Perspective on traffic control

Aspects of freeway control, intersection control and the control of transit flow in the Netherlands

January 1988

Prof.ir. P. Hakkesteegt

Faculteit der Civiele Techniek
Vakgroep verkeer

Delft University of Technology
The first part of this paper deals with the control and signalling system for motorways, directed to a more efficient use of available road capacity and to the improvement of road safety.

The second part gives some insight into the traffic conditions in urban areas and of the Dutch method of intersection control by means of dynamic multiphase control schemes; examples are given of the application of the tactics for public transport priority control at signalized intersections.

The third part deals with operational control of transit flow; it presents research into the control of services executed by trams and buses in urban areas, directed to the improvements of punctuality and regularity.

The fundamentals of TRICOPT are explained, and the effects are calculated on the efficiency of this control for the required fleet sizes.

Some results are presented of experiments with the strategy of conditioned punctuality control by means of the so called "passing moments" and of the development of a management information system for the supervision of the operational qualities in transit flow.

Finally some remarks are stated on the need for adequate management- and information systems to control data day by day of all quality aspects in transit flow, to fulfil the demands of "Public transport as a quality product".

<table>
<thead>
<tr>
<th>1. Rapportnr.</th>
<th>6. ISSN-nummer</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK 4500.201</td>
<td>0920-0592</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Titel rapport</th>
<th>7. Thema</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perspective on traffic control Aspects of freeway control, intersection control and the control of transit flow in the Netherlands</td>
<td>Traffic Control</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Schrijver(s)/redacteur(s)</th>
<th>8. Onderzoekproject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof.Ir.P.Hakkesteegt</td>
<td>TRICOPT</td>
</tr>
</tbody>
</table>

|-------------------------|----------------------|

<table>
<thead>
<tr>
<th>5. Opdrachtgever(s)</th>
<th>10. Datum publicatie</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January 1988</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11. Samenvatting</th>
</tr>
</thead>
<tbody>
<tr>
<td>The first part of this paper deals with the control and signalling system for motorways, directed to a more efficient use of available road capacity and to the improvement of road safety. The second part gives some insight into the traffic conditions in urban areas and of the Dutch method of intersection control by means of dynamic multiphase control schemes; examples are given of the application of the tactics for public transport priority control at signalized intersections. The third part deals with operational control of transit flow; it presents research into the control of services executed by trams and buses in urban areas, directed to the improvements of punctuality and regularity. The fundamentals of TRICOPT are explained, and the effects are calculated on the efficiency of this control for the required fleet sizes. Some results are presented of experiments with the strategy of conditioned punctuality control by means of the so called &quot;passing moments&quot; and of the development of a management information system for the supervision of the operational qualities in transit flow. Finally some remarks are stated on the need for adequate management- and information systems to control data day by day of all quality aspects in transit flow, to fulfil the demands of &quot;Public transport as a quality product&quot;.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12. Begeleidingscommissie</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>13. Praktijkcontacten</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>14. Bijbehorende rapporten</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>15. Aantal blz.</th>
<th>16. Prijs</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>ƒ 7,50</td>
</tr>
</tbody>
</table>
SOME ASPECTS OF FREEWAY CONTROL, INTERSECTION CONTROL AND THE CONTROL OF TRANSIT FLOW IN THE NETHERLANDS

Paper presented at the 1988 TRB Annual Meeting

Technische Universiteit Delft
Faculteit CiTG
Bibliotheek Civiele Techniek
Stevinweg 1
2628 CN Delft

Prof. Ir. Peter Hakkesteegt
Delft University of Technology
Transportation Research Laboratory
P.O. Box 5048
2600 GA Delft
the Netherlands
1. INTRODUCTION

1.1 The Netherlands is small and densely populated; 37,000 km² for nearly 15 million inhabitants, of whom more than 40% are living very close together on 15% of the area in the western part of the country, in the "Randstad" conurbation. In the last couple of years also Holland has been confronted with a spectacular growth of traffic and as a result with much traffic congestion, especially on the motorways connecting the bigger towns and the business districts. In 1986 an increase of 7% of motor car kilometers was recorded and also 1987 shows the same growth.

1.2 A broad discussion has arisen about the future of mobility and of motor car traffic. Extension of the motorway system alone is not sufficient and causes further deterioration of the environment. Not only traffic problems must be solved but also the needs of good living conditions fulfilled and urban qualities preserved. Broader actions are necessary. Cooperated national-, county- and local governments have formulated a specific (so called) mobility scenario to cope with these problems. The objective of this scenario is to maintain the accessibility of the economic centres by means of a coherent package of measures. Vital elements are the optimization of the use of the existing road networks and promoting other modes of transport (bicycles and public transport) to reduce the use of the motor car. The municipalities especially insist on the point of view that public transport has to play a more prominent part to meet the increasing demand in transportation. To fulfil this means a big challenge, which cannot be neglected, so must been accepted.

Of course optimization of traffic flow has already been carried out traditionally by the traffic control engineers, but mostly one-sided, on behalf of motorized traffic. Nowadays new tasks are waiting. Traffic control systems are no longer isolated phenomena serving only the goals for motor cars, but they come to be essential instruments for implementing transportation policies, formulated at non-technical levels.

