CHAPTER 10

Speed, Travel Time, and Delay Studies

10.1 Introduction

Speed, travel time, and delay are all related measures commonly used as indicators of performance for traffic facilities. All relate to a factor that is most directly experienced by motorists: How long does it take to get from A to B? Motorists have the obvious desire to complete their trip in the minimum time consistent with safety. The performance of a traffic facility is often described in terms of how well that objective is achieved.

In the *Highway Capacity Manual* [*1*], for example, average travel speed is used as a measure of effectiveness for arterials, for two-lane rural highways, and for more extensive facility evaluations. Control delay is the measure of effectiveness for signalized and STOP-controlled intersections. Whereas freeways use density as a primary measure of effectiveness, speed is an important component of the evaluation of freeway system operation.

Thus traffic engineers must understand how to measure and interpret data on speed, travel time, and delay in ways that yield a basic understanding of the quality of operations on a facility and in ways that directly relate to defined performance criteria. Speed is also an important factor in evaluating high-accident locations as well as in other safety-related investigations.

Speed is inversely related to travel time. The reasons and locations at which speeds or travel times would be measured are, however, quite different. Speed measurements are most often taken at a point (or a short segment) of roadway under conditions of free flow. The intent is to determine the speeds that drivers select, unaffected by the existence of congestion. This information is used to determine general speed trends, to help determine reasonable speed limits, and to assess safety. Such studies are referred to as "spot speed studies" because the focus is on a designated "spot," or location, on a facility.

Travel time must be measured over a distance. Although spot speeds can indeed be measured in terms of travel times over a short measured distance (generally < 1,000 ft), most travel-time measurements are made over a significant length of a facility. Such studies are generally done during times of congestion specifically to measure or quantify the extent and causes of congestion.

In general terms, delay is a portion of total travel time. It is a portion of travel time that is particularly identifiable and unusually annoying to the motorist. Delay along an arterial, for example, might include stopped time due to signals, midblock obstructions, or other causes of congestion.

At signalized and STOP-controlled intersections, delay takes on more importance because travel time is difficult to define for a point location. Unfortunately, delay at intersections, specifically signalized intersections, has many different definitions, and the traffic engineer must be careful to use measurements and criteria that relate to the same delay definition.

Some of the most frequently used forms of intersection delay include the following:

- *Stopped-time delay*—the time a vehicle spends stopped waiting to proceed through a signalized or STOP-controlled intersection.
- *Approach delay*—adds the delay due to deceleration to and acceleration from a stop to stopped time delay.
- *Time-in-queue delay*—the time between a vehicle joining the end of a queue at a signalized or STOP-controlled intersection and the time it crosses the STOP line to proceed through the intersection.
- *Control delay*—the total delay at an intersection caused by a control device (either a signal or a STOP-sign), including both time-in-queue delay plus delays due to acceleration and deceleration.

Control delay was a term introduced in the 1985 *Highway Capacity Manual* [2], and it is used as the measure of effectiveness for signalized and STOP-controlled intersections.

Along routes, another definition of delay may be applied: *Travel-time delay* is the difference between the actual travel time traversing a section of highway and the driver's expected or desired travel time. It is more of a philosophical approach because there are no clearly accurate methodologies for determining the expected travel time of a motorist over a given section of highway. For this reason, it is seldom used for assessing congestion along a highway segment.

Because speeds are generally studied at points under conditions of free flow and travel times and delays are generally studied along sections of roadway under congested conditions, the study techniques for each are quite different, as discussed in Chapter 8. Although sharing many similar elements, the analysis of data and the presentation of results also differ somewhat.

10.2 Spot Speed Studies

Spot speed studies are conducted to document the distribution of vehicle speeds as they pass a point or short segment of the roadway. Because the traffic engineer is interested in conducting spot speed studies under conditions of free flow (i.e., observed speeds are not impeded by volume and density conditions), they are generally not conducted when volumes are in excess of 750 to 1,000 veh/h/ln on freeways or 500 veh/h/ln on other types of uninterrupted flow facilities.

10.2.1 Speed Definitions of Interest

When the speeds of individual vehicles are measured at a given spot or location, the result is a *distribution* of speeds because no two vehicles will be traveling at exactly the same speed. The results of the study, therefore, must describe the observed distribution of speeds as clearly as possible. Several key statistics are used to describe spot speed distributions:

- *Average or time mean speed:* The average speed of all vehicles passing the study location during the period of the study.
- *Standard deviation:* In simplistic terms, the standard deviation of speeds is the average difference between observed speeds and the time mean speed during the period of the study.
- *85th percentile speed:* The speed below which 85% of the vehicles travel.
- *Median:* The speed that equally divides the distribution of spot speeds; 50% of observed speeds are higher than the median; 50% of observed speeds are lower than the median.
- *Pace:* A 10-mi/h increment in speeds that encompasses the highest proportion of observed speeds (as compared with any other 10-mi/h increment).

The desired result of a spot speed study is to determine each of these measures and to determine an adequate mathematical description of the entire observed distribution.

10.2.2 Uses of Spot Speed Data

The results of spot speed studies are used for many different purposes by traffic engineers, including:

- Establishing the effectiveness of new or existing speed limits or enforcement practices.
- Determining appropriate speed limits for application.
- Establishing speed trends at the local, state, and national level to assess the effectiveness of national policy on speed limits and enforcement.
- Specific design applications determining appropriate sight distances, relationships between speed and highway alignment, and speed performance with respect to steepness and length of grades.
- Specific control applications for the timing of "yellow" and "all red" intervals for traffic signals, proper

placement of signs, and development of appropriate signal progressions.

- Investigation of high-accident locations at which speed is suspected to be a contributing cause to the accident experience.

This list is illustrative. It is not intended to be complete because there are myriad situations that may require speed data for a complete analysis. Such studies are of significant importance and are among the tasks most commonly conducted by traffic engineers.

10.2.3 Analysis of Spot Speed Data

The best way to present the analysis of typical spot speed data is by example. The discussions of this section are illustrated using a comprehensive sample application throughout. Figure 10.1 represents a typical set of field data from a spot speed study taken at location of interest on a major arterial. The data are collected as frequencies of observances in predefined speed groups. This method of field data summary is very much related to the statistical analysis that will be applied.

Because the observed speeds form a distribution, they will eventually be described in terms of a continuous distribution function. The mathematical characteristics of a continuous distribution do not allow for the description of the probability of any distinct value occurring—in a continuous function, one discrete speed is one value in a distribution with an infinite number of such values. In more practical terms, a continuous distribution cannot describe the occurrence of a speed of exactly 44.72 mi/h. It can, however, describe the

Route 10 @ MP 125.3 — LOCATION *July 10, 2003* — DATE *1:00 - 4:00 PM* — TIME

Good - Clear, Dry — WEATHER CONDITIONS *Asphaltic concrete - good.* — ROADWAY SURFACE CONDITIONS

							TOTALS			
							PC	Trucks	Other	Total
30	32									
32	34									
34	36			II	II	I	2	2	1	5
36	38			III	II		3	2	0	5
38	40			𝍸	I	I	5	1	1	7
40	42			𝍸 𝍸	III		10	3	0	13
42	44			𝍸 𝍸 𝍸 III	III		18	3	0	21
44	46			𝍸 𝍸 𝍸 𝍸 𝍸 IIII	IIII		29	4	0	33
46	48			𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 II	II	II	42	2	2	46
48	50			𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸	II		60	2	0	62
50	52			𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 II			37	0	0	37
52	54			𝍸 𝍸 𝍸 𝍸 III			23	1	0	24
54	56			𝍸 𝍸 III		I	13	0	1	14
56	58			𝍸 II	I	I	7	1	1	9
58	60			𝍸			5	0	0	5
60	62			II			2	0	0	2
62	64									
64	66									
66	68									
68	70									

METHOD OF MEASUREMENT Signature 7/10/03

x Radar

____ Time over measured course length of ____ ft.

____ Stop watch/manual

____ Road tubes w/timer

____ Electronic contact w/timer

Figure 10.1: Field Data for an Illustrative Spot Speed Study

occurrence of a speed in the range of 44.7 to 44.8 mi/h. Therefore, the statistical analysis of speed data is based on the number of observed values within a set of defined speed ranges.

The data shown in Figure 10.1 use speed groups that are 2 mi/h in breadth. This is a practical value that is quite typical, although 1 mi/h groups are also used if the sample sizes are large enough. For statistical reasons that are explained later, speed groups of more than 5 mi/h are never used. The number of speed groups defined must relate to the expected range of the data and to the number of speeds that will be observed and recorded. For example, defining 15 speed groups and collecting only 30 speeds would be illogical because there would only be an average of two observations per group. In general, it is customary to collect from 15 to 20 speeds for each defined speed group. This *does not* imply that each group would have 15 to 20 observations; rather, the total number of observations will be sufficient to define the underlying distribution and its characteristics.

Frequency Distribution Table

The first analysis step is to take the data of Figure 10.1 and reformat it into the form of a frequency distribution table, as illustrated in Table 10.1. This tabular array shows the total number of vehicles observed in each speed group. For the convenience of subsequent use, the table includes one speed group at each extreme for which no vehicles were observed. The "middle speed" (S) of the third column is taken as the midpoint value within the speed group. The use of this value is discussed in a later section.

The fourth column of the table shows the number of vehicles observed in each speed group. This value is known as the *frequency* for the speed group. These values are taken directly from the field sheet of Figure 10.1.

In the fifth column, the percentage of total observations in each speed group is computed as:

$$\% = 100\frac{n_i}{N} \tag{10-1}$$

Table 10.1: Frequency Distribution Table for Illustrative Spot Speed Study

Speed Group							
Lower Limit (mi/h)	Upper Limit (mi/h)	Middle Speed S (mi/h)	Observed Freq. in Group n	% Freq. in Group (%)*	Cum % Freq (%)*	nS**	nS2**
32	34	33	0	0.0%	0.0%	0	0
34	36	35	5	1.8%	1.8%	175	6,125
36	38	37	5	1.8%	3.5%	185	6,845
38	40	39	7	2.5%	6.0%	273	10,647
40	42	41	13	4.6%	10.6%	533	21,853
42	44	43	21	7.4%	18.0%	903	38,829
44	46	45	33	11.7%	29.7%	1,485	66,825
46	48	47	46	16.3%	45.9%	2,162	101,614
48	50	49	62	21.9%	67.8%	3,038	148,862
50	52	51	37	13.1%	80.9%	1,887	96,237
52	54	53	24	8.5%	89.4%	1,272	67,416
54	56	55	14	4.9%	94.3%	770	42,350
56	58	57	9	3.2%	97.5%	513	29,241
58	60	59	5	1.8%	99.3%	295	17,405
60	62	61	2	0.7%	100.0%	122	7,442
62	64	63	0	0.0%	100.0%	0	0
			283	100.0%		13,613	661,691

*All percents computed to two decimal places and rounded to one; this may cause apparent "errors" in cumulative percents due to rounding.
**Computations rounded to the nearest whole number.

where: n_i = number of observations (frequency) in speed group i

N = total number of observations in the sample

For the 40–42 mi/h speed group, there are 13 observations in a total sample of 283 speeds. Thus the percent frequency is 100*(13/283) = 4.6% for this group. The cumulative percent frequency (cum %) is the percentage of vehicles traveling at or below the highest speed in the speed group:

$$cum\% = 100\left(\sum_{1-x} n_i \Big/ N\right) \qquad (10\text{-}2)$$

where: x = consecutive number (starting with the lowest speed group) of the speed group for which the cum % frequency is desired

For the 40–42 mi/h speed group, the sum of the frequencies for all speed groups having a high-speed boundary of 42 mi/h or less is found as 13 + 7 + 5 + 5 + 0 = 30. The cum % frequency is then 100 * (30/283) = 10.6%.

