An assessment of roadway capacity estimation methods

M.M. Minderhoud / H. Botma / P.H.L. Bovy

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M.M. Minderhoud
H. Botma
P.H.L. Bovy

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Faculty of Civil Engineering
Transportation Section
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11. Summary

Capacity is a central concept in roadway design and traffic control. The estimation of empirical capacity values in practical circumstances is not a trivial problem, not in the last place because it is very difficult to define capacity in an unambiguous manner.
This report deals with empirical capacity estimation for uninterrupted roadway sections. 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. Also, the priciples of the distinguished methods and their mathematical derivation of roadway capacity are studied and discussed.
Among others, the Headway Distribution approaches, the Bimodal Distribution Method, the Selected Maxima and Direct Probability Method are examined. Among the methods based on traffic volume counts, the Product Limit Method can be recommended for practical application because of the sound underlying theory. An example of the application of this promising method is shown.
Our attempts to determine the validity of existing roadway capacity estimation methods resulted in a disappointing conclusion of the many ambiguities related to the derived capacity values and distributions. Estimating a reliable and meaningful capacity value seems not yet possible. Lack of a clear definition of the notion of capacity is the main hinderance in understanding what exactly represents the estimated capacity value or distribution in the various methods.
If this deficiency is removed promising methods for practical employment in traffic engineering seem to be the Product Limit Method, the Empirical Distribution Method and the well-known Fundamental Diagram Method, in this order. The choice for a particular method strongly depends on the available data.

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AN ASSESSMENT OF ROADWAY CAPACITY ESTIMATION METHODS

M. M. Minderhoud
H. Botma
P. H. L. Bovy

Delft University of Technology, Faculty of Civil Engineering,
Department of Infrastructure, Transportation Planning and Traffic Engineering Section
P.O. Box 5048, 2600 GA Delft, The Netherlands

TU Delft

Delft University of Technology

PREFACE

It is not unlikely you ever have been amazed about the number of vehicles passing a section of a road without observable problems for the participants. Impressed by the human capacities, you may ask yourself a question, which is the topic of this report: "*What is the maximum number of vehicles this road can handle in a certain period*?".

Your first idea is probably that this value you are searching for, can be obtained without great difficulties and without doubts, and that there will be reliable methods available, until you really try to estimate this maximum volume yourself...

In addition, already three definition problems can be encountered in the question above. Firstly, what means *maximum* in this formulation of the road capacity ? Secondly, how must the term *handle* be specified more clearly? And furthermore, how long should the observation *period* be?

This report is an attempt to describe existing capacity estimation methods with their characteristic data demands and assumptions. After studying the methods, one should have a better idea about the capacity estimation problem which can be encountered in traffic engineering. Moreover, decisions to employ a particular method should be made (much) easier since advantages, disadvantages and other aspects concerning the application of the methods are discussed.

To elucidate some of the presented methods examples of their employment have been added. I hope this report will be a valuable help in research projects where capacity estimation of a road is an issue.

Michiel Minderhoud
Delft, The Netherlands, July 1996

CONTENTS

SUMMARY

The maximum volume of traffic a road can carry is the subject of this report. Although a consistent, reliable and useful method in measuring or estimating the roadway capacity for a variety of circumstances is not available yet, the existing methods can be useful under certain conditions and assumptions. These methods will be presented, explained and discussed in the following.

The capacity estimation methods described in this report can be used to estimate the capacity of an uninterrupted road section, according to the assumptions of the underlying theory. Headway, traffic volume, speed and density measurements are used to identify four groups of capacity estimation methods. Aspects such as data requirement, location choice and survey set up are investigated for each method. Furthermore, an evaluation of the validity and practical use of the methods is set out.

The Headway Distribution approaches calculate the road capacity with the hypothesis that the behaviour of constrained drivers in free flow conditions can be compared with (constrained) drivers at capacity level of the road. The benefit of these methods is that road capacity doesn't need to be achieved, but a mathematical model must be used to divide the observations into constrained and unconstrained drivers. The method seems to over-estimate the road capacity.

A Bimodal Distribution of observed flow rates from which a capacity value can be approximated, is supposed to exist when the capacity level of the road is reached during the observation period. This method might be a useful and reliable capacity estimation method in case the bimodal character can be found in all studies. However, this is doubtful since the shape of the distribution function depends strongly on the length of the observation period.

The Selected Maxima Methods, using observed maxima, can be applied only when the capacity level of the road is reached. One can conclude that such methods can easily be applied, but both observation period and averaging interval will affect the observable maximum flow rates heavily.

Also extreme value capacity estimation methods were studied, but they seem currently not to be very useful in traffic engineering.

When collected traffic flow data can be divided into free flow intensity and capacity measurements and there is a substantial amount of capacity observations in proportion to the free flow intensity observations one can use the Product Limit Method to estimate a capacity value distribution. The Product Limit Method can be recommended instead of other methods based on traffic volume counts only, because of its sound underlying theory.

The so-called Fundamental Diagram Method uses traffic volume, density (or occupancy) and/or speed observations to construct a diagram from which the maximum traffic volume can be derived. The capacity level may be reached during the observations, but this is not a requirement. The method is based on the application of a mathematical model describing the macroscopic traffic process. Advantage of this method above others is the additional information about the critical density and mean speed. A disadvantage is the need for a specified model to describe the relation between volume and density (or detector occupancy).

A real-time application in estimating road capacity is the so-called On-line procedure. A reference Fundamental Diagram is used in order to estimate the capacity under prevailing conditions. For the construction of a reference relationship between speed, volume and density under various road and weather conditions, an observation study must be carried out under selected road and weather conditions. A scaling factor is used to fit the reference relationship between intensity and detector occupancy to the actual road, weather and traffic conditions. The determination of the critical occupancy, needed to estimate the actual capacity under the prevailing road and weather conditions, is a doubtful aspect of the procedure. Results are not always reliable or useful, although the method appears to be promising for real-time applications in traffic management.

Our attempts to determine the validity of road capacity estimation methods resulted in a disappointing conclusion of the many ambiguities related to the derived capacity values or distributions. Lack of a clear definition of the notion of capacity is the main hinderance in understanding what exactly represents the estimated capacity value or distribution in the various methods.

If this deficiency is removed promising methods for practical employment seem to be the Product Limit Method, the Empirical Distribution Method and the Fundamental Diagram Method. The choice for a particular method depends strongly on the available data.

SYMBOLS

In this report, the following symbols are frequently used:

q	=	intensity[1]	[vehicles per unit time]
q_i	=	intensity value of observation *i*	[vehicles per unit time]
q_c	=	capacity value	[veh/hour]
k	=	density	[veh/km]
k_c	=	critical density	[veh/km]
k_j	=	jam density	[veh/km]
occ	=	occupancy	[%]
occ_c	=	critical occupancy	[%]
u	=	speed	[km/h]
u_f	=	free flow speed	[km/h]
u_c	=	critical speed	[km/h]
i	=	observation index	
m	=	index mean	
p,q	=	index vehicles	
h	=	gross headway	[s/veh]
s	=	gross spacing	[m/veh]
L	=	vehicle length	[m/veh]
ϕ	=	fraction (value between 0 and 1)	
T	=	critical headway	[s]
$f(.), g(.), b(.)$	=	probability density functions	
$F(.), G(.)$	=	distribution functions	
$\{C\}$	=	set of congested flow observations (see Fig. 1-5)	
$\{Q\}$	=	set of free flow intensity observations (see Fig. 1-5)	

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[1] The following terms are used to denote the number of vehicles passing a cross-section:

intensity:	the general expression for the number of vehicles passing a cross-section.
(traffic) volume:	the number of vehicles counted in an hour.
flow rate:	the number of vehicles counted per averaging interval (expressed in veh/h)

Chapter 1

INTRODUCTION

The maximum volume of traffic a road can carry is the subject of this report. Although one consistent, reliable and useful method in measuring or estimating the roadway capacity for a variety of circumstances is not available yet, the existing methods can be useful under certain conditions and assumptions. These methods will be presented, explained and discussed in the following.

In general, the capacity of a traffic 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* (HCM,1994).

Also reported in the American Highway Capacity Manual is that any change in the prevailing conditions will result in a change in the capacity of the facility, and 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 due to differences in individual driver behaviour and changing road, traffic 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 bottle-necks. Therefor, it is important that capacity is clearly defined, is measurable, and can be used in modelling and decision-making. Different capacity definitions and methods of capacity estimation are examined and described in this report.

1-1 Definitions of Roadway Capacity

Although the capacity definition described above can easily be understood, misunderstanding in the interpretation of the derived value can nevertheless easily occur. This is due to the fact that there exist different approaches to express the capacity of a road. **Figure 1-0** presents a scheme in which the various approaches are distinguished. We divided the capacity estimation problem into two categories: the *direct-empirical* and *indirect-empirical* methods. In this report we focus on the direct-empirical studies which are directed at estimation of capacity value(s) at a specific site using traffic observations from that site.

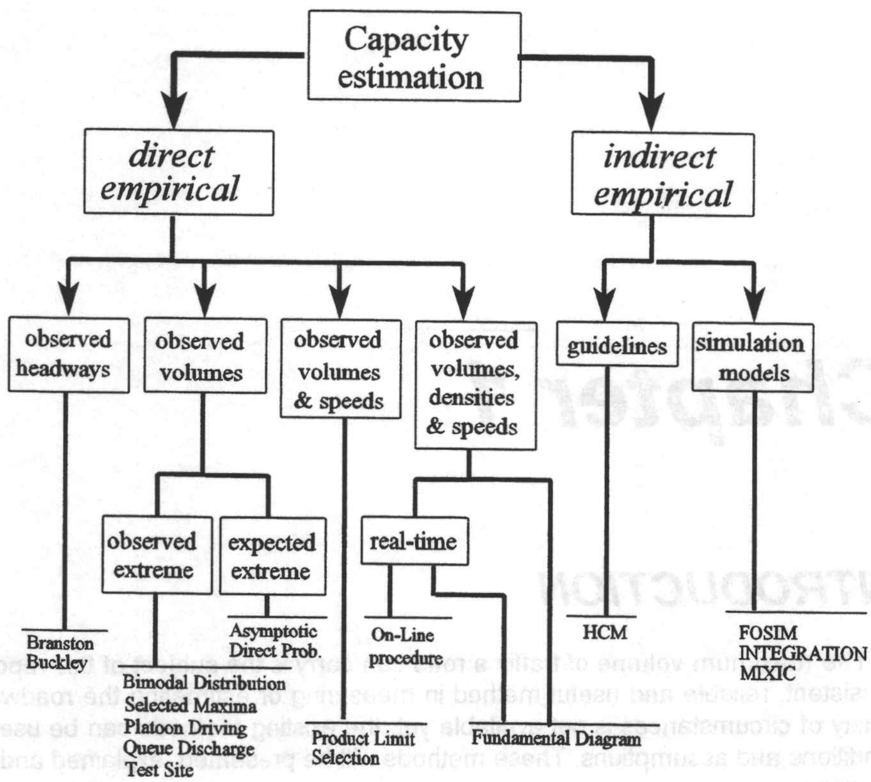


Figure 1-0 A Classification of Definitions and Methods to Determine Roadway Capacity

We will use the following definitions 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 pre-defined road and weather conditions. This value will be used for the planning and design of roads and carriageways, and may be derived from the indirect-empirical capacity estimation methods, such as included in the HCM (1994).

- **strategic capacity**
  A capacity value (possibly derived from a capacity value 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 (eg. traffic flow assignment and simulation). This

capacity value or distribution is based on observed traffic flow data using static capacity models.

- **operational capacity**
  A capacity value representing the actual maximum traffic volume 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 using dynamic capacity models, such as the On-Line procedure (Van Arem, 1992).

Despite this categorisation of roadway capacity value notions, we are not able to give a quantitative definition of roadway capacity. The capacity (distribution) of a facility can only be defined in relation to the corresponding quality of traffic flow. This quality notion includes aspects such as reliability. If a high level of quality is required, that is a low probability of disfunctioning of the facility, the corresponding capacity is low (see e.g. Hertel, 1994). Hertel states that the *maximum capacity* (or limiting capacity) of a facility is defined as *its ability to achieve the maximum througput under the full utilization of personal capabilities, means of transportation and available infrastructure.*

Instead of determining the maximum capacity it is more useful to obtain roadway capacity values under predefined, most common conditions. This will automatically result in values below this maximum, since it is assumed that the mentioned capacity affecting resources are not optimally utilized during average conditions. Or in other words: due to the not perfectly utilized capabilities of the triple human drivers, their vehicles and the available infrastructure, capacity is a stochastic variable. The stochastic nature of these factors results in a capacity value distribution. In **Figure 1-1** we visualized a number of the factors affecting the roadway capacity distribution. Each factor can be seen as a probability density function of its characteristic variable(s). In the figure, the variables have not been declared.

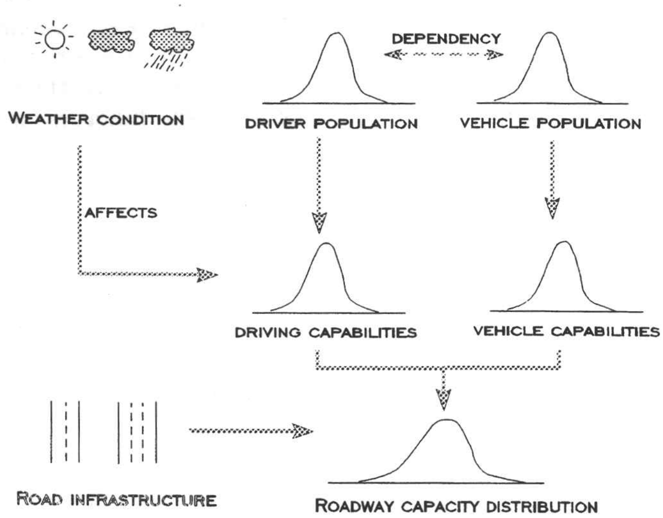


Figure 1-1 Factors Affecting the Roadway Capacity Distribution

Capacity value distributions (as depicted in **Figure 1-1** and **1-2**) can be used to chose a specific *design* or *strategic capacity* value, for example the average, the median or 90th percentile of the distribution. In the Netherlands, a design capacity of a freeway has been proposed based on economic grounds, so that a maximum of 2 % (for hinterland freeways) or 5% (for other freeways) of the drivers will be confronted with congestion.

However, there is the problem that the probability distribution function for the road capacity is not exactly known. A Gaussian-type distribution can reasonably be assumed, although mean and variance of this distribution depend on the prevailing conditions (ideal or non-ideal). We assume a Gaussian-type distribution function (**Figure 1-2**) for the stochastic variable capacity at any weather, road and traffic conditions.

Ideal circumstances are defined in the HCM (1994) by the following criteria:

- **geometric construction of the road according to design criteria**
- **excellent condition of the road**
- **good weather conditions**
- **level terrain**
- **only passenger cars**

Under these conditions at a certain cross-section of a roadway, point ***B*** in **Figure 1-2** corresponds with a capacity estimate based on the mean or median of the capacity distribution. Point ***A*** represents a situation in which driver behaviour results in a less-ideal capacity value, and point ***C*** corresponds with a temporary situation in which the driver population utilizes the road infrastructure at the measuring location more efficient than under average conditions. Point ***D*** is the location of the 95 percentile of the capacity distribution. Hence, the variance in capacity values during ideal circumstances is completely caused by the composition of the driver and car population (variables such as age, level of experience, travel purpose and thus their driving behaviour/skill) and not by the road and weather conditions.

The desired ideal conditions during which the ideal capacity value (or distribution) should be determined can mostly not be obtained. Therefore, the capacity estimation methods will mostly also be applied under non-ideal conditions, and this causes extra variance in the stochastic capacity variable, since the ideal conditions mentioned above are only partly met. Now not only the differences in driving behaviour but also the road and weather conditions affect the capacity distribution. The road capacity probability density function for the same cross-section is flattened and shifted to the left (**Fig. 1-2**).

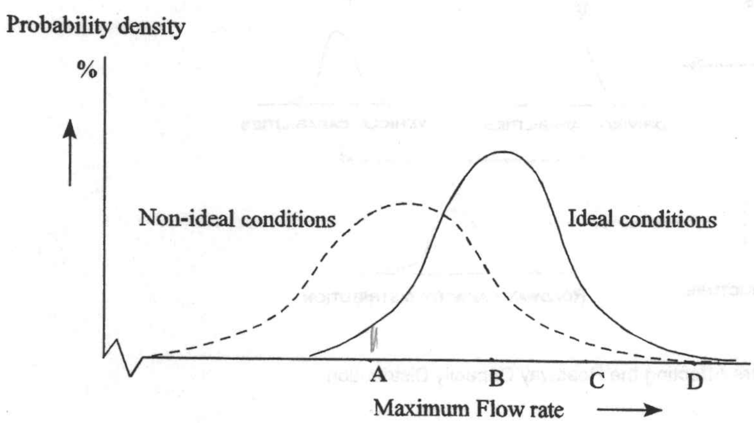


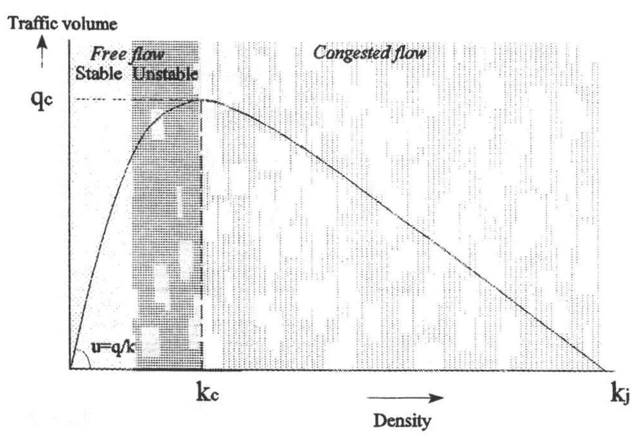
Figure 1-2 Example Capacity Probability Density Function During Ideal and Non-Ideal Circumstances at the Same Location

Some remarks with regard to the measuring unit of roadway capacity. The unit of road capacity values can be expressed in vehicles per hour or *passenger car equivalents per hour* pce/hour. We will further use the terms *(traffic) volume* to denote a specific number of cars passing a cross-section in an hour. The term *intensity* will also be used for expressing the number of cars counted in less than an hour.

The term *flow rate* is used whenever a short period of time is used for aggregating the number of cars passing a selected cross-section. The flow rate can be transformed to the unit of vehicles/hour or pce/h very easily, although the meaning is different!

In order to establish a *design* or *strategic capacity* value for engineering objectives, the use of a well chosen capacity estimation method is desired. However, the validity of many methods is not known. Therefore, the estimation of the capacity or even better the complete capacity distribution is a difficult engineering problem which was a main reason for performing this overview study. Some methods (such as the Bimodal Distribution described in **Section 3-1**) use assumptions about the shape of the capacity distribution function. Other methods use the observed data to estimate one capacity value only.

In the Highway Capacity Manual (HCM, 1994) reduction factors are used to derive the design capacity value of a road based on standardized capacity values for that specific road type for specific conditions (for example a value of 2200 pce/h per lane). These reduction factors equal one when the conditions are approximately ideal. When these conditions are not met (in most cases), for example because of the presence of heavy traffic on the road, the capacity value will decrease by multiplying with the reduction factor for the proportion of heavy traffic. The resulting value is the assumed capacity of the road and will be used for further calculations. This indirect-empirical approach (see **Figure 1-0**) will not be discussed here: only direct-empirical capacity estimation methods (thus based on direct observable traffic data) are subject of this study.



q_c = capacity value [veh/hour]
k = density [veh/km]
k_c = critical density [veh/km]
k_j = jam density [veh/km]
u = speed [km/h]

Figure 1-3 The Fundamental Diagram: the Relation between Traffic Volume and Density

1-2 Essential Elements in Roadway Capacity Estimation

1-2-1 Theory

Two essential types of traffic data needed to estimate the capacity of a road (at a cross-section) can be distinguished. These are:

- **traffic volumes**
- **headways**

However, additional information about the traffic flow conditions, such as density, occupancy and mean speed, can be gratefully used in some methods.