1.3 To improve the quality of public transport various strategies are possible. Most important are those directed towards an optimum adjustment of town planning to the characteristics of its transportation system and on the other hand a transit planning and routing according to the given locations of origins and destinations. Mostly these are long term strategies. On short term we have to deal with strategies directed at the operational aspects of the existing public public transport system, with the qualities of transit flow. Speed, regularity or punctuality and synchronism have to be improved to make transit more convenient for the important transportation task.

It is uncontested that maximizing speed has a direct relationship with traffic control, because delay times at signalized intersections can be considerable. The question arises if traffic control engineers have to pay attention also to the other quality aspects in the services executed to make public transport more reliable. In my opinion they should. They have a lot of control expertise, which can be put into operation directly to improve punctuality/regularity and synchronism.
Operational control in public transport is a large and insufficiently explored field. A lot of research is necessary to support the policies for improving the role of transit in the urban transportation system. The Transportation Research Laboratory of the Delft University of Technology will contribute to this with their TRICOPT-research.

1.4 The first part of this paper deals however with the control and signalling system for motorways, directed to a more efficient use of available road capacity and to the improvement of road safety. The second part gives some insight into the traffic conditions in urban areas and of the Dutch method of intersection control by means of dynamic multiphase control schemes; examples are given of the application of the tactics for public transport priority control at signalized intersections. The third part deals with operational control of transit flow; it presents research into the control of services executed by trams and buses in urban areas, directed to the improvements of punctuality and regularity. The fundamentals of TRICOPT are explained, and the effects are calculated on the efficiency of this control for the required fleet sizes. Some results are presented of experiments with the strategy of conditioned punctuality control by means of the so called "passing moments" and of the development of a management information system for the supervision of the operational qualities in transit flow. Finally some remarks are stated on the need for adequate management- and information systems to control data day by day of all quality aspects in transit flow, to fulfil the demands of "Public transport as a quality product".
2. THE DUTCH FREEWAY CONTROL AND SIGNALLING SYSTEM

2.1 Introduction

The Freeway Control and Signalling System (MCSS) is a tool to be used on freeways carrying high traffic volumes. It has been developed and implemented by the Traffic Engineering Division of Rijkswaterstaat (National Department of Public Works) in the Netherlands.

The original aims for the MCSS were:
* more efficient use of the available road capacity,
* improvement of road safety,
* easing of the task of maintenance crews and of the police,
* collecting research data.

MCSS has been operational now for about 5 years. It covers sites in the freeway network where rerouting of traffic and options for ramp-metering and HOV-reservations are not used or possible.

The first goal of MCSS was to learn about the possibilities of such systems by implementing one and gaining experience with it. This affected the design and the type of system. It should give a maximum flexibility of traffic management facilities and still be justified on economical grounds. Also provisions were made to include facilities about which there was not sufficient information available at the time of design to make detailed specifications. An example of such a facility was the smoothing system aimed at reducing the risk of shockwaves by monitoring traffic flows and showing appropriate speeds in time. When MCSS was conceived, not enough was known about the algorithm to be used; so a very simple algorithm was introduced and all necessary research facilities were included.

MCSS is designed along the lines of the "graceful degradation" philosophy.

The main ideas are:
- faults should not bring the whole system down,
- faults should not lead to dangerous situations,
- rather than invest enormous amounts of money in a duplication of equipment a controlled degradation of performance is acceptable and should be the design criterion in the case of component failure,
- essential tasks should be less vulnerable than non-essential ones.

This has led to a design of three functional system levels:
  i  the central computer level: full control of the system,
  ii  the outstation level: under normal conditions only monitoring of the signals and preprocessing of data; in case of system problems MCSS tasks are carried out as far as possible.
  iii  the detector-station level: the basic datacollection.
2.2 Composition of the MCSS-system

Two freeway control and signalling systems are in operation; together they cover about 120 km of motorway.

An automatic incident detection (AID) system is incorporated for detecting incidents (accidents and other disruptions in traffic flow).

The processing of traffic data for this AID system is carried out partly in the outstations and partly in the central processor. The outstations analyse the traffic situation at each lane section by applying three criteria. The first two use the exponentially averaged speed and volume of the upstream detectors and the third compares the gap distribution of the upstream and downstream detectors. The combined results determine the traffic situation for each lane section.

If for maintenance work a lane has to be closed, the system checks first whether capacity problems will result. The actual volumes are compared with two boundary values, which are related to the number of lanes needed. This can lead to a warning to the system operator or even a rejection of the proposed lane closure. If more information on expected capacity problems is required, the operator can ask for a survey giving the predicted volume and probability of queues for every quarter of an hour for the rest of the day and the whole next day. This prediction is based on historic data of the volume of traffic, which is constantly updated.
2.3 Evaluation of the system's effects

MCSS is designed in the first place to warn traffic against incidents and to set up lane reservations from a control centre. Jenezon, Klijnhout and Langelaar have highlighted a number of aspects which show that MCSS has proved to be successful within its original goals.

Some of their results of the first period of experience are summarized.