The last two columns of the frequency distribution table are simple multiplications that will be used in subsequent computations.

Frequency and Cumulative Frequency Distribution Curves

The data in Table 10.1 are used to plot two curves that lend a visual impact to the information: (1) a Frequency Distribution Curve and (2) a Cumulative Frequency Distribution Curve. These are illustrated in Figure 10.2 and plotted as follows:

- *Frequency distribution curve.* For each speed group, the % frequency of observations within the group is plotted versus the middle speed of the group (S).
- *Cumulative frequency distribution curve.* For each speed group, the % cumulative frequency of observations is plotted versus the higher boundary of the speed group.

Note that the two frequencies are plotted versus *different* speeds. The middle speed is used for the frequency distribution curve. The cumulative frequency distribution curve, however, results in a very useful plot of speed versus the percent of vehicles traveling at or below the designated speed. For this reason, the upper limit of the speed group is used as the plotting point.

In both cases, the plots are connected by a *smooth* curve that minimizes the total distance of points falling above the line and those falling below the line (on the vertical axis). A smooth curve is defined as one without any breaks in the slope of the curve. The "best fit" is done approximately (by eye), generally a lightly sketched curve in freehand. A French curve may then be used to darken the line. Some statistical packages plot such a line automatically.

It is also convenient to plot the frequency distribution curve directly above the cumulative frequency distribution curve, using the same horizontal scale. This makes it easier to use the curves to extract critical parameters graphically. Figure 10.2 also illustrates the graphic determination of several key variables that help describe the observed distribution. These parameters are defined and their determination explained in the sections that follow.

Common Descriptive Statistics

Common descriptive statistics may be computed from the data in the frequency distribution table or determined graphically from the frequency and cumulative frequency distribution curves. These statistics are used to describe two important characteristics of the distribution:

- *Central tendency:* Measures that describe the approximate middle or center of the distribution.
- *Dispersion:* Measures that describe the extent to which data spreads around the center of the distribution.

Measures of central tendency include the average or mean speed, the median speed, the modal speed, and the pace. Measures of dispersion include the 85th and 15th percentile speeds and the standard deviation.

The Mean Speed: A Measure of Central Tendency The average or mean speed of a distribution is usually easily found as the sum of the observed values divided by the number of observations. In a spot speed study, however, individual values of speed are not recorded; rather, the frequency of observations within defined speed groups is known. Computing the mean speed requires the assumption that *the average speed within a given speed group is the middle speed, S, of the group.* This is the reason that speed groups of more than 5 mi/h are never used. This assumption becomes less valid as the size of the speed groups increases. For 2 mi/h speed groups, as in the illustrative study, the assumption is usually quite good. If this assumption is made, the sum of all speeds in a given speed group may be computed as:

$$n_i S_i$$

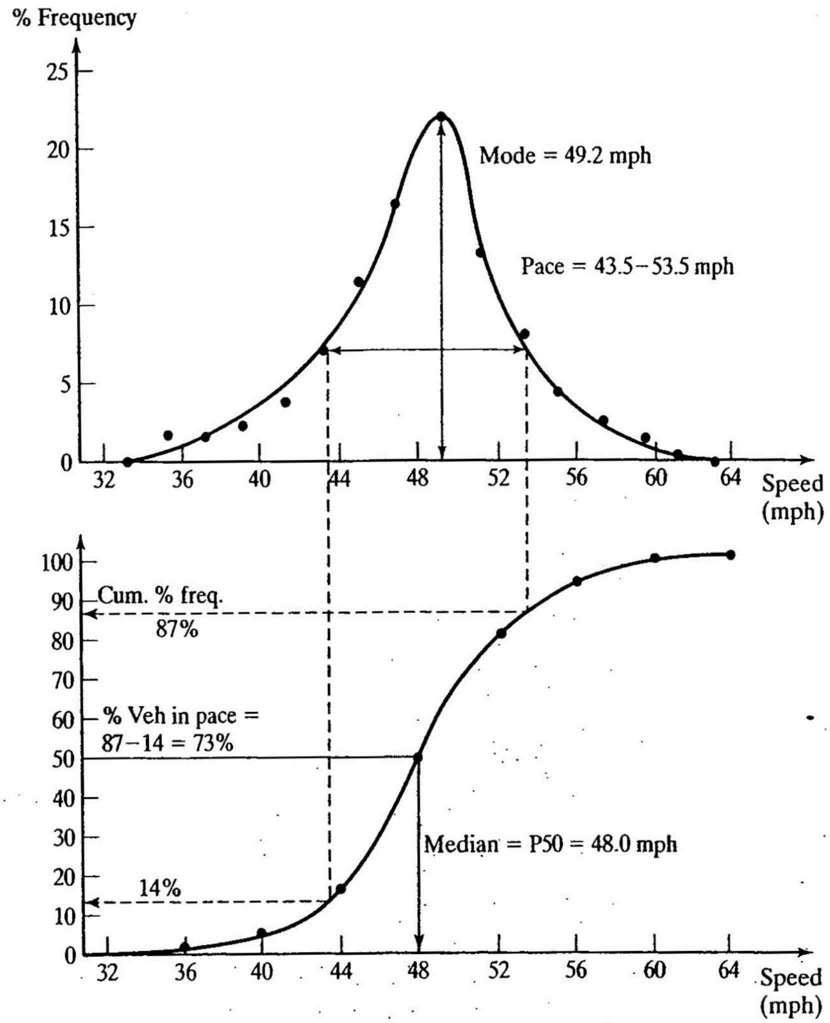

Figure 10.2: Frequency and Cumulative Frequency Distribution Curves for the Illustrative Spot-Speed Distribution

/here: n_i = frequency of observations in speed group i

S_i = middle speed of speed group i

'he sum of all speeds in the distribution may then be found by dding this product for all speed groups:

$$\sum_i n_i S_i$$

'he mean or average speed is then computed as the sum livided by the number of observed speeds:

$$\bar{x} = \frac{\sum_i n_i S_i}{N} \quad (10\text{-}3)$$

vhere: $\bar{x}$ = average speed for the sample observations, mi/h

N = total sample size

For the illustrative study data presented in Figure 10.2 and Table 10.1, the average or mean speed is:

$$\bar{x} = \frac{13{,}613}{283} = 48.1 \text{ mi/h}$$

where $\Sigma n_i S_i$ is the sum of the next-to-last column of the frequency distribution table of Table 10.1.

The Median Speed: Another Measure of Central Tendency The median speed is defined as the speed that divides the distribution into equal parts (i.e., there are as many observations of speeds higher than the median as there are lower than the median). It is a positional value and not affected by the absolute value of extreme observations.

The difference between the median and mean is best illustrated by example. Three speeds are observed: 30 mi/h, 40 mi/h, and 50 mi/h. Their average is (30 + 40 + 50)/3 = 40 mi/h. Their median is also 40 mi/h because it equally divides the distribution, with one speed higher than 40 mi/h and one speed lower than 40 mi/h. Another three speeds are then observed: 30 mi/h, 40 mi/h, and 70 mi/h. Their average is (30 + 40 + 70)/3 = 46.7 mi/h. The median, however, is still 40 mi/h, with one speed higher and one speed lower than this observation. The mean is affected by the *magnitude* of the extreme observations; the median is affected only by the *number* of such observations.

Because individual speeds have not been recorded in the illustrative study, however, the "middle value" is not easily determined from the tabular data of Table 10.1. It is easier to estimate the median graphically using the cumulative frequency distribution curve of Figure 10.2. By definition, the median equally divides the distribution. Therefore, 50% of all observed speeds should be less than the median. This is exactly what the cumulative frequency distribution curve plots. If the curve is entered at 50% on the vertical axis, the median speed is found, as illustrated in Figure 10.2. For the illustrative study:

$$P_{50} = 48.0 \text{ mi/h}$$

where P_{50} is the median or 50th percentile speed.

The Pace: Another Measure of Central Tendency The pace is a traffic engineering measure not commonly used for other statistical analyses. It is defined as *the 10-mi/h increment in speed in which the highest percentage of drivers is observed.* It is also found graphically using the frequency distribution curve of Figure 10.2. The solution recognizes that the area under the frequency distribution curve between any two speeds approximates the percentage of vehicles traveling between those two speeds, where the total area under the curve is 100%.

The pace is found as follows: A 10-mi/h template is scaled from the horizontal axis. Keeping this template horizontal, place an end on the lower left side of the curve and move slowly along the curve. When the right side of the template intersects the right side of the curve, the pace has been located. This procedure identifies the 10-mi/h increment that intersects the peak of the curve; this contains the most area and, therefore, the highest percentage of vehicles. The pace is shown in Figure 10.2 as:

$$43.5 - 53.5 \text{ mi/h}$$

The Modal Speed: Another Measure of Central Tendency The mode is defined as the single value of speed that is most likely to occur. Because no discrete values were recorded, the modal speed is also determined graphically from the frequency distribution curve. A vertical line is dropped from the peak of the curve, with the result found on the horizontal axis. For the illustrative study, the modal speed is:

$$49.2 \text{ mi/h}$$

The Standard Deviation: A Measure of Dispersion The most common statistical measure of dispersion in a distribution is the standard deviation. It is a measure of how far data spreads around the mean value. In simple terms, the standard deviation is the average value of the difference between individual observations and the average value of those observations. Where discrete values of a variable are available, the equation for computing the standard deviation is:

$$s = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{N - 1}} \qquad (10\text{-}4)$$

where: s = the standard deviation

x_i = observation i

$\bar{x}$ = average of all observations

N = number of observations

The difference between a given data point and the average is a direct measure of the magnitude of dispersion. These differences are squared to avoid positive and negative differences canceling and summed for all data points. They are then divided by $N - 1$. One statistical *degree of freedom* is lost because the mean of the distribution is known and used to compute the differences. If there are three numbers and it is known that the differences between the values and the mean for the first two are "3" and "2," then the third or last difference must be "–5," because the sum of all differences must be zero. Only the first "$N - 1$" observations of differences are statistically random. A square root is taken of the results because the values of the differences were squared to begin the computation.

Because discrete values of speed are not recorded, Equation 10-3 is modified to reflect group frequencies:

$$s = \sqrt{\frac{\sum n_i (S_i - \bar{x})^2}{N - 1}}$$

which may be manipulated into a more convenient form, as follows:

$$s = \sqrt{\frac{\sum n_i S_i^2 - N\bar{x}^2}{N - 1}} \qquad (10\text{-}5)$$

where all terms are as previously defined. This form is most convenient because the first term is the sum of the last column of the frequency distribution table of Table 10.1. For the illustrative study, the standard deviation is:

$$s = \sqrt{\frac{661{,}691 - 283 * 48.1^2}{183 - 1}} = 4.96\,mi/h$$

Most observed speed distributions have standard deviations that are close to 5 mi/h because this represents most driver behavior patterns reasonably well. Unlike averages and other central speeds, which vary widely from location to location, most speed studies yield similar standard deviations.