Speed data are needed to determine the state of traffic (stable, unstable and congested traffic flow), see **Figure 1-3**. Since congested flow (mean speed drops below a certain value) upstream a bottle-neck means that the capacity level has been reached in the bottle-neck itself, it is possible to make a more reliable capacity estimate. A method based on this principle is explained in detail in **Section 4-2**.

A stable traffic flow exists when the drivers can hold their desired speed. With an increasing density (the number of vehicles per kilometer 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: congestion. **Figure 1-3** shows a graphical presentation of the terminology used.

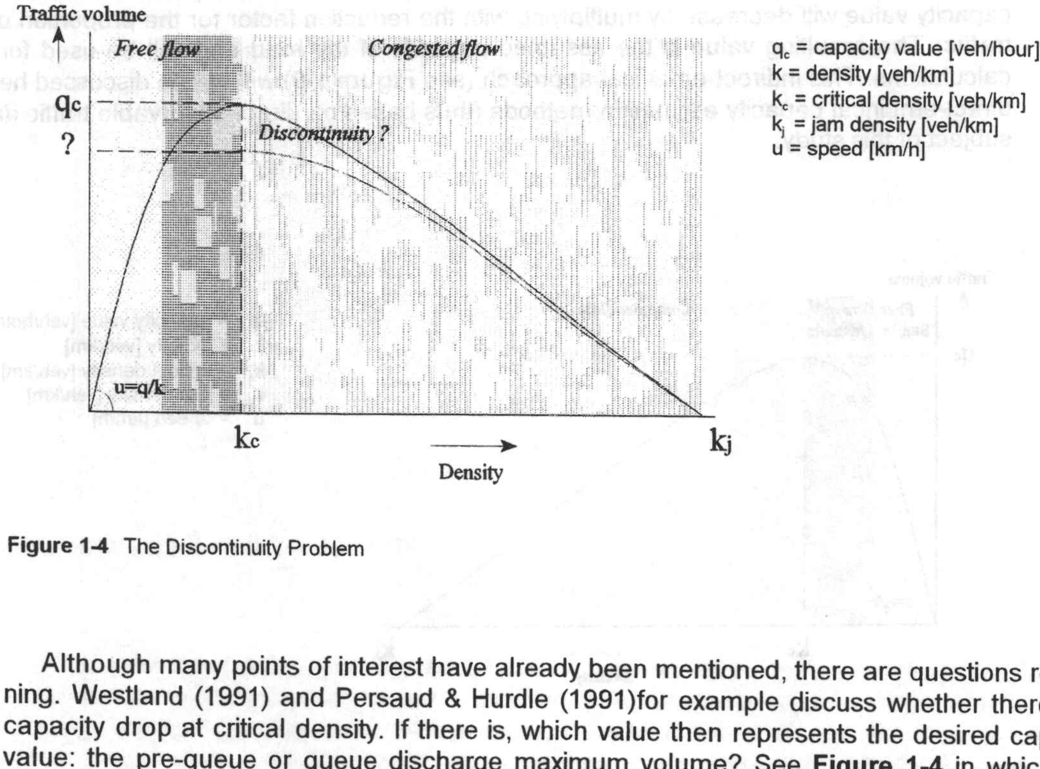


Figure 1-4 The Discontinuity Problem

Although many points of interest have already been mentioned, there are questions remaining. Westland (1991) and Persaud & Hurdle (1991)for example discuss whether there is a capacity drop at critical density. If there is, which value then represents the desired capacity value: the pre-queue or queue discharge maximum volume? See **Figure 1-4** in which this problem is visualized. The dicontinuity question will not be discussed here in detail, nonetheless it should be borne in mind when interpreting results. Therefor, each capacity estimation method in the report will be accompanied with information about whether the estimated value is a maximum free flow intensity or a maximum congested flow value or a mix of both values (see also **Fig. 1-5**).

1-2-2 Elements of the Observations

Having set out the basic theory, we will divide the capacity estimation problem into a number of essential points of interest. In this Section, we will discuss each element in turn which may serve as kind of a survey setup manual as well:

a. type of data to be collected
b. location choice for the observations
c. choice for an appropriate averaging interval
d. needed observation period
e. required traffic state
f. the whole carriageway or just one lane

a. Type of data to be collected

One should first of all chose between traffic volume and headway as the basic variable in the capacity estimation methods. Then, additional data that possibly can be obtained (such as average or individual speed, density or occupancy measurements) may complete the data demand of a certain method. To be consistent in the teminology of the traffic volume measurements we refer to **Figure 1-5** where we distinguish the used definitions of traffic flow observations in this report.

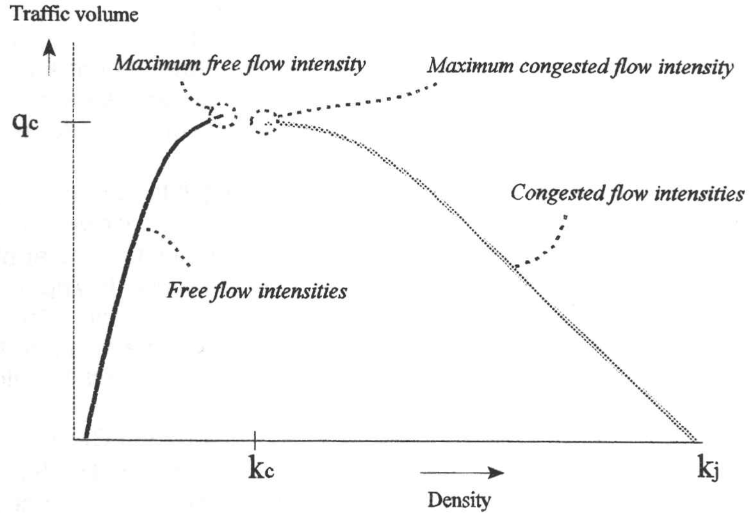


Figure 1-5 Categorization of Traffic Volume Observations

b. Location choice for the observations

The traffic data with which the capacity of a road will be estimated should be collected at one or more cross-sections of a road. Some methods require observations at the capacity level of the road, for example the Product Limit Method (**Section 4-1**). To ensure this condition congestion has to occur upstream the measuring point at a bottle-neck. Downstream and at the measuring point no congestion is allowed, otherwise the congested flow capacity of the road at the cross-section can not be reliably determined: this is the case when the real bottle-neck is located further downstream. See **Figure 1-6**.

When observing individual headways, no special conditions for the cross-sections are required which is one of the benefits of Headway approaches.

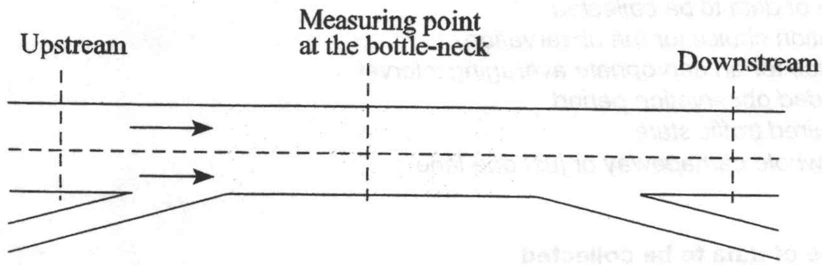


Figure 1-6 Capacity Value Estimation at The Bottle-neck of a Roadway

c. **Choice for an appropriate averaging interval** (counting unit)
The duration of the smallest period in which the number of passing cars will be counted and aggregated (definition: the *averaging interval*[2]) is to a large extent arbitrary, and the results must be interpreted with this in mind. In particular, it is well known that very large rate of flows can be observed over very short periods, e.g. one minute, but they occur much less frequently over longer periods.
The fluctuations in rate of flows counted in short averaging intervals (such as 10 or 30 seconds) are local and depend mainly on the arrival process of the individual cars, in which we are not particularly interested. When large averaging interval times are applied, such as 1 hour or even 1 day, the traffic volumes counted include both free flowing and congested traffic: a specific traffic state can mostly not retain for more than a hour. So, these values are also not of our interest when we want to determine a reliable maximum traffic volume a road can handle. In most cases, an averaging interval between 1 and 15 minutes will be chosen.
The five minutes period was reported as a reliable choice in a recent German study (Keller & Sachse, 1995). In this study they compared the capacity value estimates of stationary periods with 1, 5, 15, 30 and 60 minutes averaging intervals. Other sources (eg. HCM, 1995 and Van Toorenburg, 1986) prefer the fifteen minutes interval as a valid compromise. Their explanation is that with this counting unit the independency of the observations among averaging intervals can be defended, local fluctuations are smoothed out and the maximum traffic volume could hold for more than the interval duration.

d. **Needed observation period**
The total *observation period* which consists of one or more averaging intervals can be, for example, one hour (e.g. during the morning or evening rush), or one hour repeated every day for a certain number of days. Many observation periods and strategies can be found in literature (see for example Persaud & Hurdle, 1991).
It is mostly assumed that during the observation period the rate of flows measured over the averaging intervals are drawn out of the same distribution (identically distributed). The needed total observation period also depends on the chosen averaging interval duration. To collect a sufficient number of observations a compromise between averaging interval duration and observation period has to be made. For example a one hour observation period with 1 minute intervals has the same number of observations as five hours with 5 minute intervals. However, it is reasonably to assume that with a longer observation period, and therefore more intervals, a large number of highly flow rates may be observed, and

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2 In literature sometimes indicated by *aggregating interval*

this will strongly affect the estimation of the capacity value with Extreme Value methods, as will be shown in **Chapter 3**.

e. **Required traffic state**
A 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, or following the terminology of **Figure 1-5**, we measure free flow intensities.
When upstream a measuring point congestion or traffic with low speed has been observed, we refer here to **Figure 1-6**, the traffic demand at the bottle-neck is assumed to be higher than the capacity of the bottleneck. Some methods require a specific (stationary) traffic state during which the data should be collected. This aspect will be explained later for each method in combination with the corresponding location choice.

f. **Lane or carriageway**
Most methods can be employed for a whole cross-section including all the lanes of the road in one direction. Reversibly, one can conclude that these methods can also be applied for one lane only. The Headway Models (**Section 2-1**) are an exception to this rule. Until now these models can only be applied for a single lane.

These important aspects concerning the survey set up will be discussed for each method in the relevant sections.

1-3 Setup Of The Report

Each estimation method has a number of characteristic assumptions about the behaviour of *driver-vehicle elements* in a traffic stream to explain the mathematical estimate of the capacity value or distribution. This is the *principle of the method* and will be discussed at the beginning of each section. Furthermore, special requirements regarding the *data*, *the location choice, the observation period* and *averaging interval* will be explained. Also the *capacity calculation* will be presented, and illustrated with an *example*, after which a short *evaluation* of the method will be given.

This report covers four groups of capacity estimation methods. A main distinction in the report has been made into the traffic data types that can be collected and used for the capacity value estimation. In **Chapter 2** the Headway approaches are discussed. **Chapter 3** concerns the capacity estimation with measured traffic volumes where a further distinction has been made into Observed Extreme Value Methods and Expected Extreme Value Methods. In **Chapter 4** speed data is used to estimate the capacity with the additional information about the traffic state. **Chapter 5** presents methods in which the density is also used. At last in **Chapter 6**, a conclusion and a summary are drawn up.

Chapter 2

CAPACITY ESTIMATION WITH HEADWAYS

In this chapter the capacity estimation methods using the individual headways between vehicles are investigated. The headway models are based upon the theory that at the capacity level of the road all *driver-vehicle elements* are constrained (travel speed is restricted to the traffic state). Until now, these models can only be applied for a Single Lane. In the case of a multiple lane freeway the lanes are treated separately, also called *decomposition per lane*. Useful Headway Distribution Models for more than one single lane treating the roadway completely haven't been developed until now, but there are some Semi-Multiple Lane Models available (see for example Stipdonk, 1987). That is, models which use a combination of Single Lane Headway Models to estimate the capacity of a road over an entire cross-section. These models will not be discussed here.

2-1 Headway Distribution Models for a Single Lane

The distribution of headways has long been a subject for study. Two well-known headway models will be described:

- **Branston's Generalised Queuing model**
- **Buckley's Semi Poisson model**

Both approaches are based on the Poisson point process, but with some slight differences in the assumptions concerning driver behaviour in traffic flows.

2-1-1 Principle of the Method

Before we discuss the two headway models, we will repeat some basic traffic flow theory on which the models are based.

First of all, the time headway distribution observed at a cross-section of a road can be derived from a *Space-Time-Frame* as visualized in **Figure 2-1**. The horizontal distance between two trajectories at a certain cross-section represents the individual time headway for a driver-vehicle element. The vertical distance between two trajectories is called the spacing between two vehicles *p* and *r*, see also **Figure 2-2**.

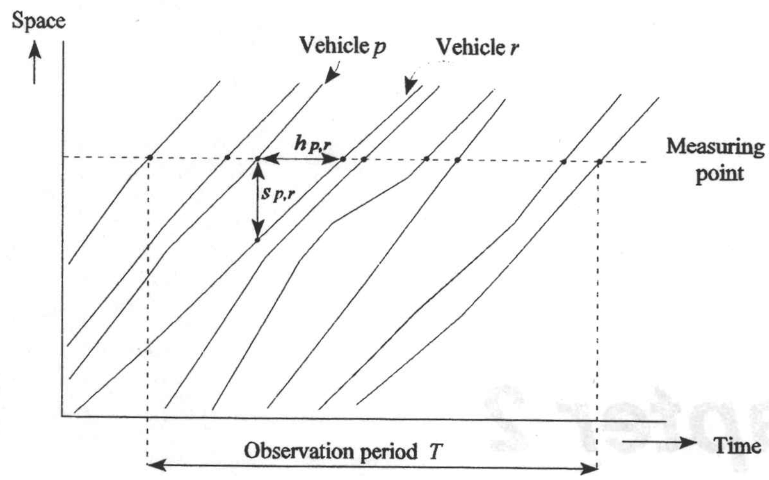


Figure 2-1 Space-Time-Frame with Trajectories, Spacings *s* and Individual Time Headways *h*

The mean time headway and mean intensity during observation period *T* can be derived from the Space-Time-Frame, see equations 2.1 and 2.2a. These equations are the basis for capacity estimation with headway distribution models (n = number of observed vehicles).

$$h_m = \textstyle\sum_p h_{p,r} / n \quad \text{[s/veh]} \tag{2.1}$$

$$q = n / T = 1 / h_m \quad \text{[veh/s]}$$

$$q = 3600 / h_m \quad \text{[veh/h]} \tag{2.2a}$$

where

$h_{p,r}$	=	time headway vehicle *p* to *r* [s/veh]
h_m	=	mean time headway [s/veh]
q	=	intensity
n	=	total number of vehicles passing the measuring point during time period T
T	=	observation period [s]

The models are based on the theory that driver-vehicle elements in any traffic stream can be divided into two groups: the *constrained* (followers) and the *free* (leaders) drivers. Since it is assumed that at the capacity level of the road all drivers are constrained, one is able to say something about this maximum traffic volume *without having reached the capacity level.* An important assumption using a headway distribution model to estimate the capacity of a road, is the independency of the estimated capacity value of the traffic volume.

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.

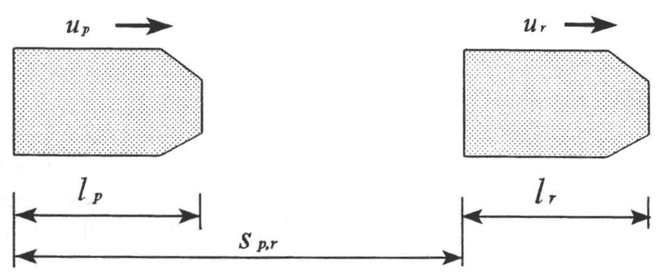
Therefore, the definition for the capacity at a cross section of the road can be stated as: *The capacity of a single lane of a road at a specific cross-section is the inverse of the mean time headway of constrained vehicles since it is assumed that during capacity conditions of a road all drivers are constrained drivers .*

Thus:

$$q_c = 3600 \; / \; h_{m,\,constr} \tag{2.2b}$$

2-1-2 Traffic Data

The time headway is defined by the time successive vehicles (measured from rear bumper to rear bumper) pass a given point on a lane of a roadway. The vehicle length is included, so the headway time measured is always greater than zero. See **Figure 2-2**. Headway data is needed to estimate the capacity with this method.



where

u_p = speed vehicle *p*
L_p = length vehicle *p*
$s_{p,r}$ = gross spacing

Figure 2-2 Car Following Theory Notations

Speed data is not needed for this method, although information about speeds and accelerations can be used to divide a traffic stream more exactly and reliably into followers and non-followers (Botma & Papendrecht & Westland, 1980) using the *pendel-following-criterion*. In the study refered to, the driver-vehicle elements are divided into one of four possible states, see also **Figure 2-3**:

- **transition-state**
  The state in which a driver decreases or increases its speed by acceleration or deceleration.

- **following-state without intention to pass**
  The state in which a driver adapts its speed to the driver in front, without the intention to pass.

- **following-state with intention to pass**
  The state in which a driver adapts its speed to the driver in front, however, he has the intention to pass.

- **passing-state**
  The state in which a driver is just starting a passing manoeuvre.

The model by Branston and Buckly described further in this section distinguish only the following and free driving state of the driver-vehicle element.

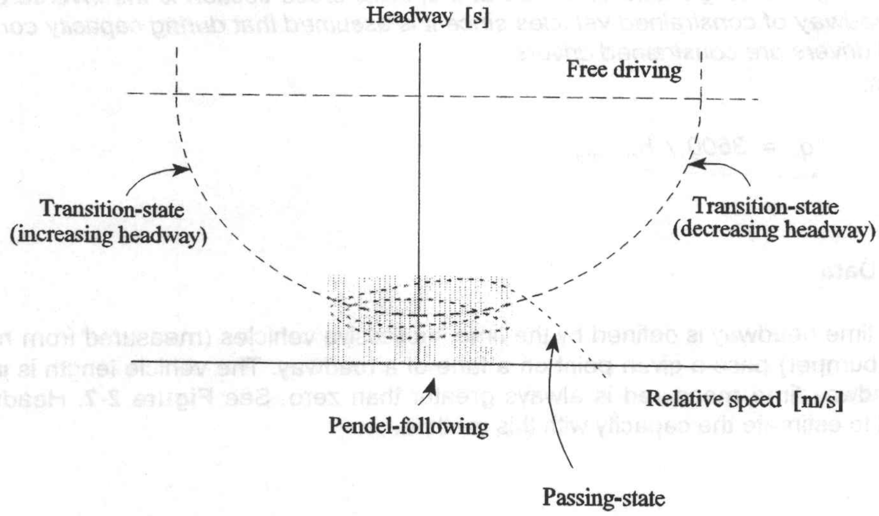


Figure 2-3 Definition of the Different States of a Driver-Vehicle Element

2-1-3 Location of Data Collection

The advantage of the use of headway models to estimate the capacity value, is that only headways at one cross-section of an arterial at an intensity below capacity are needed. Hence, it is not necessary to wait for the occurence of a traffic state at about capacity level. It is therefore not important to measure the headways at a bottleneck.

2-1-4 Observation Period and Averaging Interval

The total observation period and averaging interval duration are not questions of interest using headway models. In addition, the number of headways desired should be defined. Furthermore, the number of data sets with simular traffic volume observations should be determined. The independency of the capacity estimate from the traffic volume can be studied this way. For example, in Buckley (1968), seven volume groups were distinguished, and each group consist of more than 1000 available headways. Branston (1976) used sixteen traffic volume groups or classes with a minimum sample size of 200 headways.

Wasielewski (1979) used volume intervals of 100 vehicles/hour, and provided 12 data groups over a range of volumes between 900 and 2000 veh/h, with at least 2800 headways in most of the groups. He concluded that the distribution of car-followers headways can be considered independent of the flow rate. But this does not mean that data can be analyzed independent of the flow rate! To make a reliable estimation, the headways must be collected at a certain constant traffic flow rate (interval) since mixing observations from different traffic volume intervals is not allowed.

2-1-5 Required Traffic State

The headway models for a single lane can be applied during stable and unstable traffic. This is also one of the advantages of the headway models for estimating road capacity. Some literature reports the value of 750 veh/h per lane stated as the minimum intensity at which headway models may be applied appropriately.

2-1-6 Road Capacity Estimation

Two well known models with slightly different approaches for estimating road capacity are presented in this sub section. The complete derivation of the models can be found in the references, Buckley (1968) , Branston (1976) and Hoogendoorn (1996).

