

# Assessment of Roadway Capacity Estimation Methods

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Capacity is a central concept in roadway design and traffic control. Estimation of empirical capacity values in practical circumstances is not a trivial problem; it is very difficult to define capacity in an unambiguous manner. Empirical capacity estimation for uninterrupted roadway sections has been studied. Headways, traffic volumes, speed, and density are traffic data types used to identify four groups of capacity estimation methods. Aspects such as data requirement, location choice, and observation period were investigated for each method. The principles of the different methods and the mathematical derivation of roadway capacity are studied and discussed. Among the methods studied are the headway distribution approaches, the bimodal distribution method, the selected maxima, and the direct probability method. Of the methods based on traffic volume counts, the product limit method is recommended for practical application because of sound underlying theory. An example of the application of this promising method is presented. Attempts to determine the validity of existing roadway capacity estimation methods were disappointing because of the many ambiguities related to the derived capacity values and distributions. A reliable and meaningful estimation of capacity is not yet possible. Lack of a clear definition of the notion of capacity is the main hindrance in understanding what exactly represents the estimated capacity value or distribution in the various methods. If this deficiency is corrected, promising methods for practical use in traffic engineering are the product limit method, the empirical distribution method, and the well-known fundamental diagram method, in that order. The choice of a particular method strongly depends on the available data.

In general, the capacity of a facility is defined as the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions (1).

Any change in the prevailing conditions results in a change in the capacity of the facility. It is also important to note that capacity refers to a rate of vehicular or person flow during a specified period. Furthermore, capacity is assumed to be of a stochastic nature because of differences in individual driver behavior and changing road and weather conditions.

The capacity of a road, and especially the capacity of freeways, is an essential ingredient in the planning, design, and operation of roads. It is desirable for a traffic analyst to be able to predict the times and places where congestion will occur, the amount of delay involved, and the volumes to be expected in bottlenecks. Therefore, it is important that capacity is clearly defined, is measurable, and can be used in modeling and decision making.

This paper deals with methods for estimating empirical capacity values in practical conditions. It is based on a study conducted by

Minderhoud et al. (2) to which the reader is referred for a more detailed examination of capacity-estimation methods.

After describing the difficulty of defining the notion of capacity, a short description is given of the basic elements used in the various empirical capacity-estimation methods. This concerns the type of data used, measurement location, data selection, and so forth. Methods are reviewed according to the type of traffic data needed in the estimation method—that is, headways or traffic volumes—in combination with traffic speeds or densities as auxiliary variables to determine the state of traffic during the measurements.

## DEFINITIONS

Although the capacity definition described above can easily be understood, misunderstanding in interpreting the derived value can easily occur. This is because there are different approaches to expressing the capacity of a road. Figure 1 presents a scheme in which the various approaches (with corresponding definitions) are distinguished. The capacity-estimation problem was divided into two categories: the direct-empirical and indirect-empirical methods. In this paper, the focus is on direct-empirical studies, which are directed at estimation of capacity value(s) at a specific site with traffic observations from that site.

The following definitions are used to distinguish the different meanings of the various roadway capacity value notions:

- **Design capacity:** A single capacity value (possibly derived from a capacity distribution) representing the maximum traffic volume that may pass a cross section of a road with a certain probability under predefined road and weather conditions. This value is used for planning and designing roads and carriageways and may be derived from the indirect-empirical capacity estimation methods, as described in the *Highway Capacity Manual* (HCM) (1).
- **Strategic capacity:** A capacity value (possibly derived from a capacity distribution) representing the maximum traffic volume a road section can handle, which is assumed to be a useful value for analyzing conditions in road networks (e.g., traffic flow assignment and simulation). This capacity value or distribution is based on observed traffic flow data by static capacity models.
- **Operational capacity:** A capacity value representing the actual maximum flow rate of the roadway, which is assumed to be a useful value for short-term traffic forecasting and with which traffic control procedures may be performed. This value is based on direct-empirical capacity methods with dynamic capacity models, such as the on-line procedure (3).