The 85th and 15th Percentile Speeds The 85th and 15th percentile speeds give a general description of the high and low speeds observed by most reasonable drivers. It is generally thought that the upper and lower 15% of the distribution represents speeds that are either too fast or too slow for existing conditions. These values are found graphically from the cumulative frequency distribution curve of Figure 10.2. The curve is entered on the vertical axis at values of 85% and 15%. The respective speeds are found on the horizontal axis, as shown in Figure 10.2. For the illustrative study, these speeds are:

$$P_{85} = 52.7 \text{ mi/h}$$
$$P_{15} = 43.7 \text{ mi/h}$$

The 85th and 15th percentile speeds can be used to roughly estimate the standard deviation of the distribution, although this is not recommended when the data are available for a precise determination:

$$s_{est} = \frac{P_{85} - P_{15}}{2} \qquad (10\text{-}6)$$

where all terms are as previously defined. For the illustrative spot speed study:

$$s_{est} = \frac{52.7 - 43.7}{2} = 4.5 \text{ mi/h}$$

In this case, the estimated value is relatively close to the actual computed value of 4.96 mi/h.

The 85th and 15th percentile speeds give insight to both the central tendency and dispersion of the distribution. As these values get closer to the mean, less dispersion exists and the stronger the central tendency of the distribution becomes.

Percentage Vehicles Within the Pace The pace itself is a measure of the center of the distribution. The percentage of vehicles traveling within the pace speeds is a measure of both central tendency and dispersion. The smaller the percentage of vehicles traveling within the pace, the greater the degree of dispersion in the distribution.

The percentage of vehicles within the pace is found graphically using both the frequency distribution and cumulative frequency distribution curves of Figure 10.2. The pace speeds were determined previously from the frequency distribution curves. Lines from these speeds are dropped vertically to the cumulative frequency distribution curve. The percentage of vehicles traveling at or below each of these speeds can then be determined from the vertical axis of the cumulative frequency distribution curve, as shown. Then:

% Vehicles under 53.5 mi/h	= 87.0%
% Vehicles under 43.5 mi/h	= 14.0%
% Veh between 43.5 and 53.5 mi/h	= 73.0%

Even though speeds between 34 and 62 mi/h were observed in this study, over 70% of the vehicles traveled at speeds between 43.5 and 53.5 mi/h. This represents expected traffic behavior with a standard deviation of approximately 5 mi/h.

Using the Normal Distribution in the Analysis of Spot Speed Data

Most speed distributions tend to be statistically normal (i.e., they can be reasonably represented by a normal distribution). Chapter 7 contains a detailed description of the normal distribution and its properties that should be reviewed in conjunction with this section.

If observed speeds are assumed to be normally distributed, then several additional analyses of the data may be conducted. Recall that the standard notation $x{:}N[40,25]$ signifies that the variable "x" is normally distributed with a mean of "40" and a variance of "25." The standard deviation is the square root of the variance, or "5" in this case. Recall also that a value of "x" on any normal distribution can be converted to an equivalent value of "z" on the standard normal distribution, where $z{:}\ N[0,1]$:

$$z_i = \frac{x_i - \mu}{\sigma} \qquad (10\text{-}7)$$

where: x_i = a value on any normal distribution $x{:}N[\mu, \sigma^2]$

μ = the true mean of the distribution of values x_i

σ = the true standard deviation of the distribution of values x_i

z_i = equivalent value on the standard normal distribution $z{:}N[0,1]$

In practical terms, the true values, μ and σ are unknown. What results from a spot speed study are estimates of the true mean and standard deviation of the distribution based on a measured sample, $\bar{x}$ and s. A table of values of the standard normal distribution is included in Chapter 7 and used in the analysis of the illustrative data.

Precision and Confidence Intervals When a spot speed study is conducted, a single value of the mean speed is computed. For the illustrative study of this chapter, the mean is 48.1 mi/h, based on a sample of 283 observations. In effect, this value, based on a finite number of measured speeds, is being used to estimate the true mean of the underlying distribution of all vehicles traversing the site under uncongested conditions. The number of such vehicles, for all practical and statistical purposes, is infinite. The measured value of $\bar{x}$ is being used as an estimate for μ. The first statistical question that must be answered is: How good is this estimate?

In Chapter 7, the standard error of the mean, E, was introduced and defined. If a variable x is normally distributed:

$$x{:}N[\mu, \sigma^2]$$

it can be shown that the distribution of sample means (of a set of means with a constant sample size, n) is also normally distributed, as follows:

$$\bar{x}_n{:}N\left[\mu,\left(\sigma^2 \Big/ n\right)\right]$$

Assume that 100 speed observations had an average value of 50 mi/h. The speeds are then arranged in 10 groups of 10 speeds, and 10 separate averages are computed (one for each group). The average of the 10 group averages would still be 50 mi/h because the mean of the distribution of sample means is the same as the mean of the original distribution. The standard deviations, however, would be different because the grouping and averaging process significantly reduces the occurrence of extreme values. For example, in a distribution with an average speed of 50 mi/h, it is conceivable that some observations of 70 mi/h or more would be obtained. However, at the same site, it is highly unlikely that the average of any 10 observed speeds would be 70 mi/h or higher.

The standard error of the mean, E, is simply the standard deviation of a distribution of sample means with a constant group size of n:

$$E = s/\sqrt{n} \qquad (10\text{-}8)$$

where: E = standard error of the mean

s = standard deviation of the original distribution of individual values

n = number of samples in each group of observations

The characteristics of the normal distribution are also discussed in Chapter 7. These characteristics, together with the standard error of the mean, can be used to quantify the quality of the sample estimate of the true mean of the underlying distribution. In effect, the entire illustrative spot speed study (with its sample size of 283 values) is considered to be a single point on a distribution of sample means, all with a group size of 283. Assuming a normal distribution, it is known that 95% of all values lie between the mean $\pm$ 1.96 standard deviations; 99.7% of all values lie between the mean $\pm$3.00 standard deviations. Thus it is 95% certain that the sample mean (48.1 mi/h) is within the range of the true mean $\pm$1.96 standard deviations. The standard deviation is, in this case, the standard error of the mean. Then:

$$\bar{x} = \mu \pm 1.96E \Rightarrow \mu = \bar{x} \pm 1.96E \qquad (10\text{-}9)$$

95% of the time. The percentage is referred to as the confidence interval, whereas the precision of the measurement is given by the term 1.96 E. For the illustrative spot speed study:

$$E = \frac{4.96}{\sqrt{283}} = 0.295\,\text{mi/h}$$
$$\mu = 48.1 \pm 1.96(0.295) = 48.1 \pm 0.578$$
$$\mu = 47.522 - 48.678\,\text{mi/h}$$

Rounding off the values, it can be stated that we are 95% *confident* that the true mean of the underlying speed distribution lies between 47.5 and 48.7 mi/h. For a 99.7% confidence level:

$$\bar{x} = \mu \pm 3.00E \Rightarrow \mu = \bar{x} \pm 3.00E$$
$$\mu = 48.1 \pm 3.00(0.295)$$
$$\mu = 48.1 \pm 0.885$$
$$\mu = 47.215 - 48.985\text{ mi/h} \qquad (10\text{-}10)$$

Again rounding off these values, it can be stated that we are *99.7%* confident that the true mean of the underlying speed distribution lies between 47.2 and 49.0 mi/h.

These statements provide a quantitative description of the precision of the measurement and the confidence with which the estimate is given. Note that as the confidence level increases, the precision of the estimate decreases (i.e., the range of the estimate increases). Given that speeds are normally distributed, we can be 100% confident that the true mean speed lies between 48.10 mi/h $\pm\ \infty$.

Such a statement is useless in engineering terms. Because spot speed studies represent a sample of measurements selected from a virtually infinite population, the average an never be measured with complete precision and 100% onfidence. The most common approach uses the 95% confidence interval to compute the precision and confidence of the ample mean as an estimator of the true mean of the underlying distribution.

stimating the Required Sample Size Although it is useful know the confidence level and precision of a measured ample mean after the fact, it is more useful to determine what ample size is required to obtain a measurement that satisfies a redetermined precision and confidence level. Given that the *recision* or *tolerance* (e) of the estimate is the ± range around e mean:

$$95\% : e = 1.96E = 1.96(s/\sqrt{n})$$

$$99.7\% : e = 3.00E = 3.00(s/\sqrt{n})$$

hese equations can now be solved for the sample size, n. To btain a desired precision with 95% confidence:

$$n = \frac{3.84s^2}{e^2} \tag{10-11}$$

o obtain a desired precision with 99.7% confidence:

$$n = \frac{9.0s^2}{e^2} \tag{10-12}$$

here all variables are as previously defined.

Consider the following problem: How many speeds must collected to determine the true mean speed of the underlying stribution to within ±1.0 mi/h with 95% confidence? How do e results change if the tolerance is changed to ±0.5 mi/h and e confidence level to 99.7%?

The first problem is that the standard deviation of the stribution, s, is not known because the study has not yet en conducted. Here, practical use is made of the knowledge at most speed distributions have standard deviations of proximately 5.0 mi/h. This value is assumed, and the results e shown in Table 10.2.

A sample size of 96 speeds is required to achieve a tolerance of ±1.0 mi/h with 95% confidence. To achieve a tolerance of ±0.5 mi/h with 99.7% confidence, the required sample size must be almost 10 times greater. For most traffic engineering studies, a tolerance of ±1.0 mi/h and a confidence level of 95% are quite sufficient.

Before and After Spot Speed Studies

In many situations, existing speeds at a given location should be reduced. This occurs in situations where a high accident and/or accident severity rate is found to be related to excessive speed. It also arises where existing speed limits are being exceeded by an inordinate number of drivers.

Many traffic engineering actions can help reduce speeds, including lowered speed limits, stricter enforcement measures, warning signs, installation of rumble strips, and others. The major study issue, however, is to demonstrate that speeds have indeed been successfully reduced.

This is not an easy issue. Consider the following scenario: Assume that a new speed limit has been installed at a given location in an attempt to reduce the average speed by 5 mi/h. A speed study is conducted before implementing the reduced speed limit, and another is conducted several months after the new speed limit is in effect. Note that the "after" study is normally conducted after the new traffic engineering measures have been in effect for some time. This is done so that stable driver behavior is observed, rather than a transient response to something new. It is observed that the average speed of the "after" study is 3.5 mi/h less than the average speed of the "before" study. Statistically, these two questions must be answered:

- Is the observed reduction in average speeds real?
- Is the observed reduction in average speeds the intended 5 mi/h?

Although both questions appear to have obvious answers, they in fact do not. There are two reasons that a reduction in

Table 10.2: Sample Size Computations Illustrated

Tolerance e (mi/h)	Confidence Level 95%	Confidence Level 99.7%
1.0	$n = \frac{3.84(5)^2}{(1.0)^2} = 96$	$n = \frac{9.0(5)^2}{(1.0)^2} = 225$
0.5	$n = \frac{3.84(5)^2}{(0.5)^2} = 384$	$n = \frac{9.0(5)^2}{(0.5)^2} = 900$

average speeds could have occurred: (1) the observed 3.5-mi/h reduction could occur because the new speed limit caused the true mean speed of the underlying distribution to be reduced; (2) the observed 3.5-mi/h reduction could also occur because two different samples were selected from an underlying distribution that did not change. In statistical terms, the first is referred to as a *significant* reduction in speeds, and the latter is statistically *not significant.*

The second question is equally tricky. Assuming that the observed 3.5-mi/h reduction in speeds is found to be statistically significant, it is necessary to determine whether the true mean speed of the underlying distribution has likely been reduced by 5 mi/h. Statistical testing will be required to answer both questions. Further, it will not be possible to answer either question with 100% certainty or confidence.