Buckley's Semi Poisson Headway Distribution Model

The basis of Buckley's model is the simple conjecture that in a single traffic lane the only inhibition to the underlying Poisson traffic process is the existence of a zone of emptiness in front of the rear of each vehicle (vehicle length included). In **Figure 2-2** this 'zone of emptiness' is indicated by $s_{p,r}$.

The aim of the semi-Poisson model is to calculate for each headway value the fraction of vehicles that are followers using plausible assumptions about the transition from leading to following for individual vehicles. See the distribution functions in **Figure 2-4**. These assumptions can be outlined as follows:

a. A vehicle on the road is either leading or following, although, the drivers might not experience their state as leader or follower. The overall probability density function of headways *f(h)* is given by:

$$f(h) = \phi \cdot g(h) + (1-\phi) \cdot b(h) \qquad (2.3)$$

where

ϕ	=	fraction of followers (constrained drivers) $0 \leq \phi \leq 1$
g(h)	=	followers' probability density function of tracking headway
b(h)	=	leaders' probability density function of free headway

The value *f(h)* represents the probability a headway of value *h* can be found in the traffic process. The physical interpretation of the ratio

$$\phi \cdot g(h) : (1-\phi) \cdot b(h)$$

is the number of tracking drivers in proportion to unconstrained drivers at headway value *h*.

b. Each driver has a preferred tracking headway, which he will adopt when the vehicle catches up to a slower vehicle with no immediate passing opportunity. Disturbances to this ideal, preferred tracking headway are introduced due to drivers perception capabilities, travel purpose, travel speed, traffic and road conditions and vehicle characteristics, see for example the trajectories in the Space-Time-Frame, which are not constantly spaced (**Figure 2-2**). The tracking headways of the observed population is distributed with a probability density function *g(h)* and includes the personal disturbances mentioned.

c. The followers proceed at the average speed of the vehicle ahead, with the headways distributed according to *g(h)*.

d. The leaders proceed at their own choice of speed, not influenced by the vehicle immediately ahead. The leaders headway probability density function *b(h)* is assumed to be exponential in form (for large headway values):

$$f(h) = b_1(h) = A \, \lambda \, e^{-\lambda h} \qquad \text{for } h>T \qquad (2.4)$$

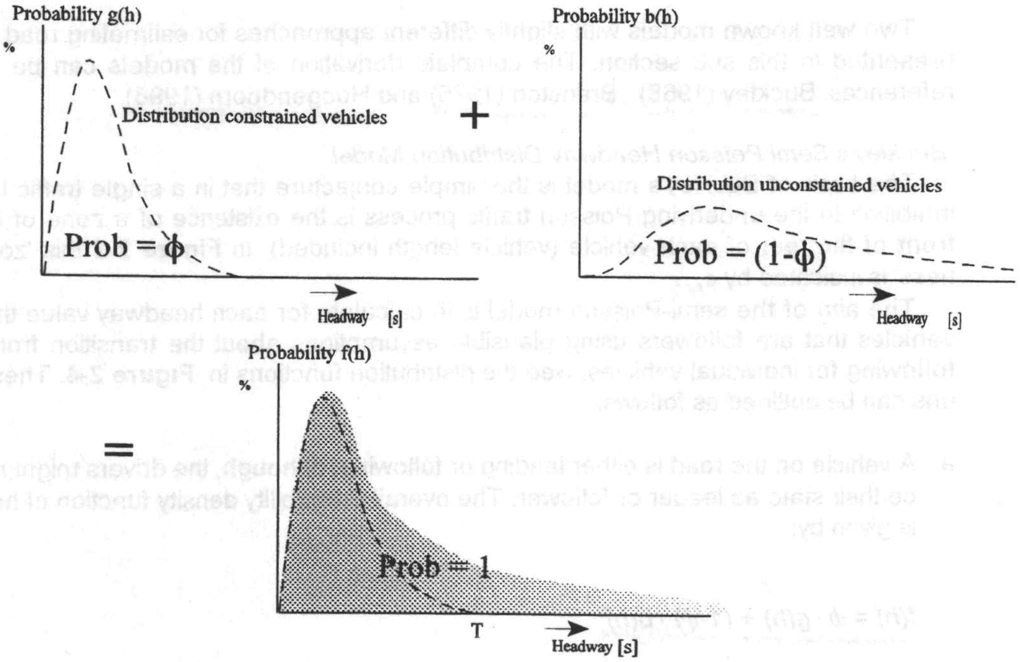


Figure 2-4 The Headway Distribution can be separated into the Headway Distribution of Constrained and Unconstrained Drivers

where

h	=	total headway
T	=	upper limit of headway of followers: driver-vehicle elements with h>T are free drivers, drivers with h<T can be either free or following
$b_1(h)$	=	unnormalized density function: $b_1(h) = (1-\phi) \cdot b(h)$
A, λ	=	parameters

For headway values with $h<T$ (see **Fig. 2-4**) interaction exist between leaders and followers. A correction is needed: removing the fraction of vehicles that have headways greater than h, since the assumption is that no vehicle will be found at less than its tracking headway. This fraction α is given by:

$$\alpha = \int_h^\infty g(u)\, du \tag{2.5}$$

$$b_1(h) = A\lambda e^{-\lambda h} (1-\alpha) \quad = \quad A\lambda e^{-\lambda h} \int_0^h g(u)\, du$$

or

$$b_1(h) = (A\lambda / \phi) e^{-\lambda h} \left(\int_0^h (f(u) - b_1(u))\, du \right) \tag{2.6}$$

The parameters A and λ can be evaluated from the observed headways in the range $h>T$ following equation 2.4. Then the integral equation 2.6 can be solved numerically subject to the constraint ϕ.

Point of interest is the determination of the critical headway time T allowing the discrimination between free and constrained vehicles. The determination of T can be found in Wasielew-

ski, 1979. One other problem is to find a reasonable distribution for the tracking headways.
The gamma distribution can take the general shape visualized in **Figure 2-4** (when very small headways occur the value *G(h)* which is the cumulative probability density distribution of g(h), is also small). Exponential or displaced exponential distribution functions can also be applied. Disadvantage of all these distributions is the absence of an upper limit.
Eventually, the capacity definition makes it possible to estimate the capacity with equation 2.2b. With regard to the discontinuity problem, the estimated capacity value is an estimation of the maximum free flow intensity as indicated in **Figure 1-5**.

Branston's Generalized Queuing Model
The movement of traffic passing a point can also be compared to the output of a queuing system having random input. A generalization of the queue output model leads to Branston's headway model, with a mixture of two distributions representing following and non-following headways in appropriate proportions. A basic assumption is that the total time headway consists of two independent random variables: a *tracking* headway and a *free* headway.
The distribution resulting from the modification takes the general form for mixed models, like equation 2.3. Each headway *h* is the sum of a following headway *s* drawn from the probability density function g(h) and a gap *h-s* which is assumed to be negative exponentially distributed with parameter λ, the flow rate. The total headway distribution can now be derived:

$$b(h) = \int_0^h g(s) \cdot \lambda \ e^{-\lambda(h-s)} \, ds \qquad (2.7)$$

$$f(h) = \phi \cdot g(h) + (1-\phi) \cdot \lambda e^{-\lambda h} \cdot \int_0^h g(s) \cdot \lambda e^{\lambda s} \, ds \qquad (2.8)$$

Other notations can be found in literature due to the different methods of derivation.

The difference between the two headway models described above is that in the Semi-Poisson model each non-following headway is obtained by comparing an exponential headway with a following headway, while in the queuing models each nonfollowing headway is obtained by adding an exponential gap to a following headway.

2-1-7 Example

For a recent application of the headway model we refer to Hoogendoorn (1996). In this study, traffic measurements at two-lane rural roads in the Netherlands were used to assess an improved method for parameter estimation of Branstons headway model.
The data under consideration was collected at an off-peak period and composed of 1577 headways. The minimum, maximum and mean headway in the sample are given by 0.3, 72.6 and 5.6 s respectively. Hence, the flow during the period of measurement is 639 vehicles per hour per lane. Various parameter estimation methods were compared in the study, such as the maximum likelihood, empirical density, empirical distribution and the weighted frequencies. The best estimates can be obtained using the empirical distribution method or the weighted frequency method, resulting in an estimated traffic volume of 649 veh/h/l and 705 veh/h/l respectively. The road capacity was derived in the study at 1846 veh/h/lane and 2114 veh/h/lane respectively.

The parameter estimates based on the empirical distribution seems to deliver realistic flow rates and consistent (less biased) results, although the weighted frequency method in some cases performed better following the performed Kolmogorov-Smirnov test.

2-1-8 Evaluation

The differences between the Buckley and Branston Headway model for estimating road capacity appear to be insignificant, as observed in the study by Botma & Papendrecht & Westland (1980). Therefore, one can conclude that both approaches to the capacity estimation problem will result in approximately the same value for the road capacity for a single lane. Personal favour for one of these models is probably the most decisive factor for the application of one of the Headway Distribution Models as a means for estimating the road capacity of a single lane.

Furthermore, it should be remarked that several investigations with these models resulted in a general conclusion that the Headway Models overestimate the observed road capacity substantially. Of course, we have no knowledge about the real capacity value, however we can compare results with capacity values found in guidelines or found in earlier studies. The over-estimation is probably caused by the implicit assumption of the models that the distribution of constrained drivers $g(h)$ at maximum free flow intensity (the capacity estimate) can be compared with the distribution $g(h)$ at any other free flow intensity. Also, there is not taken account of the interaction between the different lanes of the road which is probably a function of the intensity of the road. Therefore, we may conclude that the Headway approaches should not be the first choice for estimating a reliable (strategic) capacity value.

Chapter 3

CAPACITY ESTIMATION WITH TRAFFIC VOLUMES

The direct-empirical capacity estimation methods based solely on observed traffic volumes can be divided into two extreme value approaches, namely based on observed extreme and expected extreme methods respectively (see **Figure 1-0**).

Observed extreme value methods estimate the capacity of a road using only known maximum traffic volumes acquired over a certain period. In this chapter, the Bimodal Distribution and the Selected Maxima Method are described as examples of the observed extreme value methods. It should be remarked here that there exist a few other methods to determine the capacity based on observed maximum traffic volumes. However, these experimental methods can not be applied in normal daily traffic conditions:

- **Queue Discharge Flow Method**, which is based on observing the maximum volume that can pass a cross-section (bottle-neck) after congestion has occurred (Westland, 1994). Since an upstream queue can artificially be created by blocking the road for a certain period, one can create a (non-existing) bottle-neck everywhere. The capacity estimation corresponds with a maximum congested flow intensity (see **Fig. 1-5**). This method has some important similarities with the Empirical Distribution Method (see **Section 4-1**).

- **Platoon Driving Method**. All vehicles on a freeway in one direction are constrained drivers due to special instructed cars driving at specified speeds to obtain a homogeneous travel speed on the freeway. Herewith, at different speeds the maximum volume can be quantified (compare this method with the construction of the Fundamental Diagram in **Section 5-**

1). It is not known whether this Belgian approach to create a stable and safe traffic state for special occasions has been analyzed in a scientific way. This method will also result in a capacity value corresponding with a maximum congested free flow intensity

- **Test Site Method**, which uses a special environment with instructed test drivers to approximate a capacity value. To restrict the number of drivers, a circular track can be used. In addition, this method can result in capacity values related to the radius of the applied circular tracks (Wardrop, 1963). The derived values correspond with maximum free flow intensities.

The *expected extreme value methods* also use observed extreme traffic volumes to determine a (strategic) capacity value, however, these methods use extreme flow rates observed in the averaging intervals to predict a higher unobserved capacity value using statistical methods adopted from other areas (e.g. astronomy). Since the main interest is the probability with which a certain extreme value will occur, the results are sometimes denoted with the term *limiting capacity* (Hyde & Wright, 1986).

In **Section 3-3** an example of this kind of methods resulting in an extreme value for the road capacity is described. Some assumptions are required about the distribution function of the observed traffic volumes. In **Section 3-4** a more complicated extreme value method is presented. This method doesn't require assumptions about a particular distribution form of the observed traffic volumes. More advanced methods use additional speed data and/or density data to ensure that the capacity situation is reached during the observation intervals. These kind of methods will be explained in **Chapter 4**.

3-1 Bimodal Distribution Method

3-1-1 Principle of the Method

When the observed traffic stream includes some intensities at about the point of capacity of the road a bimodal distribution may be observed (Cohen, 1983). The special character of the intensity distribution can be explained by the existence of two different traffic states, one representing the traffic demand and one representing the stochastic maximum flow level (both collected during the observation period). Two separated distributions are assumed to represent the compound distribution of the observed flow rates.

The definition of capacity according to this bimodal distribution method could be stated as: *The capacity of the road is the expectation (or some other location characteristic) of the probability density function representing the (stochastic) maximum flow variable, in case a bimodal distribution of intensities is observed during the observation period.*

3-1-2 Traffic Data

For this method, only traffic volumes have to be counted at a cross-section of a road. The Bimodal Distribution method can be used when the conditions concerning the location choice and survey aspects have been satisfied.

3-1-3 Location of Data Collection

The location for data acquisition has to be at a bottleneck. Also, the traffic demand has to be higher than the capacity of the road. Otherwise, only the traffic demand will be acquired and no sign of a capacity restraint will be found in the distribution of the observed flow rates.

3-1-4 Observation Period and Averaging Interval

The duration of the averaging interval time has to be chosen feasible to collect sufficient data with high traffic volumes. The observation period may not have any influence on the existence of such a bimodal distribution. As mentioned in the section about the required location for the data acquisition, the observed flow rates must include congested flow observations. It is therefore advisable to use more than one cross-section to determine the traffic state, as will be explained in **Section 4-1**. Low traffic volumes, for example measured at night, provide no extra information with regard to the capacity of the road. These unrelevant observations can be excluded from the data set, or even better: not measured at all.

3-1-5 Required Traffic State

As mentioned in the section about the required location for the data acquisition, the observed flow rates must include congested flow observations. In general, this will mean that somewhere upstream the measuring point congested traffic flow should be observed during the observation period.

3-1-6 Roadway Capacity Estimation

The capacity state of the traffic may be visualized as a Gaussian-type density (**Fig. 3-1**). This assumption is well suited for the road capacity which is seen as a stochastic random variable, as discussed earlier.

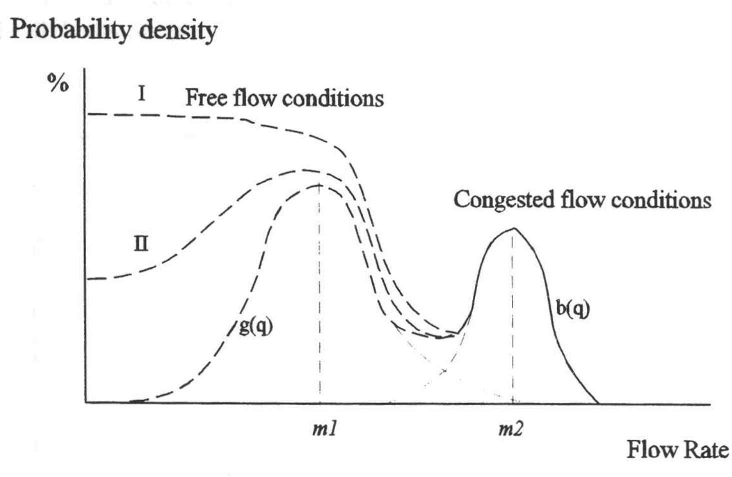


Figure 3-1 Probability Density of Observed Flow Rates in the Bottle-neck as a Function of the Upstream Traffic Conditions

The distribution of the traffic demand depends strongly on the total observation period. Curve I (**Fig. 3-1**) represents an observation time with many low intensities (e.g. counted at night), situation II can be found when observing day and evening. Data collected only during the day can probably be depicted as a Gaussian curve. In the example of **Figure 3-2**, only data acquisition during the day has been carried out. Night observations with low traffic volumes were excluded. The general form for a compound probability density function can be used:

$$f(q) = \phi \cdot g(q) + (1-\phi) \cdot b(q) \tag{3.1}$$

When applying two Gaussian densities, we define g(q) and b(q) as:

$$g(q) = 1/\sqrt{(2\pi\sigma_1^2)} \cdot exp[-(q-m_1)/(2\sigma_1^2)]$$
$$b(q) = 1/\sqrt{(2\pi\sigma_2^2)} \cdot exp[-(q-m_2)/(2\sigma_2^2)] \tag{3.2}$$

where

ϕ = fraction of the probability density function representing the traffic demand below capacity
g(q) = probability density function representing free flow intensities
b(q) = probability density function representing congested flow intensities

The five parameters in the model can be estimated by minimizing the squared error between data and the proposed function. The expectation of function b(q) represents the estimation of the road capacity in this method.

3-1-7 Example

Two normal Gaussian distributions have been proposed to cover the traffic data encountered in the study where this method was presented (Cohen, 1983). Five parameters have to be estimated: the proportion parameter ϕ, the means m_1, m_2 and the variances σ_1^2 and σ_2^2. **Figure 3-2** shows an example of the three-lane carriageway of the study, in which the Bimodal distribution is very clearly apparent.

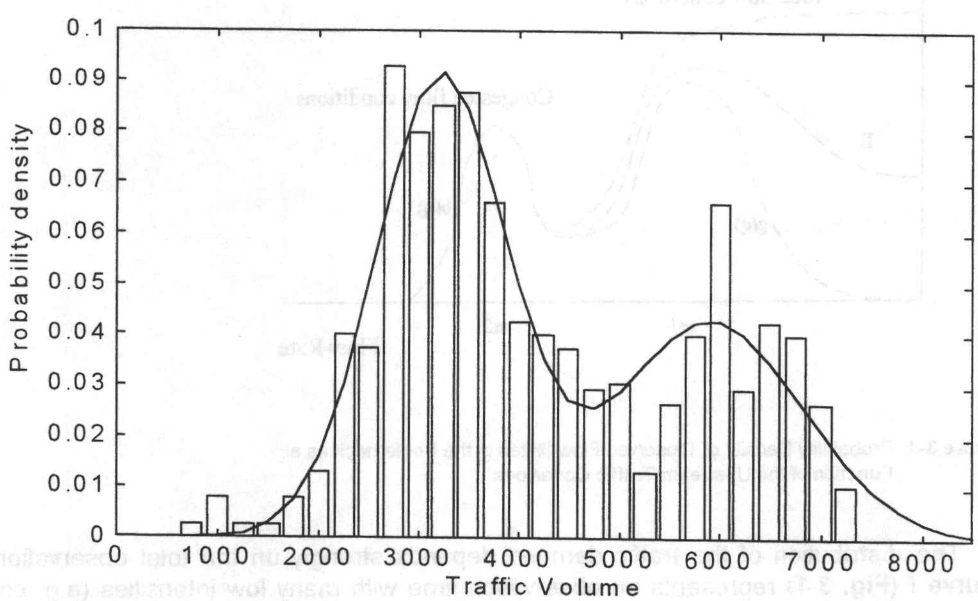


Figure 3-2 The Bimodal Distribution with two Gaussian Functions [reconstructed data, day observations only, ϕ=0.6, capacity (median) =5900 veh/h]

There are of course observation studies in which the distribution is not like this well shaped curve, and it can be stated that when one choses another (larger) averaging interval, the bimodal distribution can vanish. In the shown example (Cohen, 1983), one-minute intervals were used to aggregate the traffic counts. The traffic data in **Figure 3-2** is indicated with bars (in intervals of 250 vehicles/hour). The estimated probability density function with the five parameters is given by the uninterrupted line. The fraction ϕ is here 0.6. The road capacity (the mean m_2) is about 5900 vehicles/hour for three lanes.

3-1-8 Evaluation

A major problem with the application of the Bimodal Distribution Method is the choice for the free flow probability density function. The assumption that capacity can be estimated with a Gaussian-type distribution can be accepted without great resistance. But the assumption that the free flow intensity distribution also can be represented with a Gaussian distribution is doubtful and depends mainly on the selected observation period. Therefore, we may conclude that the Bimodal method is a method with a limited practical use since its theory and hypothesis will not be consistent in all cases. The Bimodal method has some simularities with the Product Limit Method (**Section 4-2**) but the latter can be applied without assuming distribution functions for the two types of intensity measurements.

