a MMS because it depends on the type and number of sensors installed. Training costs and costs due to software incompatibility are not considered because of the wide variation in these factors. Overall, the one-time cost for the vehicle systems employing digital image capture technologies is significantly higher than the one-time equipment cost of the manual method.

CONCLUSIONS

Data collected during the four experiments on the selected inventory elements indicated a mixed pattern regarding overestimation or underestimation. Based on the experimental findings, we conclude the following:

- The accuracy of roadway descriptive inventory data depends on the method of collection. Even though for some inventory elements under certain roadway environments data collection by MMSs results in higher accuracy of descriptive data, the manual method overall provides data that are somewhat more accurate.
- The accuracy of descriptive inventory data depends on the roadway environment. Specifically, whether an inventory element is in a two-lane rural, rural interstate, or urban environment affects the accuracy of descriptive data.
- The type of roadway inventory element affects the descriptive data accuracy. As expected, elements closer to the observer or cameras were estimated more accurately.
- Data collection by MMSs is speedier in the field as compared with the manual method. However, data processing and extraction of descriptive data from digital images with photogrammetric software packages takes more time in the office as compared with the manual method.
- The total time consumed by the manual method was less than the time required by MMS methods on the sample of elements tested in this research.

The conclusions are valid only for the inventory elements, the three roadway environments, and the particular MMSs used in this study. Further, the inventory elements were chosen based on their ability to be measured by both the manual and the MMS methods. It is possible that certain inventory elements can only be measured by one of the two methods, in which case that method would have a clear advantage over the other.

The MMS method offers several advantages over the manual method, including avoidance of sending out large crews for field data collection and the opportunity to keep agency personnel off the dan-

gerous highway environments,² the resulting temporal and spatially stamped digital imagery that can be used by several units within an agency, avoidance of subsequent field trips, and the ability to make measurements on inventory elements that would otherwise require closure of a lane (e.g., bridge clearance) or significant traffic control measures. Results from this study indicate that MMSs may not result in significantly improved descriptive inventory data accuracy, at least for the elements considered in this study, or substantial benefits from limited use of MMS. Transportation agencies looking to improve inventory data collection practices, however, may choose to consider nonaccuracy-related benefits that accrue from the use of MMSs.

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² Field data collectors are highly vulnerable because of the nature of their job and the amount of mileage involved in inventory processes.

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