Automatic incident detection measures
A fully automatic closed loop mode for taking queue measures without any operator interference proved to be much more reliable and faster than an open loop system, where an operator verifies the computer recommendations.

A lack of insight in the traffic behaviour, caused by a lack of sufficiently detailed research information means a gross underestimation of the number and character of queues. The MCSS takes on average 7 times more queue actions than foreseen. Especially the number of very short flow disruptions was underestimated; some 20% of the MCSS queue measures lasts less then 5 minutes. Timely warning of these short lasting queues contributes some 30-50% to the positive accident reduction effect of MCSS.

Lane reservations
The lane reservation facility is used mainly for the repair work crews, only 2% of the use is for accident handling.

The lane reservation facility of MCSS has a very positive effect on the throughput past the bottleneck, which is the merging area. With standard signing it is found that 1100-1400 veh/h can smoothly merge from 2 lanes into 1, with MCSS traffic does not break down with volumes up to 1750 veh/h.

The effect is a double one. MCSS does not only reduce the number of traffic queues, but also shortens the time period of the lane reservations.

Smoothing traffic
When AID-legends are shown over crawling traffic the speed difference is reduced by some 20 km/h, the number of shockwaves bringing the traffic to a full stop is reduced by a factor 3 resulting in an increase of 5-6% more traffic that can be handled past bottleneck sites.

Fog measures
Analysis of fog accidents showed that all major fog accidents started as minor shockwave- or queueing problems. Therefore the system relies fully on the automatic incident detection mechanism to warn drivers against queues or crawling traffic. So during fog periods no blanket speeds are used but the legends are changed frequently up to 500 times over 50 km of motorway.

As a result it has been found that the exponentially smoothed speed averages measured in fog were 50-55 and 70-75 km/h respectively.

*) MOTORWAY CONTROL AND SIGNALLING
There was a 50 or 70 slow down legend operational as part of AID measures. Since the installation of MCSS some dangerous fog situations have occurred; simple calculations showed that statistically 2-5 people should have been killed and 40-70 injured on the sections controlled by MCSS, but actually there have not been any serious accidents at all in these fog periods.

**Reduction of accidents**

Reduction of accidents is mainly obtained by a reduction of secondary accidents as a result of warning the drivers by the AID mechanism. On all road sections more than 30% of the accidents reported were secondary accidents; on 15% of the road sections the amount of secondary accidents was even 50%.

A reduction in the total number of accidents is found of about 15-25%, i.e. 265 to 500 registered accidents per year. With a registration rate of about 46% this results in a reduction of 600-1100 accidents per year. Because of the third power relation found between the average daily traffic volume (ADV) and the number of secondary accidents the effectiveness of the MCSS system will grow with the ADV.

**Capacity**

Under congested conditions the throughput of traffic is about 5.5% higher with MCSS than without, mainly as a result of a considerable reduction in heavy shockwaves, obtained by showing advisory speeds during congestions.

**Comparison of costs and benefits**

The costs of installation and operation of the MCSS system over a period of ten years are reported to be in millions of Dutch guilders:

- installation: 75
- renewals: 3
- maintenance: 25
- exploitation: 8
- total (price level 1982): 111

The benefits (as far as possible to express and relevant to the goals of the system) are over a period of ten years:

- reduction of accidents: 40-74
- reduction of travel time lost: 77
- easing tasks of road managers and police: 2
- total benefits (price level 1982): 119-153

Although they are rather strong, the effects of the growing traffic volumes are not taken into account. Every percent increase in traffic volume per year leads to an increase of 2-3% in the benefits for that year.

Besides there are intangibles such as:

- human affliction caused by deaths and injured persons,
- higher safety for the road workers,
- results of research data collection.

So MCSS is a traffic management tool that operates economically on freeways with high traffic volumes. Analysis has shown that on dual two freeway a traffic volume of 60,000 or more veh/day justifies the installation of MCSS; dual three freeways should carry 100,000 or more vehicles a day.
2.4 Further research

The Traffic Engineering Division of the National Department of Public Works have now more than 5 years of practical experience with the Dutch Motorway Control and Signalling System. During this period they have carried out extensive research, improved their knowledge and adjusted the original assumptions. Further research is directed to upgrade the AID-algorithm; applicable mathematical background information is needed for the design of an automatic on-line smoothing algorithm to reduce the risk of shockwaves. The MCSS is an excellent instrument to collect research data. This makes it possible to study traffic on these aspects. Research is also needed to predict the capacity of freeways.

With the MCSS the capacity distribution function for a 3-lane one-directional roadway has been measured between 6000 and 9000 pcph and this offers great opportunity for optimization by using capacity estimation for dynamic traffic control.

The capacity estimation based upon traffic flow models of the semi-Poisson type, which divides the small headways of a stream of vehicles into a following and a non-following group. In order to validate these semi-Poisson models a special following criterion was developed, that takes into account the behaviour of two succeeding cars over a distance of 300 meter and discriminates between following or non-following.

Theory building with measured short-, normal- and long-following car drivers on the estimated capacity.