3-2 The Selected Maxima Method

3-2-1 Principle of the 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 traffic flow maxima (distribution) observed during the total observation period. An example of a very easy application of the Selected Maxima Method is taking the average of observed maximum day intensities (see **Fig. 3-3**). The observation of flow rates should take place over several days until sufficient data is collected for analysis purposes.

Road capacity may be defined here as: *The average maximum flow based on selected observations over the observation period (or some other location characteristic of the observed distribution of maximum flows).*

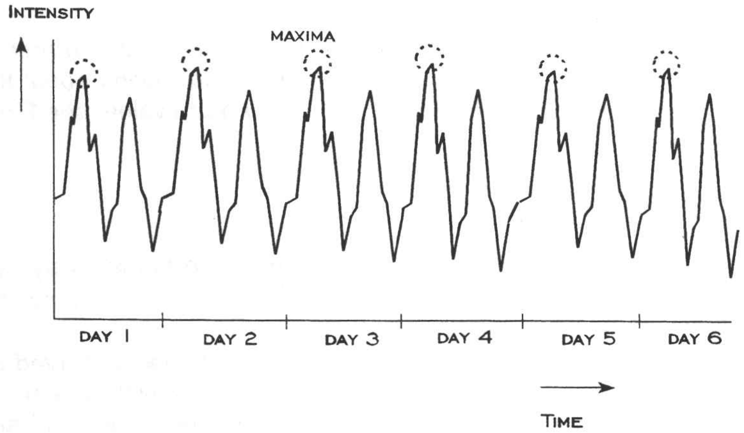


Figure 3-3 Principle of The Selected Maxima Method

3-2-2 Traffic Data

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.

3-2-3 Location of Data Collection

The capacity-state of the road in question at the cross-section for measurements must be reached at least once during the observation period.

3-2-4 Observation Period and Averaging Interval

The observation period can vary from one survey study to another. For example, an observation period of a year with a hourly averaging interval will result in 365 maxima which can be used for analysis purposes.

3-2-5 Required Traffic State

Since the method needs traffic flow maxima, it is clear that these observations can only be obtained when the capacity-state of the road is reached.

3-2-6 Road Capacity Estimation

The calculation of road capacity using a selected maxima approach is usually an easy procedure. Mostly, the road capacity q_c is assumed to be equal to the averaged traffic flow maxima observed during the total observation period. Thus:

$$q_c = \Sigma_i \, q_i \, / \, n \tag{3.3}$$

where

q_c = capacity value [veh/h]
q_i = maximum flow rate observed over period i
n = number of periods *i (cycles)*
i = period over which a maximum flow rate is determined
(*T= n . i* , thus the observation period *T* is divided into *n* periods of duration *i*)

The estimated road capacity is the calculated value q_c, which may be a maximum free flow intensity or a maximum congested flow intensity. Without more information about the type of measurements we are not able to determine the type of the maximum value (see **Fig. 1-5**).

3-2-7 Example

The study reported by Cohen (1995) took place at a three lane carriageway, which is of major importance for traffic flow in the Paris region. The high level of demand means the ensurance that capacity was reached during peak periods.

The maximum hourly volumes (i.e. the highest of the 24 hourly flows observed during the day) are collected during weekdays, the values for weekends and holidays being excluded. The monthly maximum (hourly) volumes were then subjected to time series analysis. For the site in question monthly data is available for as far back as 1980. Two four year periods have been compared: 1980-1983 and 1990-1993. The maximum monthly values during the period 1990-1993 show a significant increase compared with the period 1980-1983.

Each of the two time series (**Figure 3-4**) may be analyzed by an additive seasonal model:

$$q_t = q_c + e_{s,t} + e_{r,t} \tag{3.4}$$

in which q_t is the maximum volume for month *t*, q_c is the constant assumed capacity value, $e_{s,t}$ is the seasonal component of month *t*, $e_{r,t}$ is the random component.

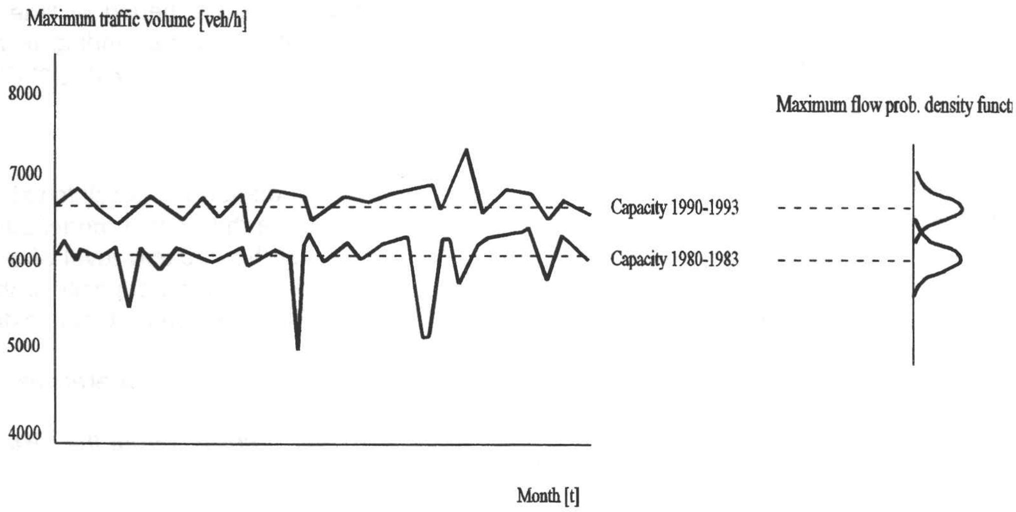


Figure 3-4 Observed Monthly Maximum Traffic Volumes [Source: Cohen (1995)]

All the parameters are expressed in veh/h. A numerical comparison between the seasonal models confirms the rising trend. In this example, the capacity of the road changed from 6150 veh/h to 6700 veh/h, that is, an increase of approximately 9% in ten years.

An explanation for the observed increase of road capacity (assuming no adaptations in the infrastructure) can be one of the following:

a. The capacity of a road is considered to increase over time due to changes (replacements) in motor vehicle fleet and driving behaviours. The continuous reduction in accidents which have been occuring since the motor car was developed, indicates such an improvement in dynamic performance and higher driving skills.

b. It could be that not only the *capacity*, but also the *number of capacity measurements* has been increased considerably, due to the car mobility growth between 1980 and 1990 in the study area. It is easy to understand that the more capacity measurements are made in one month, the higher the observed monthly maximum will be.

Taking into consideration ad. b., we must conclude that the yearly capacity increase will be *less* than the 0.9 % per year as was derived above.

3-2-8 Evaluation

According to the main topic of this report, the validity of the capacity estimation methods, we are inclined to conclude negatively for the underlying method. A reliable estimation of the capacity value can not be given since the number of capacity measurements will affect this estimation as mentioned in the example above. In addition, chosing the average value is rather arbitrary; taking the 90th percentile point for example might be useful as well.

3-3 Direct Probability Method

What are the characteristics of the extreme flow rate values which occur occasionally in everyday traffic condition? If maxima are recorded over a suitable period of time, can any useful information be deduced from them? These questions were the starting point for the development of the Direct Probability method which can be found in Hyde & Wright (1986).

3-3-1 Principle of the Method

With this expected extreme value 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 requires that the capacity level of a road has been reached during the observation period. Here, the approach to the capacity problem is to consider variations in volumes over time during 'normal' traffic conditions (no congestion at the measuring point or accidents).

The capacity estimate resulting from the calculations can be considered as a certain exceptional value of the maximum flow.

The capacity of a road is the expected maximum flow rate predicted from the distribution of traffic counts given an assumed traffic arrival process (see Figure 3-5).

3-3-2 Traffic Data

The Direct Probability method uses flow rates to calculate the expectation of the largest value, the assumed capacity of the road.

3-3-3 Location of Data Collection

At any location under the condition that the capacity situation will be reached. Assumptions about the arrival process of the vehicles at the cross-section are needed.

3-3-4 Observation Period and Averaging Interval

It seems that an observation period of one day is sufficient to make an estimation of the road capacity, however data of more than one day is to be preferred. The daily flow rate records can be examined for evidence of significant variations in mean volume through the hours of the day and the days of the week (evidence for identically distributed observations). The total number of observations (and thus the observation period) naturally affects the capacity estimate, as described in Persaud & Hurdle (1991).

Furthermore, it is well known that very large flow rates can be observed over very short averaging interval periods, but they occur much less frequently over longer periods. The duration of the averaging interval has to be chosen such that collection of sufficient data is feasible. However, the measurements must be independently and identically distributed. Therefor the method requires averaging interval durations of at least 5 minutes, a value reported by Keller & Sachse (1995) as a valid choice for the minimum averaging interval duration.

3-3-5 Required Traffic State

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 element of the same distribution function) distributed. This implies among other things that the mean flow rate during the observation period is constant. Nonetheless, during the observation period the capacity level of the road must be reached for the capacity investigation with the Direct Probability method, since only then maximum flows can be obtained.

3-3-6 Road Capacity Estimation

The maximum of a set of random variables can be considered as a random variate with its own probability distribution. When considering a statistical model to represent traffic flow it is clearly important to distinguish between the types of variability which the model is intended to take account for, and those it is not. The intention here is to examine very localised flow rate variations which could reasonably treated as random, with the long-term mean flow rate held constant. Assume that there are n consecutive averaging intervals during the observation period T and denote the intensities observed in the respective averaging intervals by $q_1, q_2, .., q_n$. See **Figure 3-5** where part of the theory is shown: the flow rate measurements are supposed to be distributed according to a chosen distribution of arrivals.

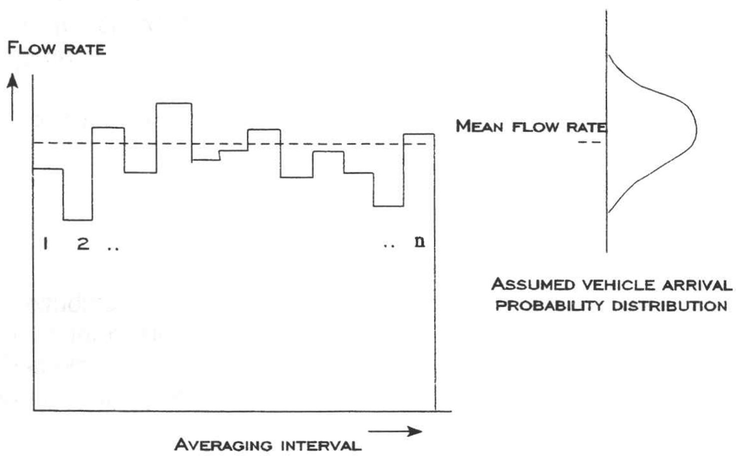


Figure 3-5 Principle of the Direct Probability Method

Let the probability that the flow rate q_i in any given sampling interval i is less than or equal to q vehicles be:

$$Prob(q_i \leq q) = F(q) \quad (3.4)$$

then the probability that the intensities in all of the n intervals are less than or equal to q is:

$$Prob(\max_{1 \leq i \leq n} q_i \leq q) = Prob(q_1 \leq q) \cdot Prob(q_2 \leq q) \cdot .. \cdot Prob(q_n \leq q) = F^n(q) \quad (3.5)$$

where:

n	=	number of averaging intervals
q_i	=	observed intensity in averaging interval i
$F^n(q)$	=	(compound) probability distribution function

The probability density distribution of the *maximum flow* is denoted by $g(q_i)$ and can easily be derived (equation 3.6). The expectation of the maximum flow rate is then given by equation 3.7. This expesion may serve as a mathematical expression for the capacity, and its value is an estimation of the maximum congested flow intensity (Fig. 1-5).

$$g(q_i) = dF(q_i)/dq = F^n(q_i) - F^n(q_{i-1}) \tag{3.6}$$

$$E(max_{1 \leq i \leq n}\ q_i \leq q) = \Sigma_i\ q_i \cdot g(q_i) \tag{3.7}$$

$$Var(max_{1 \leq i \leq n}\ q_i \leq q) = \Sigma q_i^2 \cdot g(q_i) - [\Sigma q \cdot g(q)]^2 \tag{3.8}$$

To apply these formulae, one must first choose a functional form for the traffic volume counting distribution $F(q)$ as indicated in **Figure 3-5**. In the case of freely flowing traffic, the Poisson form is the natural choice. If the mean flow per sampling interval is sufficiently large, an alternative is using the lognormal, beta, normal or Gaussian distribution as an approximation.

We refer to Gumbel (1958) for a more analytical approach of this Direct Probability method.

3-3-7 Example

Hyde and Wright (1986) use a normal curve instead of the Poisson distribution, because the variance to mean ratio of the flow rates for the 30 seconds averaging intervals were all greater than unity. A prediction for the maximum flow in each of the five selected datasets (days) was then calculated via equation 3.7, for each of the applied averaging interval durations. The results for the five datasets were very similar.

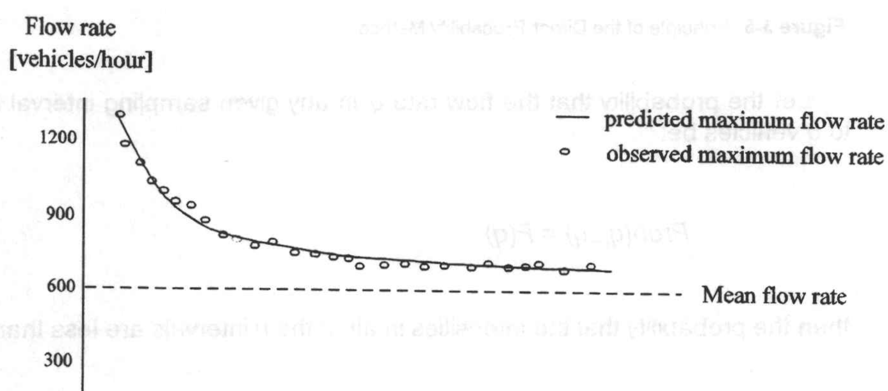


Figure 3-6 Observed and Predicted Maximum Flow Rates for Various Durations of The Averaging Interval [Source: Hyde & Wright (1986)]

Figure 3-6 shows an example of the derived relation between the maximum predicted and observed flow rate. Also, the applied averaging interval is shown. The solid line is the estimated theoretical curve following the calculation in Section 3-3-6. The observed flow rate maxima are shown as open circles. The interrupted line is the mean flow rate over the observation period, and its value is insensitive to the size of the averaging interval.

3-3-8 Evaluation

One can conclude that the mean flow rate over observation period T is a more simple, consistent estimate for the capacity which is independent of the averaging interval duration. Since the data has to be obtained during the capacity state of the road the average traffic volume seems to be a better alternative for the capacity value estimation instead of the described Direct Probability procedure.

3-4 Asymptotic Method

The Asymptotic Method (Hyde & Wright, 1986) is another approach (instead of the Direct Probability Method, **Section 3-3**) to solve the extreme value estimation problem. The assumptions and capacity definition will be explained here.

3-4-1 Principle of the Method

The method relies on the theory that the behaviour of the extreme values arising from any natural process can be described in terms of a simple statistical model. The model turns out to have two parameters, whose values can be estimated from observed maxima when analyzed in the appropriate way. This estimation gives a direct indication of whether the variable has an absolute upper limit, and if so, its value. The upper limit will lie outside the range of the observed data, and in such cases the validity of the method depends on the extent to which the data satisfies the assumptions on which the method is based (Gumbel, 1958).

Instead of trying to estimate the exceptional maximum flow rate what is done in **Section 3-3**, one is trying to estimate a (yet unobserved) limit, which can be referred to as the 'maximum' or 'limiting' capacity. Here, also the assumption is made that the traffic volume observations for all averaging intervals are independently and identically distributed.

The capacity of a road is defined as:

The expected maximum flow rate predicted from the distribution of observed extremes in selected intervals (cycles). (See Figure 3-7).

3-4-2 Traffic Data

The Asymptotic method uses vehicular flow rates to calculate the expectation of the limit value, the assumed capacity of the road.

3-4-3 Location of Data Collection

Any location is suitable under the condition that the capacity situation will be reached. There are no assumptions about the arrival process of the vehicles at the cross-section.

3-4-4 Observation Period and Averaging Interval

The observed values of the flow rate are used to determine the parameters of the model. The total observation period *T* exist of *c* cycles. Furthermore, a cycle is divided into averaging intervals. See **Figure 3-7**. The largest aggregated value is identified within each cycle, and the set of maxima forms the data input for analysis. Hence, large quantities of data are required for calibration. In meteorological work, the natural choice for the cycle duration is one year, each cycle consisting of 365 daily observations. Data is collected over a period of several years and the annual maxima are extracted and used in the analysis.

Hyde and Wright use for the maximum cycle duration (applied for traffic flows) a period of an hour, while the data is collected over some weeks.

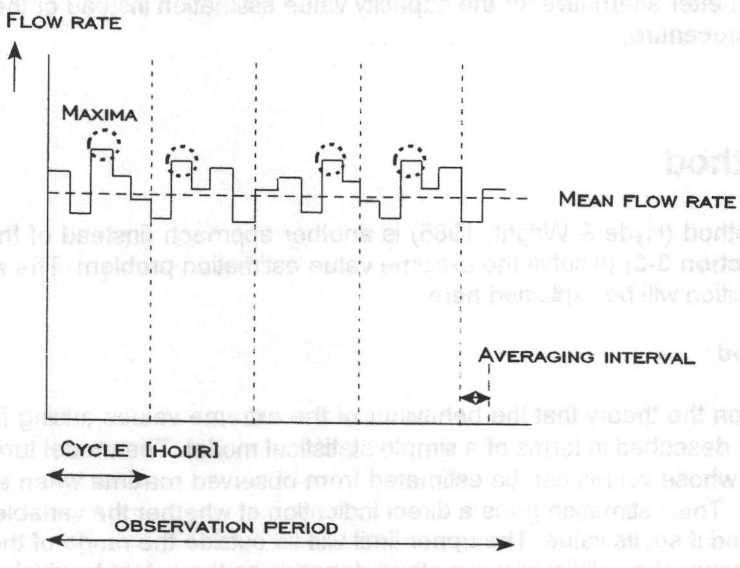


Figure 3-7 Principle of the Asymptotic Method

3-4-5 Required Traffic State

One important requirement is that the observations for all averaging intervals are independently (flow rates between sampling intervals are not related) and identically (all countings are element of the same distribution function) distributed. This implies among other things that the mean flow rate during the observation period is constant.

3-4-6 Road Capacity Estimation

The characteristic extreme q_{ex} is defined as the value which on average is exceeded just once in a set of averaging intervals of size *n*. Thus (see **Figure 3-8**):

$$1 = n\,[1-F(q_{ex})]$$

or alternatively (3.9)

$$F(q_{ex}) = 1-(1/n)$$

The initial cumulative distribution *F* can be expanded about the characteristic extreme and after simplification we obtain (see for a derivation Hyde & Wright (1986) or Gumbel (1958)):

$$Lim_{\,n\to\infty}\ F(q) = 1-(e^{-q_{re}}/n) \quad (3.10)$$

where we introduce the reduced largest value q_{re} defined by

$$q_{re} = \alpha \cdot (q - q_{ex})$$

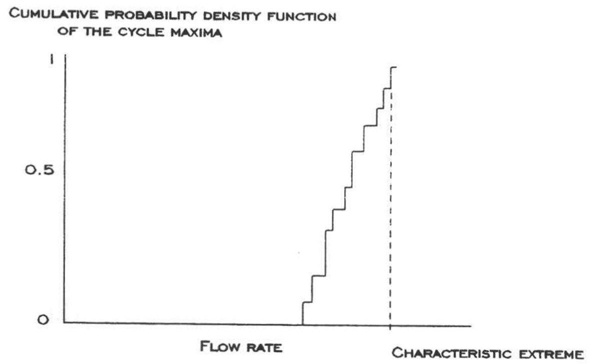


Figure 3-8 The Characteristic Extreme

Let us denote the cumulative distribution of the maxima by $H_n(q)$. Now since the probability that *all* the values in a sample of size n are less than q is $F^n(q)$ (Section 3-3, eq. 3.5), we have

$$H_n(q) = F^n(q) = [1 - (e^{-q_{re}} / n)]^n \tag{3.11}$$

Consider a set of maxima which are distributed each conform a (unknown) probability function, then the distribution of the maximum of this set tend to have a functional form which can be derived from the functional forms of the original observations in the set.