Chapter 7 introduced the concepts and methodologies for before-and-after testing for the significance of observed differences in sample means. The concept of truth tables was also discussed. The statistical tests for the significance of observed differences have four possible results: (1) the actual difference is significant, and the statistical test determines that it is significant; (2) the actual difference is not significant, and the statistical test determines that it is not significant; (3) the actual difference is significant and the statistical test determines that it is not significant; and (4) the actual difference is not significant and the statistical test determines that it is significant. The first two outcomes result in an accurate assessment of the situation; the last two represent erroneous results. In statistical terms, outcome (4) is referred to as a Type I, or α error; outcome (3) is referred to as a Type II, or β error.

In practical terms, the traffic engineer must avoid making a Type I error. In this case, it will appear that the problem (excessive speed) has been solved, when in fact it has not been solved. This may result in additional accidents, injuries, and/or deaths before the "truth" becomes apparent. If a Type II error is made, additional effort will be expended to entice lower speeds. Although this might involve additional expense, it is unlikely to lead to any negative results.

The statistical test applied to assess the significance of an observed reduction in mean speeds is the normal approximation. As discussed in Chapter 7, this test is applicable as long as the "before" and "after" sample sizes are more than or equal to 30, which will always be the case in properly conducted speed studies. To certify that an observed reduction is significant, we wish to be 95% confident that this is so. In other words, we wish to ensure that the chance of making a Type I error is less than 5%.

The normal approximation is applied by converting the observed reduction in mean speeds to a value of z on the standard normal distribution:

$$z_d = \frac{(\bar{x}_1 - \bar{x}_2) - 0}{s_y}$$

$$s_y = \sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}} \qquad (10\text{-}13)$$

where: z_d = standard normal distribution equivalent to the observed difference in sample speeds

$\bar{x}_1$ = mean speed of the "before" sample, mi/h

$\bar{x}_2$ = mean speed of the "after" sample, mi/h

s_y = pooled standard deviation of the distribution of sample mean differences

s_1 = standard deviation of the "before" sample, mi/h

s_2 = standard deviation of the "after" sample, mi/h

N_1 = sample size of the "before" study (must be ≥ 30)

N_2 = sample size of the "after" study (must be ≥ 30)

The standard normal distribution table of Table 7.3 (Chapter 7) is used to find the probability that a value equal to or less than z_d occurs when both sample means are from the same underlying distribution. Then:

- If Prob $(z \leq z_d) \geq 0.95$, the observed reduction in speeds is *statistically significant.*
- If Prob $(z \leq z_d) < 0.95$, the observed reduction in speeds is *not statistically significant.*

In the first case, it means that the observed difference in sample means would be exceeded less than 5% of the time, assuming that the two samples came from the same underlying distribution. Given that such a value was observed, this may be interpreted as being less than 5% probable that the observed difference came from the same underlying distribution and more than 95% probable that it resulted from a change in the underlying distribution.

Note that a *one-sided* test is conducted (i.e., we are testing the significance of an observed *reduction* in sample means, *not* an observed *difference* in sample means). If the observations revealed an increase in sample means, no statistical test is conducted because it is obvious that the desired result was not achieved.

If the observed reduction is found to be statistically significant, the second question can be entertained (i.e., was the target speed reduction achieved?). This is done using only the results of the "after" distribution. Note that from the normal distribution characteristics, it is 95% probable that the true mean of the distribution is:

$$\mu = \bar{x} \pm 1.96E$$

If the target speed lies within this range, it can be stated that it was successfully achieved.

Consider the following results of a before-and-after spot speed study conducted to evaluate the effectiveness of a new speed limit intended to reduce the average speed at the location to 60 mi/h:

Before Results		After Results
65.3 mi/h	$\bar{x}$	63.0 mi/h
5.0 mi/h	s	6.0 mi/h
50	N	60

A normal approximation test is conducted to determine whether the observed reduction in sample means is statistically significant:

Step 1: Compute the pooled standard deviation.

$$s_y = \sqrt{\frac{5.0^2}{50} + \frac{6.0^2}{60}} = 1.05\text{mi/h}$$

Step 2: Compute z_d.

$$z_d = \frac{(65.3 - 63.0) - 0}{1.05} = 2.19$$

Step 3: Determine the prob ($z \leq 2.19$) from Table 7.3.

$$\text{Prob}\,(z \leq 2.19) = 0.9857$$

Step 4: Compare results with the 95% criteria.

As 98.57% > 95% the results indicate that the observed reduction in sample means was statistically significant.

Given these results, it is now possible to investigate whether or not the target speed of 60 mi/h was successfully achieved in the "after" sample. The 95% confidence interval for the "after" estimate of the true mean of the underlying distribution is:

$$E = 6/\sqrt{60} = 0.7746$$

$$\mu = 63.0 \pm 1.96(0.7746)$$

$$\mu = 63.0 \pm 1.52$$

$$\mu = 61.48 - 64.52\text{mi/h}$$

Because the target speed of 60 mi/h does not lie in this range, it cannot be stated that it was successfully achieved.

In this case, although a significant reduction of speeds was achieved, it was not sufficient to achieve the target value of 60 mi/h. Additional study of the site would be undertaken and additional measures enacted to achieve additional speed reduction.

The 95% confidence criteria for certifying a significant reduction in observed speeds should be well understood. If a before-and-after study results in a confidence level of 94.5%, it would not be certified as statistically significant. This decision limits the probability of making a Type I error to less than 5%. When we state that the observed difference in mean speeds is not statistically significant in this case, however, it is 94.5% probable that we are making a Type II error. Before expending large amounts of funds on additional speed-reduction measures, a larger "after" speed sample should be taken to see whether or not 95% confidence can be achieved with an expanded database.

Testing for Normalcy: The Chi-Square Goodness-of-Fit Test

Virtually all of the statistical analyses of this section start with the basic assumption that the speed distribution can be mathematically represented as normal. For completeness, it is therefore necessary to conduct a statistical test to confirm that this assumption is correct. As described in Chapter 7, the chi-square test is used to determine whether the difference between an observed distribution and its assumed mathematical form is significant. For grouped data, the chi-squared statistic is computed as:

$$\chi^2 = \sum_{N_G} \frac{(n_i - f_i)^2}{f_i} \tag{10-14}$$

where: χ^2 = chi-squared statistic

n_i = frequency of observations in speed group i

f_i = theoretical frequency in speed group i, assuming that the assumed distribution exists

N_G = number of speed groups in the distribution

Table 10.3 shows these computations for the illustrative spot speed study. Speed groups are already specified, and the observed frequencies are taken directly from the field sheet of Figure 10.1.

For convenience, the speed groups are listed from highest to lowest. This is to coordinate with the standard normal distribution table of Chapter 7, which gives probabilities of $z \leq z_d$. The upper limit of the highest group is adjusted to "infinity" because the theoretical normal distribution extends to both positive and negative infinity. The remaining columns of Table 10.3 focus on determining the theoretical frequencies, f_i and on determining the final value of χ^2.

Table 10.3: Chi-Square Test for Normalcy on Illustrative Spot Speed Data

Average Speed = 48.10 mi/h Standard Deviation = 4.96 mi/h Sample Size = 283

Speed Group									
Upper Limit (mi/h)	Lower Limit (mi/h)	Observed Frequency n	Upper Limit (Std. Normal) z_d	Prob. $z \le z_d$ Table 7.3	Prob. of Occurrence in Group	Theoretical Frequency f	Combined Groups n	Combined Groups f	χ^2 Group
∞	60	2	∞	1.0000	0.0082	2.3206			
60	58	5	2.40	0.9918	0.0146	4.1318	7	6.4524	0.0465
58	56	9	2.00	0.9772	0.0331	9.3673	9	9.3673	0.0144
56	54	14	1.59	0.9441	0.0611	17.2913	14	17.2913	0.6265
54	52	24	1.19	0.8830	0.0978	27.6774	24	27.6774	0.4886
52	50	37	0.79	0.7852	0.1372	38.8276	37	38.8276	0.0860
50	48	62	0.38	0.6480	0.1560	44.1480	62	44.1480	7.2188
48	46	46	−0.02	0.4920	0.1548	43.8084	46	43.8084	0.1096
46	44	33	−0.42	0.3372	0.1339	37.8937	33	37.8937	0.6320
44	42	21	−0.83	0.2033	0.0940	26.6020	21	26.6020	1.1797
42	40	13	−1.23	0.1093	0.0577	16.3291	13	16.3291	0.6787
40	38	7	−1.63	0.0516	0.0309	8.7447	7	8.7447	0.3481
38	36	5	−2.04	0.0207	0.0134	3.7922	10	5.8581	2.9285
36	34	5	−2.44	0.0073	0.0073	2.0659			
Total					**1.0000**	**283**	**283**	**283**	**14.3574**

$\chi^2 = 14.3574$

Degrees of Freedom = 12 − 3 = 9

The theoretical frequencies are the numbers of observations that would have occurred in the various speed groups *if the distribution were perfectly normal.* To find these values, the probability of an occurrence within each speed group must be determined from the standard normal table of Chapter 7. This is done in columns 4 through 7 of Table 10.3, as follows:

1. The upper limit of each speed group (in mi/h) is converted to an equivalent value of z on the standard normal distribution, using Equation 10-8. This computation is illustrated for the speed group with an upper limit of 60 mi/h:

$$z_{60} = \frac{60.00 - 48.10}{4.96} = 2.40$$

Note that the mean speed and standard deviation of the illustrative spot speed study are used in this computation.

2. Each computed value of z is now looked up on the standard normal table of Chapter 7. From this, the probability of $z \le z_d$ is found and entered into column 5 of Table 10.3.

3. Consider the 48 to 50 mi/h speed group in Table 10.3. From column 5, 0.6480 is the probability of speed ≤ 50 mi/h occurring on a normal distribution; 0.4920 is the probability of a speed ≤ 48 mi/h occurring. Thus the probability of an occurrence between 48 and 50 mi/h is 0.6480 − 0.4920 = 0.1560. The probabilities of column 6 are computed via sequential subtractions as shown here. The result is the probability of a speed being in any speed group, assuming a normal distribution.

4. The theoretical frequencies of column 7 are found by multiplying the sample size by the probability of an occurrence in that speed group. Fractional results are permitted for theoretical frequencies.

5. The chi-square test is valid only when all values of the theoretical frequency are 5 or more. To achieve this, the first two and last two speed groups must be combined. The observed frequencies are similarly combined.

6. The value of chi-square for each speed group is computed as shown. The computation for the 40 to 42 mi/h speed group is illustrated here:

$$\chi_i^2 = \frac{(n_i - f_i)^2}{f_i} = \frac{(13 - 16.3291)^2}{16.3291} = 0.6787$$

These values are summed to yield the final value of x^2 for the distribution, which is 14.3574.