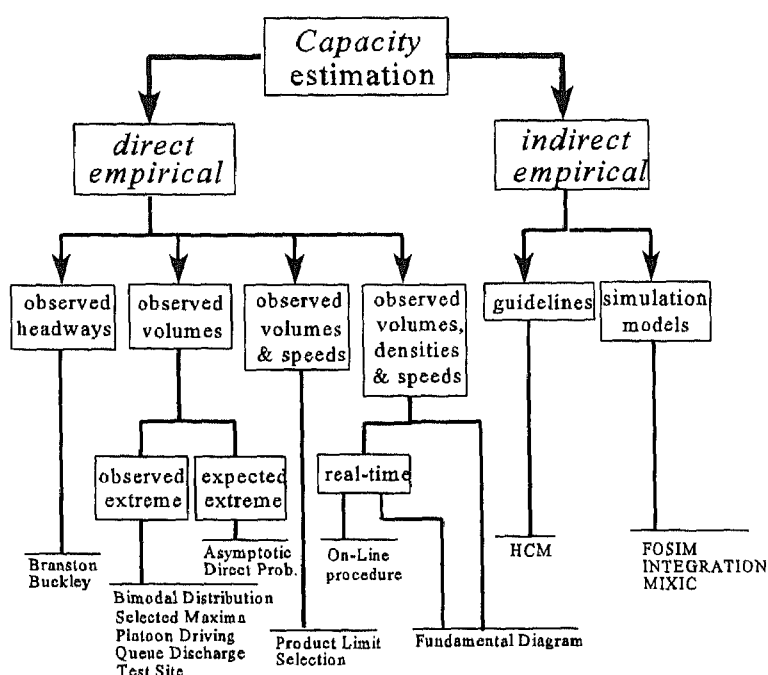


FIGURE 1 Classification of roadway capacity-estimation methods.

Given the dependence on traffic control, weather, and other changing conditions, there is no generally valid single capacity value, but capacity is much more a stochastic variate following a distribution function. Such capacity distributions can be used to choose a suitable capacity value, for example, the average, median, or 90th percentile of the distribution. However, the type of distribution is not yet known. As a lot of factors with a large or small effect on capacity act in an additive way and no clear lower and upper limit can be given, a Gaussian distribution appears to be a reasonable first assumption. The empirical evidence (4) so far gives no reason to reject that assumption. The mean and variance of this distribution depend on prevailing conditions.

Even under ideal conditions, as defined in the HCM (1), capacity is not a constant because in such a flow unobservable variations in driver and vehicle characteristics are present. The desired ideal conditions for determining the ideal capacity value (or distribution) often cannot be obtained. Therefore, the capacity-estimation methods are also applied under nonideal conditions, and this causes extra variance in the stochastic capacity variable (see Figure 2).

To establish a design, strategic, or operational capacity value for engineering objectives, well-defined and well-established methods are desired. However, so far the comparative performance and validity of most methods are not sufficiently known. Capacity is a theoretical notion that lacks a generally accepted operational definition from which an unambiguous method of measurement may be derived.

The estimation of a capacity value or, even better, a complete capacity distribution is a difficult engineering problem, which was one of the reasons for performing this overview study. The remainder of the paper is confined to an elaboration and comparison of the direct-empirical estimation methods from the literature. Only methods for capacity estimation of uninterrupted roadway sections will be involved.

Table 1 gives an overview of the methods reviewed here. It includes the most important characteristics that may be applied as criteria for assessment, namely, data needs (headways, traffic counts, speeds, and density/occupancy), required traffic state (free-flow intensity measurements and/or congested flow measurements), outcome (a single capacity value, a capacity value distribution), and capacity type (prequeue or queue discharge), respectively, indicated in columns 2 to 10. A tentative value is given for the practical validity of each method (column 11). These values, which are a subjective judgment of the methods based on the criteria, are as follows: -- (very bad), - (bad), o (mediocre), + (good), and ++ (very good). Additional criteria include the computational demand of the estimation procedure, viability of the theory, and expected uncertainties of the outcomes. For example, headway approaches were judged negatively because this estimation procedure results in a single capacity value and it is assumed that this value overestimates road capacity. The product limit method was judged positively because

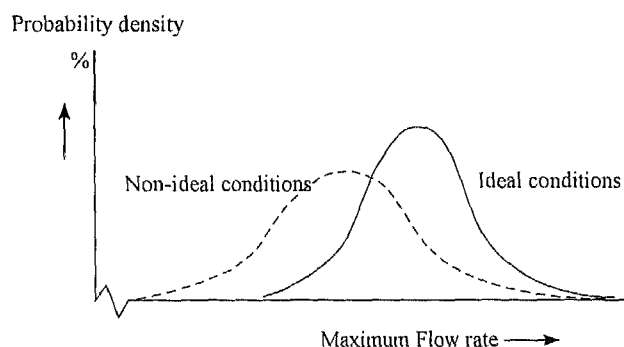


FIGURE 2 Capacity as a stochastic variable.

TABLE 1 Overview of Capacity-Estimation Methods and Their Characteristics

	1	2	3	4	5	6	7	8	9	10	11
Section	Method:	Data needs:				Traffic State <sup>a</sup> :		Capacity:		Type <sup>b</sup> :	Validity:
		h	q	v	k	{Q}	{C}	q <sub>c</sub>	F(q)		(- , -, o, +, ++)
4-1	Headway Models	Yes				Yes		Yes		1	-
4-2-1	Blmodal Distr.		Yes			Yes	Yes		Yes	m	o
4-2-2	Selected Maxima		Yes			Yes	Yes		Yes	m	o
4-2-3	Direct Probability		Yes				Yes	Yes		d	-
4-2-3	Asymptotic		Yes				Yes	Yes		d	--
4-3-1	Empirical Distr.		Yes	Yes			Yes		Yes	2	+
4-3-1	Product Limit		Yes	Yes		Yes	Yes		Yes	m	++
4-3-1	Selection		Yes	Yes		Yes	Yes	Yes		m	-
4-4-1	Fundamental Dgrm.		Yes	(Yes)	Yes	Yes		Yes		d	+
4-4-2	On-Line Procedure		Yes	Yes	Yes	Yes		Yes		1	o

<sup>a</sup> {Q} represents free flow intensities, {C} represents congested flow intensities (under the condition of a congested traffic state upstream leading to *maximum* congested flow intensities).