Since a linear transformation does not change the form of the distribution and if we denote the asymptotic distribution of the maximum by $\theta(q)$ we can write

$$\theta^n(q) = \theta(a_n \cdot q + b) \tag{3.12}$$

$$q = a \cdot [1 - e^{-k \cdot q_{re}}] \tag{3.13}$$

where a and k are constants such that $a.k$ is positive. The three solutions correspond to three different shapes of curve according to the value of the parameter k:

- *type I:* $k<0$: dq_{re}/dq decreases with increasing q_{re}, there exist a lower limit;
- *type II:* $k=0$: dq_{re}/dq is constant, there is no asymptotic limit;
- *type III:* $k>0$: dq_{re}/dq increases with increasing q_{re}, there exist an upper limit;

When there is a physical limit to the number of vehicles which can pass a given point in a given time, the upper extremes will be a *type III* variate. The location of the asymptote can be deduced graphically or numerically.

3-4-7 Example

The form of most data allow considerable freedom to experiment with different combinations of values of averaging interval duration and cycle duration, and the results themselves give some indication of the variability of the parameters. The example depicted in **Figure 3-6** demonstrates the features which occur generally throughout the results from the study in Hyde & Wright (1986). The distribution follows a distinct curve, which suggests the presence of an upper limit for the traffic volume. The limiting intensity values are shown as vertical (dotted) lines.

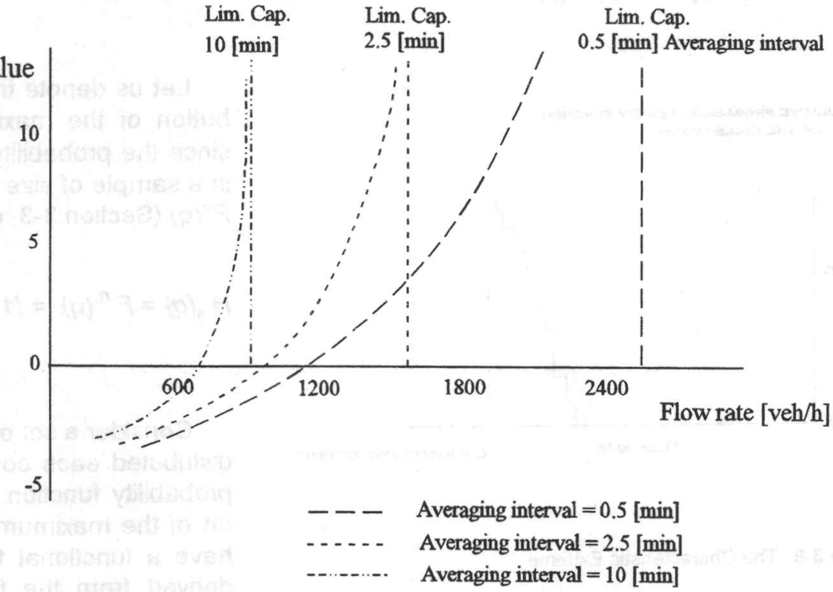


Figure 3-9 Predicted q_{re}-Values Plotted Against q For Three Sampling Interval Durations (10:00-15-00 hr, Weekdays) [Source: Hyde & Wright (1986)]

The estimates of the limiting traffic volume vary substantially with the duration of the averaging interval. This feature can also be found when examining maximum flow rates. One can conclude that a road can provide a very high capacity for a short time, however the road capacity cannot be sustained. An averaging interval duration of about 10 minutes or more tends to a limiting capacity of about the mean intensity. This average flow rate, when calculated during the capacity level of the road, may serve as a more consistent, reliable and less complicated capacity estimate.

3-4-8 Evaluation

Since the estimated limiting capacity value strongly depends on the averaging interval duration (see **Figure 3-9**), just like the Direct Probability Method (**Section 3-3**), it seems that the Expected Maximum Methods have little practical value for freeway design or modelling. The main cause of the great variance in the capacity values lies in the fact that only the high traffic volumes are used in the calculations. Moreover, as mentioned before, high flow rates are observed more often in small averaging intervals. Of course, also very extreme low intensities will be measured in such intervals, but these values are not taken into account in the calculation of the upper limit. The averaging interval duration with the application of, for example, the Fundamental Diagram Method (**Section 5-1**) is less problematic, since the *mean* flow rate over an averaging interval will be used instead of a single *maximum* observed value.

Chapter 4

CAPACITY ESTIMATION WITH TRAFFIC VOLUMES AND SPEEDS

Road capacity estimation methods based on both traffic volumes and speed data can be used to investigate the traffic state related to the observed volumes. Herewith, a better way to approach the capacity problem is available since it should be clear that a good estimation of the capacity value can only be made when the traffic state (capacity level reached or not) is known by the observer. To this end speed measurements can be used.

Three methods are presented in this Chapter. Firstly, the Empirical Distribution Method which is a simple case of the Product Limit Method, is presented (**Section 4-1**). Secondly, the Product Limit Method (**Section 4-2**) which uses a selection of free flow intensities and congested flow (capacity) observations, is described. Thirdly, the Selection Method (**Section 4-3**), a more ad hoc approach with which only a lower limit of the capacity can be determined is presented.

4-1 Empirical Distribution Method

4-1-1 Principle of the Method

The theory of the method is based on an explicit division of the flow observations that have been made over the observation period. The idea is that a capacity value can be derived from the distribution of capacity measurements.

It can easily be understood that a flow rate measurement can be divided into one of the following categories if the traffic state is observed upstream the measuring point:

- **measurements representing the traffic demand** (a free flow intensity measurement)
- **measurements representing the capacity-state of the road** (a maximum congested flow intensity)

indicated with observation elements of set {Q} and {C} respectively. With this division, it is possible to estimate the Empirical Capacity Distribution function *F(q)*. This categorisation of observations is also an important aspect of the Product Limit Method (**Section 4-2**).

The definition of road capacity according to the Empirical Distribution Method is the following:

A capacity distribution (and a capacity value at a certain location characteristic) may be derived using intensities observed at a bottle-neck during upstream congestion conditions.

4-1-2 Traffic Data

The Empirical Distribution Method is based on observations of traffic volumes at a well chosen measuring point at a bottleneck, see **Figure 4-1**. Speed measurements upstream a bottleneck (location *a*) are necessary to ascertain a traffic state with congestion. It is mostly assumed that speed measurements below a certain level (e.g 70 km/h) imply this congestion-state. In addition, this means that traffic in the bottle-neck (location *b)* is at the capacity-state of the road. However, speed observations downstream the bottleneck, location *c,* are required to determine the traffic state and the possible occurence of congestion. If congestion is measured at that point *c*, a bottle-neck further downstream the freeway affects the observed intensities at location *b*, so that roadway capacity at *b* is not yet reached. The bottle-neck observations are then no longer representative for a capacity situation, and therefore the observations are included in neither set {Q} nor {C}.

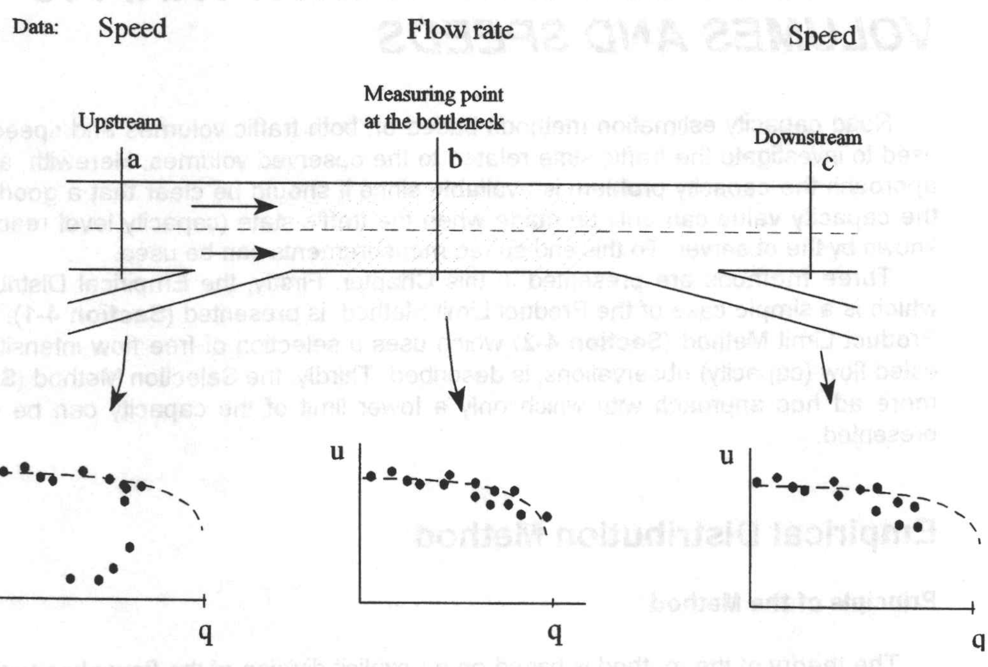


Figure 4-1 Measuring Points for The Application of TheEmpirical Distribution, Product Limit and Selection Method and Examples of Corresponding Fundamental Diagrams

4-1-3 Location of Data Collection

A bottle-neck should be chosen since the traffic volume measurements must include intensities representing the capacity state of the roadway (see **Figure 4-1**).

4-1-4 Observation Period and Averaging Interval

In the study by Van Toorenburg (1986), the rate of flow is observed in averaging intervals of 15 minutes. Keller and Sachse (1995) reported that the 5 minute period is a valid averaging time period for capacity estimation. However, the time period chosen is always a compromise, since extreme large volumes will not appear using one-hour intervals whereas too small averaging intervals (e.g. one minute) will show extreme fluctuations in the flow rates. A reliable analysis of the observations could require more than a single day of volume and speed measurements.

4-1-5 Required Traffic State

A bottle-neck location should be chosen to be sure about the occurrence of the capacity state of the road whenever congestion upstream is detected. Therefore, the required state is a capacity situation although a free flow state is allowed.

4-1-6 Roadway Capacity Estimation

Figure 4-2 shows the general form of a continuous, cumulative Empirical Capacity Distribution function.

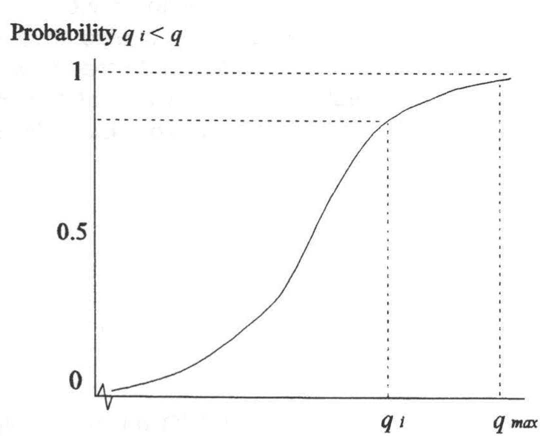


Figure 4-2 The Cumulative Capacity Distribution

A discrete Empirical Capacity Distribution function can easily be determined with equation 4.1 with applying only intensities that are element of the capacity set {C}.

$$F(q) = Prob(q_i<q) \qquad , q_i \in \{C\} \qquad (4.1)$$

More specific, we can write eq. 4.1 as:

$$F(q) = N_c / N \qquad (4.2)$$

where

F(q)	=	cumulative distribution function of capacity
q_c	=	capacity value
q_i	=	intensity value counted at averaging interval i
N_c	=	number of observation elements i in set {C} with intensities q_i less than q
N	=	total number of observation elements i in set {C}

This discrete Empirical Distribution function can be used for chosing a single capacity value q_c, for example at the median, 50 or 95 percentiel. The capacity estimate corresponds with the average maximum congested flow intensity, defined in **Figure 1-5**.

With equation 4.3 the variance of the intensities can be calculated as a indicator for the acceptability of the derived capacity value.

$$Var(F(q)) = F(q) \cdot (1 - F(q)) / N \qquad (4.3)$$

4-1-7 Example

See **Appendix B** for an elaborated example of the application of this general approach.

4-1-8 Evaluation

The Empirical Distribution Method is a straight forward capacity estimation method, and its major advantage is the clear and unbiased capacity value and distribution based on intensity measurements during congestion conditions upstream. This brings us also to a point of discussion: only capacity measurements are desired and used while made free flow intensity measurements are not employed. Even when these values exceed most of the observed capacity intensities. So, the method does not use all available information about the capacity value and this disadvantage can be argued.

4-2 Product Limit Method (PLM)

4-2-1 Principle of the Method

The theory of the PLM method (Van Toorenburg, 1986) is based on an explicit division of the flow observations that have been made over the observation period. The categorisation already mentioned in **Section 4-1-1** is an important aspect of the Product Limit Method. The idea is that we can use free flow intensity measurements to improve our capacity estimate based on capacity measurements only, since these measurements can give us a better indication about the real capacity value. Therefor, the Product Limit Method takes into account all free flow intensities which are equal or exceed the lowest capacity measurement made during the observation period.

The road capacity definition according to the Product Limit Method is therefore:

The capacity is a location characteristic (mean, median, a percentile point) of the estimated distribution of capacity. This estimated distribution is derived from the empirical distribution of capacity observations using information contained in the free flow observations.

4-2-2 Traffic Data

The Product Limit Method is based on observations of traffic volumes at a well chosen measuring point at a bottle-neck, see **Figure 4-1**. Speed measurements upstream a bottle-neck (location *a*) are necessary to ascertain a traffic state with congestion. It is mostly assumed that speed measurements below a certain level (e.g 70 km/h) imply this congestion-state. In addition, this means that traffic in the bottle-neck (location *b)* is at the capacity-state of the road. However, speed observations downstream the bottle-neck, location *c,* are required to determine the traffic state and the possible occurrence of congestion.

When congestion is measured at that point *c*, a bottle-neck further downstream the freeway affects the observed intensities at location *b*, so that roadway capacity at *b* is not yet reached. The bottle-neck observations are then no longer representative for a capacity situation, and therefore the observations are included in neither set {Q} nor {C}.

4-2-3 Location of Data Collection

A bottle-neck should be chosen since the traffic volume measurements should include intensities representing the capacity state of the roadway (see **Figure 4-1**).

4-2-4 Observation Period and Averaging Interval

In the study by Van Toorenburg (1986), the rate of flow is observed in averaging intervals of 15 minutes. Keller and Sachse (1995) reported that the 5 minute period is a valid averaging time period for capacity estimation. However, the time period chosen is always a compromise, since extreme large volumes will not appear using one-hour intervals whereas in too small averaging intervals (e.g. one minute) will show extreme fluctuations in the flow rates will be observed. In addition, the total observation period can be relatively short when 5, 10 or 15 minutes periods are applied instead of one hour intervals. A reliable analysis of the observations require more than a single day of volume and speed measurements.

4-2-5 Required Traffic State

A bottleneck location should be chosen to be sure about the occurrence of the capacity state of the road whenever congestion upstream is signalled. Therefore, the required state is a capacity situation although a free flow state is allowed.

4-2-6 Roadway Capacity Estimation

Table 4-1 is an example how to assign an aggregated flow rate of a certain averaging interval to a set. This is the first step in the PLM approach.

We define function $G(q)$ as the probability that the capacity value is higher than a certain intensity q. The function $F(q)$ is defined by $1\text{-}G(q)$. In equation 4.5 the general expression of the Product Limit Method is given. In the special case of only capacity observations this expression is similar to eq. 4.2.

$$G(q) = Prob(q_i > q) \qquad (4.4)$$

$$G(q) = \prod_{q_i} \frac{K_{q_i} - 1}{K_{q_i}} \quad , \quad q_i \in \{C\} \tag{4.5}$$

where

K_q	=	number of observation elements i in set {S} with intensity q_i larger than or equal q
{C}	=	set of observed congested flow intensities
{Q}	=	set of observed free flow intensities
{S}	=	{Q} ∪ {C}, {S} is set of all observations i

Interval	*Upstream speed [km/h]*	*Intensity in the bottleneck [veh/h]*	*Downstream speed [km/h]*	*Conclusion:*
15.15-15:30	<u>65</u>	4500	79	{C} Capacity obs.
15.30-15:45	90	4200	90	{Q} Free flow obs.
15:45-16:00	85	4250	80	{Q} Free flow obs.
16:00-16:15	65	4350	<u>68</u>	None: bottleneck further downstream

Table 4-1 Assigning Observations to Set {C} or {Q}

4-2-7 Example

A simple example to understand the Product Limit Method is based on eight observations, using 15 minutes averaging intervals. During the two hour observation period congestion upstream ocurred, so there were some capacity observations at the bottleneck. The measured intensity values are expressed here in vehicles per hour. See **Table 4-2**.

1	*2*	*3*	*4*	*5*	*6*	*6*
Interval i	*q [veh/h]*	*Set*	*Rank*	K_q , $q_i \in \{C\}$	*G(q)*	*F(q)*
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 ·3/4 ·2/3 =0.41	0.59
6 16.45-00	4500	Q	7	-		
7 17.00-15	4600	C	8 highest	1	5/6 ·3/4 ·2/3 ·0/1= 0	1
8 17.15-30	4100	C	5	4	5/6 ·3/4 = 0.62	0.38
Observation Period	*Average intensity*	*Total obs. =8*				
2 hours	3812					

Table 4-2 Example Product Limit Method

In the first column of Table 4-2 the averaging interval is indicated. The corresponding hourly values are presented in the second column. We assume that speed data is 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, whereafter the discrete function *G(q) and F(q)=1-G(q)* was calculated.

In **Figure 4-3** not only the calculated discrete distribution function is depicted, but also a possible continuous distribution function is shown. In applications of the PLM method so far capacity estimations were only based on the discrete distribution function. 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 4200 vehicles/hour/2 lanes. If only capacity observations would have been used an average value of 4125 veh/h/2 lanes would have resulted. In **Appendix C** another example of the application of the Product Limit Method is given.

4-2-8 Evaluation

The Product Limit Method is based on the theory that a reliable capacity estimation is only possible when the traffic state is known. Therefor, the method distinguishes two types of measurements: free flow intensities and capacity measurements with which a distribution of the capacity can be determined.

A disadvantage of the method is the required amount of capacity measurements. Suppose a situation in which only free flow measurements are made (no congestion upstream detected during observation period) then the Product Limit Method gives no information about the capacity distribution. This raises the question what the proportion of capacity to intensity measurements should be, to make a reliable capacity (distribution) estimation. This problem is also encountered in the following Section 4-3.

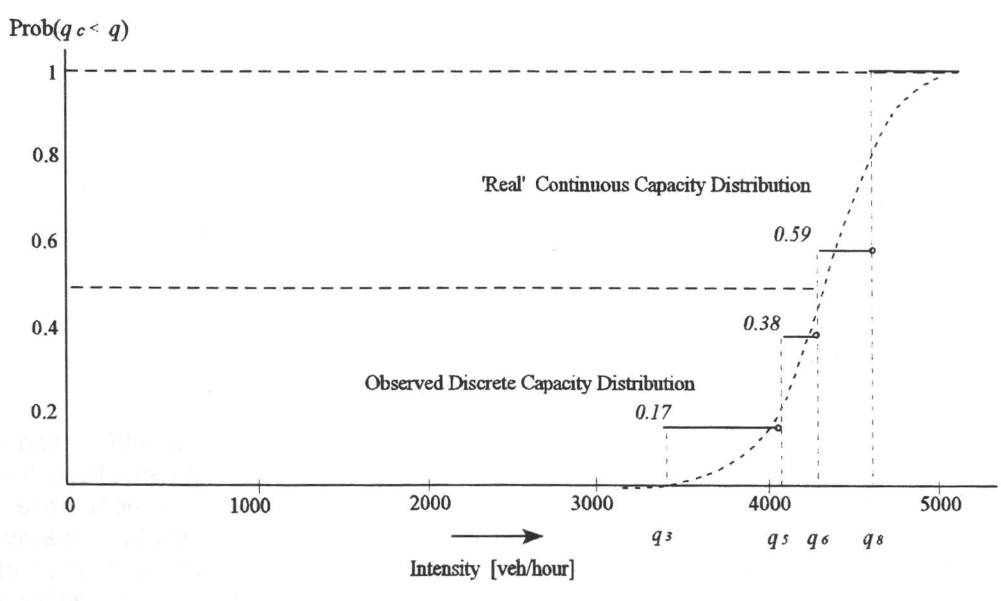


Figure 4-3 Example of Capacity Distribution Function based on Product Limit Method

4.3 Selection Method

4-3-1 Principle of the Method

The application of the Selection Method is a possibility in case there are insufficient capacity measurements collected for an appropriate use of the Product Limit Method, although until now no quantitative expression for this needed proportion is given. The Selection method will result in a single value instead of a capacity distribution. The basic procedure of the Selection Method, assigning observations to one of the two possible categories has already been explained in **Section 4-1-1**.