![Graph showing estimated capacity as a function of fractions short-, normal- and long-followers (a,b,c)]

Estimated capacity as a function of the fractions short-, normal- and long-followers (a,b,c)

The use of detailed (historical) traffic patterns for the planning of road works, can reduce the chance of congestions. So standards can be developed to be used for maintenance and reconstruction activities.

Through comprehensive data collection and processing accurate values concerning the road capacity and relations between traffic volumes and the probability of congestion information can be obtained, which is very important for short- and long term traffic management. The advanced data collection system is also used by other (foreign) researchers and contributes to a good international cooperation. Traffic management requires systems even faster than MCSS and with a much better operator interface. On top of that comes the need to control tunnel situations as well.
3. SOME ASPECTS OF THE DUTCH METHOD OF TRAFFIC CONTROL

3.1 Traditionally almost any part of the network in urban areas has to deal with various modes of transport, such as motor cars, trams and/or buses, bicycles and pedestrians. Each mode of traffic has its own characteristics (flow behaviour as well as demand variations) and safety requirements, which should be taken into account. Since they are historical towns, they have mostly a radial type of network, with unequal distances between intersection, heterogenous characteristics of road sections and a big directional distribution of traffic at crossings. To reduce (potential) conflicts turning movements are mostly protected. So there are many specific lanes and phases for turning traffic, bicycles and pedestrians.

3.2 Almost every city in the Netherlands has taken measures to speed up public transport. Many road sections have lanes for transit only or exclusive approaches to the intersections. Those for streetcars are mostly in the middle of the road and cause extra (potential) conflicts to be protected, with a peak when the transit route itself turns right or left. Over 70% of the Dutch public transport vehicles are provided with special identification equipment (VETAG); this makes it quite easy to pass information on each individual vehicle to the road side e.g. to control processors. During 1986 Philips introduced a system for two-way vehicle communication, named VECOM. With this, vehicles can not only transmit but also receive information, offering the possibility of on-line transport processing on a distributed

3.3 In addition there are specific transportation policies giving priority to pedestrians and to bicycle traffic. The city of Delft, for instance, has taken a variety of measures to promote the use of bicycles. They scored a great success because more than 40% of all daily trips inside the whole town are made by this mode of transport. This means a lot for the environmental quality as well as for the capacity of the network, for cycles need less than 10% of traffic space for motorcars. It is clear, these policies influence the traffic management goals for the control at signalised intersections. Requirements of bike traffic should not be subordinated to those for motorcars but, on the contrary, the control system must give as much priority to it as possible to obtain a minimum of waiting times together with a maximum of safety.
3.4 In summary, traffic control conditions at intersections in the Netherlands are rather complex; there are many traffic movements to be controlled separately, and specific traffic management goals to favour public transport, bicycles and pedestrians, even (or just) when traffic demand draws near to or exceeds capacity. Each intersection needs a made-to-measure approach, to fulfill all the requirements.

In co-operation with the controller industry research has been carried out and a standard formulated, based on traffic functions rather than hardware dictations.

The whole control process is considered to be an aggregation of the control of individual traffic streams. Each traffic stream has a green interval (green phase), a change interval (amber phase) and a red interval (red phase). The aggregation of one green phase, one amber phase and one red phase for one individual traffic stream is defined as the phase cycle. With the phase cycle as the elementary unit, any control system and control program is built up.

This concept has stimulated the industry to develop a wide range of highly sophisticated traffic controllers, which can fulfill all control strategies and control tactics and further any requirement of any traffic control engineer. As a reaction, there is an even wider range of traffic control solutions, created by the various traffic control engineers of independent traffic and transportation departments.

3.5 Mostly multiphase control schemes are applied, based on a fully actuated operation; all signal phases are controlled by detector- and push button actuations, so the control schemes react dynamically to all relevant fluctuations in traffic demand.

Since the (so called) internal lost time of traffic control dramatically influences the performance, there is a primary control strategy for minimizing these lost times.

Two main types are distinguished: the clearance lost time and the idle times.

Due to the complex intersection geometrics and the many protected traffic streams, the clearance lost time can be considerable. Safety conditions require that the clearance periods have to be related to the slowest vehicle passing the stopping line at the end of the change interval, contra the fastest vehicle starting in the subsequent green interval. Because of the use of the intersections by various traffic modes, with heterogeneous speed and flow characteristics, and the fail-safe requirements for traffic safety, the disadvantageous effect of inefficient controlled clearance times can be considerable. To minimize this, the mututal clearance conditions are taken into account separately.
3.6 Minimizing idle times, caused by unused or inefficiently used green periods due to variations in traffic demand, is much more complex. Especially if specific strategies have to be fulfilled to favour public transport, bicycles and/or pedestrians. It can only be achieved by the most efficient distribution of time among conflicting traffic streams. This makes the design of complex control programs vital, with many conditions for the control of the individual traffic streams.

Much research has been carried out by the controller industry to develop system orientated methods for the design of traffic control programs, such as the interactive program generator GEN 34 and NISCOL (Nederland-Haarlem), Basic Intersection Control BIC (Philips) and ASMOGEN (Siemens).