<sup>b</sup> type 1 denotes a capacity value estimation representing the maximum free flow intensity, type 2 denotes a capacity value estimation representing the maximum congested flow intensity, *m* stands for type 1 and 2 mixed into one capacity estimate and *d* stands for the dependency with the study set up (either type 1 or 2 is possible).

the theory is well-documented and the calculation will give a capacity distribution instead of a single value.

## ESSENTIAL ELEMENTS IN ROADWAY CAPACITY ESTIMATION

### Theory

Two essential types of traffic data are needed to estimate the capacity of a road (at a cross section): traffic volumes and headways. However, additional information about traffic flow conditions, such as density, occupancy, and mean speed, are helpful. Speed data are needed to determine the state of traffic (stable, unstable, and congested traffic flow). Because congested flow (mean speed drops below a certain value) upstream of a bottleneck means that the capacity level has been reached in the bottleneck itself, it is possible to make a more reliable capacity estimate. A stable traffic flow exists when drivers can hold their desired speed. With increasing density (number of vehicles per kilometer of roadway), the average speed decreases and the traffic process becomes unstable. This unstable situation can suddenly change into a situation with lower speeds and lower intensities, so-called congestion.

Although many points of interest have already been mentioned, other questions remain. Westland (5) and Persaud and Hurdle (6), for example, discuss whether there is a capacity drop at critical density. If there is, which value then represents the desired capacity value, the prequeue or the queue discharge maximum volume? The

discontinuity question is not discussed here in detail; nonetheless, it should be kept in mind when interpreting results (see column 11 in Table 1).

### Elements of the Observations

The capacity-estimation problem consists of a series of essential points of interest.

#### Type of Data To Be Collected

The first choice is between traffic volume and headways as the basic variable in the capacity-estimation methods. Additional data (such as average or individual speed, density, or occupancy measurements) may complete the data demand of a certain method.

#### Location Choice for Observations

The traffic data with which the capacity of a road is estimated should be collected at one or more cross sections of the road. Some methods require observations at the capacity level of the flow, for example, the product limit method. To ensure this condition, congestion has to occur upstream of the measuring point at a bottleneck (Figure 3). Downstream and at the measuring point, no congestion is allowed, otherwise the capacity of the road at the cross section cannot be reliably determined; this is the case when the real bottleneck is located further downstream.

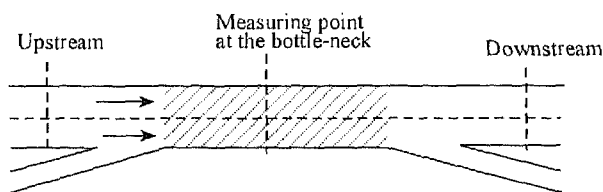


FIGURE 3 Measuring point at bottleneck.

#### Choice for Appropriate Averaging Interval

The duration of the smallest period in which the number of passing cars is counted and aggregated (definition, the averaging interval) is to a large extent arbitrary, and the results must be interpreted with this in mind. In particular, it is well known that a very large rate of flows can be observed over very short periods, for example, 1 min, but they occur much less frequently over longer periods. The 15-min interval appears to be a good compromise because the independence of the observations between the averaging intervals can be defended, local fluctuations are smoothed out, and the maximum traffic volume can hold for more than the duration of the interval (4).

#### Needed Observation Period

The total observation period, which consists of one or more averaging intervals, can be, for example, 1 hr (e.g., during the morning or evening peak period), or 1 hr repeated every day for a certain number of days. It is mostly assumed that during the observation period the rate of flows measured over the averaging intervals is drawn out of the same distribution (identically distributed). The needed total observation period also depends on the duration of the chosen averaging interval.

#### Required Traffic State

Traffic flow is considered to be uncongested when the traffic demand does not exceed the capacity of the road for a longer period. Under this condition, the measured traffic flow rate equals the traffic demand. When congestion or traffic with low speed has been detected upstream, the traffic demand at the downstream bottleneck is assumed to be higher than the capacity of the bottleneck.

#### Lane or Carriageway

Most methods can be used for a whole cross section, including all the lanes of the road in one direction. One may conclude that these methods can also be applied for one lane only.

### CAPACITY ESTIMATION METHODS

Important aspects concerning the survey set up as described above are discussed for each method in the following sections.

