Traffic Data Collection Using Video-Based Systems

JAMES A. BONNESON AND JOEL W. FITTS

Sources of bias and variability in the measurement of time-based traffic events by using video recording-and-playback systems are described. Bias can affect accuracy, whereas the lack of precision can increase the minimum sample size. Equations are described that can be used to estimate the adjustment needed to remove bias from the recorded data and to estimate the standard deviation of the measurement process. The equations are sensitive to the method of extracting the individual traffic event times from the videotape. These methods include manual extraction, which uses a frame-by-frame analysis, and automated extraction, which uses a video imaging system to analyze the tape during playback at normal speed. The manual method is found to yield less bias and lower variability than the automated method.

One of the principal elements in the design of a traffic data collection plan is event measurement accuracy and precision. The need for accuracy is obvious: measurements must be accurate to be useful for either model calibration or system evaluation. Threats to accuracy typically stem from some distortion in the measurement process that introduces a bias in the measured quantity relative to its true value. This bias can stem from a variety of sources (e.g., measurement device out of calibration, measurements taken in the wrong plane of reference) and typically can be eliminated by device calibration in advance of the study or by adjustment of the data after the study.

Measurement precision is also important to study design. The precision of an estimate of the population mean is dependent on the number of observations, the variance in the population, and the variance of the measurement process. The relationship among these variables is

$$N = \left(\frac{t_{\alpha/2}\, s_p}{e} \right)^2 \qquad (1)$$

where

- N = sample size needed for a $1 - \alpha$ level of confidence,
- $t_{\alpha/2}$ = test statistic corresponding to $\alpha/2$ (two-tail test) for normal distribution,
- s_p = pooled standard deviation, and
- e = permissible error (or precision) of the estimate of the true population mean.

The pooled standard deviation combines the variance in the population and the variance in the measurement process as

$$s_p = \sqrt{s^2 + s_m^2} \qquad (2)$$

where s is the population standard deviation and s_m is the standard deviation of the measurement process.

The objective of this paper is to describe the sources of bias and variability in the measurement of traffic events by using video-based recording-and-playback systems. Equations developed to describe these sources can be used to estimate the adjustment needed to remove the bias in the recorded data and to estimate the standard deviation of the measurement process (for sample size estimation). For this paper it is assumed that the traffic events of interest have a time base (e.g., headway, speed), that these events have been previously recorded on videotape, and that the data are extracted while the videotape is being replayed.

DATA EXTRACTION CONSIDERATIONS

Data Extraction Methods

Two methods of data extraction are described, manual and automated. Manual extraction entails a frame-by-frame analysis in which event time is computed either by reading the in-picture stopwatch image or by counting the number of elapsed frames and multiplying by the known frame time interval. Either variation of this method requires stopping the videotape at each event to record the time. Automated extraction uses video imaging technology to detect events and record their time of occurrence. The time base for this method is an external clock; thus it does not require that the videotape be stopped to record event time. The video imaging system used for this research is the Autoscope 2003 (software version 3.23), as described by Michalopoulos et al. (*1*).

Field of View

Several terms can be used to describe the field of view obtained from the video camera. These terms include landscape or station and approaching, departing, or overhead.

Landscape and Station Views

Two terms that have been used by Doctor and Courage (*2*) to describe the orientation of the camera in a vertical plane are "landscape" and "station." A landscape view includes the horizon in the upper half of the field of view. The camera is directed outward, and the angle between the center of the field of view and a vertical line is generally 45 degrees or more. This view is best suited to the monitoring of a long [say, greater than 200-ft (61-m)] length of roadway. It can be used to obtain traffic counts and estimates of queue length.

Department of Civil Engineering, University of Nebraska–Lincoln, Lincoln, Nebr. 68588–0531.

A station view is used to obtain traffic data similar to those gathered by a permanent traffic recording station. The camera is directed downward with a viewing angle to the vertical of 45 degrees or less. This view is best suited to the monitoring of a short (say, less than 200-ft) section of roadway. It can be used to obtain precise estimates of headway, travel time, and speed.

Approaching, Departing, and Overhead Views

The view of the traffic lanes can also be categorized as approaching, departing, and overhead. The terms "approaching" and "departing" describe the direction of vehicular travel relative to the camera location. With respect to the video display, traffic moves vertically from top to bottom and from bottom to top for the approaching and departing views, respectively. The overhead view describes the situation in which the camera's field of view is perpendicular to the travel direction and traffic moves horizontally from left to right (or right to left) on the display. These three views are shown in Figure 1.

Some views represent a combination of two of these view types. For example, the camera may be oriented such that traffic flows from the upper left corner to the lower right corner of the video display. The resulting view is often considered desirable because it yields the widest coverage of the roadway. This view would represent a combination of the overhead and approaching view types.