To assess this result, the chi-square table of Chapter 7 is used. Probability values are shown on the horizontal axis of the table. The vertical axis shows *degrees of freedom.* For a chi-square distribution, the number of degrees of freedom is the number of data groups (after they are combined to yield theoretical frequencies of 5 or more), minus 3. Three degrees of freedom are lost because the computation of χ^2 requires that three characteristics of the measured distribution be known: the mean, the standard deviation, and the sample size. Thus, for the illustrative spot speed study, the number of degrees of freedom is $12 - 3 = 9$.

The values of χ^2 are shown in the body of chi-square table. For the illustrative data, the value of χ^2 lies between the tabulated values of 11.39 (Prob = 0.25) and 14.68 (Prob = 0.10). Note also that the probabilities shown in table represent the probability of a value being *greater* than or equal to χ^2. Interpolation is used to determine the precise probability level associated with a value of 14.3574 on a chi-square distribution with 9 degrees of freedom:

Value	Probability
11.3900	0.25
14.3574	*p*
14.6800	0.10

$$p = \text{Prob}(\chi^2 \geq 14.3574)$$

$$= 0.10 + (0.15)\left[\frac{14.6800 - 14.3574}{14.6800 - 11.3900}\right] = 0.1147$$

From this determination, it is 11.47% probable that a value of 14.3574 or higher would exist if the distribution were statistically normal. The decision criteria are the same as for other statistical tests (i.e., to say that the data and the assumed mathematical description are *significantly different,* we must be 95% confident that this is true). For tables that yield a probability of a value *less than or equal to* the computed statistic, the probability must be 95% or more to certify a significant difference. This was the case in the normal approximation test. The corresponding decision point using a table with probabilities greater than or equal to the computed statistic is that the probability must be *5% or less* to certify a significant statistical difference. In the case of the illustrative data, the probability of a value of 14.3574 or greater is 11.47%. This is more than 5%. Thus the data and the assumed mathematical description are *not significantly different,* and its normalcy is successfully demonstrated.

A chi-square test is rarely actually conducted on spot speed results because they are virtually always normal. If the data are seriously skewed or take a shape obviously different from the normal distribution, this will be relatively obvious, and the test can be conducted. It is also possible to compare the data with other types of distributions. A number of distributions have the same general shape as the normal distribution but have skews to the low or high end of the distribution. It is also possible that a given set of data can be reasonably described using a number of different distributions. This does not negate the validity of a normal description when it occurs. As long as speed data can be described as normal, all of the manipulations described here are valid.

If a speed distribution is found to be not normal, then other distributions can be used to describe it, and other statistical tests can be performed. These are not covered in this text, and we refer you to standard statistics textbooks.

10.3 Travel-Time Studies

Travel-time studies involve significant lengths of a facility or group of facilities forming a route. Information on the travel time between key points within the study area is sought and is used to identify those segments in need of improvements. Travel-time studies are often coordinated with delay observations at points of congestion along the study route.

Travel-time information is used for many purposes, including the following:

- To identify problem locations on facilities by virtue of high travel times and/or delay.
- To measure arterial level of service, based on average travel speeds and travel times.
- To provide necessary input to traffic assignment models, which focus on link travel time as a key determinant of route selection.
- To provide travel-time data for economic evaluation of transportation improvements.
- To develop time contour maps and other depictions of traffic congestion in an area or region.

10.3.1 Field Study Techniques

Because significant lengths of roadway are involved, it is difficult to remotely observe vehicles as they progress through the study section. The most common techniques for conducting travel time studies involve driving test cars through the study section, while an observer records elapsed times through the section, and at key intermediate points within the section. The observer is equipped with a field sheet pre-defining the intermediate points for which travel times are desired. The observer uses a stop-watch that is started when the test vehicle enters the study section, and records the elapsed time at each intermediate point, and when the end of the study section is reached. A second stop-watch is used to measure the length of midblock and intersection stops. Their location is noted, and if the cause can be identified, it is also noted.

To maintain some consistency of results, test-car drivers are instructed to use one of three driving strategies:

1. *Floating Car Technique:* In this technique, the test-car driver is asked to pass as many vehicles as pass the test car. In this way, the vehicle's relative position in the traffic stream remains unchanged, and the test car approximates the behavior of an average vehicle in the traffic stream.
2. *Maximum Car Technique:* In this procedure, the driver is asked to drive as fast as is safely practical in the traffic stream, without ever exceeding the design speed of the facility.
3. *Average Car Technique:* The driver is instructed to drive at the approximate average speed of the traffic stream.

The floating car and average car techniques result in estimates of the average travel time through the section. The floating car technique is generally applied only on two-lane highways, where passing is rare, and the number of passings can be counted and balanced relatively easily. On a multilane freeway, such a driving technique would be difficult at best, and might cause dangerous situations to arise, as a test vehicle attempts to "keep up" with the number of vehicles that have passed it. The average car technique yields similar results with less stress applied to the driver of the test vehicle.

The maximum car technique does not result in measurement of average conditions in the traffic stream. Rather, the measured travel times represent the lower range of the distribution of travel times. Travel times are more indicative of a 15th percentile speed than an average. Speeds computed from these travel times are approximately indicative of the 85th percentile speed.

It is important, therefore, that all test car runs in a given study follow the same driving strategy. Comparisons of travel times measured using different driving techniques will not yield valid results.

Issues related to sample size are handled similarly to spot speed studies. When specific driving strategies are followed, the standard deviation of the results is somewhat constrained, and fewer samples are needed. This is important. As a practical issue, too many test cars released into the traffic stream over a short period of time will affect its operation, in effect altering the observed results. For most common applications, the number of test car runs that will yield travel time measurements with reasonable confidence and precision ranges from a low of 6-10 to a high of 50, depending upon the type of facility and the amount of traffic. The latter is difficult to achieve without affecting traffic, and may require that runs be taken over an extended time period, such as during the evening peak hour over several days.

Another technique may be used to collect travel times. Roadside observers can record license plate numbers as vehicles pass designated points along the route. The time of passage is noted along with the license plate number. The detail of delay information at intermediate points is lost with this technique. Sampling is quite difficult, as it is virtually impossible to record every license plate and time. Assume that a sample of 50% of all license plates is recorded at every study location. The probability that a license plate match occurs at two locations is 0.50×0.50, or 0.25 (25%). The probability that a license plate match occurs across three locations is $0.50 \times 0.50 \times 0.50 = 12.5\%$. Also, as there is no consistent driving strategy among drivers in the traffic stream, many more license plate matches are required than test-car runs to obtain similar precision and confidence in the results.

In some cases, elevated vantage points may be available to allow an entire study section to be viewed. The progress of individual vehicles in the traffic stream can be directly observed. This type of study generally involves videotaping the study section, so that many, or even all, vehicle travel times can be observed and recorded.

An alternative to the use of direct observation is to equip the test vehicle with one of several devices that plots speed vs. distance as the vehicle travels through the test section. Data can be extracted from the plot to yield checkpoint travel times, and the locations and time of stopped delays can be determined.

The sample data sheet of Table 10.4 is for a seven-mile section of Lincoln Highway, which is a major suburban multilane highway of six lanes. Checkpoints are defined in terms of mileposts. As an alternative, intersections or other known geographic markers can be used as identifiers. The elapsed stopwatch time to each checkpoint is noted. Section data refer to the distance between the previous checkpoint and the checkpoint noted. Thus, for the section labeled MP 16, the section data refers to the section between mileposts 16 and 17. The total stopped delay experienced in each section is noted, along with the number of stops. The "special notes" column contains the observer's determination of the cause(s) of the delays noted. Section travel times are computed as the difference between cumulative times at successive checkpoints.

In this study, the segments ending in mileposts 18 and 19 display the highest delays and therefore the highest travel times. If this is consistently shown in *all* or *most* of the test runs, these sections would be subjected to more detailed study. Because the delays are indicated as caused primarily by traffic control signals, their timing and coordination would be examined carefully to see if they can be improved. Double parking is also noted as a cause in one segment. Parking regulations would be reviewed, along with available legal parking supply, as would enforcement practices.

10.3.2 Travel Time Along an Arterial: An Example of the Statistics of Travel Times

Given the cost and logistics of travel-time studies (test cars, drivers, multiple runs, multiple days of study, etc.), there is a natural tendency to keep the number of observations, N, as small as possible. This case considers a hypothetical arterial on which the true mean running time is 196 seconds over a three-mile section. The standard deviation of the running time is 15 seconds. The distribution of running

Table 10.4: A Sample Travel-Time Field Sheet

Site: Lincoln Highway *Run No. 3* *Start Location: Milepost 15.0*
Recorder: William McShane *Date: Aug 10, 2002* *Start Time: 5:00 PM*

Checkpoint	Cum. Dist. Along Route (mi)	Cum. Trav. Time (min:sec)	Per Section: Stopped Delay (s)	No. of Stops	Section Travel Time (min:sec)	Special Notes
MP 16	1.0	1:35	0.0	0	1:35	
MP 17	2.0	3:05	0.0	0	1:30	
MP 18	3.0	5:50	42.6	3	2:45	Stops due to signals at: MP17.2 MP17.5 MP18.0
MP 19	4.0	7:50	46.0	4	2:00	Stops due to signal MP18.5 and double parked cars.
MP 20	5.0	9:03	0.0	0	1:13	
MP 21	6.0	10:45	6.0	1	1:42	Stop due to School bus.
MP 22	7.0	12:00	0.0	0	1:15	
Section Totals	**7.0**		**88.6**	**8**	**12:00**	

times is normal. Note that the discussion is, at this point, limited to *running times*. These do not include stopped delays encountered along the route and are not equivalent to *travel times*.

Given the normal distribution of running times, the mean running time for the section is 196 seconds, and 95% of all running times would fall within 1.96(15) = 29.4 seconds of this value. Thus the 95% interval for travel times would be between 196 – 29.4 = 166.6 seconds and 196 + 29.4 = 225.4 seconds. The speeds corresponding to these running times (including the average) are:

$$S_1 = \frac{3\text{mi}}{225.4\text{s}} * \frac{3600\text{s}}{\text{h}} = 47.9\,\text{mi/h}$$

$$S_{av} = \frac{3\text{mi}}{196\text{s}} * \frac{3600\text{s}}{\text{h}} = 55.1\,\text{mi/h}$$

$$S_2 = \frac{3\text{mi}}{1666.6\text{s}} * \frac{3600\text{s}}{\text{h}} = 64.8\,\text{mi/h}$$

Note that the average of the two 95% confidence interval limits is (47.9 + 64.8)/2 = 56.4 mi/h, *not* 55.1 mi/h. This discrepancy is due to the fact that the *running times* are normally distributed and are therefore symmetric. The resulting running speed distribution is skewed. The distribution of speeds, which are inverse to running times, cannot be normal if the running times are normal. The 55.1 mi/h value is the appropriate average speed, based on the observed average running time over the three-mile study section.

So far, this discussion considers only the *running times* of test vehicles through the section. The actual *travel-time* results of 20 test-car runs are illustrated in Figure 10.3.

This distribution does not look normal. In fact, it is not normal at all because the total travel time represents the *sum* of running time (which is normally distributed) and stop time delay that follows another distribution entirely. Specifically, it is postulated that:

No. of Signal Stops	Probability of Occurrence	Duration of Stops
0	0.569	0s
1	0.300	40s
2	0.131	80s

The observations of Table 10.4 result from the combination of random driver selection of running speeds and signal delay effects that follow the relationship just specified.