#### Estimation with Headways

The headway models are based on the theory that, at the capacity level of the road, all driver-vehicle elements are constrained.

These models can be applied only for a single lane. In the case of multiple-lane freeways, the lanes are treated separately (also called decomposition per lane). Two well-known headway models are used frequently, namely, Branstons generalized queueing model (7) and Buckley's semi-Poisson model (8). Both approaches are based on the Poisson point process but with some slight differences in the assumptions concerning driver behavior in traffic flows. Equations 1 and 2 are the basis for capacity estimation with headway distribution models. The time headway is defined by the time between successive vehicles (measured from rear bumper to rear bumper) that pass a given point in a lane in a traffic stream:

$$h_m = \sum h_p / n \quad (\text{sec per vehicle})$$

$$q = n/T = 1/h_m \quad (\text{vehicles per sec}) \quad (1)$$

$$q = 3,600/h_m \quad (\text{vehicles per hr}) \quad (2)$$

where

$h_p$  = time of headway vehicle  $p$  to preceding vehicle (sec per vehicle);

$h_m$  = mean time headway (sec per vehicle);

$q$  = intensity; and

$n$  = total number of vehicles passing the measuring point during time  $T$ .

The models are based on the theory that driver-vehicle elements in any traffic stream can be divided into two groups: the constrained drivers (followers) and the free drivers (leaders). The distribution of tracking headways of constrained drivers at the capacity level of the road is expected to be the same as for constrained drivers in any stable (stationary) traffic stream. Therefore, the capacity at a cross section of the road can be estimated with the reciprocal of the mean time headway of constrained vehicles. Derivation of the models is in references (7–9). The basic principle is determination of the parameters of the compound probability density function of headways  $f(h)$ , given by

$$f(h) = \phi \times g(h) + (1 - \phi) \times b(h) \quad (3)$$

where

$\phi$  = fraction of followers (constrained drivers) ( $0 \leq \phi \leq 1$ );

$g(h)$  = followers' probability density function of tracking headway; and

$b(h)$  = leaders' probability density function of free headway.

The advantage of headway models in estimating the capacity is that only headways at one cross section of an arterial observed at an intensity below capacity are needed. Hence, it is not necessary to wait for a traffic state at about capacity level. In addition, the headway models for a single lane can be applied for both stable and unstable traffic conditions.

Several investigations with these models resulted in a general conclusion that the headway models substantially overestimate observed road capacity (9,10). This is probably caused by the implicit assumption of the models that the distribution of constrained drivers  $g(h)$  at capacity level can be compared with the distribution  $g(h)$  at an intensity below capacity. The headway method, therefore, is probably not the best way to derive a reliable capacity value.

## Estimation with Traffic Volumes

Capacity-estimation methods based solely on observed traffic volumes can be divided into two extreme value approaches based on observed and expected extremes (Figure 1). Observed extreme value methods, such as the bimodal and selected maxima methods, estimate the capacity of a road by using only known maximum traffic volumes acquired over a certain period.

The expected extreme value methods, such as the direct probability and asymptotic methods, also use observed extreme traffic volumes to determine a capacity value; however, these methods use extreme flow rates observed in the averaging intervals to predict a higher (unobserved) capacity value by statistical methods used in other disciplines (e.g., astronomy).

### Bimodal Distribution Method

When the observed traffic stream includes intensities at about the point of capacity of the road, a bimodal distribution may be observed (see Figure 4) (11). The special character of the intensity distribution may be explained by the existence of two different traffic states, one representing the traffic demand and the other representing the stochastic maximum flow level (both collected during the observation period). Two separate distributions are assumed to represent the compound distribution of the observed flow rates.

For this method, only traffic volumes are counted at a cross section of a road (a bottleneck). The traffic demand distribution depends strongly on the total observation period. Curve I in Figure 4 represents an observation period with many low intensities (e.g., counted at night); curve II represents a situation observed in days and evenings. Data collected only during the day can probably be depicted as a Gaussian curve. The general form for a compound probability density function can be used to estimate the capacity. Its value may be estimated as the expectation of the mean by probability density function  $b(q)$

$$f(q) = \phi \times g(q) + (1 - \phi) \times b(q) \quad (4)$$

where

- $\phi$  = fraction of the probability density function representing the traffic demand below capacity;
- $g(q)$  = probability density function representing the traffic demand below capacity; and
- $b(q)$  = probability density function representing the capacity state.

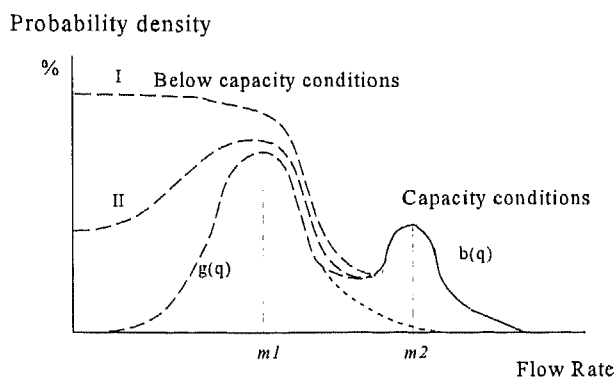


FIGURE 4 Bimodal distribution of intensities.