Figure 4-4 shows that an observed maximum 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. The difference between the depicted situations A and B can be described as the difference of a complete (situation B) or incomplete (situation A) Capacity Distribution function. In other words: in situation A some of the free flow intensities observed are higher than the highest measured capacity value. Therefore, the Capacity Distribution will show no absolute maximum, while in the case of situation B a maximum value will be found. The same holds for A' and B'. The situations ***A'*** and ***B'*** differ from ***A*** and ***B*** because now only a few capacity measurements are collected.

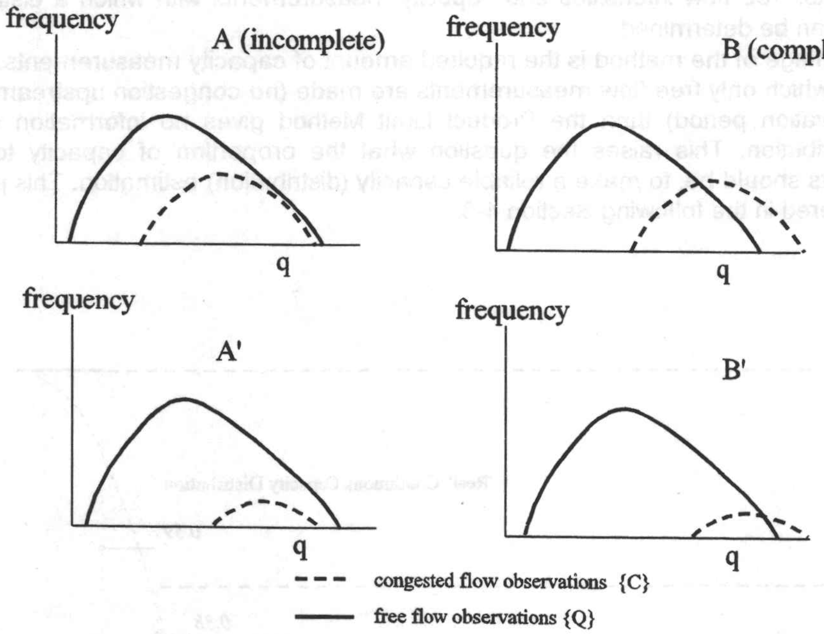


Figure 4-4 Four Possible Observed Traffic Situations at the Same Bottleneck

However, what is the implication of the differences between A, B and A' and B' for the capacity estimation result? First of all, we must remark that for both situations A and B the Product Limit Method may be applied, since there are sufficient capacity observations in comparison with the number of intensity observations. As a result, a reliable capacity distribution based on the PLM procedure can be determined. For situations such as A' and B' the Selection Method is a feasible alternative to the Product Limit Method. The definition for this capacity value is:

A single capacity value is derived from the empirical distribution of capacity observations using information contained in the free flow observations in case the proportion capacity to free f low observations is insufficient for an appropriate PLM capacity estimation.

4-3-2 Traffic Data

The Selection Method uses the same traffic data as the Empirical Distribution Method described in **Section 4-1** and **Section 4-2** (the Product Limit Method).

4-3-3 Location of Data Collection

The Selection Method uses the same observation location as the methods described in **Section 4-1 and 4-2**. A road section that represent traffic behaviour as in a bottleneck should be chosen since the traffic volume measurements should contain intensities representing the capacity state of the road (see **Figure 4-1**).

4-3-4 Observation Period and Averaging Interval

The Selection Method uses the same observation period and averaging interval as the methods described in **Section 4-1 and 4-2**. Thus an averaging interval duration between 5 to 15 minutes, and a preferred observation period of more than a single day.

4-3-5 Required Traffic State

A bottle-neck location should be chosen to be sure about the occurence of the capacity state of the road. Therefore, the required traffic state should include both stable and forced traffic over the observation period.

4-3-6 Road Capacity Estimation

First step is to calculate the mean of the intensities of set *{C}*. This value reflects the average flow rate under congested circumstances upstream and the assumed capacity state of the bottle-neck at which the observations are made.

$$q_{set\,\{C\},m} = \textstyle\sum_i q_i \;/\; N \qquad\qquad q_i \in \{C\} \qquad\qquad (4.6)$$

Second step is to select all observations of set {Q} with intensity values higher than the average volume $q_{set\{C\},m}$. Although the capacity wasn't reached when measuring these flow rates, they were higher than average under congestion. These observations should be used for calculating the capacity value or distribution since they contain valuable information about the possible intensities the roadway can handle and thus affecting the road capacity value.

Let a new collection of selected observations {A} include the elements of collection {C} and those selected observations of set {Q}.

$$\{A\} = \{C\} \cup \{Q \mid q_i > q_{set\{C\},m}\} \qquad\qquad q_i \in \{Q\} \qquad\qquad (4.7)$$

than the mathematical definition for the design capacity value is with this Selection Method:

$$q_c = \textstyle\sum_i q_i \;/\; N_A \qquad\qquad q_i \in \{A\} \qquad\qquad (4.8)$$

where

N	=	number of observation elements *i* in set {C}
N_A	=	number of observation elements *i* in set {A}
q_i	=	observation *i* [veh/h]
$q_{set\{C\},m}$	=	average intensity in bottle-neck during congestion upstream [veh/h]
q_c	=	capacity value [veh/h]

4-3-7 Example

We will apply the method using the same data of the example in **Section 4-2-7**.

1	2	3	4	5
Interval i	*q_i [veh/h]*	*Set*	*Selection*	*all $q_i \in \{Q\}$ and q_i>4125*
1 15.30-45	3000	Q		-
2 15.45-00	2500	Q		-
3 16.00-15	3500	C	3500	-
4 16.15-30	4000	Q		-
5 16.30-45	4300	C	4300	-
6 16.45-00	4500	Q		4500
7 17.00-15	4600	C	4600	-
8 17.15-30	4100	C	4100	-
Observation Period 2 hours	*Average Intensity* 3812	*Total 8 observations*	*Average set {C}* 4125	*Capacity* 3500+4300+4600+4100 +4500 / 5 = 4200

Table 4-3 Example Selection Method

In the first column of Table 4-3 the averaging interval periods are given. The corresponding hourly intensity values are shown in the second column. We assume that speed data is used to categorize the observations into set {C} or set {Q}, the capacity and free flow measurements, as done in column 3. Then in the fourth column the intensity values of set {C} are summed and divided by the total number of observations of set {C}. The last column shows the used additional data of set {Q} for the final capacity estimation.

This procedure results in a capacity value of 4200 veh/hour/2 lanes which is equal to the capacity estimate with the more advanced PLM procedure. Some other capacity measures can be derived from our examples to illustrate the variety in the possible capacity values, such as the average of all observations (3812 veh/h), the average of all congested observations (4125 veh/h) and the median of the Empirical Capacity distribution (also at about 4200 veh/h).

4-3-8 Evaluation

Estimating road capacity with the Selection Method will result in a value representing the assumed lower limit of the capacity distribution. The distribution itself is not determined in contrast with a capacity estimation using the Product Limit Method. Why this method with the proposed mathematical calculations should lead to a lower limit, as reported in Van Toorenburg (1986) is not very clear. Our example resulted in the same capacity value as derived with the Product Limit Method.

Furthermore, there are still capacity measurements needed to apply this rather arbitrary method. Theoretically, one capacity observation would be sufficient to apply the Selection Method under the condition that a sufficient number of intensity observations were made. Therefore one can conclude that every capacity observation will strongly affect the capacity estimation. The derived capacity value will give the engineer only an indication of the road capacity without information about its reliability or an estimation of its error.

Chapter 5

CAPACITY ESTIMATION WITH TRAFFIC VOLUMES, SPEEDS AND DENSITIES

Capacity estimation methods based on observed traffic volumes, speeds and densities are using mathematical models to estimate the maximum traffic volume which has occurred (or can occur) on the road. One can distinghuish two kinds of methods in this category: the real-time, dynamic capacity estimation models and the off-line, static capacity models.

The described On-Line Method in this report (**Section 5-2**), for capacity value estimation under prevailing conditions, is an example of a dynamic capacity estimation model. However, the Fundamental Diagram Method may also be applied as a dynamic capacity estimation model although only the static version is described in the report (**Section 5-1**).

The additional data for the capacity estimation with these methods is the density, which expressess the number vehicles per kilometer roadway in relation to intensity and speed. However, the occupancy variable will replace the density variable in most methods since this local variable is directly measurable.

5-1 Fundamental Diagram Method

Already in the first decades of the 20th century, relations between intensities, speeds and headways were drafted. An example is the capacity formula drawn up by A.N.Johnston and extended into the relation:

$q = 5280 \cdot u / (15 + u^2/15)$

In a next stage, density k was also used as a parameter to calculate the road capacity. A linear relation was found between speed and density in the OHIO-study in 1934. After further calculations with the data, the researchers concluded that each intensity value should correspond to two different speeds and two differnet densities. The investigations into the exact relations between the parameters intensity, speed and density (the Fundamental Diagrams) were initiated. A brief description of the method will be given in this section.

5-1-1 Principle of the Method

The theory behind the use of the Fundamental Diagram is the existence of a relation between the three variables q (traffic volume), harmonic mean speed u and the density k (or local density expressed as occupancy *occ*) (May, 1990). It is sufficient to measure two variables to construct the diagrams. When the parameters of the function are estimated, not only the capacity can be determined, but also the *critical density* (the density at which the capacity will be reached) and the belonging traffic mean speed, the *jam density* (the density at which the traffic volume and mean speed will be reduced to zero). An example of the Diagrams are given in **Figure 5-1**.

5-1-2 Traffic Data

Currently, freeway monitoring systems can automatically collect traffic data. These systems can measure the number of cars, speed and (local) density aggregated into one-minute or even thirty-seconds averaging intervals. The Fundamental Diagram Method requires this data, but mostly aggregated into larger averaging intervals.

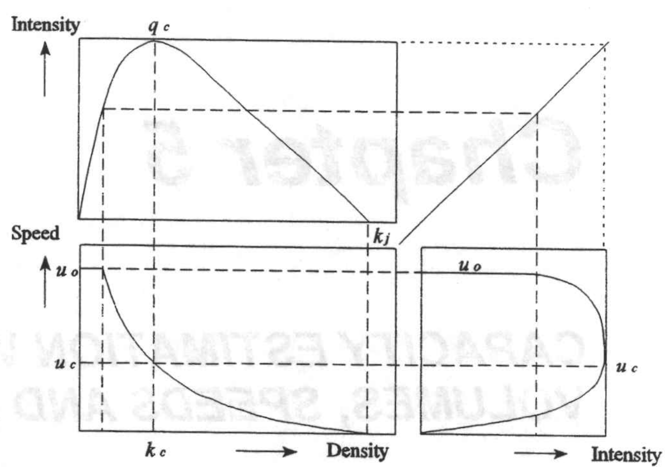


Figure 5-1 The Construction of the Fundamental Diagrams

5-1-3 Location of Data Collection

For the application of the Fundamental Diagram Method, it is not necessary to acquire data at a bottle-neck.

5-1-4 Observation Period and Averaging Interval

The averaging interval duration has to be chosen sufficiently long to exclude random traffic demand variation. Fifteen minutes seems to be a good compromis between local and global fluctuations, following Van Toorenburg (1986), however the 5 minutes period is used and proposed by other authors (Keller & Sachse, 1995). The total duration of the observation period depends of the chosen averaging interval duration, because this affects the total number of collected intensities and corresponding densities and speed measurements.

5-1-5 Required Traffic State

One has to observe traffic at different volume levels to make a reliable curve fitting possible, see **Figure 5-1**. If the observed traffic state is unstable or even worse: congested, the results of the curve fitting are mostly too much dependent on the type of curve chosen, because of the great variance in these observed values. This is an important disadvantage of the method.

5-1-6 Road Capacity Estimation

After having selected an appropriate function to fit the observed data, the practical application of the Fundamental Diagram is estimating the maximum of the curve. This procedure can be performed dynamically, to estimate the operational road capacity value, or statically for off-line analyzing purposes. The maximum flow rate is located at a certain *critical* density k_c. With the relation (see e.g. May, 1990)

$$k = u / q \tag{5.1}$$

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

However, mostly density is hard to determine since one should observe a complete and uniform road section and count the total number of cars present at any moment. Instead, the local density (the occupancy *occ*) is used in calculations. The occupancy is defined as the percentage of time that there is a vehicle above a loop detector of (imaginary) length zero. Herewith, the traffic observations can be plotted directly in the diagram *q - occ*. The relation between occupancy and density is given by

$$occ = k\,L \tag{5.2}$$

where L denotes the (average) car length. In **Section 5-2** the virtual loop length is calculated to ensure a reliable registration of car lengths. The occupancy will be used for further examination of the method.

The curve *q - occ* can be determined by observations, several statical methods and theories. The capacity definition can graphically be derived from **Figure 5-1**:
The capacity is the maximum intensity derived from the estimated mathematical model for the relationship intensity and density (occupancy).

Different models are available to fit the data (the observed traffic flow rates and the corresponding occupancy rates), and so the capacity depends on the model chosen. The following models can be found in literature (Cohen, 1983):

- *the linear model of Greenshields:* $q = a \cdot occ^2 + b \cdot occ$
- *the model of Drew:* $q = a \cdot \sqrt{occ^3} + b \cdot occ$
- *the logaritmic model of Greenberg:* $q = a \cdot occ \cdot \log(occ) + b \cdot occ$
- *the exponential of Underwood:* $q = a \cdot \exp(-b \cdot occ)$
- *the exponential of May:* $q = a \cdot occ \cdot \exp(-b \cdot occ^2)$
- *the two regimes models*

In general, the capacity q_c can be derived by calculating the maximum of the curve, where the derivative of the function equals zero (the existence of this point depends of course on the applied model) :

$$dq \,/\, d\,occ = 0 \tag{5.3}$$

Since the models in general do not distinguish a discontinuity, the estimated capacity value is based on a mix from both free flow and congested flow intensities.

5-1-7 Example

The study which will be described here (Cohen, 1995) was carried out at a three lane carriageway which is of major importance for the traffic in the Paris region. The high level of demand here, means that the capacity level was reached during peak periods.

The observation period was one weekday during June, for the year 1979 and 1994 for the same measurement site. The data to be analyzed were intensities speed and occupancy measurements supplied at 6 minutes averaging intervals.

Regression analysis, based on the data and the use of May's exponential model, showed a good fit. The maximum volume or capacity was estimated at 6080 veh/h/3 lanes for the year 1979 and 6690 veh/h/3 lanes in 1994 with the fitted curves

$q = 347 \cdot occ \cdot exp(-0.0006 \cdot occ^2)$ and

$q = 413 \cdot occ \cdot exp\,(-0.0007 \cdot occ^2)$ respectively.

The critical occupancy has been estimated at 28% and 27% respectively. The shift of the Fundamental Diagram is depicted in **Figure 5-2**. It shows that there has been a significant change in capacity, an increase of approximately 10%. This more or less doubtful conclusion was already drawn in **Section 3-2** with the application of a Selected Maxima Method, also extracted from the study by Cohen (1995). Also, it appears that the free speed has considerably increased with (413-347)/413 = 16%.

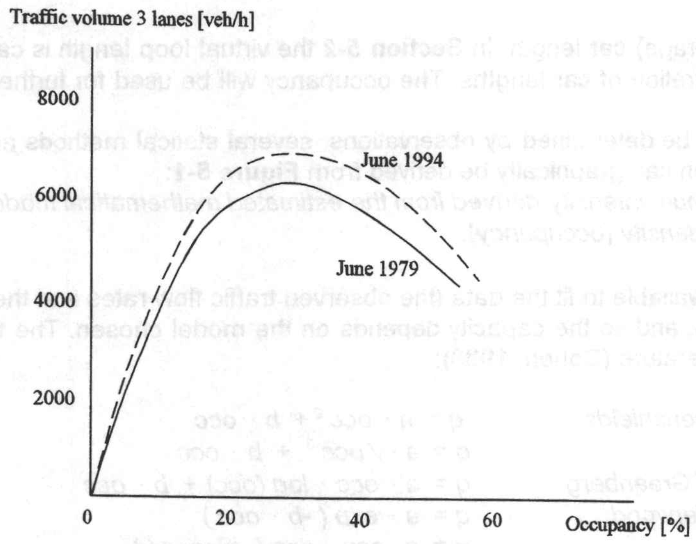


Figure 5-2 Application of the Fundamental Diagram: Change in Traffic Flow Conditions [Source: Cohen, 1995]

5-1-8 Evaluation

Major disadvantage of the method is the requirement of a mathematical model that should fit the observed data pairs. Moreover, the parameters of the chosen model should be obtained for each location anew, since prevailing conditions differ. Furthermore, Duncan (1976) reported the (mostly unobserved) fake correlation between speed and density since this relation is based on speed and intensity pairs which show no correlation at all. It is therefore necessary to collect sufficient data over a broad range of intensities to make a reliable curve fitting possible.

5-2 On-line Procedure for Actual Capacity

Current developments in traffic engineering are directed towards an extended use of *dynamic traffic management systems,* which make an effective use of the infrastructure possible by distributing information to the potential users of the infrastructure. This information can be used for optimizing users' needs (travel information, route information), optimizing local conditions (traffic lights) or for optimizing the system as a whole (traffic/parking/incident information and regulation).

Optimizing the whole system, which can briefly be defined by minimizing the summed travel times and enhancing the number of vehicles able to use the infrastructure is the main interest within the framework of this study, since this approach tries to enhance the capacity and level of service of a network. Real-time information about the traffic state is needed for these applications, which includes information about the road capacity of links under prevailing road, traffic and weather conditions. The estimation of real-time road capacity is therefore topic of this section.

5-2-1 Principle of the Method

Although the On-line procedure for estimating capacity (Van Arem & Van der Vlist, 1992) and (Van der Vlist, 1995) is based on the Fundamental Diagram Method (**Section 5.1**) it is certainly not a dynamic, real-time version of the Fundamental Diagram Method.

The influence of the prevailing road, traffic and weather conditions is the main issue of the On-line method for estimating actual road capacity. This real-time capacity estimate will crucially depend on a correctly updated reference Fundamental Diagram. How to update the reference Diagram and how to determine the critical occupancy under prevailing road, traffic and weather conditions are the most important elements of the method.

The capacity definition is therefore: *The on-line capacity is the estimated maximum intensity that may pass a cross-section under actual prevailing road, traffic and weather conditions.*

5-2-2 Traffic Data occ/k?

Occupancy, speed and naturally intensity data are needed for the method. Traffic speed is indirectly used to determine the corrected occupancy, since the relative influence of the loop length on the occupancy measurements is larger for shorter vehicles. The normalized occupancy for a virtual loop length of zero meter can be approximated by the following formula:

$$occ = occ^* - 100\% \cdot L \cdot q / (60 \cdot u) \qquad (5.4)$$

where:

q	=	number of vehicles [vehicles per minute]
u	=	average speed [m/s]
occ*	=	occupancy over loop length L [seconds per 60 seconds] expressed in [%]
L	=	loop length [m]

5-2-3 Location of Data Collection

At any cross-section, however there are some requirements for the needed traffic state to make a reliable estimation of actual capacity.

5-2-4 Observation Period and Averaging Interval

In the reported study (Van Arem & Van der Vlist, 1992) the averaging interval for the observed data is one minute. Because of the character of the method, no end of the observation period is specified.

5-2-5 Required Traffic State

The on-line procedure checks whether the traffic is free flowing and whether the intensity is larger than a specified traffic volume. If one of these requirements is not met, a scaling factor needed for the prediction of the traffic state the next minute, will not be updated. This procedure is explained in more detail in Section 5-2-6.