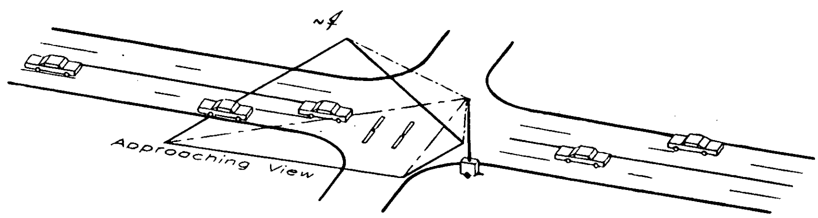
Tape Drag

Times obtained from the automated method or from the manual method (when frame counts are used) must be adjusted to yield the true event time whenever the tape advance mechanism plays more slowly than real time (or drags). Tape drag will also affect event time accuracy when it is measured by an external stopwatch during tape replay (such as when a portable computer is used to record the time that certain keyboard keys are pressed in response to an observed event on the video monitor). The true time can be estimated as

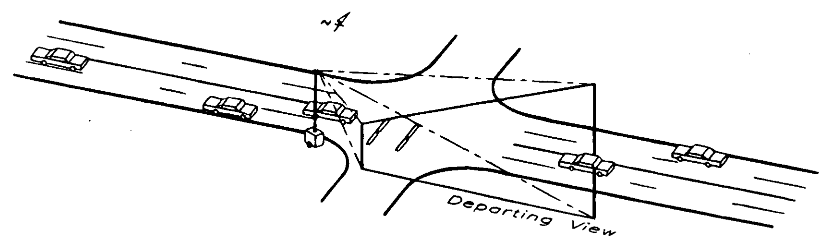
$$T_t = T_r(1 + t_d) \tag{3}$$

with

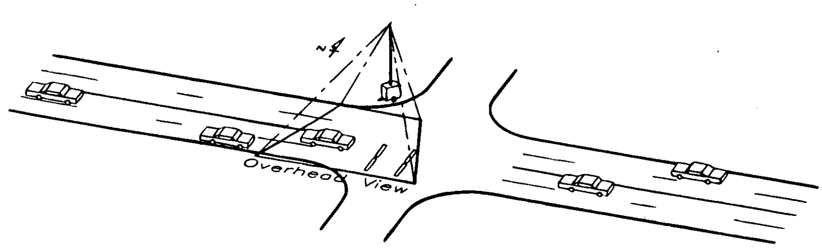
$$t_d = \frac{T_t - T_r}{T_r} \tag{4}$$



a) Approaching view.



b) Departing view.



c) Overhead view.

FIGURE 1 Camera field-of-view categories.

where

T_t = true event time (sec),
T_r = event time measured with an external time clock during tape playback (sec), and
t_d = tape drag adjustment factor (sec/sec).

The adjustment factor t_d can be computed by first videotaping the event and a clock image together (by positioning the clock in the field of view) and then, during playback, comparing the event time obtained from the external clock T_r with the event time obtained from the clock in the video image T_t. The adjustment factor is then computed by using Equation 4. In general, the adjustment factor is a small negative value, indicating that the tape plays more slowly than real time.

As an alternative, T_t and T_r can be obtained from player-recorders that have digital in-picture time clocks and frame-by-frame playback capability. In this situation the tape is replayed frame by frame, stopping at each event to record the in-picture time and the frame count. The frame counts, converted to clock time, represent T_r, whereas the recorded digital time represents T_t. For the player-recorders used in this study the digital frame counts are reported in hours, minutes, seconds, and frames using an internal conversion based on the ratio of 1 sec to 30 frames (1:30). However, the correct ratio is 1:29.970 for color images. Thus, the reported hours, minutes, and seconds first had to be converted back to total frames and then divided by 29.970 to yield the time T_r.

With both techniques a drag of −0.0016 sec/sec was observed for a consumer-grade VHS videotape recorder and −0.00020 sec/sec was found for a professional-grade Hi8 recorder. The drag value for the consumer-grade recorder increased (from −0.0011 to −0.0022 sec/sec) with time into the tape (i.e., the length of tape from the beginning of the reel), whereas no increase was noted for the Hi8 recorder.

One problem with the frame-count technique is that the precision of most camcorder time clocks is limited to the nearest second. This is generally too imprecise to measure traffic event intervals of 10 sec or less. To improve measurement precision, an in-picture time generator device can be inserted into the video feed cable between the camera and the recorder. This generator can then be used to superimpose a digital time image over the camera's video signal. These generators typically provide a precision to 0.01 sec (which exceeds the precision of a video frame, i.e., 1/30 sec).

Relative Reference Linewidth

Measurement of traffic event times by either the automated or the manual method is based on the establishment of a reference line on the video display. For the manual method this line can be physically drawn on the video display screen. For the automated method this line would be represented by a video detection zone. In either case the line is typically oriented perpendicular to the travel direction. For example, the line could be located over the stop line of an intersection approach (i.e., physically drawn over the stop line as it is shown on the video display). In this manner the reference line could be used to measure vehicle headways.