A major problem with the bimodal distribution method is the choice for the below-capacity probability density function. The assumption that capacity can be estimated with a normal, Gaussian-type distribution can be accepted without much resistance. However, the assumption that the traffic demand (the free-flow observations) also can be represented with a Gaussian-type distribution is doubtful and depends on the observation period chosen.

### Selected Maxima Method

Methods based on the selected maxima principle use the maximum flow rates measured over the observation period. The road capacity is assumed to be equal to the selected traffic flow maxima (distribution) observed during the total observation period. The observation of flow rates should take place over several days (cycles) until sufficient data are collected for analysis.

The data to be used with the selected maxima methods consist of hourly traffic volumes or flow rates observed in an averaging interval less than an hour. The capacity state of the road must be reached at least once during a cycle. The observation period can vary from one survey study to another. For example, an observation period of a year with an hourly averaging interval will result in 365 cycles and corresponding cycle maxima, which can be used for analyses. The capacity  $q_c$  is mostly assumed to be equal to the averaged traffic flow maxima observed during the total observation period. Thus,

$$q_c = \sum_i q_i / n \quad (5)$$

where

- $q_c$  = capacity value (vehicles per hour);
- $q_i$  = maximum flow rate observed over period  $i$ ;
- $n$  = number of cycles; and
- $i$  = length of cycle (period over which a maximum flow rate is determined).

( $T = ni$ , thus the observation period  $T$  is divided into  $n$  cycles of duration  $i$ .)

When applying this basic method, the number of capacity observations strongly affects the reliability of the calculated capacity value. In addition, choosing the average value is rather arbitrary; taking the 90th percentile point, for example, might also be useful.

### Expected Extreme Value Methods

With the direct probability method, a prediction of the largest possible value can be made on the assumption that the traffic volumes conform to a theoretical model such as the Poisson process. The direct probability method (12) may be applied when the capacity level of the road has been reached. The capacity estimate resulting from the calculations can be considered as a certain exceptional value of the maximum flow. Thus, the capacity of a road is based on the expected maximum flow rate predicted from the distribution of traffic counts given an assumed traffic arrival process.

Assumptions about the arrival process of the vehicles at the cross section are needed. One important requirement is that the observations for all sampling intervals are independently (flow rates between sampling intervals are not related) and identically (all countings are elements of the same distribution function) distributed. This implies, among other things, that the mean flow rate during the observation period must be constant.

From the results of one study (12), it appears that the predicted capacity value strongly depends on the duration of the averaging interval. One may conclude from this that the mean traffic volume over a certain observation period as an estimate for the capacity is a more consistent approach, resulting in a value independent of the averaging interval duration, whereas the mathematical calculation is less complicated. Refer to Figure 5, in which the principle of direct probability is compared with the asymptotic method.

The asymptotic method (12) is another approach for solving the extreme value estimation problem. The method relies on the theory that behavior of the extreme values arising from any natural process can be described in terms of a simple statistical model. Here also, it is assumed that the traffic volume observations for all averaging intervals are independently and identically distributed. The capacity is calculated as the expected maximum flow rate predicted from the distribution of observed extremes in selected intervals.

The capacity estimate resulting from the calculations can be considered as a certain not-yet-observed exceptional value of the maximum flow (the assumed upper limit).

Because the capacity estimate with this method strongly depends on the duration of the averaging interval, it appears that the expected maximum methods (although mathematically appealing) have little practical value for freeway design or modeling. The main reason for the great variance in the capacity values observed lies in the fact that only high traffic volumes are used in the calculations; as mentioned previously, high flow rates are observed more often with small averaging intervals. Of course, very extreme low intensities are also measured in such intervals, but these values are not taken into account in calculation of the upper limit.

### Estimation with Traffic Volumes and Speeds

Road capacity-estimation methods based on both traffic volumes and speed data (see Figure 1) take into account the traffic state. It should be clear that a good estimation of the capacity value can be made only when the traffic state upstream of the measuring point is known by the observer. To this end, speed measurements may be used.

The theory behind the product limit method is based on explicit division of flow observations. It can easily be understood that a flow rate measurement at a cross section (see Figure 3) can be divided into

one of two categories if the upstream traffic state is observed (4): measurements representing traffic demand (a free-flow intensity measurement) and measurements representing the capacity state of the road (upstream congestion).

This categorization of observations is an important aspect of the product limit method. This allows estimation of the capacity distribution function  $F(q)$  with both free-flow intensities and capacity observations. The idea is that free-flow intensity measurements can be used to improve capacity estimates based on capacity only, because these measurements give a better indication of the location and shape of the capacity distribution. In other words, the empirical distribution of capacity observations is adapted from the information contained in the high-volume free-flow observations.