The actual mean travel time of the observations in Figure 10.3 is 218.5 seconds, with a standard deviation of 38.3 seconds. The 95% confidence limits on the average are:

$$218.5 \pm 1.96(38.3/\sqrt{20}) = 218.5 \pm 16.79$$

$$201.71 - 235.29\text{s}$$

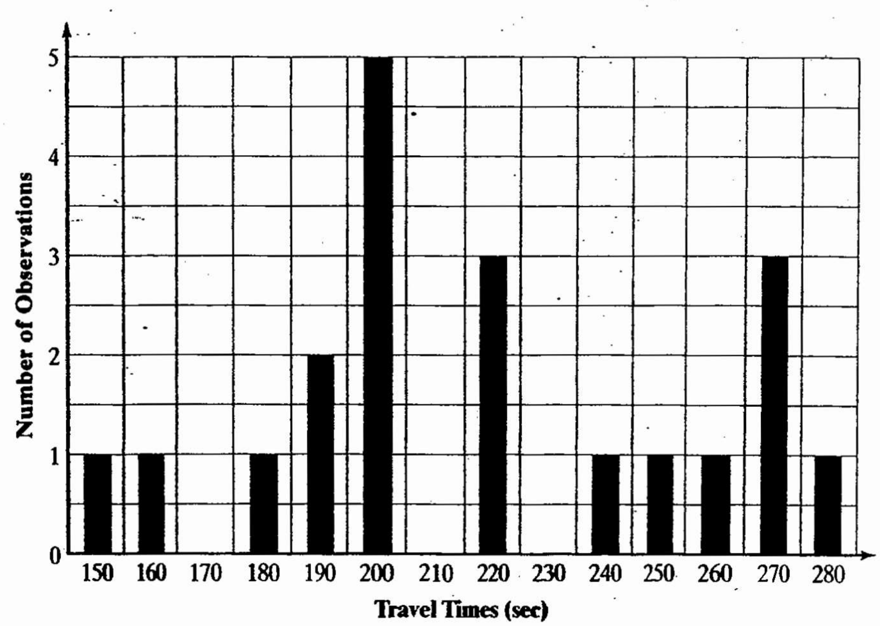

Figure 10.3: Histogram of Hypothetical Travel-Time Data for 20 Runs over a 3-Mile Arterial Segment

The speeds associated with these average and limiting ravel times are:

$$S_1 = \frac{3\text{mi}}{235.29\text{s}} * \frac{3600s}{h} = 45.9\,\text{mi/h}$$

$$S_{av} = \frac{3\text{mi}}{218.5\text{s}} * \frac{3600s}{h} = 49.4\,\text{mi/h}$$

$$S_2 = \frac{3\text{mi}}{201.71\text{s}} * \frac{3600s}{h} = 53.5\,\text{mi/h}$$

Another way of addressing the average travel time is to ıdd the average running time (196 seconds) to the average lelay time, which is computed from the probabilities just ıoted as:

$$d_{av} = (0.569*0) + (0.300*40) + (0.131*80) = 22.5s$$

'he average travel time is then expected to be 196.0 + 22.5 = :18.5s, which is the same average obtained from the ıistogram of measurements.

10.3.3 Overriding Default Values: Another Example of Statistical Analysis of Travel-Time Data

'igure 10.4 shows a default curve calibrated by a local high-/ay jurisdiction for average travel speed along four-lane rterials within the jurisdiction. As with all "standard" alues, the use of another value is always permissible as long s there are specific field measurements to justify replacing ıe standard value.

Assume that a case exists in which the default value of travel speed for a given volume, V_1 is 40 mi/h. Based on three travel-time runs over a two-mile section, the measured average travel speed is 43 mi/h. The analysts would like to replace the standard value with the measured value. Is this appropriate?

The statistical issue is whether or not the observed 3 mi/h difference between the standard value and the measured value is *statistically significant*. As a practical matter (in this hypothetical case), practitioners generally believe that the standard values of Figure 10.4 are too low and that higher values are routinely observed. This suggests that a one-sided hypothesis test should be used.

Figure 10.5 shows a probable distribution of the random variable $Y = \Sigma t_i/N$, the estimator of the average travel time through the section. Based on the standard and measured average travel speeds, the corresponding travel times over a two-mile section of the roadway are (2/40) * 3,600 = 180.0s and (2/43) * 3,600 = 167.4 s. These two values are formulated, respectively, as the null and alternative hypotheses, as illustrated in Figure 10.5. The following points relate to Figure 10.5:

- Type I and Type II errors are equalized and set at 5% (0.05).
- From the standard normal table of Chapter 7, the value of z_d corresponding to Prob. $(z \le z_d) = 0.95$ (corresponding to a one-sided test with Type I and II errors set at 5%) is 1.645.
- The difference between the null and alternate hypotheses is a travel time of 180.0 − 167.4 = 12.6, noted as Δ.
- The standard deviation of travel times is known to be 28.0s.

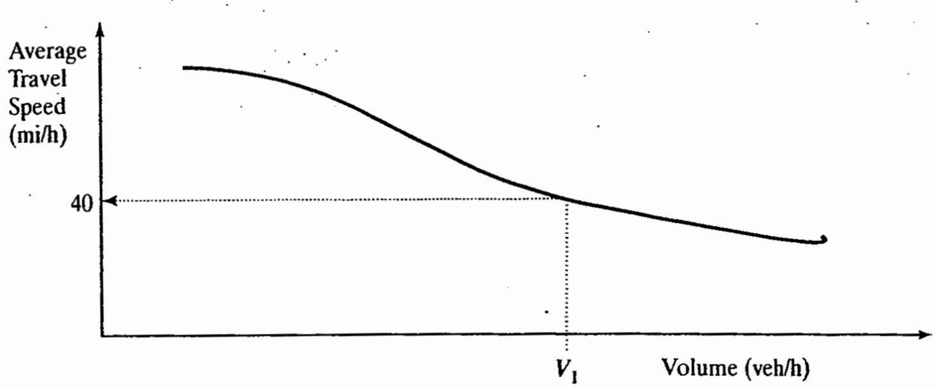

Figure 10.4: Default Curve Specified by Agency (Illustrative)

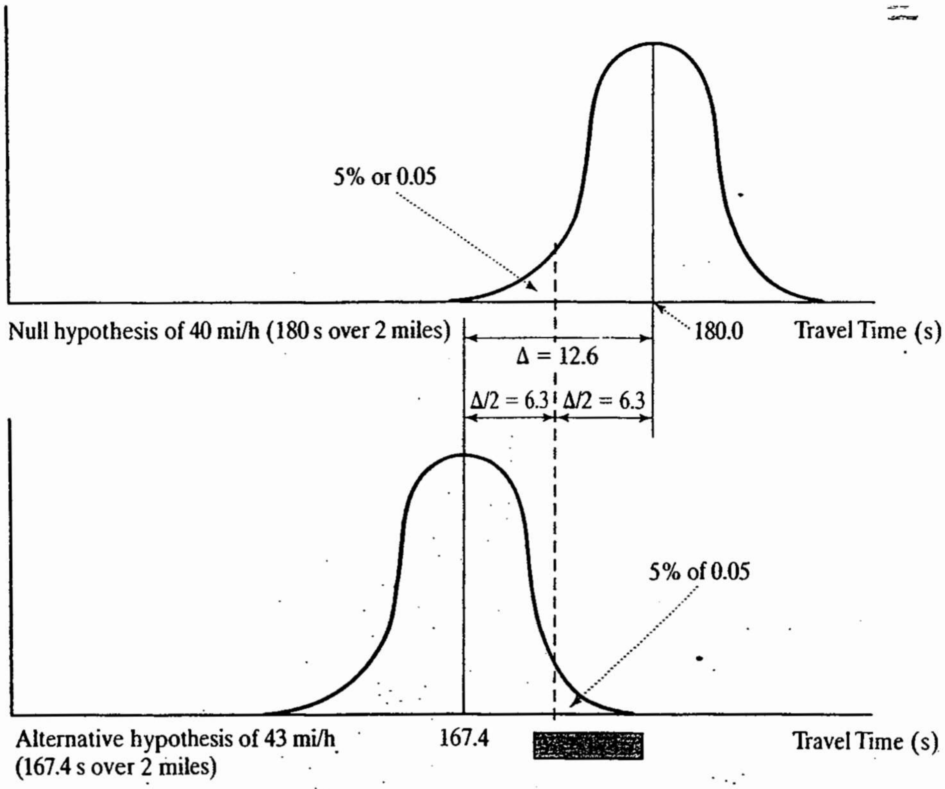

Figure 10.5: Testing the Default (Null Hypothesis) Against the Proposed Alternative Hypothesis

From Figure 10.5, for the difference between the default and alternative hypotheses to be statistically significant, the value of $\Delta/2$ must be equal to or larger than 1.645 times the standard error for travel times, or:

$$\Delta/2 \geq 1.645\left(s \big/ \sqrt{N}\right)$$

$$6.3 \geq 1.645\left(28 \big/ \sqrt{3}\right) = 26.6$$

Obviously, in this case the difference is not significant, and the measured value of 43 mi/h cannot be accepted in place of the default value. This relationship can, of course, be solved for N:

$$N \geq \frac{8{,}486}{\Delta^2}$$

using the known value of the standard deviation (28). Remember that Δ is stated in terms of the difference in *travel times* over the two-mile test course, not the difference in average travel speeds. Table 10.5 shows the sample size

Table 10.5: Required Sample Sizes and Decision Values for the Acceptance of Various Alternative Hypotheses

Default Value (Average Travel Speed) (mi/h)	Alternative Hypothesis (Average Travel Speed) (mi/h)	Required Sample Size N	Decision Point (Average Travel Speed) Y (mi/h)
40	42	≥115	41.0
40	43	≥54	41.4
40	44	≥32	41.9
40	45	≥22	42.4

quirements for accepting various alternative average travel ɪeeds in place of the default value. For the alternative ɪpothesis of 43 mi/h to be accepted, a sample size of $486/(12.6)^2 = 54$ would have been required. However, as ustrated in Figure 10.5, had 54 samples been collected, the ternative hypothesis of 43 mi/h would have been accepted long as the average travel time was less than 173.7 s (i.e., e average travel speed was greater than (2/173.7) * 3,600 = .5 mi/h. Table 10.5 shows a number of different alternative ɪpotheses, along with the required sample sizes and decision ɪints for each to be accepted.

Although this problem illustrates some of the statistical ıalyses that can be applied to travel-time data, you should .amine whether the study, as formulated, is appropriate. ıould the Type II error be equalized with the Type I error? oes the existence of a default value imply that it should not? ıould an alternative value higher than any measured value ˈer be accepted? (For example, should the alternative ɪpothesis of 43 mi/h be accepted if the average travel speed om a sample of 54 or more measurements is 41.6 mi/h, hich is greater than the decision value of 41.5 mi/h?)

Given the practical range of sample sizes for most travel-time studies, it is very difficult to justify overriding default values for individual cases. However, a compendium of such cases—each with individually small sample sizes—can and should motivate an agency to review the default values and curves in use.