The reference linewidth on the video display is relatively thin and presumably constant (as measured in the direction of travel). For example, the Autoscope typically makes its detectors slightly less than 2.5 mm (0.1 in.) wide on a 305-mm (12-in.) display. However, the projection of this line onto the pavement can be much wider, depending on the angle between the camera and a vertical line. A consequence of this increase is a decrease in the precision of event time measurement. For example, in a station view of an intersection stop line the relative width of the projected reference line can be approximately equal to that of the stop line itself, yielding relatively precise measurements of vehicle crossing time. On the other hand, in a landscape view the relative width can exceed that of the observed vehicle, thereby making it impossible to ascertain the exact time when the vehicle crosses the stop line.

The relative reference line width is shown in Figure 2 for a camera positioned 9.8 m (32 ft) above and approximately 6.1 m (20 ft) offset from the centerline of the roadway. Widths are shown for both 6- and 8-mm (0.2- and 0.3-in.) lenses. The camera angle to the vertical was varied between 40 and 60 degrees to generate the data used in the figure. Trigonometric equations were used to transform the reference line coordinates on the video display to the plane of the roadway pavement. These coordinates were then used to compute the transformed linewidth and the horizontal distance between the camera and the equivalent line in the plane of the roadway.

As Figure 2 illustrates, the reference linewidth increases exponentially with the distance between the camera and the reference line. Longer distances correlate with reference lines (or Autoscope detectors) located higher on the video display. The effect on linewidth is most pronounced for the approaching view and least for

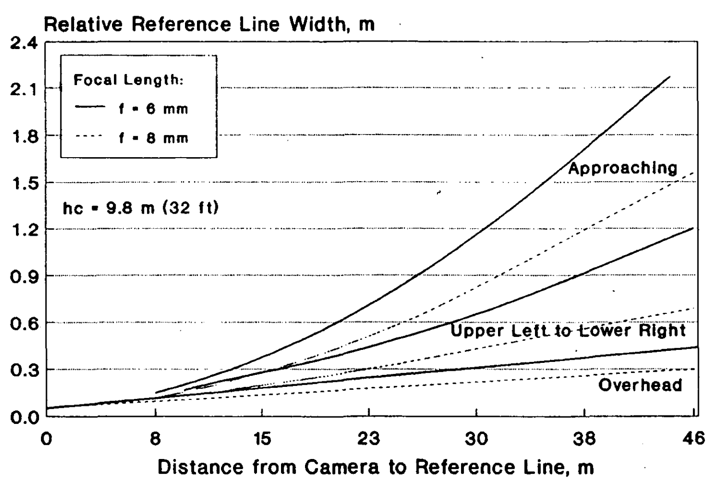


FIGURE 2 Relative reference linewidth (1 m = 3.3 ft).

the overhead view because the distortion of length is greater in the vertical plane of the camera field of view than in the horizontal.

Figure 2 also shows the effect of camera-lens focal length. The more magnified view of the higher-focal-length lens yields shorter linewidths than the lower-focal-length lens. Although this characteristic of higher-focal-length lenses may be advantageous, it must be balanced by the reduced field of view obtained from these lenses. Moreover, the discussion of speed measurement in the next section will suggest that the advantages of a wide field of view may override any benefits obtained from a magnified view. The authors' experience indicates that 6 to 8 mm may be the most useful range of focal lengths, with preference given to the 6-mm lens. The results presented in the next section are based on a 6-mm lens.

VARIABILITY IN TRAFFIC EVENT MEASUREMENT

Effect of Data Extraction Method

The method of event time measurement can have a significant effect on measurement precision. For the automated method the video imaging system monitors the video tape recorder's video signal and identifies vehicles by focusing on user-specified detection zones. Each zone consists of a small rectangular grid of light pixels on the video screen. Changes in pixel intensity are analyzed over one or more video frames to determine whether the change is due to the passage of a vehicle. If the change is attributed to a vehicle, the time is then recorded. As a result of this variable-frame processing there is always some uncertainty in the recorded event time relative to the true event time.

The manual method of data extraction is based on a technician's playing back the videotape frame by frame. This method requires considerably more time for data extraction than the automated method because the tape is played frame by frame rather than at normal speed. On the other hand, event times obtained from the manual method can be measured to the nearest frame. As a result, this method has less uncertainty than the automated method.

Headway Measurement

The procedure for measuring vehicle headways by using video images is identical to that which uses observers in the field. A reference line is established on the pavement and on the vehicle. Then the successive vehicular crossing times are recorded and differenced to yield the resultant time headway. The capture of these crossing times with videotape offers several advantages of convenience but, as described below, also reduces the precision of the crossing time measurement.

One source of variability inherent in video-based measurement methods stems from video's discretization of time. The video image is composed of a series of still frames, each of which is analogous to a photograph of events occurring at one instant in time. As these frames are taken every 1/30 sec, manual measurement of event time is limited to an error range of one frame (i.e., ±0.017 sec). Automated measurement of event time has been found to have an error range of two to four frames, depending on the quality of video recording equipment and pavement coloration. The errors from this type of process effectively follow a uniform distribution with a standard deviation of

$$\sigma_F = \frac{n}{30\sqrt{12}} = 0.0096n \qquad (5)$$

where σ_F is the standard deviation of measurement associated with frame error (sec), and n is the number of frames in error range (manual, $n = 1$; automated, $n = 2$ to 4).