Reliable analysis of the data requires more than a single day's volume and speed measurements. Furthermore, a bottleneck location should be chosen to be sure about the capacity state of the road whenever congestion is detected upstream.

The derivation is given of a simplified approach in estimating road capacity with traffic volume and speed data with only capacity observations available. This ideal situation leads to the so-called empirical distribution function of the capacity. The discrete empirical distribution function can easily be determined from Equation 6 and is the basis for the product limit method (and can be applied when only capacity observations are made).

$$F(q) = \text{Prob}(q_c \leq q) \quad (6)$$

More specifically, Equation 6 can be written as

$$F(q) = N_c / N \quad (7)$$

where

- $F(q)$  = cumulative distribution function of capacity values;
- $q_c$  = capacity value;
- $q_i$  = observed intensity at interval  $i$ ;
- $N_c$  = number of observation elements  $i$  from  $\{C\}$  with intensities  $q_i$  less than or equal to  $q$ ;
- $N$  = total number of observations  $i$  in set  $\{C\}$ ; and
- $\{C\}$  = set of observed congested flow measurements.

A single capacity value  $q_c$  is estimated, for example, choosing the median [ $F(q) = 0.5$ ].

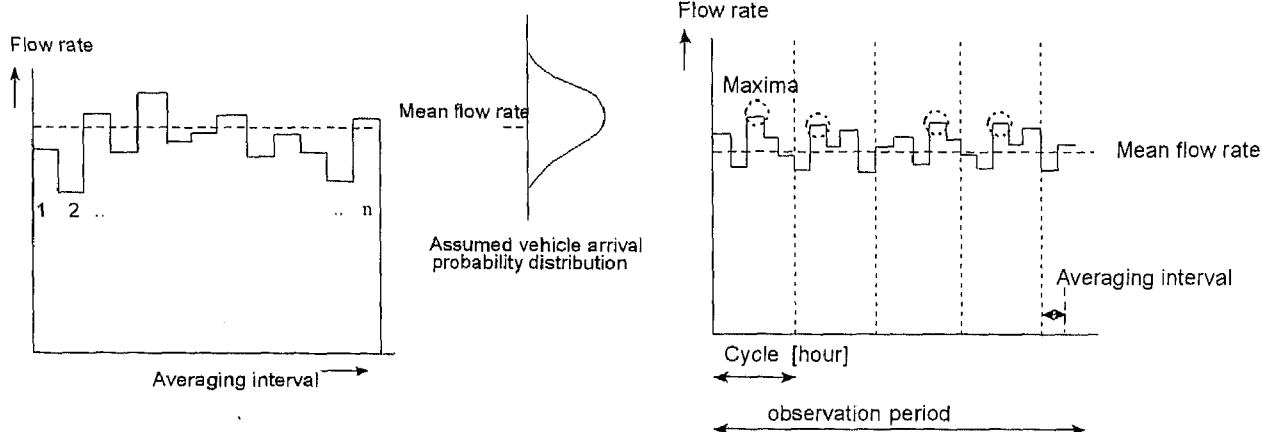


FIGURE 5 Comparison of direct probability method (left) and asymptotic method (right).

However, in a more practical situation there are also a number of free-flow measurements. In the general approach of the product limit method, these measurements are not thrown away but are applied as measurements, giving useful additional information about road capacity value. Function  $G(q)$  is defined as the probability that the capacity value  $q_c$  is higher than a given value  $q$ . The function  $F(q)$  is defined by  $1 - G(q)$ . In Equation 9 the general expression of the product limit method is given

$$G(q) = \text{Prob}(q_c > q) \quad (8)$$

$$G(q) = \prod_{q_i} \frac{K_{q_i} - 1}{K_{q_i}} \quad q_i \in \{C\} \quad (9)$$

where

$K_q$  = number of observation elements  $l$  in set  $\{S\}$  with intensity  $q_l$  larger than or equal to  $q$ ;

$\{C\}$  = set of observed congested flow intensities;

$\{Q\}$  = set of observed free-flow intensities;

$\{S\} = \{Q\} \cup \{C\}$  and  $\{S\}$  is set of all observations  $l$ .

A simple example for understanding the product limit method is based on eight observations, using 15-min averaging intervals (see Table 2). During the 2-hr observation period, congestion upstream occurred, so there were some capacity observations at the bottleneck. The measured intensity values are expressed here in vehicles per hour.

In the first column of Table 2, the averaging interval is indicated. The corresponding hourly intensity values are presented in the second column. It is assumed that speed data are used to categorize the observations into set  $\{C\}$  or set  $\{Q\}$ , which is done in the third column. Furthermore, the rank of the intensity values is determined in the fourth column, after which the discrete functions  $G(q)$  and  $F(q) = 1 - G(q)$  were calculated.