10.3.3 Travel-Time Displays

Travel-time data can be displayed in many interesting and informative ways. One method that is used for overall traffic planning in a region is the development of a travel-time contour map, of the type shown in Figure 10.6. Travel times along all major routes entering or leaving a central area are measured. Time contours are then plotted, usually in increments of 15 minutes. The shape of the contours gives an immediate visual assessment of corridor travel times in various directions. The closer together contour lines plot, the longer the travel time to progress any set distance. Such plots can be used for overall planning purposes and for identifying corridors and segments of the system that require improvement.

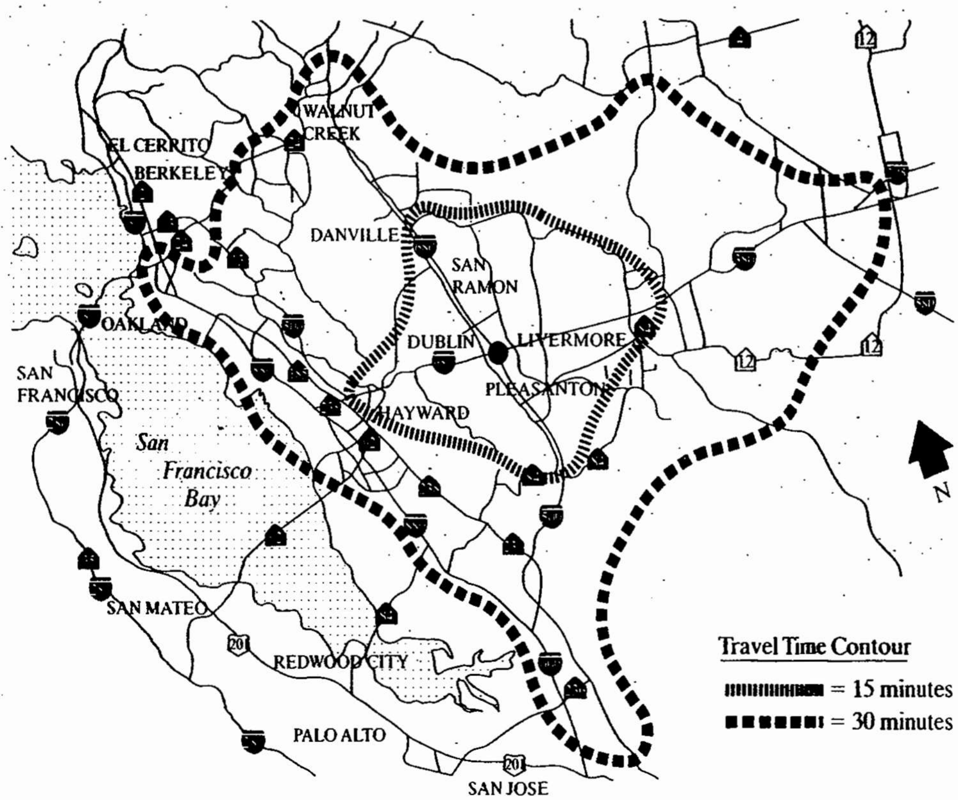

Figure 10.6: A Travel-Time Contour Map

(*Source:* Used with permission of Prentice-Hall Inc, from Pline, J., Editor, *Traffic Engineering Handbook*, 4th Edition, Institute of Transportation Engineers, Washington DC, 1992, p. 69.)

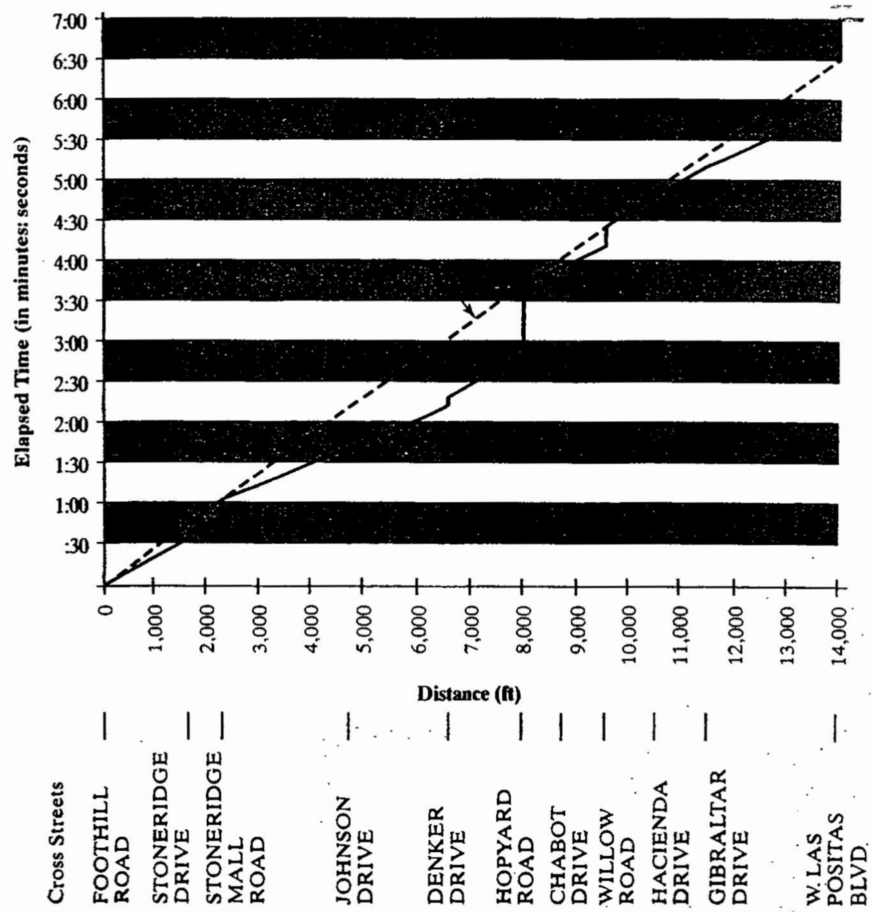

Figure 10.7: A Plot of Elapsed Time Versus Distance

(*Source*: Used with permission of Prentice-Hall Inc, from Pline, J., Editor, *Traffic Engineering Handbook*, 4th Edition, Institute of Transportation Engineers, Washington DC, 1992.)

Travel time along a route can be depicted in different ways as well. Figure 10.7 shows a plot of cumulative time along a route. The slope of the line in any given segment is speed (ft/s), and stopped delays are clearly indicated by vertical lines. Figure 10.8 shows average travel speeds plotted against distance. In both cases, problem areas are clearly indicated, and the traffic engineer can focus on those sections and locations experiencing the most congestion, as indicated by the highest travel times (or lowest average travel speeds).

10.4 Intersection Delay Studies

Some types of delay are measured as part of a travel-time study by noting the location and duration of stopped periods during a test run. A complicating feature for all delay studies lies in the various definitions of delay, as reviewed earlier in the chapter. The measurement technique must conform to the delay definition.

Before 1997, the primary delay measure at intersections was stopped delay. Although no form of delay is easy to measure in the field, stopped delay was certainly the easiest. However, the current measure of effectiveness for signalized and STOP-controlled intersections is *total control delay*. Control delay is best defined as time-in-queue delay plus time losses due to deceleration from and acceleration to ambient speed. The 2000 *Highway Capacity Manual* [1] defines a field measurement technique for control delay using the field sheet shown in Figure 10.9.

The study methodology recommended in the *Highway Capacity Manual* is based on direct observation of

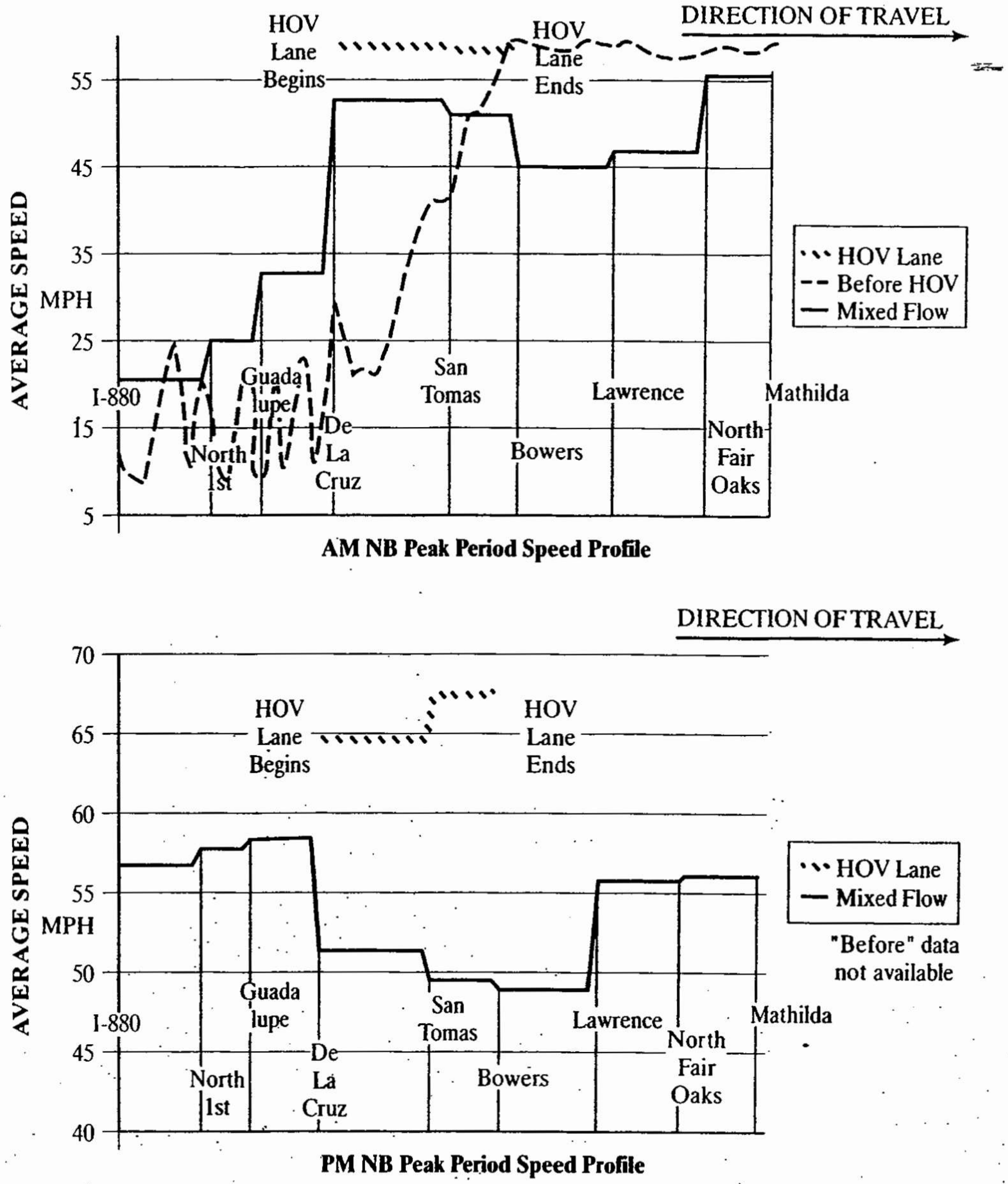

Figure 10.8: Average Travel Speeds Plotted Versus Segments of a Route

(*Source:* Used with permission of Prentice-Hall Inc, from Pline, J., Editor, *Traffic Engineering Handbook*, 4th Edition, Institute of Transportation Engineers, Washington DC, 1992.)

vehicles-in-queue at frequent intervals and requires a minimum of two observers. The following should be noted:

1. The method is intended for undersaturated flow conditions, and for cases where the maximum queue is about 20 to 25 vehicles.
2. The method does not directly measure acceleration-deceleration delay but uses an adjustment factor to estimate this component.
3. The method also uses an adjustment to correct for errors that are likely to occur in the sampling process.
4. Observers must make an estimate of free-flow speed before beginning a detailed survey. This is done by driving a vehicle through the intersection during periods when the light is green and there are no queues and/or by measuring approach speeds at a position where they are unaffected by the signal.