A number of studies have been conducted by the authors to determine the conditions that dictate the number of frames needed by their automated system (i.e., the Autoscope). These studies indicate that the quality of the video equipment has a significant effect on this number. In particular, professional-grade recording equipment was found to have a range of two to three frames, whereas consumer-grade equipment was found to have a range of three to four frames. Within each of these ranges there is evidence to suggest that the lower number is associated with a light concrete pavement background and the upper value is associated with a black asphaltic pavement background. For subsequent figures presented in this paper, $n = 2.3$ frames was used for the automated method.

A second source of variability stems from the width of the pavement reference line. A wider reference line can increase the uncertainty (i.e., variability) in the resultant estimate of crossing time. The error range is equal to the vehicle travel time across the reference line. The variance of this process can be written as

$$\sigma_W^2 = \mathrm{VAR}\left(\frac{fW_d}{V}\right) \qquad (6)$$

where

σ_W^2 = variance of measurement error associated with reference linewidth (sec²),
f = uniformly distributed random variable representing the proportion of the reference line crossed when the event is first identified,
W_d = width of the reference line/detector (m), and
V = vehicle speed [miles per second (mps)].

The methods for computing approximate moments described by Benjamin and Cornell (*3*) can be used to yield the following estimate of σ_W:

$$\sigma_w = \sqrt{\left(\frac{\bar{f}W_d}{\bar{V}^2}\right)^2 \sigma_v^2 + \left(\frac{W_d}{\bar{V}}\right)^2 \sigma_f^2} \qquad (7)$$

The bar, or line, over a variable denotes its mean value. For the uniformly distributed variable f with a range of 0.0 to 1.0, $\bar{f}$ equals 0.5 and σ_f equals $1/\sqrt{12}$. In addition, data provided in the *Traffic Engineering Handbook* (*4*) indicate the following relationship between V and σ_v:

$$\sigma_v \approx 0.15\bar{V} \qquad (8)$$

Combining these relationships with Equation 7 yields

$$\sigma_w = \sqrt{\left(\frac{0.15W_d}{2\bar{V}}\right)^2 + \left(\frac{W_d}{\sqrt{12}\bar{V}}\right)^2} = 0.30\,\frac{W_d}{\bar{V}} \qquad (9)$$

A final source of variability stems from the location of the vehicle reference point relative to the plane of the pavement (which contains the reference line). Specifically, a video imaging system typically locks onto the first part of the vehicle (or its shadow) that crosses the detector. This part is generally the hood, the bumper, or an extended vehicle shadow for the departing, overhead, and approaching views, respectively. Whenever the imaging system locks onto a part of the vehicle that is above the plane of the pavement, the recorded crossing time will be different from the actual time when the vehicle crosses the detector. Heights of 0.9 m (3 ft), 0.5 m (1.5 ft), and 0.0 m were used for the departing, overhead, and approaching views, respectively, in the development of subsequent figures presented in this paper.

Fortunately, the variability associated with an elevated lock-on point can often be avoided. For automated methods this would require an approaching view and sufficient sunlight to create an extended vehicle shadow. For manual methods the camera would be slightly offset from the roadway (as shown in Figure 1) such that the vehicle's tires were in view and the observer would be instructed to use the tire–pavement contact point when the crossing time is recorded.

Based on the geometric relationships shown in Figure 3, the error in crossing time can be computed as

$$e_t = \frac{\delta x}{V} = \frac{Lh_{vs}}{Vh_c} \tag{10}$$

where

e_t = crossing time measurement error (sec),
δx = distance between the reference line/detector and the vehicle location measured along the center line of the travel path ($=Lh_{vs}/h_c$) (m),
L = distance between the reference line/detector and the camera measured along the centerline of the travel path (m);
h_{vs} = height of vehicle signature (i.e., lock-on point) (m), and
h_c = height of camera above plane of roadway (m).

Although this error represents a biased crossing time estimate for any one vehicle, the expected bias for the population of vehicle crossing times is constant and will cancel out when successive pairs of crossing times are differenced to yield the headway. Therefore, the average headway computed from crossing times obtained with an automated method will be an unbiased estimate of the true mean headway.

The measurement variability that stems from locking onto the vehicle above the plane of the roadway can be computed as the variance of e_t. This quantity can be stated as follows:

$$\sigma_{vs}^2 = \mathrm{VAR}(e_t) \tag{11}$$

where σ_{vs}^2 is the variance of measurement error from nonzero vehicle signature height (sec²).