In Figure 6, the calculated discrete distribution function is depicted together with a possible continuous distribution function. In applications of the product limit method described so far, capacity estimations were based only on discrete distribution functions. Constructing a reliability interval is possible with the variance equation. In this example, defining the capacity at  $F(q) = 0.5$  (the median) would result in a road capacity of 4,200 vehicles/hr per two lanes. If only capacity observations were used, an average of 4,125 vehicles per hr per two lanes would have been the result.

Figure 7 illustrates that an observed intensity can be an element of set  $\{Q\}$  or  $\{C\}$  and that the proportion of the number of measurements in the sets can be different. In situation A, some of the free-flow intensities observed are higher than the highest measured capacity value, whereas in case B most of the congested flow or capacity measurements are higher than the highest free-flow intensities. The same holds for A' and B', but now the proportions of the two types of measurements are substantially different; there are relatively few capacity measurements.

What is the implication of the differences between A, B, A', and B' for the capacity estimation result? First, note that for both situations A and B the product limit method may be applied, because there are sufficient capacity observations in comparison with the number of free-flow intensity observations. The situations A' and B' differ from A and B because only a few capacity measurements are available. In these situations, the selection method (2,4) is proposed as an alternative to the product Limit Method. However, the usefulness of the method is dubious because there is no information about the quality (reliability, precision) of the estimated capacity value.

### Estimation with Traffic Volumes, Speeds, and Densities

One can distinguish two kinds of methods in this category: the dynamic on-line method for a capacity estimate under prevailing conditions and the static long-term (off-line) approach with use of the fundamental diagram (see Figure 1).

#### Fundamental Diagram Method

The fundamental diagram method is based on the existence of a relation between the three variables  $q$  (traffic volume), harmonic mean speed  $u$ , and density  $k$  (or local density expressed as occupancy, occ) (13), the so-called fundamental diagram. It is sufficient to measure two variables to construct one of the diagrams.

One advantage of the method is that it is not necessary to acquire data at a bottleneck. One must observe traffic at different volumes to make a reliable curve fitting possible. If the observed traffic state is unstable or, even worse, congested, the results of the curve fitting depend too much on the type of curve chosen because of the great variance in these observed values.

TABLE 2 Product Limit Method Calculation

1	2	3	4	5	6	7
Interval $i$	$q_i$	Set	Order $j$	$K_q, q_i \in \{C\}$	$G(q)$	$F(q)$
[veh/h]						
1 15.30-45	3000	Q	2	-		
2 15.45-00	2500	Q	1 lowest	-	1	0
3 16.00-15	3500	C	3	6	$5/6 = 0.83$	0.17
4 16.15-30	4000	Q	4	-		
5 16.30-45	4300	C	6	3	$5/6 \cdot 3/4 \cdot 2/3 = 0.41$	0.59
6 16.45-00	4500	Q	7	-		
7 17.00-15	4600	C	8 highest	1	$5/6 \cdot 3/4 \cdot 2/3 \cdot 0/1 = 0$	1
8 17.15-30	4100	C	5	4	$5/6 \cdot 3/4 = 0.62$	0.38
2 hours	Average Total $i=8$ intensity $i$ in $\{Q\} = 4$ 3812 $i$ in $\{C\} = 4$					

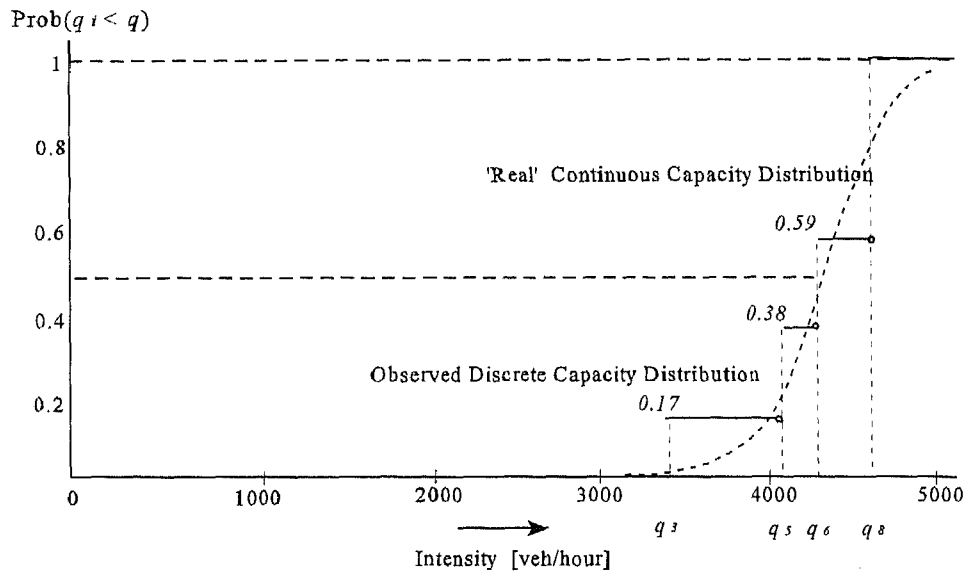


FIGURE 6 Capacity distribution based on product limit method.