Actual measurements start at the beginning of the red phase of the subject lane group. There should be no overflow queue from the previous green phase when

INTERSECTION CONTROL DELAY WORKSHEET

General Information	Information
Analyst ______	Intersection ______
Agency or Company ______	Area Type ☐ CBD ☐ Other
Date Performed ______	
Analysis Time Period ______	Analysis Year ______

Input Initial Parameters

Number of Lanes, N ______	Total Vehicles Arriving V_T ______
	Stopped Vehicle Count V_{STOP} ______
Survey Count Interval I_s ______	Cycle Length D (s) ______

Input Field Data

Clock Time	Cycle Number	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
Total											

Figure 10.9: Field Sheet for Signalized Intersection Delay Studies

(*Source:* Used with permission of Transportation Research Board, *Highway Capacity Manual*, 4th Edition, Washington DC, p. 16-173.)

measurements start. The following tasks are performed by the two observers:

Observer 1

- Keeps track of the end of standing queues for each cycle by observing the last vehicle in each lane that stops due to the signal. This count includes vehicles that arrive on green but stop or approach within one car length of queued vehicles that have not yet started to move.
- At intervals between 10 seconds and 20 seconds, the number of vehicles in queue are recorded on the field sheet. The regular intervals for these observations should be an integral divisor of the cycle length. Vehicles in queue are those that are included in the queue of stopping vehicles (as just defined) and have not yet exited the

intersection. For through vehicles, "exiting the intersection" occurs when the rear wheels cross the STOP line; for turning vehicles, "exiting" occurs when the vehicle clears the opposing vehicular or pedestrian flow to which it must yield and begins to accelerate.

- At the end of the survey period, vehicle-in-queue counts continue until all vehicles that entered the queue during the survey period have exited the intersection.

Observer 2

- During the entire study period, separate counts are maintained of vehicles arriving during the survey period and of vehicles that stop one or more times during the survey period. Stopping vehicles are counted only once, regardless of how many times they stop.

For convenience, the survey period is defined as an integer number of cycles, although an arbitrary length of time (e.g., 15 minutes) could also be used and would be necessary where an actuated signal is involved.

Each column of the vehicle-in-queue counts is summed; the column sums are then added to yield the total vehicle-in-queue count for the study period. It is than assumed that the average time-in-queue for a counted vehicle is the time interval between counts. Then:

$$T_Q = \left(I_s * \frac{\sum V_{iq}}{V_T} \right) * 0.90 \qquad (10\text{-}15)$$

where: T_Q = average time-in-queue, s/veh
I_s = time interval between time-in-queue counts, s
$\sum V_{iq}$ = sum of all vehicle-in-queue counts, vehs
V_T = total number of vehicles *arriving* during the study period, vehs
0.9 = empirical adjustment factor

The adjustment factor (0.9) adjusts for errors that generally occur when this type of sampling technique is used. Such errors usually result in an overestimate of delay.

A further adjustment for acceleration/deceleration delay requires that two values be computed: (1) the average number of vehicles stopping per lane, per cycle, and (2) the proportion of vehicles arriving that actually stop. These are computed as:

$$V_{SLC} = \frac{V_{STOP}}{N_c * N_L} \qquad (10\text{-}16)$$

where: V_{SLC} = number of vehicles stopping per lane, per cycle (veh/ln/cycle)
V_{STOP} = total count of stopping vehicles, vehs
N_c = number of cycles included in the survey
N_L = number of lanes in the survey lane group

$$FVS = \frac{V_{STOP}}{V_T} \qquad (10\text{-}17)$$

where FVS = fraction of vehicles stopping
other variables as previously defined

Using the number of stopping vehicles per lane, per cycle, and the measured free-flow speed for the approach in question, an adjustment factor is found in Table 10.6.

The final estimate of control delay is then computed as:

$$d = T_Q + (FVS * CF) \qquad (10\text{-}18)$$

where: d = total control delay, s/veh
CF = correction factor from Table 10.6
other variables as previously defined

Table 10.7 shows a facsimile of a field sheet, summarizing the data for a survey on a signalized intersection approach. The approach has two lanes, and the signal cycle length is 60 seconds. Ten cycles were surveyed, and the vehicle-in-queue count interval is 20 seconds.

The average time-in-queue is computed using Equation 10-15:

$$T_Q = \left(20 * \frac{132}{120} \right) * 0.90 = 19.8 s/veh$$

To find the appropriate correction factor from Table 10.6, the number of vehicles stopping per lane per cycle is computed using Equation 9-16:

$$V_{SLC} = \frac{75}{10 * 2} = 3.75 \text{vehs}$$

Using this and the measured free-flow speed of 35 mi/h, the correction factor is +5 seconds. The control delay is now estimated using Equations 10-17 and 10-18:

$$\text{FVS} = \frac{75}{120} = 0.625$$

$$d = 19.8 + (0.625 * 5) = 22.9 s/veh$$

A similar technique and field sheet can be used to measure stopped time delay as well. In this case, the interval counts

Table 10.6: Adjustment Factor for Acceleration/Deceleration Delay

Free-Flow Speed (mi/h)	Vehicles Stopping Per Lane, Per Cycle (V_{SLC})		
	≤7 vehs	8–19 vehs	20–30 vehs
≤37	+5	+2	−1
>37 − 45	+7	+4	+2
>45	+9	+7	+5

(*Source:* Used with permission of Transportation Research Board, *Highway Capacity Manual*, 4th Edition, Washington DC, 2000, Exhibit A16-2, p. 16-91.)

Table 10.7: Sample Data for a Signalized Intersection Delay Study

Clock Time	Cycle Number	Number of Vehicles in Queue		
		+0 s	+20 s	+40 s
5:00 PM	1	4	7	5
5:01 PM	2	6	6	5
5:02 PM	3	3	5	5
5:03 PM	4	2	6	4
5:04 PM	5	5	3	3
5:05 PM	6	5	4	5
5:06 PM	7	6	8	4
5:07 PM	8	3	4	3
5:08 PM	9	2	4	3
5:09 PM	10	4	3	5
	Total	40	50	42

$\Sigma V_{qi} = 132$ vehs $V_T = 120$ vehs $V_{STOP} = 75$ FFS = 35 mi/h

include only vehicles stopped within the intersection queue area, not those moving within it. No adjustment for acceleration/deceleration delay would be added.

10.5 Closing Comments

Time is one of the key commodities that motorists and other travelers invest in getting from here to there. Travelers most often wish to minimize this investment by making their trips as short as possible. Travel-time and delay studies provide the traffic engineer with data concerning congestion, section travel times, and point delays. Through careful examination, the causes of congestion, excessive travel times, and delays can be determined and traffic engineering measures developed to ameliorate problems.

Speed is the inverse of travel time. Although travelers wish to maximize the speed of their trip, they also wish to do so consistent with safety. Speed data provide insight into many factors, including safety, and are used to help time traffic signals, set speed limits, locate signs, and in a variety of other important traffic engineering activities.

References

1. *Highway Capacity Manual*, 4th Edition, Transportation Research Board, National Science Foundation. Washington DC, 2000.

. Highway Capacity Manual, 3rd Edition, *Special Report 209*, Transportation Research Board, National Science Foundation, Washington DC, 1985.

roblems

-1. Consider the spot speed data here, collected at a rural highway site under conditions of uncongested flow:

Speed Group (mi/h)	Number of Vehicles Observed (N)
15–20	0
20–25	4
25–30	9
30–35	18
35–40	35
40–45	42
45–50	32
50–55	20
55–60	9
60–65	0

(a) Plot the frequency and cumulative frequency curves for this data.

(b) Determine the median speed, the modal speed, the pace, and the percentage of vehicles in the pact from the curves, and show how each was found.

(c) Compute the mean and standard deviation of the speed distribution.

(d) What are the confidence bounds of the estimate of the true mean speed of the distribution with 95% confidence? With 99.7% confidence?

(e) Based on the results of this study, a second is to be conducted to achieve a tolerance of ± 0.8 mi/h with 95% confidence. What sample size is required?

(f) Can this data be adequately described as "normal?"

2. A before-and after speed study was conducted to determine the effectiveness of a series of rumble strips installed approaching a toll plaza to reduce approach speeds to 40 mi/h.

Item	Before Study	After Study
Average Speed	43.5 mi/h	40.8 mi/h
Standard Deviation	4.8 mi/h	5.3 mi/h
Sample Size	120	108

(a) Were the rumble strips effective in reducing average speeds at this location?

(b) Were the rumble strips effective in reducing average speeds to 40 mi/h?

10-3. The following data were collected during a delay study on a signalized intersection approach. The cycle length of the signal is 60 seconds.

(a) Estimate the time spent in queue for the average vehicle.

(b) Estimate the average control delay per vehicle on this approach.

Clock Time	Cycle Number	Number of Vehicles in Queue			
		+ 0 s	+ 15 s	+ 30 s	+ 45 s
9:00 AM	1	3	4	2	4
9:01 AM	2	1	2	3	3
9:02 AM	3	4	3	3	4
9:03 AM	4	2	3	3	4
9:04 AM	5	0	1	2	3
9:05 AM	6	2	1	1	2
9:06 AM	7	4	3	4	3
9:07 AM	8	5	5	6	4
9:08 AM	9	2	3	4	3
9:09 AM	10	0	3	2	2
9:10 AM	11	1	2	3	1
9:11 AM	12	1	0	1	0
9:12 AM	13	2	2	1	2
9:13 AM	14	2	3	2	2
9:14 AM	15	4	3	3	3

Note: $V_T = 435$ vehs; $V_{STOP} = 305$ vehs; FFS = 35 mi/h.223.

10-4. A series of travel time runs are to be made along an arterial section. Tabulate the number of runs required to estimate the overall average travel time with 95% confidence to within ±2 min, ±5 min, ±10 min, for standard deviations of 5, 10, and 15 minutes. Note that a 3 × 3 table of values is desired.

10-5. The results of a travel time study are summarized in the table that follows. For this data:

(a) Tabulate and graphically present the results of the travel time and delay runs. Show the average travel speed and average running speed for each section.

(b) Note that the number of runs suggested in this Problem (5) is not necessarily consistent with the results of Problem 10-3. Assuming that *each vehicle* makes five runs, how many test vehicles would be needed to achieve a tolerance of ±3 with 95% confidence?

Erin Blvd   Recorder: XYZ   Summary of 5 Runs

Checkpoint Number	Cumulative Section Length (mi)	Cumulative Travel Time (min:sec)	Per Section	
			Delay (s)	No. of Stops
1	—	—	—	—
2	1.00	2:05	10	1
3	2.25	4:50	30	1
4	3.50	7:30	25	1
5	4.00	9:10	42	2
6	4.25	10:27	47	1
7	5.00	11:54	14	1