5-2-6 Road Capacity Estimation

The Fundamental Diagram, in particularly the relation between intensity and occupancy, is not static, but will change in time due to changes in the prevailing road, traffic and weather conditions.

In the reported study (van Arem & van der Vlist, 1992) it is assumed that a multiple of the relation for dry weather and good visibility yields a good description of the relation for rainy weather. Therefore, they assume that the q_i for different conditions differ only by a scaling factor R_i:

$$q_i = R_i . f(occ_i) \tag{5.5}$$

It has been found in the refered study that a quadratic function serves well for the basic relation between occupancy and traffic volume during free-flowing traffic:

$$q_i = \alpha . occ_i + \beta . (occ_i)^2 \tag{5.6}$$

The capacity estimation procedure can be summarized with the following five-step scheme:

- **set scaling factor $R_i = 1$**
  First, to initiate the procedure, the scale factor R_i is set at the standard value, corresponding with the reference situation.

- **gather new data**
  During a one minute period *i* data is collected. We observe the occupancy occ_i, intensity q_i, speed u_i over this averaging interval *i*.

- **check traffic state**
  With the data we can check whether the traffic is free flowing (speed measurements above a pre-defined free-flow speed boundary, for example 70 km/h) and whether the flow rate is larger than about 300 pce/h/lane (average). If one of these requirements is not met, the scaling factor is not updated.

  In case the traffic is not free flowing, the collected data is possibly affected by an unstable traffic flow and can not be used for a reliable curve fitting. If the intensity is not larger than 300 pce/h/lane (average) the traffic intensity is too low for a reliable fit. A free flow situation can be assumed, and the scaling factor is not adapted:

$$R_{i+1} = R_i \tag{5.7}$$

- **compute the intensity**
  When the above conditions are met, we begin the scaling factor procedure. First, we should estimate the traffic intensity $q_{est,\,i}$ of the current observed minute *i*. We calculate this value with the occupancy data collected over this averaging interval *i* and applying the last updated scaling factor R_{i-1}, according to:

$$q_{est,\,i} = R_{i-1} \cdot f(occ_i) \tag{5.8}$$

Since we use only data gather over one minute time, the reliability of the measurements is limited. An updated scaling factor R_i will now be calculated partly based on how the estimation matches with the observations, the ratio $R_{i-1} \cdot (q_{c,i+}/ q_i)$ and partly based on the last updated scaling factor R_{i-1}. The two parts are then weighted by an adaptation factor z, resulting in the following proposed update procedure:

$$R_i = (1\text{-}z)\, R_{i-1} + z \,.\, R_{i-1} \,.(q_i/q_{est,i}) \tag{5.9}$$

The default value for weight factor *z* is set at 0.1.

- **estimate the current capacity**
  Now we can calculate the current capacity $q_{c,\,i}$ after we have established an updated critical occupancy $occ_{c,i}$, which is a function of prevailing conditions and thus of the scaling factor.

$$occ_{c,i} = g(R_i) \tag{5.10}$$

The current capacity estimation results in the following equation:

$$q_{c,i} = R_i \,.\, f(occ_{c,i}) \tag{5.11}$$

where

q_i	= observed intensity over averaging interval *i*
$q_{est,\,i}$	= estimated intensity over *i*
$q_{c,\,i}$	= calculated actual capacity value
occ_i	= observed occupancy rate over averaging interval i
$occ_{c,i}$	= critical occupancy rate (depends on road, traffic and weather)
R_{i-1}	= scaling factor for averaging interval *i-1*
R_i	= updated scaling factor (for averaging interval *i*)

Traffic volumes can be expressed in *passenger car equivalents* (pce) or in *vehicles*. In Van Arem & Van der Vlist et al (1994a) the volumes are expressed in pce/h. They distinguish three types of vehicles with respectively $pce_1 = 1$, $pce_2 = 2.3$ and $pce_3 = 4.5$ based on a large data set obtained at the A2 freeway between Utrecht and Amsterdan in the Netherlands. These values were taken as default for current capacity estimation in the GERDIEN NSMP system.

Since a scaling factor is introduced (see eq. 5.5), a particular data set should be chosen as a reference with which other observation studies can be compared with. The reference data set chosen in the study by Van Arem & Van der Vlist consisted of all morning peak measurements during dry weather for the entire A2 motorway cross-section in the eastern direction. The factor R_i appeared to be less then 1 for rainy periods, as expected.

In the procedure, the critical occupancy $occ_{c,i}$ is used to estimate the current capacity, see eq. 5.10. The critical occupancy is based upon one minute averaging interval data collected during free-flowing traffic and homogeneous road and weather conditions. For each of these minutes the average occupancy is computed over the minute considered and the 4 preceding minutes. The critical occupancy (under that particular weather condition) is then estimated by the maximal average value found for that particular situation. This maximum can thus be seen as a function of prevailing roadway and weather conditions, and therefore also expressed into a variable, a function of scaling factor R_{cur}, see **Figure 5-3** . However, in the application of the GERDIEN NSMP system the critical occupancy has been assumed constant, and is estimated by taking the average observed critical occupancies over some selected intervals (Van Arem & Van der Vlist et al, 1994a).

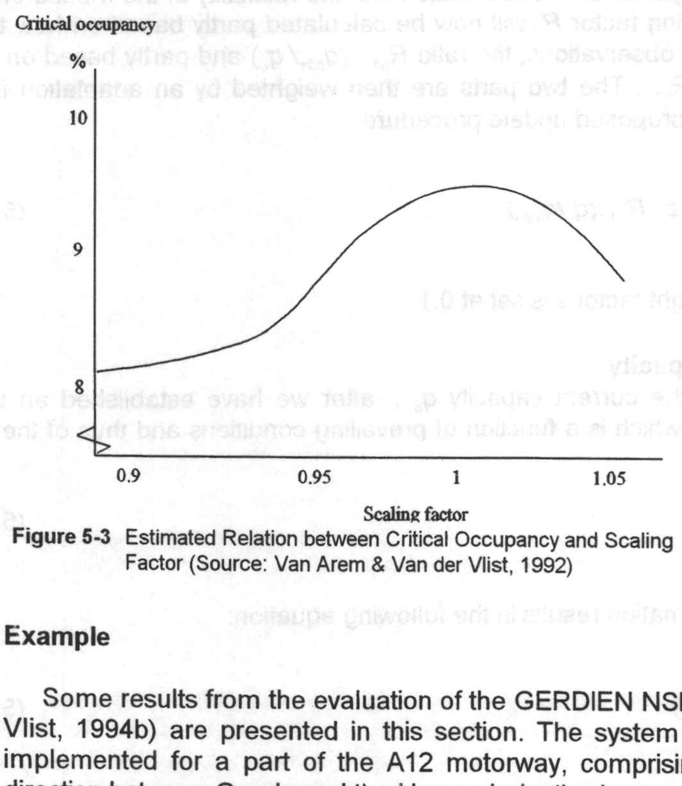


Figure 5-3 Estimated Relation between Critical Occupancy and Scaling Factor (Source: Van Arem & Van der Vlist, 1992)

5-2-7 Example

Some results from the evaluation of the GERDIEN NSMP pilot study (Van Arem & Van der Vlist, 1994b) are presented in this section. The system for actual capacity estimation was implemented for a part of the A12 motorway, comprising about 16 km of length in each direction between Gouda and the Hague. Inductive loops are present on this road section.

First parameters α and β (eq. 5.6) were estimated with traffic volumes and occupancy observations from several weeks using a least square criterion. The second stage was the estimation of the critical occupancy attainable under free-flowing conditions as a five-minute average. Only those observations exceeding 9% were taken into account. If there were no such observations, the critical occupancy was taken equal to 9%. For each loop the formula with its parameters was applied. **Table 5-1** gives some of the results of this experiment.

LOCATION	α	β	occ_c	q_c	*Accepted*
31	879.1	-9.6	10.1	2642	yes
34	912.2	-18.4	10.4	2492	yes
36	907.8	-7.3	9.0	2526	no
37	654.7	-15.6	12.1	2827	no
39	895.0	-6.55	9.0	3762	no
42	615.3	-14.9	9.0	2165	no
45	596.7	-10.45	10.2	2493	yes
			[%]	[pce/h/l]	

Table 5-1 Parameter Estimates from tuning Experiments [Source: Van Arem & Van der Vlist, 1994b]

The lane capacity q_c is given for average conditions, scaling factor equal to 1. The final column indicates whether the capacity estimate was considered acceptable or not. To be acceptable the lane capacity had to be in the range 2200-2800 pce/h and there had to be at least three occupancy observations exceeding 9%.

Figure 5-4 shows an example of the current capacity estimation over a day. Also, the observed traffic volumes are given and the weather conditions during the day. The results of the capacity estimation procedure seems (intuitively) to suit fine to the real observed traffic volumes.

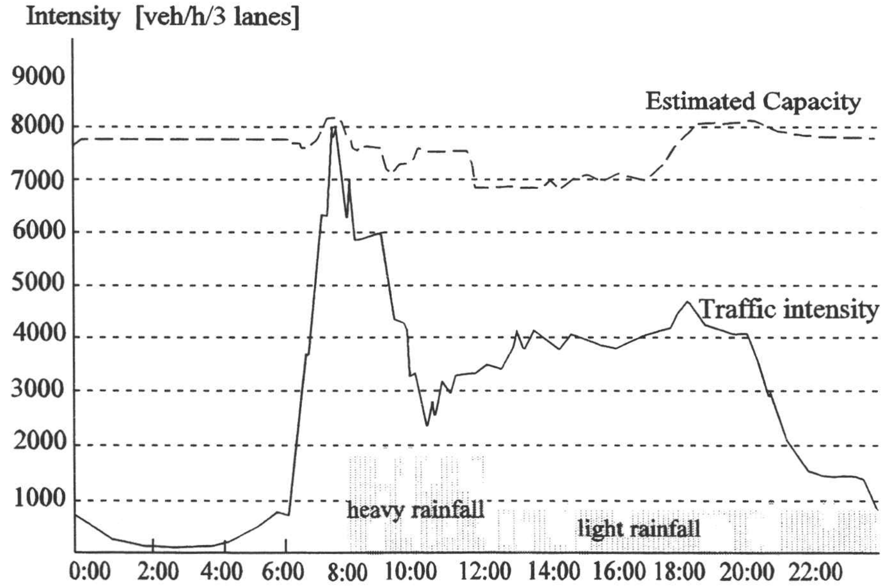


Figure 5-4 Constructed Example based on the Evaluation of GERDIEN NSMP at the A12

5-2-8 Evaluation

The On-line method seems to be useful for real-time applications, although the resulting capacity estimates are not always reliable (and therefore not always useful). Main problem is the short interval duration in which sufficient data has to be collected.

Another problem is the determination of the critical occupancy which is assumed to depend on the scaling factor, but a comprehensive relationship hasn't been found yet. Furthermore, the critical occupancy is mainly based on empirical data (reference situation) and has no connection with the momentary traffic situation other than that of an updated scaling factor.

We also notice the use of extreme high *pce*-values which are assumed having a constant value independent of the traffic state (free flowing/unstable). These high values do not seem realistic since during the capacity state of a road all traffic will progress at about the same speed and a heavy truck will only use a little more space than a passenger car. The impact of the traffic fleet composition and thus vehicle length variations on road capacity seems therefore strongly overestimated (see also Minderhoud, 1996).

Let us finish with a remark stated in Van der Vlist (1995) which says that it could not be expected that the on-line method will always produce a reliable or useful value due to the assumptions and restrictions of the method.

Chapter 6

SUMMARY AND CONCLUSIONS

The capacity estimation methods described in this report can be used to estimate the capacity of a roadway under certain conditions, according to the assumptions of the underlying theory. Criteria for the employment of a particular method can be for example the following:

- must the capacity level of the road being reached? [1]
- must a statistical model being estimated to represent the observed data? [2]
- does a total observation time duration of (a part of) a day be sufficient? [3]
- is the result of the method a single capacity value or a capacity distribution? [4]

These criteria are answered in **Section 6-1** together with a brief summary and some critical notes of each method. At the end of the Section a comprehensive table with all methods and their most important characteristics is given. In **Section 6-2** a recommendation will be given for the use of some promising methods for estimating roadway capacity at a cross-section (at an uniform section) of a road.

6-1 Summary

In this report, several capacity estimation methods have been examined. Headway, traffic volume, speed and density were used to identify four groups of capacity estimation methods. Aspects like data measurement, location choice and other survey setup aspects were investigated for each method. Furthermore, an evaluation of the validity and practical use of the method was set out. The methods were illustrated with examples of their employment.

We will summarize each method in the following.

- **Headway Distribution Models (for a Single Lane)**
  The capacity of a single lane can be estimated with the headway data type. Basic hypothesis is that constrained drivers in free flow conditions are comparable with that of (constrained) drivers at the capacity level of the road. [1] The road capacity doesn't need to be achieved. [2] The observations must fit into a mathematical model. [3] The observation period can be less than a day. [4] The method leads to a single capacity value.
  Major disadvantage of the headway models is the dependency on the traffic volume. This implies that short observation periods should be selected for analysis (otherwise a complicated distinction into different classes of traffic volumes should be made). The resulting capacity estimates seem to be higher than are observed in real traffic. This method should therefore not be the first choice when investigating the capacity of a road.

- **Bimodal Distribution Method**
  When traffic volumes are collected during the day, the constructed frequency function may show a bimodal distribution with which the capacity can be approximated. Therefore [1] the capacity level of the road must have been reached and a partly unknown mathematical model [2] must be applied. The data can be collected within a day [3]. A capacity distribution can be assessed [4].
  This method might be a nice and reliable capacity estimation method if a bimodal character would be found in every observation study, however, this is doubtful.

- **Selected Maxima Method**
  Methods based on the Selected Maxima approach are supposed to be applied only when [1] the capacity level of the road has been reached. [2] The Selected Maxima Method doesn't use a specific mathematical model with which the observed data should correspond. [3] The observation period should cover more then one day, but this depends on the applied method. One will derive a single capacity value with the method [4].
  One can conclude that such methods can easily be applied, but observation period and averaging interval will heavily influence the maxima encountered. Furthermore, the capacity estimates are derived directly from observed volumes without further information about changes in traffic demand and driving skill during longer periods of time, and this can cause some interpretation failures in certain applications of the method.

- **Direct Probability Method**
  Traffic volume counts are used to make a prediction about the unknown extreme value. For a good estimation of the so-called limiting capacity, [1] the capacity level at the measuring point must be reached and [2] a model must represent the traffic process. [3] The observation period can be a part of a day.
  The derived limiting capacity is not a practical value for analyzing purposes while its value will strongly depend on the averaging interval duration.

- **Asymptotic Method**
  The Asymptotic Method is a complicated method with which the limiting capacity of the road can be estimated. [1] The capacity has to be reached, [2] no pre-defined mathematical model is required to represent the traffic process, however the derivation of the capacity is based on complex mathematical calculations. [3] More days must be observed to get a good picture of the traffic volume maxima. Nonetheless, the method will lead to a single capacity value [4]. This method seems (also) to be of no practical use for traffic engineers.

- **Empirical Distribution Method**
  When the collected data can be divided into free flow and capacity observations, and we focus on the capacity observations, one can construct a Empirical Capacity Value Distributi-

on. [1] The capacity level of the road must be reached frequently. [2] A selection of the observed data will be used to derive the capacity value. It should also be possible to apply a generalized mathematical model to fit the distribution function. [3] The observation period must cover more days to collect sufficient data. A capacity distribution will be derived with the estimation procedure [4].
The Empirical Distribution Method is a straight forward method with a clear meaning of its estimated capacity distribution. However, some questions remain. It can be debated that in general not all observations will be employed in the capacity estimation procedure, for example the free flow intensities with larger flow rates than the lowest capacity measurement. The Product Limit Method is a more advanced method which does take account of these observations.

- **Product Limit Method**
When the collected data can be divided into free flow and capacity observations, and there are many capacity observations in relation to the intensity observations, one can use the Product Limit Method to estimate the capacity distribution. [1] The capacity level of the road must be reached frequently. [2] The observed data will be used to derive the capacity value, but it should also be possible to apply a generalized mathematical model to fit the distribution function. [3] The observation period must cover more days to collect sufficient data. A capacity distribution will be derived with the estimation procedure [4].
The Product Limit Method is recommended instead of other methods based on traffic volume counts since its underlying theory is well-argumented. However, some questions remain. How many observations are needed from the two data sets, and what should be an appropriate proportion of these two types of measurements? Is the impact of the lowest observed capacity value on the total distribution function acceptable?

- **Selection Method**
When the collected data can be divided into free flow and capacity observations, and there are many intensity observations compared to the number of capacity observations, one can use the Selection Method to estimate the under limit of the capacity distribution. [1] The capacity level of the road must be reached a sufficient number of times. [2] The observed data will be used directly to derive the capacity value. [3] The observation period must cover more days, for example only during the rush hours, to collect sufficient data. A single capacity value will eventually result [4].
The Product Limit Method is recommended instead of the more ad hoc approach of the Selection Method.

- **Fundamental Diagram Method**
Traffic volumes, density and/or speeds are used to construct a flow-density or flow-occupancy diagram with which the maximum traffic volume can be derived. [1] The capacity level hasn't to be reached during the observation period. [2] The method is based on a mathematical model which describes the macroscopic traffic process. [3] Data measurements carried out during a single day should be sufficient for the estimation of the parameters of the proposed model.
The major advantage of the method is that it may be employed in situations where the capacity level hasn't been reached, although there should be enough data points to make curve fitting possible. A disadvantage of the procedure is the need for a specified model to describe the relation between flow q and density k or occupancy *occ*.

- **On-line Procedure for Actual Capacity Estimation**
This method determines the actual, operational capacity under the prevailing road, traffic and weather conditions.
A reference Fundamental Diagram must be used in order to estimate the actual capacity. For constructing the reference Diagram and determining critical occupancies, the Fundamental Diagram method must be applied under different road and weather conditions. After this procedure, [1] the capacity level isn't required, [2] the basic mathematical model

is already known and [3] the observation period is about one minute. A single capacity value is derived [4].
The determination of the critical occupancy under prevailing road and weather conditions can be argued. Results are not always very reliable or useful, but for real-time applications it can be seen as a practical method.

In **Table 6-1** a schematic overview is given of the methods and their most important characteristics, namely: the data needs (headways, traffic counts, speeds and density/occupancy), the required traffic state (free flow intensity measurements and/or capacity measurements), the results (a single capacity value, a capacity value distribution) and its capacity type according to **Figure 1-5**, respectively columns 2 to 11. Also a tentative value (column 12) is given for the practical validity of each method. This value is a subjective judgement based on criteria as described in the introduction of Chapter 6. For example, we judged negatively about the Headway approaches, since this estimation procedure will result in a single capacity value and is probably overestimating road capacity according to our findings in literature. We judged positively about the PLM method since the underlying theory sounds well and the outcome of the procedure is a capacity distribution. See **Table 6-1** for the characteristics and judgement of the various estimation methods.

1 *Section:*	2 *Method:*	3 *Data needs:*	4	5	6	7 *Traffic State*[1]*:*	8	9 *Capacity:*	10	11 *-type*[2]*:*	12 *Validity:*
		h	q		k	{Q}	{C}	q_c	F(q)		
2-1	Headway Model	Yes				Yes		Yes		1	-
3-1	Bimodal Distr.		Yes			Yes	Yes		Yes	m	o
3-2	Selected Maxima		Yes			Yes	Yes		Yes	m	o
3-3	Direct Probability		Yes				Yes	Yes		d	-
3-4	Asymptotic		Yes				Yes	Yes		d	- -
4-1	Empirical Distr.		Yes	Yes			Yes		Yes	2	+
4-2	Product Limit		Yes	Yes		Yes	Yes		Yes	m	++
4-3	Selection		Yes	Yes		Yes	Yes	Yes		m	-
5-1	Fundamental Dgrm.		Yes	(Yes)	Yes	Yes		Yes		d	+
5-2	On-Line Procedure		Yes	Yes	Yes	Yes		Yes		1	o

1) {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).

2) 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 (see Fig. 1-5), *m* stands for type 1 and 2 mixed into one capacity estimate and *d* stands for the dependency with the study set up (both type 1 or 2 is possible).