By the method of approximate moments, σ_{vs}^2 can be estimated as

$$\sigma_{vs} = \left(\frac{L}{h_c}\right)\sqrt{\left(\frac{\bar{h}_{vs}}{\bar{V}^2}\right)^2 \sigma_V^2 + \left(\frac{1}{\bar{V}}\right)^2 \sigma_{hvs}^2} \tag{12}$$

An examination of the relationship between average vehicle hood height and the standard deviation of hood height for 50 vehicles indicated that a trend existed and that the following relationship was reasonable:

$$\sigma_{hvs} \approx 0.15\,\bar{h}_{vs} \tag{13}$$

Combining this relationship and Equation 8 with Equation 12 yields

$$\sigma_{vs} = \left(\frac{L}{h_c}\right)\sqrt{\left(\frac{0.15\,\bar{h}_{vs}}{\bar{V}}\right)^2 + \left(\frac{0.15\,\bar{h}_{vs}}{\bar{V}}\right)^2} = 0.21\,\frac{L\,\bar{h}_{vs}}{h_c\bar{V}} \tag{14}$$

The variance of the event time measurement process is represented by the summation of the previously described component variances. The basis for this formulation stems from the additive nature of component variances of error sources. Similarly, the variance of a headway measurement (i.e., the difference of two event times) is twice that of an individual event time, again because of the additive nature of the variances of a sum (or difference) of random variables. As a result, the combined variance of the three components is

$$\sigma_s^2 = 2\,(\sigma_F^2 + \sigma_W^2 + \sigma_{vs}^2) \tag{15}$$

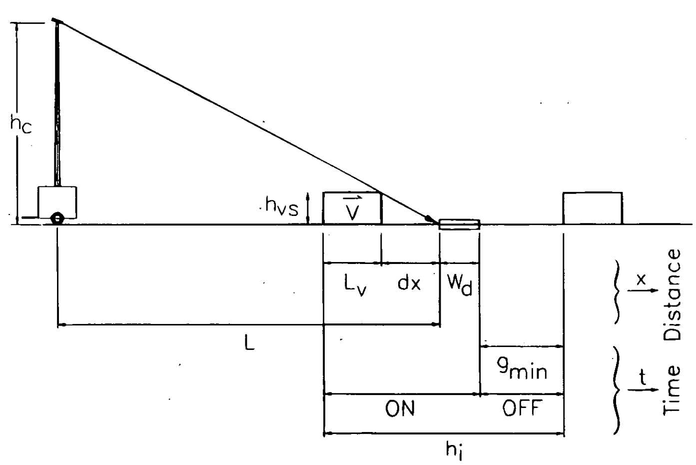


FIGURE 3 Geometric relationships among the video camera, the reference line, and the vehicle.

One final factor that must be considered in estimating headway measurement variance is autocorrelation of the error in successive measurements. An error in measurement of the event time for a subject vehicle affects the headway measured between the subject and preceding vehicle as well as the headway measured between the subject and following vehicle. The resultant measurement error in these two headways is equal but opposite in sign and thus follows a first-order autoregressive process. The implication is that the resultant variability in measurement, as defined by Equation 15, is increased.

Neter et al. (*5*) show that the variance of the error that is due to autocorrelation can be estimated as

$$\sigma^2(\varepsilon_t) = \frac{\sigma^2}{1 - \rho^2} \tag{16}$$

where

$\sigma^2(\varepsilon_t)$ = variance of the error in the first-order autocorrelated random variables,
σ = variance of the error in random error of independent random variables, and
ρ = autocorrelation parameter.

The autocorrelation parameter can be estimated by regressing the measurement error e_h (=true headway − measured headway) for successive headways (e_{hi}, e_{hi-1}). The parameter is equal to the slope of a first-order linear regression model ($e_{hi} = \beta_0 + \rho e_{hi-1}$).

Two tests were conducted to determine the degree of correlation between successive headway measurements. The first test examined several thousand simulated headways, each of which was given a small random measurement error. The headways were assumed to be exponentially distributed, and the measurement errors were assumed to be normally distributed. The autocorrelation parameter from this test was found to be −0.50 regardless of the magnitude of the measurement error variance or average headway. The second test examined several hundred vehicle headways measured with the Autoscope video imaging system. The autocorrelation parameter was found to be approximately −0.45. Giving preference to the latter empirically derived parameter, a value of −0.45 was selected for use in the development of the subsequent figures presented in this paper.

Extending Equation 16 to headway measurement yields the following equation for estimating the variance of the headway measurement process:

$$\sigma_h^2 = \frac{2(\sigma_F^2 + \sigma_W^2 + \sigma_{vs}^2)}{1 - \rho^2} \tag{17}$$

The variables σ_F, σ_W, and σ_{vs} can be obtained from Equations 5, 9, and 14, respectively. This variance represents the error variance that is due to measurement with an imprecise measuring device (i.e., a video-based system). This value would be substituted for s_m^2 in Equation 2.

The standard deviation of the headway measurement process, σ_h, is shown in Figure 4 for a 6-mm lens mounted at a height of 9.8 m (32 ft). As Figure 4 indicates, the standard deviation is lower for higher vehicle speeds because the σ_w and σ_{vs} terms tend toward zero with increasing speed. In addition, the standard deviation increases as the travel direction becomes oriented more toward the camera than perpendicular to it. This increase is due primarily to the effect of view orientation on reference linewidth. The standard deviation is lower when the manual method is used because the event can be measured to the nearest frame (i.e., $n = 1$ in Equation 5) and because the observer is able to measure the event in the plane of the roadway (i.e., $h_{vs} = 0$ in Equation 14).