Moreover the Transportation Research Laboratory of the Delft University of Technology has developed a general methodology for traffic control design (TRAFCOD), in which all kind of signalization conditions are defined by elementary tactical functions. In this, complex signalization problems for varying traffic conditions, are unravelled into a limited number of special function variables. They form the base for an elementary approach, which can fulfill all requirements of the various control strategies in a standardized way. For a description of the fundamentals of this approach, see (2).

A short explanation can be given.

Apart from a set of system routines, a TRAFCOD control program consists of two parts:

* for all traffic streams together: a conflict matrix,
  a time table,
* for any traffic stream apart

The conflict matrix is used to function systematically with all different clearance times individually. It indicates which traffic streams are mutual parallel or conflicting and it contains the individual clearance times.

Since the conflict matrix is part of the control program, it delivers directly the control condition \( K_i \).

This condition is governed fully by system routines and is equal to the conflict function \( KF_i \) of any conflicting green phase.

This function is set by the start of the conflicting green phase \((i)\) and reset by the end of the clearance time concerned \((TO_{ij})\). So \( K_i = \sum KF_{ij} \).

<table>
<thead>
<tr>
<th>Conflict matrix with clearance times</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 5 6 8 11 12 28 31 32 44</td>
</tr>
<tr>
<td>2 0 0 - 3 2 1 - -</td>
</tr>
<tr>
<td>5 4 - 0 - 1 6 5 2 -</td>
</tr>
<tr>
<td>6 2 - 1 4 - - - - -</td>
</tr>
<tr>
<td>8 - 4 1 - 0 0 - - - 2 -</td>
</tr>
<tr>
<td>11 1 1 4 - - 1 - - -</td>
</tr>
<tr>
<td>12 3 4 2 - - 1 - 5 4</td>
</tr>
<tr>
<td>- 2 - 4 4 - - - - -</td>
</tr>
<tr>
<td>31 6 - - - - - - - -</td>
</tr>
<tr>
<td>32 - - - 3 2 - - - - -</td>
</tr>
<tr>
<td>- - 2 3 4 1 - - 0 2 - - - - -</td>
</tr>
</tbody>
</table>

"-" means: mutual parallel green phases

(2) Hakkesteegt, P.: TRAFCOD: a method for systematic traffic control design.
Delft University of Technology, the Netherlands, 1987.
Since a green phase is allowed only to start if the conflict function is reset, the conflict matrix assures completely the safety of control on software level. Besides, the conflict matrix forms a very useful instrument for the systematic design of dynamic multiphase control schemes, but this method will not be discussed now.

3.8 Minimizing idle times requires a very accurate reaction to all fluctuations in traffic demand, sensed by detector and push button actuations. Different types of idle times have to be prevented:

i. the needless realization of green phases, when no vehicles are present nor approaching.

ii. the needless continuation of green phases when there is no longer traffic flow at all or (far) below saturation flow.

The traffic function \(F_\text{ij}\) discriminates traffic demand. This function is set by any detector/push button actuation \(D_\text{ij}\) during the non-green period and reset if during the green period the applied measurement criterion \(\text{MK}_\text{ij}\) has been exceeded. For the tactic of platoon responsive control \(\text{MK}_\text{ij}\) the measurement criterion is the gap time value \(\text{TDH}_\text{ij}\).

\[
\begin{align*}
F_\text{ij} &= \text{GN}_\text{ij} \cdot D_\text{ij} \\
\text{FN}_\text{ij} &= \text{MG}_\text{ij} \cdot \text{MKN}_\text{ij} \\
\text{MK}_\text{ij} &= \text{TDH}_\text{ij} \\
\text{TDH}_\text{ij} &= D_\text{ij}
\end{align*}
\]  
(3.8.1)

The prevention of "needless continuation of green phases" by ending timely the green phase is only valid however if, due to the continuation of insufficiently used green periods the start of subsequent green phases, for which traffic demand is sensed, is delayed. Thus the end of green phases is conditioned to traffic demand, both on its own approach as well as on subsequent approaches.

Finally there is a third type of idle times, namely if the start of a certain green phase is skipped due to the lack of traffic demand, but traffic demand arises during the part of the cycle allocated to a combination of green phases (i.e. traffic movements) of which the green phase concerned can form part of. To avoid these unused times control conditions enable the start of such a green phase anyway, provided that due to this no other idle times arise. So actuation ranges are defined during which the start of a green phase is possible.

Minimizing idle times deals thus with all individual short term reactions in traffic demand.

*) TRAFCOD used the rules of the positive logic and has two relation operators

"=" This means "Is equal to"; the logical value of the instruction section is always equal to the logical value of the reference section.

"." This means "Arises as soon as"; the instruction section is giving the logical value '1' as soon as the logical value of the reference part becomes '1'. Thereupon the logical value of the instruction section is independent of the reference section. The logical value of the instruction section changes only by means of other control formulae.
To realize all possible combinations of parallel traffic movements, the green phase of the phase cycle is divided into five sub-phases: advanced green (VS), fixed-time green (FG), waiting green (WG), extension green (VG) and parallel green (MG). Since for a given phase cycle the duration of the amber phases has a fixed value and the red phase is the supplement of the other phases, only the start and the end of the green sub-phases are decisive for the whole control process.