Table 6-1 Overview of Capacity Estimation Methods and their Characteristics

6-2 Conclusions

Various existing direct-empirical capacity estimation methods have been examined and discussed. It appears that roughly two approaches are followed in the estimation procedures: the calculation of a capacity value with observed maxima (using extreme value statistics) and estimation with (specified) sets of observations. With the methods, a capacity value or capacity distribution can be derived. A capacity distribution is preferred since its enables selection of a capacity value based on certain quality considerations. The main question was, and still is, the validity and practical use of each method. We are inclined to give the following general conclusion concerning the capacity estimation methodologies:

Attempts to determine the capacity of a road with existing methods will generally result in a capacity value estimation, but the validity of this value is hard to investigate due to the lack of a reference capacity value which is supposed to be absolutely valid.

A clear, reliable method doesn't appear to be available at this moment. Some methods can be improved to enhance the validity of the capacity estimate. At the moment, the recommended order of application of existing methods (considering the advantages and disadvantages of each method) could be the following:
(1) The Product Limit Method, (2) The Empirical Distribution Method and (3) The Fundamental Diagram Method.

6-3 Further Research

We noticed that several capacity estimation methods are based on appropriate theories concerning macroscopic traffic flow although their capacity estimation procedures seem to be a little disappointing. A further improvement of the promising Product Limit Method (and the derived Selection Method) may possibly 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.

In this report we have only discussed the direct-empirical capacity estimation methods (see **Figure 1-0**). However, traffic engineers will apply the other category methods, the indirect-empirical capacity determination methods, in many situations in which a carriage way does not yet exist. The validity of road capacity estimation procedures in handbooks or applied in simulation models are another research topic which should be investigated in more detail.

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

And at last, we want to remark that until now a definition of network capacity is lacking in the traffic engineering terminology, although this performance-index is possibly of more importance than the link capacity which has been subject of this report. Further research is needed to establish a definition for network capacity and system performance.

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Appendix A:

Data for Employment of Capacity Estimation Methods

The appendices B, C, D and E in this paper deal with the application of several methods discussed earlier. For this capacity analysis we used traffic data generated by FOSIM, a microscopic freeway traffic simulation model. We specified a roadway with a bottle-neck, an upstream and a downstream detector. In this way we could registrate the type of observation, e.g. a congested flow or free flow measurement.

The design of the representative bottle-neck configuration is depicted in **Figure A.1**

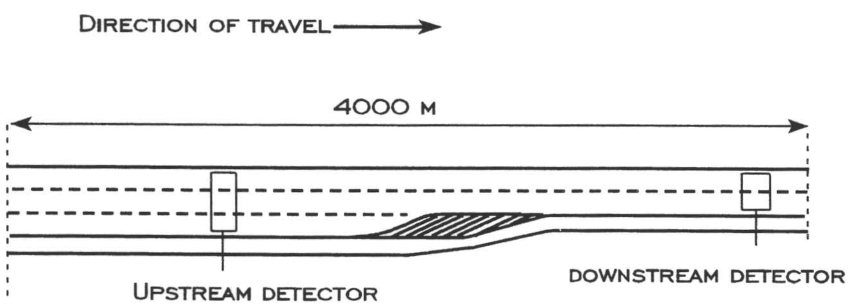

Figure A.1 Geometry bottle-neck

We performed four series of simulations, each with a length of an hour. Since we used a 5-minute aggregated interval this means a total of 12 observed intensities per serie and 48 traffic volumes overall. The total observation period of four hours, including both stable and unstable traffic should be sufficient for a first rough capacity estimate with the selected methods.

To be more precise, series 1, 2 and 3 were simulating a slowly increasing traffic demand from 4000 veh/h at the beginning towards 5500 veh/h at the end of a run. Each run was initiated with an other random seed value resulting in two different simulation runs. The fourth series was specified at a constant traffic demand of 4750 veh/h during the total observation time. Here, the observations were all maximum congested flow observations (capacity observations) since congestion upstream the bottle-neck occurred.

The frequency of the traffic volumes observed at the downstream detector are depicted in **Figure A.2**. A separation has been made between capacity and free flow intensity observations, one of the conditions for an appropriate application of the Selection and Product Limit Method. When we had chosen other simulation-scenarios we would have had an other picture of the frequency distribution, and as a consequence an other capacity estimate. Notice the presence of many intensity measurements above the highest observed congested flow measurement.

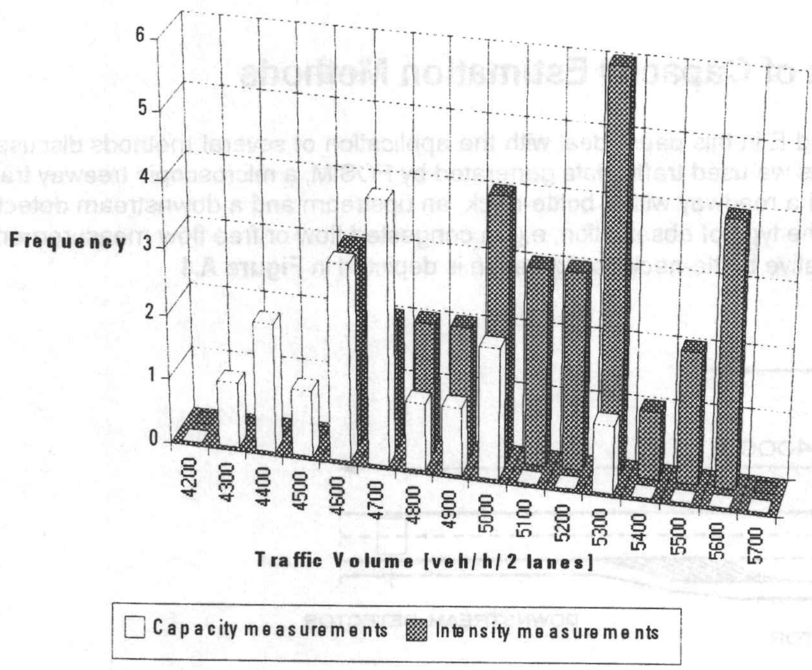

Figure A.2 Frequency of the capacity and free flow intensity measurements at the downstream detector.

Appendix B:

Empirical Capacity Distribution Method

For a detailled explanation of the method, a special case of the PLM , we refer to the report. In this approach the distinction between the two subsets in the observed traffic data is needed. The Empirical Distribution method uses only capacity-measurements to estimate roadway capacity. See **Figure B.1**. where the empirical (cumulative) probability function with the generated data is depicted.

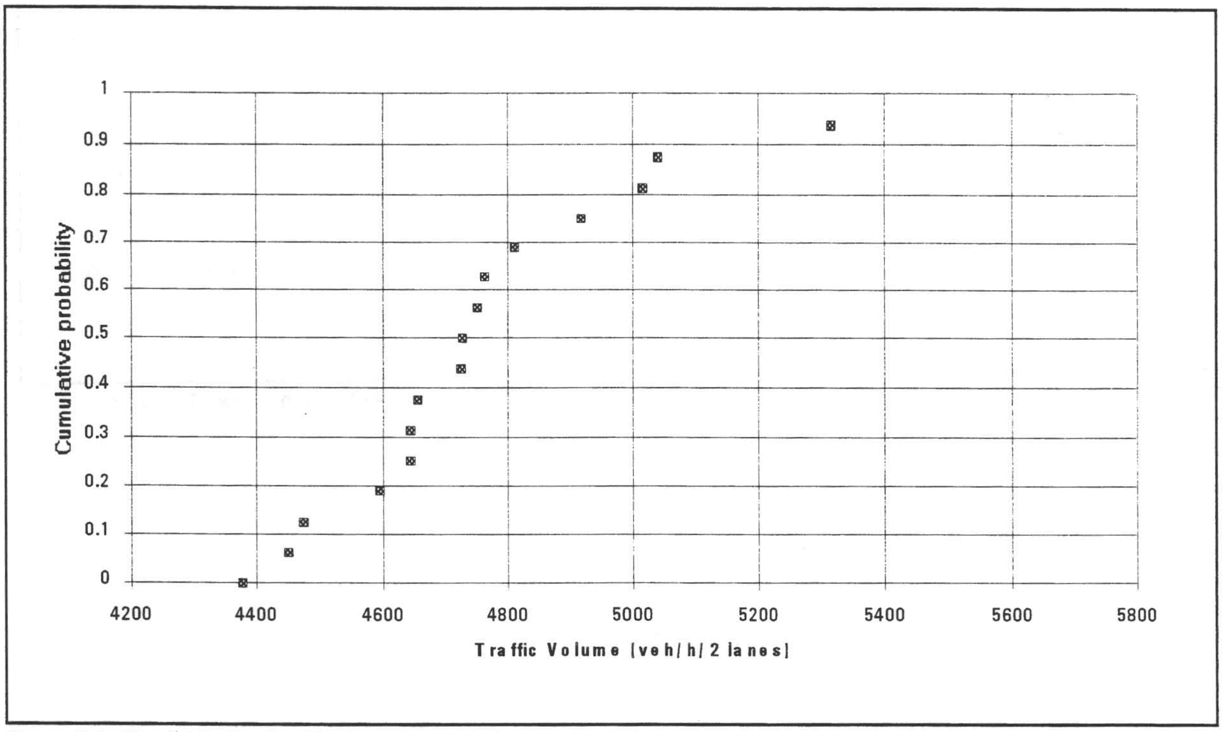

Figure B.1 The distribution function based on capacity measurements only

We may now, for example, estimate the capacity of the bottle-neck at the 50th percentile of the distribution. The correponding traffic volume represents an intensity value at which a fifty percent chance on congestion exists. At the 50th percentile we will find a capacity value of <u>4730 veh/h/2lanes</u>.

In **Figure B.2** we fitted a normal (Gaussian) distribution function, which seems to be an appropriate choice. The capacity estimate is than the expectation of the probability function: here, the mean is equal to this expectation so the capacity value is also about <u>4730 veh/h/ 2 lanes</u>.

We would have no doubt about the reliability of these capacity estimators if there were no other measurements. However, often intensity-measurements are available and some of these measurements will even have higher values than the lowest capacity-observation. This is also the case with our generated traffic data.

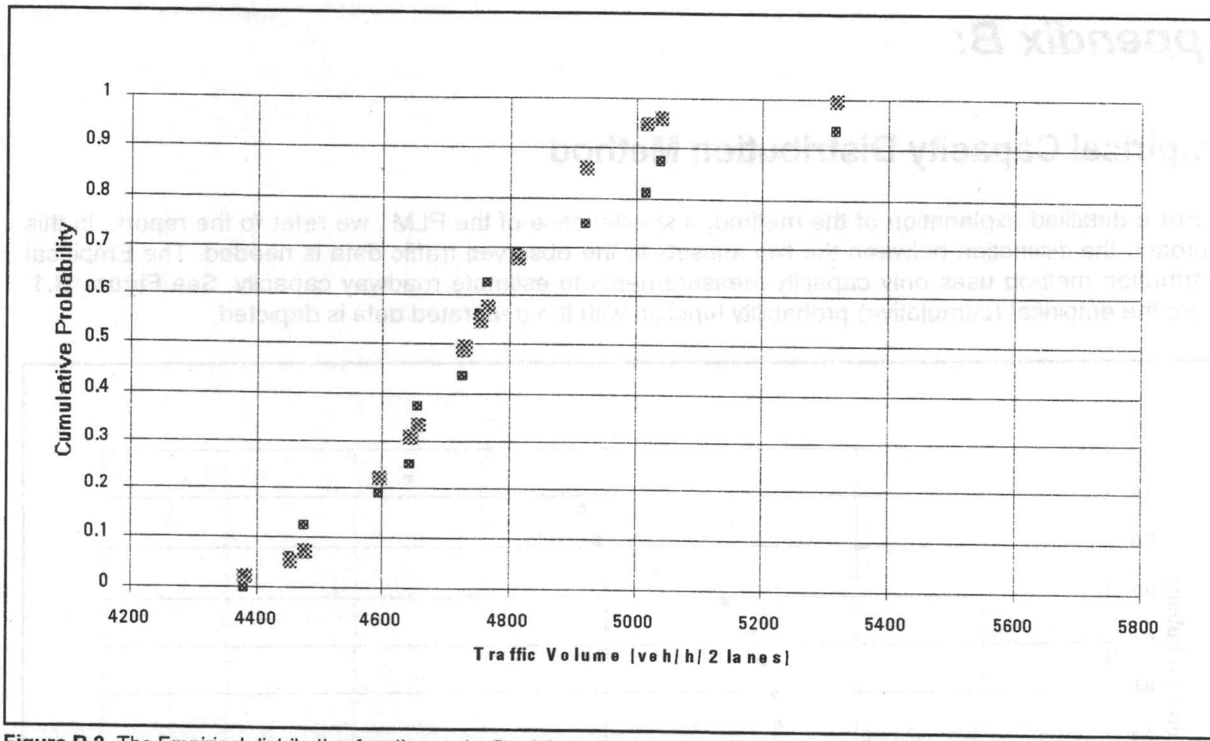

Figure B.2 The Empirical distribution function and a fitted Gaussian-type distribution [mean: 4730 veh/h, st. dev. 175 veh/h]

Appendix C:

Product Limit Method

The Product Limit Method (**Section 4-1**) makes use of the observed *free flow intensities* in the capacity value estimation. One condition for the application of the PLM instead of the Empirical Distribution approach followed in the section above, is that the *highest* free flow observation is larger than the *lowest* capacity observation. As can be seen in **Figure A.2**, this is the case.

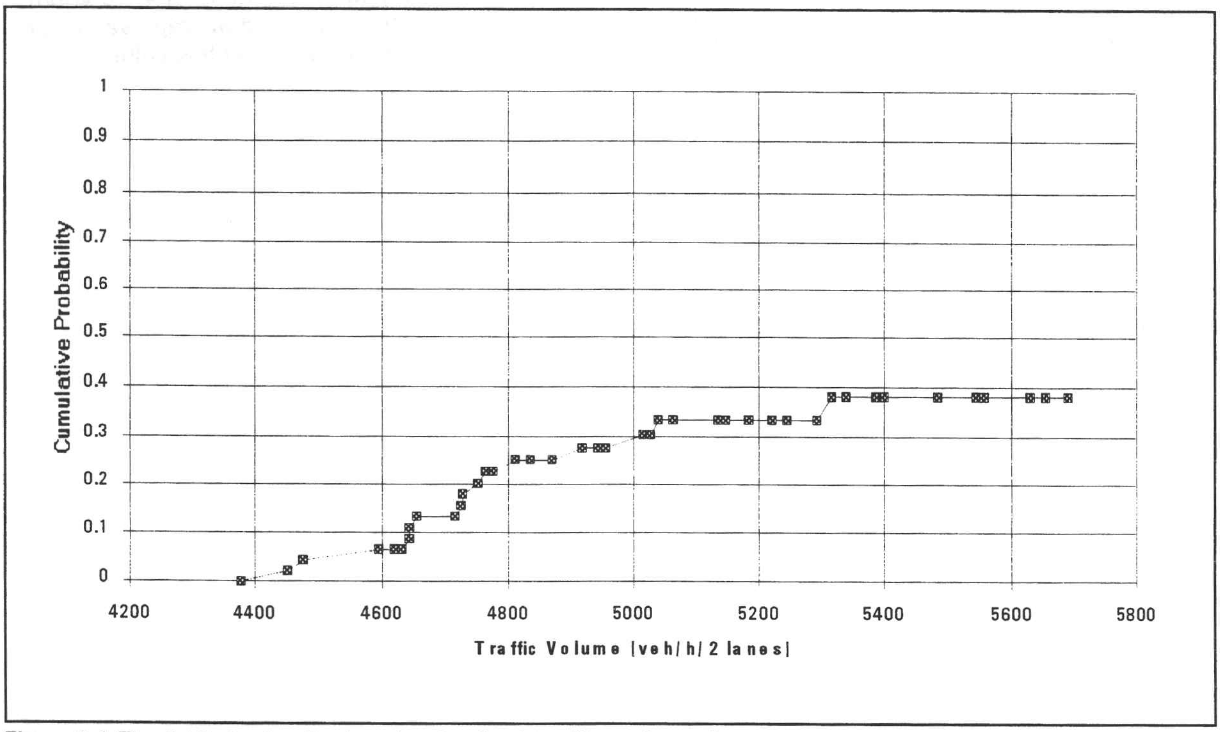

Figure C.1 The distribution function based on free flow intensities and capacity measurements (PLM approach)

The capacity estimate at the 50th percentile of the given discrete distribution (see Fig. C.1) is not possible. At the 25th percentile the capacity is about <u>4800 veh/h/2 lanes</u>. Fitting a distribution function is a possibility.

Appendix D:

Selection Method

The Selection Method (**Section 4-2**) is a simplified Produkt Limit Approach. In the method, only a single capacity value is estimated instead of a capacity distribution from which a capacity value may be determined.

The calculation procedure is as follows: All capacity observations are averaged and the resulting value is used as a lower boundary for the capacity estimate. This first step lead to a value of 4746 veh/h. All free flow intensity observations above this value are used to enlarge the calculated average value. So we may estimate roadway capacity at <u>5072 veh/h/2 lanes</u>. We question the meaning of this value.

Appendix E:

Selected Maxima Methods

Since our simulation data were based on four series of runs they could easily be interpreted, for example, as four observed rush-hours at the same bottle-neck.

The capacity estimation with the Selected Maxima method (**Section 3-2**) is very simple: select the traffic volume maxima in the predetermined periods (cycles) and calculate the average intensity. The method doesn't distinguish the two types of measurements in particular.

In our example this would lead to the following calculation:

Period 1 maximum: 5688 veh/h/2 lanes (a free flow observation)
Period 2 maximum: 5484 veh/h/2 lanes (a free flow observation)
Period 3 maximum: 5688 veh/h/2 lanes (a free flow observation)
Period 4 maximum: 5040 veh/h/2 lanes (a capacity observation)

The average of the selected maxima is thus <u>5475 veh/h/2 lanes</u>, which can be used as a capacity estimate. We can also think of an adapted method in which we select only the maximum capacity measurements in each period, and thus using the difference in the two types of data:

Period 1 capacity maximum: 5316 veh/h/2 lanes
Period 2 capacity maximum: 4643 veh/h/2 lanes
Period 3 capacity maximum: 4812 veh/h/2 lanes
Period 3 capacity maximum: 5040 veh/h/2 lanes

The average is than <u>4953 veh/h/2</u> lanes which differs substantially with the 5475veh/h/2 lanes derived above. This proves that, when there exist a discontinuity in reality, the estimation of the capacity value with the selected maxima method depends strongly on the used information about the traffic state.

Appendix F:

Comparison Derived Capacity Values

In **Table F-1** the previous calculations are ordered. When we select the 25th percentile PLM capacity value as reference we conclude that the values are spread in a range between -1% to +14% of this value.

Although the deviations seems to be moderate, for roadway capacity determination point of view they are substantially different. For example, most local ITS appplications (such as ramp-metering) are expected to have capacity gains in this range.

Empirical Distr.	*Prod. Limit Meth.*	*Selection Meth.*	*Maxima (of all)*	*Maxima (cap. only)*
4730	4800 (25th perc)	5072	5475	4953
Relative compared with PLM capacity:				
-1%	-	+6%	+14%	+3%

Table F-1 Comparison derived capacity values [veh/h/2 lanes]

Since we have no reference value of which we could say that it is 100% reliable, an evaluation is hard to make. It seems that we under-estimate the roadway capacity when we employ methods based solely or mainly on capacity observations. This is also an indication that there exist a discontinuity as pointed out in **Section 1-2**. Herewith rises the question what capacity value is wanted by the engineer: the pre-queue or queue discharge flow (See **Figure 1-5**).

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Sectie
Verkeerskunde

Sectie Verkeerskunde

De sectie Verkeerskunde houdt zich bezig met onderwijs en onderzoek op het gebied van planning, ontwerp en exploitatie van vervoer- en verkeers-systemen voor personen en goederen, alsmede het functioneel ontwerp van verkeersinfrastructuur.

De sectie Verkeerskunde maakt deel uit van de vakgroep Infrastructuur van de TU Delft, Faculteit der Civiele Techniek, en participeert in de onderzoekschool TRAIL.

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