It is worth noting that both the automated and the manual methods yield more precise time estimates than could be obtained by using an external stopwatch during tape replay. Kite et al. (*6*) had a technician observe the video monitor during replay and record (by keyboard toggle) more than 2,300 event times, using a computer-based clock-software package. Each event was measured twice. Kite et al. reported the standard deviation of the difference between these two measurements as 0.4 sec. As a headway is also the difference between two time measurements, a value of approximately 0.4 sec would also be obtained for the standard deviation of headway measurements by this toggle technique. This value is much

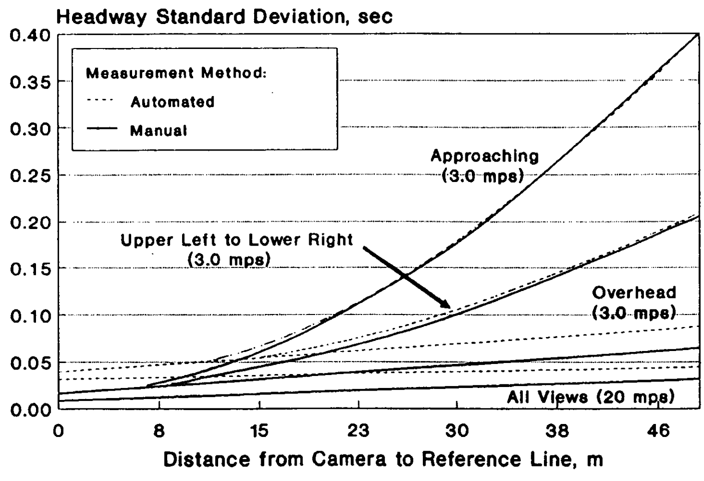


FIGURE 4 Standard deviation of the headway measurement process (1 mps = 3.3 fps).

larger than that obtained from either the automated or the manual method, as shown in Figure 4.

Minimum Measurable Headway

An imaging system typically detects a vehicle by noting when the pixel intensity in the detection zone changes relative to the background or pavement intensity. As a result of this detection technique the system must be able to see the pavement for a minimum duration of time between vehicles to minimize multiple detections (caused by multicolored vehicles or bright reflections) and to refresh its memory as to the background intensity level.

To determine the minimum intervehicle gap time (measured from the back bumper of the lead vehicle to the front bumper of the following vehicle) needed by the imaging system, the gaps between several hundred queued vehicles were measured by both the manual and the automated methods. This study revealed that gaps of less than 0.10 sec were consistently missed by the Autoscope (i.e., it reported two successive vehicles as one long vehicle). On the other hand, gaps of 0.23 sec or longer were always detected by the Autoscope.

The consequence of the imaging system's need for a minimum time gap is that it creates a minimum measurable headway (measured from back bumper to back bumper). This headway can be computed by using the geometric relationships shown in Figure 3 as

$$h_{min} = g_{min} + \frac{1}{V}\left(L_v + \frac{Lh_{vs}}{h_c} + W_d\right) \quad (18)$$

where

h_{min} = minimum headway measurable by imaging system (sec),
g_{min} = minimum intervehicle gap measurable by imaging system (Autoscope: 0.23 sec) (sec), and
L_v = length of vehicle (m).

The minimum headway measurable by the Autoscope 2003 is shown in Figure 5. As this figure indicates, the effect of speed is more significant than view orientation or distance. It also suggests that vehicles moving at low speeds and short headways (e.g., those departing the intersection stop line) may not be individually detectable; rather, they may be detected as one long vehicle. Of course, this operation still allows the Autoscope to function as it is primarily intended (i.e., as a traffic detector for signalized intersection control) because queued vehicle presence is always accurately detected. As speed increases, the minimum measurable headway rapidly decreases to values that are sufficiently short to pose no threat to the precise measurement of individual headways on freeways or expressways.

Travel Time Measurement

The procedure for measuring vehicle travel time by using video images is based on the observation of vehicle crossing times at two reference lines. If the distance between these two lines (in the plane of the roadway) is known, then the speed of the vehicle can be computed. The sources of bias and error variability in this measurement process are similar to those described for headway measurement and are described below.

Travel Time Variability

The variability of measurement stemming from frame error also exists in travel time measurement. As there are two event times measured and differenced to determine travel time, the variability that is due to frame error is additive, as it is with headway. However, direct summation of two quantities of σ_F^2 will overestimate the frame error because of a correlation between the errors of these two measurements (i.e., the errors are not independent). Specifically, the variability in total frame error is reduced somewhat because the same vehicle is being measured at both reference lines. As a result, the measurement errors will be offsetting to some degree. The variance of the error in travel time measurement can be computed as

$$\begin{aligned}\sigma_{F_t}^2 &= \sigma_F^2 + \sigma_F^2 - 2r\sigma_F^2 \\ &= 2\sigma_F^2(1 - r)\end{aligned} \quad (19)$$