3.9 To minimize idle times the start and the end of the individual green phases are controlled very accurately. Investigation of all potentialities shows that the following conditions are determinant for the start of any green phase:
* there must be traffic demand, ($F_i$)
* the green phase must be in turn, ($CN_i$)
* no other conflict phases must be running, ($KN_i$)
* the minimum red period must have expired, ($RGN_i$)
* no conflicting greenphase must have priority, ($PN_i$)
* the coordination conditions should be fulfilled, ($XN_i$)
* the start must not be delayed to synchronize it with the start of any other green phase, ($UN_i$)

So: $G_i = F_i \cdot CN_i \cdot KN_i \cdot RGN_i \cdot PN_i \cdot XN_i \cdot UN_i$  (3.9.1)

This is simplified to distinguish by sub-routines:
* an actuation condition, ($A_i = F_i \cdot CN_i$ and $AN_i = EVG_i$)
* a block condition; ($BL_i = RGN_i + PN_i + XN_i + UN_i$)

So: $G_i = A_i \cdot KN_i \cdot BLN_i$  (3.9.2)

The same approach is valid for the end of any green phase; these conditions are:
* the measurement criterion for traffic demand must be exceeded, ($MKN_i$)
* the minimum green period must have expired, ($GGN_i$)
* no parallel green phases must be running, ($YMN_i$)

In between control tactics act upon the duration of the green phase. This can either be extension or shortening.

For the first tactic there are specific extension functions:
* to adjust the start of the fixed-time period, ($YS_i$)
* to adjust the start of the extension period, ($YW_i$)
* to extend the duration of the green phase after its own measurement criterion has exceeded, ($YM_i$)

For the latter tactic there is a specific cutoff function, ($Z_i$)

Finally there are situations, that external conditions forces to skip the realization of green phases at all and terminates running green phases (on behalf of railway crossing, bridges). For this a specific skip function is defined ($O_i$).
If a green phase is realized TRAFCOD routines complete all sub-phases in a given sequence, possibly with a time value approaching zero. The last one is the sub-phase "parallel green" (MG), which arises as soon as during the sub-phase "extension green" (VG) the measurement criterion has been exceeded.

So: \( GN_{1} = MG_{1} + GN_{1} (YMN_{1} + Z_{1} + O_{1}) \) \hspace{1cm} (3.9.3)

All conditions are regarded separately; this enables to put into action any control tactic in a very detailed and uniform manner. For the ease of the designer TRAFCOD has default formulae for most of the conditions and default values for the function variables. Full attention can be paid to the important design elements.

3.10 The operation of dynamic multiphase control plans can be represented by a flow diagram of the consecutive green phase combinations and structure schemes, indicating the sequence of the green/amber phases of the phase cycles and the various conflict conditions. The flow diagram and the structure scheme are designed systematically with the use of the conflict matrix and the given optimization criteria; this method is not discussed now.
These schemes are drawn on the assumption of a continuous input of traffic demand. Thus the flow diagram gives the so-called "maximum combinations". It must be clear that due to the variations in traffic demand sub-combinations can be formed, and more transitions possible. For instance, the green phase combination (c) included also the following sub-combinations.

A maximum performance requires the exploitation of also the last seconds; not only for the start and the termination of green phases, but also a possible extension.

For instance: if a green phase is running, and the traffic platoon has passed, so the measurement criterion has been exceeded, it should be ended, but as long as parallel green phase runs, it can be extended to favour low dense flow but only if no traffic demand is sensed for a conflicting green phase.

Example: for the given intersection green phase 6 runs parallel with 5, 12, 28, 31 and 32; so green phase 6 can be extended parallel to green phase 5, if there is no demand for 12, or with 28 if there is no demand for 2, 8 or 44, etc.

The control formula for the general extension functions becomes:
\[ Y_{M6} = A_5 \cdot A_{N1} + A_{12} \cdot A_{N1} + A_{28} \cdot A_{N8} \cdot A_{N44} + A_{31} \cdot A_{N3} + A_{N3} + A_{N44} + A_{32} \cdot A_{N1} + A_{N11} \cdot A_{N44} \]

The design of such control formulae seems to be rather complex. Research has been carried out to develop design rules and design formulae.

For this example: \[ Y_{M4} = \Sigma (A_{p1} \cdot (A_{Np1} \cdot k_i)) \]

In words: the extension function of the sub-phase "parallel green" is equal to the actuation function of any green phase (p), parallel to (i), provided there is no actuation function for green phases, which are parallel to (pi), but conflicting with (i).
Such an approach is valid for all function variables. Since these variables are regarded separately, the control formulae have a general character.

3.11 Flow diagram and structure scheme show simply the possibilities of priority control for bicycles, pedestrians and public transport. For instance a demand for bicycle green phase 28 sensed during combination (a) is effectuated directly, one sensed during combination (f) is effectuated via the combination (i), and a demand sensed during combination (k) is effectuated in the combinations (m), (n) or (a). (For the codes of the traffic streams: see intersection scheme under 3.6.)