The maximum intensity being sought is located at a certain critical density,  $k_c$ . With the relation

$$k = u/q \quad (11)$$

the density in vehicles per kilometer can be calculated when speed and flow rate are known.

However, density is often difficult to determine because one should observe a complete and uniform road section and count the total number of cars present at any moment. Instead, local density (the occupancy,  $occ$ ) is used in the calculations. The capacity value can graphically be derived from the fundamental diagram.

Different models are available to fit the data, and so capacity depends on the model chosen [see, e.g., May (13)]. Capacity  $q_c$  can be derived by calculating the maximum of the curve, where the derivative of the function equals zero.

A major disadvantage of the method is the requirement of a mathematical model that fits the observed data pairs. Moreover, the parameters of the chosen model should be obtained for each location anew, because prevailing conditions differ. Furthermore, it is necessary to collect sufficient data over a broad range of intensities to make a reliable curve fitting possible.

#### On-Line Procedure for Actual Capacity Estimation

For real-time traffic predictions and control, knowledge is required of the actual prevailing capacities of road sections. These actual capacities depend on prevailing traffic composition and other conditions. The method is based on an updating procedure of a reference fundamental diagram, which was determined under earlier, predefined conditions. It has been found that a quadratic function ( $q = \alpha \cdot occ + \beta \cdot occ^2$ ) serves well for the relationship between intensity and (detector) occupancy (3). In addition, it is assumed that this relation (and its calibrated parameters) may be adapted with a scaling factor only to fit the intensity-occupancy curve under various prevailing road, weather, and traffic conditions.

The capacity-estimation procedure concentrates on determining a valid scaling factor, which is done by comparing predicted and measured intensities every minute. The actual capacity value is then estimated by calculating the (free-flow) intensity that corresponds with the assumed critical occupancy at that minute.

Determination of the critical occupancy in the capacity-estimation procedure is in question. A constant value of 9 percent occupancy is used in recent applications of the method.

The reader is referred to Van Arem and Van der Vlist (3) and Minderhoud et al. (2) for a detailed explanation of the method.

#### CONCLUSIONS

Various existing direct-empirical capacity estimation methods have been examined and discussed. It appears that two approaches are

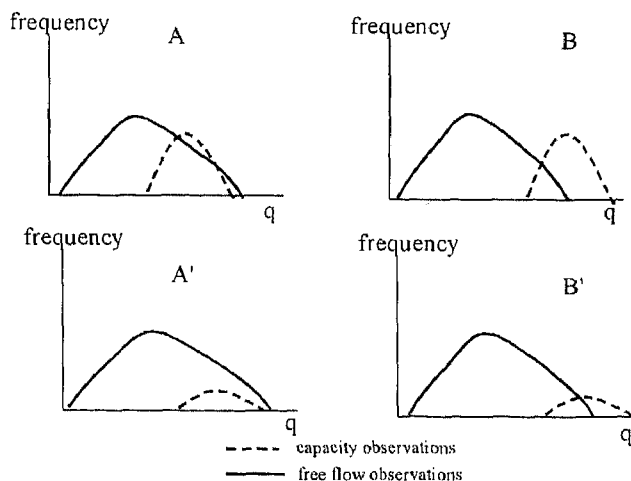


FIGURE 7 Four possible configurations of observed intensities.



followed in the estimation procedures: calculation of a capacity value using observed maxima (applying extreme value statistics) or estimation using (specified) sets of flow observations (Figure 1). With these methods, a capacity value or capacity distribution can be derived. A capacity distribution is preferred because it allows the choice of a capacity value based on certain quality considerations.

The main question was, and still is, the validity and practical use of each method. An assessment has been made (Table 1) and the following general conclusion concerning capacity-estimation methodologies is given: Attempts to determine the capacity of a road by existing methods will generally result in a capacity value estimate, but the validity of this value is hard to investigate because of the lack of a reference capacity value, which is supposed to be absolutely valid. A clear, reliable method does not appear to be available at this moment. Some methods can be improved to enhance the validity of the capacity estimate. Currently, the recommended order of application of existing methods (considering the advantages and disadvantages of each method) is as follows: (a) the product limit method, (b) the empirical distribution method, and (c) the fundamental diagram method.

Although several capacity-estimation methods are based on appropriate theories concerning macroscopic traffic flow, the capacity-estimation procedures appear to be a little disappointing. A further improvement of the promising product limit method may lead to a more reliable road capacity-estimation approach. The same holds for the on-line procedure, which can be improved by a better estimation of the critical occupancy and scaling factor.

Finally, an empirically well-measurable, theoretically valid, quantitative expression of roadway capacity is still lacking and further research must be carried out to establish a useful definition for link capacity for various applications.

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*Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.*