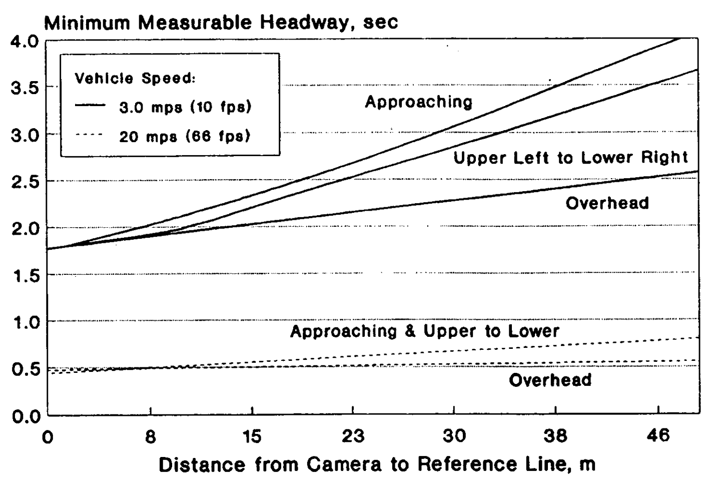


FIGURE 5 Minimum measurable headway with automated data extraction (1 mps = 3.3 fps).

where

σ_{Ft}^2 = variance of travel time measurement error associated with frame error (sec^2),
σ_F = standard deviation of measurement associated with frame error (Equation 5) (sec), and
r = correlation parameter.

The correlation parameter can be computed by regressing the two event time measurement errors associated with a travel time estimate. The parameter is equal to the slope of a first-order linear regression model. This approach is similar to that described for computing the autocorrelation in headway measurement; however, in this instance the correlation reduces the variability in travel time error.

The correlation between the errors in successive event time measurements for the same vehicle was evaluated by the aforementioned regression approach. This examination indicated that the correlation parameter was approximately +0.35 for both the automated and the manual measurement methods.

The two remaining sources of variability stem from the variability associated with reference linewidth and vehicle signature height. The variance associated with these measurement error sources can be derived from Equations 9 and 14, respectively. As there are two measurements made for each travel time, the total measurement variance for each source can be computed as the sum of the variance of each event time measurement. Thus, the variance of the error that is due to reference linewidth can be computed as

$$\sigma_{Wt}^2 = \left(0.30\ \frac{1}{\overline{V}}\right)^2 (W_{d2}^2 + W_{d1}^2) \tag{20}$$

where

σ_{Wt}^2 = variance of travel time measurement error associated with reference linewidth (sec^2),
W_{d1} = width of the first reference line/detector traversed (m), and
W_{d2} = width of the second reference line/detector traversed (m).

In a similar manner, the variance of the error that is due to vehicle signature height can be computed as

$$\sigma_{vst}^2 = \left(0.21\ \frac{\overline{h}_{vs}}{h_c\ \overline{V}}\right)^2 (L_2^2 + L_1^2) \tag{21}$$

where

σ_{vst}^2 = variance of travel time measurement error associated with nonzero vehicle signature height (sec^2),
L_1 = distance between the first reference line/detector traversed and the camera measured along the center line of the travel path (m), and
L_2 = distance between the second reference line/detector traversed and the camera measured along the center line of the travel path (m).

The total variance of travel time error that is due to measurement with videotape systems can be computed as

$$\sigma_{tt}^2 = \sigma_{Ft}^2 + \sigma_{Wt}^2 + \sigma_{vst}^2 \tag{22}$$

Travel Time Bias

Vehicle travel time is computed as the difference between two reference line crossing times. However, the automated method can introduce a bias into this travel time computation if the vehicle signature (i.e., lock-on point) lies above the plane of the roadway. With reference to Figure 3, it can be shown that the expected travel time between the reference lines is

$$E[tt] = E\left[\left(t_2' + \frac{\delta x_2}{V} + \frac{fW_{d2}}{V}\right) - \left(t_1' + \frac{\delta x_1}{V} + \frac{fW_{d1}}{V}\right)\right] \tag{23}$$

$$= E[t_2' - t_1'] + \frac{D\overline{h}_{vs}}{\overline{V}h_c} + \frac{1}{2\overline{V}}|W_{d2} - W_{d1}| \tag{24}$$

where

tt = travel time between reference lines (sec),
t_1', t_2' = event time measured by the automated method at reference lines 1 and 2 (sec),
D = distance between the two reference lines measured along the center line of the travel path ($=L_2 - L_1$) (m).

The last two terms in Equation 24 represent the average bias in travel time that is due to measurement with the automated method. Both terms are positive quantities, implying that the measured travel time is always shorter than the true travel time. Examination of the terms of this equation indicates that the bias decreases as speed and camera mounting height increase. Alternatively, the bias increases as the distance between the two reference lines increases.

Speed Measurement

Speed Based on Travel Time

An error in the measurement of this travel time translates into an error in the estimate of speed. The method of approximate moments can be used to derive the following equation for estimating the variability of the speed measurement error:

$$\sigma_V = \frac{D}{\overline{tt}^2}\sigma_{tt} \tag{25}$$

where σ_V is the standard deviation of speed measurement error (mps).