According to (3.9.1) only the sequence condition is accountable for the tactic of multiple realization of green phases. Since there is a default formula for $C_{i}=SG_{i}$ ($SG_{i}$ means: start of green phase (i)), the addition of the control tactic formula $CN_{28}=SG_{12}$ and $P_{5}=A_{28}$ enables an extra realization of green phase 28 after green phase 12 (see also the structure scheme). The same approach is valid for the control of the green phases for pedestrians and public transport. Without specific control conditions delay times for public transport are rather long.

WITHOUT PRIORITY CONTROL:
LONG WAITING TIMES.

THE MULTIPLE REALIZATION-TACTIC PREVENTS EXCESSIVELY LONG WAITING TIMES.
The multiple realization tactic prevents excessive long waiting times. To speed up public transport as much as possible traffic management goals are often formulated to reduce transit delay times towards a minimum. Then the cutoff tactic and the extension tactic are applied.

The cutoff tactic is active if an approaching transit vehicle is sensed during the running of conflicting green phases; these green phases are ended by $Z_i=F44.CN44$. System routines provide for the further settlement. With appropriate detector location the transit vehicle passes without any delay.

The extension tactic is active if a transit vehicle approaches during the running of parallel green phases. To prevent such phases (according to their own traffic demand) from ending they are extended by $YM=F44.CN44$. According to system routines the parallel green phase concerned remains running at least until the moment the transit green phase starts. After that both green phases become independent (according to this formula).

Using these principles of priority control for transit flow, a part of the metro system in Rotterdam operates without a tube infrastructure. This part of the metro-line crosses 21 at grade signalized intersections with no delay at all.

In situations with heavy traffic demand priority control could cause undesired congestion in other traffic streams. This is avoided by the tactic of conditioned priority. The information on congestion can be derived from either queue detection (DQ) or control conditions (HQ). Say: $DQ_1$ is set as soon as congestion at approach (1) is sensed and reset as soon as there is no longer congestion. The control tactic formula $Z_1=F44.CN44.DQN_1$ prevents effectuation of the cutoff tactic during these traffic conditions.

Say: $HQ_1=EG_1.F_1$. This means that the queue help function is set if during the green phase the measurement criterion has not been exceeded (see 3.8.1) and by that the traffic function ($F_1$) is not reset.

Say furthermore: $HN_1=EG_1.FN_1$ (the reset of the queue help function).

The control tactic formula $Z_1=F44.CN44.HQN_1$ prevents now fully loaded green phases from being cutoff.

Conditioned priority can also be used to promote regularity in the services executed by the transit vehicles. If they are early they do not need priority, if they are late they need absolute priority. Say: the scheduled interval times of the transit vehicles are $T_{x}$ and a timer starts when a transit vehicle passes the detector D44 ($IT_{44}=ED44$) and that the logical value of $T_{44}$ is '1' as long as the
timer runs. Using the control tactic formula $C_{44}=T_{44}<T_{x}$ transit vehicles are kept until the interval time has expired. This is a very rough tactic. More common is the prevention of the cutoff tactic and/or the multiple realization tactic for those vehicles, which are early.

The next chapter will show that in the case of regularity and punctuality control most of the transit vehicles are more or less early. So the tactic of conditioned priority can be integrated in a comprehensive public transport control system.

3.12 Discussion
Due to the traffic conditions and transportation policies many control systems in the Netherlands are directed to a maximum performance by minimizing all types of lost times. To achieve this dynamic multiphase control schemes are applied to be able to react effectively to all kind of variations in traffic demand, and directed to the exploitation of even the last second other strategies are put into action as soon as (as long as) the demand/capacity ratio allows. So co-ordinations for signal progression are not fixed, but very flexible.

Any moment the system can fall back into: "maximizing the performance by minimizing lost times".

This type of traffic control enables simply to effectuate priority control for pedestrians, bicycles and transit vehicles. Much research has been carried out for a systematic design of the complicated traffic control programs: all kind of signalization conditions are unravelled into control tactics for specific functions, and each function has its own logical variable to describe the tactic concerned, design rules are available to formulate the control tactic formulae uniformly; default formulae for the initial tactics and default values for the function variables ease the design work, so full attention can be paid to complicated tactics for isolated intersection control and for co-ordinated control, with various types of flexible traffic dependent linking between controllers.

Besides simulation models are developed for these dynamic multiphase control schemes, which accept directly the designed traffic control formulae as an input for the simulation process (FLEXSYT). This makes it possible to evaluate easily the performance of controlled intersections as a function of the fluctuating traffic input and the various control strategies and tactics.
4. THE CONTROL OF TRANSIT FLOW

4.1 Introduction

As discussed before a lot of measures have been taken in the Netherlands to speed up transit, such as lanes for trams and buses only and priority control at signalized intersections. This resulted in a remarkable gain in circuit times. However, the irregularity in transit flow remained, thus a clustering of vehicles, unequal degrees of vehicle load and long waiting times for the passengers at the stops.

Hence the need arose for punctuality or regularity control.

In train and metro exploitation punctuality or regularity control is quite common; the exclusive infrastructure makes the services independent of other traffic. Trams and buses however are influenced considerably by other modes of traffic, by (signalized) intersections and varying stop conditions. Besides the drivers have to be more attentive to all kind of unsafe conditions. No wonder fluctuations in the services executed cannot be avoided, they are there by nature. The traffic control engineers have to deal with these fluctuations to improve punctuality or regularity.