The standard deviation of speed measurement is shown in Figure 6 as a function of reference line separation distance D. In the context of speed measurement this distance is referred to as the speed-trap length. As Figure 6 indicates, the uncertainty in measured speed is larger for shorter trap lengths and for automated methods. Depending on the speed being measured and the method of measurement, the uncertainty appears to level off beyond a specific trap length. For low speeds this length is approximately 8 m (25 ft) for both methods. For high speeds using the manual method the length is approximately 23 m (75 ft), and for the automated method it is approximately 46 m (150 ft). These trends are contrary to those noted with respect to travel time error variance because of the travel time term in the denominator of Equation 25. The square of this term tends to be larger and thus more dominant than the σ_{tt} term.

Autoscope Speed Detector

The Autoscope video imaging system has a special detector that is able to measure vehicle speed directly. The use of this detector

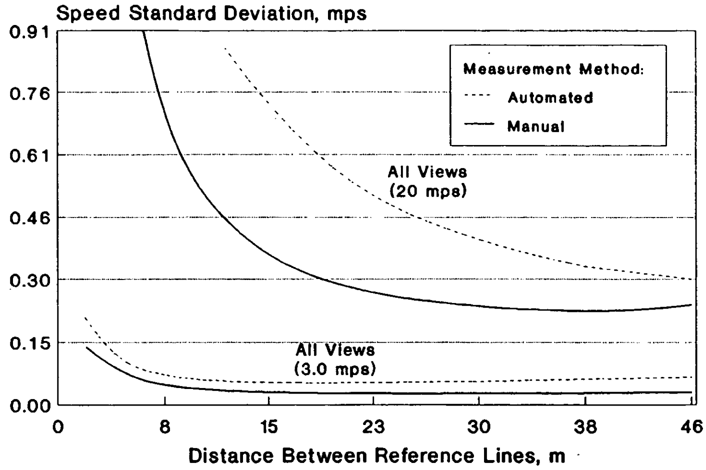


FIGURE 6 Standard deviation of the speed measurement process (1 mps = 3.3 fps).

requires that distances in the plane of the roadway and the height of the camera be input during the calibration step. Once calibrated to the field of view, the Autoscope tracks each vehicle through a short detection zone and estimates its travel speed.

A test was conducted to determine how well the Autoscope's speed detector could measure speed relative to the automated (via travel time) and manual methods. True speeds were measured for 50 vehicles for each of five different fields of view at three different study sites. These true speeds were measured with a tape switch data collection system, as previously described by Moen et al. (*7*). The camera height was 9.8 m (32 ft). Fields of view included approaching from upper left to lower right, departing from lower left to upper right, and overhead. All views were of the station category. The true speeds ranged from 18 mps (58 fps) to 20 mps (64 fps).

The error, or difference between the true speed and that predicted by the Autoscope, was computed. The standard deviation of this error ranged from 0.84 mps (2.8 fps) to 3.7 mps (12 fps). Comparison of this range with the 20-mps lines in Figure 6 indicates that the range is consistent with the standard deviation obtained with the manual method using 6- to 7-m trap distances. As the length of the Autoscope's speed detector is within this range, this suggests that the Autoscope detector is able to measure speed with the precision of the manual method but with the efficiency of the automated method. However, it also suggests that the precision of the autoscope's speed detector could be improved by increasing its length.

CONCLUSIONS

Time-based traffic events, such as headway and travel time, can be accurately and precisely measured with videotape recording-and-playback systems. The methods of extracting the individual traffic events include (a) manual extraction using a frame-by-frame analysis (using either the in-picture stopwatch image or the frame counter), and (b) automated extraction, using a video imaging system to analyze the tape during playback at normal speed. When data are extracted automatically (or manually by using frame counts), the event times may be biased because of a tape drag effect. The amount of tape drag can vary from system to system, although it is probably lower for systems with professional-grade components.

The automated extraction of vehicle headways may be limited to higher-speed vehicles. The minimum headway that can be reliably detected for vehicles moving at 3.0 mps (10 fps) is ~1.7 sec. The minimum headway for vehicles moving at 20 mps (66 fps) is ~0.5 sec. Manual extraction of headways does not share this limitation.

There are several sources of error variability in the measurement of time-based traffic events by using videotape records. These sources increase the uncertainty in the measurement of an individual event time and, as a result, increase the sample size needed to estimate the mean event time with a desired level of confidence.

One source of error variability in the measurement of event time is due to the discrete time interval between video frames. Another source of error variability stems from the width of the reference line drawn on the video display when it is transformed to the plane of the roadway. A final source of error variability stems from the video imaging system's tendency to lock onto the first part of the vehicle that crosses the detector/reference line. When this part lies above the plane of the roadway, the recorded event time does not equal the actual time when the vehicle reaches the detector's position in the plane of the roadway.

Both automated and manual methods can be used to measure headways, travel times, and speeds. The manual method has lower variability than the automated method in all cases. Thus, the greater precision of the manual method will yield smaller sample sizes than the automated method; however, the automated method can extract data more rapidly. The benefits of each method should be considered on a case-by-case basis.

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