Variations in the circuit times of transit vehicles are rather big. As an example the line times for tram line 5 in Rotterdam are shown. It concerns a tram line with scheduled interval times of 5 minutes, a circuit length of 16 kilometers and about 40 stops.

The difference between the fast and the slow vehicles is about 12 minutes or 20% of the route times. It is clear by this regularity in the transit flow is out of question.

Under these circumstances the waiting times for the passengers at the stops are much higher than planned, according to:

\[ TWM = 0.5 \times TIT (1 + (\sigma / TIT)^2) \]

with:
- \( TWM \): mean waiting time
- \( TIT \): time table inter-arrival time
- \( \sigma / TIT \): variation coefficient in the inter-arrival times.

Besides some other questions arise:
* what is the effect of irregularity on the variations in the passengers load of the vehicles. In other words: what is the effect on the essential fleet size necessary to achieve a certain level of service in the transportation quality?
* is it possible to improve the regularity in transit flow and what are the consequences of it?
* what type of operational control would serve best the objectives of quality improvement?

The economic situation does not allow big investments, so an improvement in the operational quality must be found in an optimum
use of the existing infrastructure and with the rolling stock and staff available.

To analyse these items the Transportation Research Laboratory of the Delft University developed TRICOPT (TRIptime Control and Optimization in Public Transport), a research package for transit flow control. TRICOPT consists, amongst others, of:

* DATACOL a tool for (semi) automatic data collection and processing.
* TRITAPT a tool to analyse the operational aspect of transit flow.
* TRIPSIM a tool to evaluate all possible control strategies and control tactics by means of simulation of trips, using collected data and relationships detected.
* TRISCAL a tool to calculate time tables and dynamic passing moments.
* TRIRVAL a tool to determine the quality index of transit flow.

This research package has been tested for usefulness and applied on a number of case studies.

4.2 The fundamentals of TRICOPT

Each transit line can be described by vehicles, following a defined route, stopping at (or passing) defined stops in conformity to a defined time table. The time table describes the service planned and is the aggregation of planned moments of arrival/departure at given stops. Complementary to the service planned is the service executed.

To model the operation process a transit line is unraveled into sub-processes, viz.:

* the stop process describes the alighting and boarding of passengers
* the running process describes the unhindered movement of vehicles
* the delay process describes the hindrance to the free flow of vehicles
* the control process describes the regulations of the vehicles according to the defined control strategies
* the terminal process describes the stay of vehicles at terminal stops (at the end of circuits or of single trips).

Thus any service executed can be described by the aggregation of these five sub-processes. All have the same dimension: time.

The times of individual processes fluctuates strongly. It is never possible to predict exactly the time a certain process will take. However, each process is one of a set. So if sufficient survey data are available, it is possible to formulate probability density functions to express the chance of a given time required for a certain sub-process.

TRICOPT aims at describing transit flow with the aid of probability density functions for the times taken by the individual sub-processes.

In the operation process of each vehicle, sub-processes occur an indefinite number of times. An accurate description calls for an elementary unit consisting of a fixed number of sub-processes. This elementary unit is found by the STOP MODULE.
The stop module \(HM_k\) is the aggregation of:
- the road section(s) between stop \(H_{k-1}\) and stop \(H_k\).
- the next stop \(H_k\).

By definition a stop module contains:
- a running process, expressed by the running time \((TR_{i,k})\) between stop \(H_{k-1}\) and stop \(H_k\).
- a delay process, expressed by the delay time \((TD_{i,k})\) between stop \(H_{k-1}\) and stop \(H_k\).
- a stop process, expressed by the stop time \((TH_{i,k})\) at stop \(H_k\).

The standard stop module consists of a road section (length can be zero), a disturbing point (can be skipped), a road section (length can be zero) and a stop.

So the following configurations are associated with the standard:
- stop module with no disturbing point
- stop module with initial disturbing point
- stop module with en-route disturbing point
- stop module with end disturbing point.

If a stop module contains more than one disturbing point, dummy stops can be used to link road sections together. By giving all dummy stops the identification code of the stop module, the computer program automatically composes the desired stop module.

real situation:

linked standard modules:
The stop time is the number of time units between the moment "doors opened" and the moment "doors (can be) closed".

\[ THA_{i,k} = MCD_{i,k} - MOD_{i,k} \]

The running time (\( TRA_{i,k} \)) includes the effects of acceleration and deceleration at stops. The running time plus the delay time makes the passage time.

\[ TPA_{i,k} = TRA_{i,k} + TDA_{i,k} \]

The passing time (\( TPA_{i,k} \)) is thus the number of time units between the "end of stop" moment (i.e. the moment the doors (can be) closed at stop \( H_{k-1} \) (\( MHF_{i,k-1} \)) and the "start of stop" moment at stop \( H_k \) (\( MHS_{i,k} \)).

The delay time is the number of time units obtained by subtracting the free flow passage time from the actual passage time.

\[ TDA_{i,k} = TPA_{i,k} - TPF_{i,k} \]

Data collection is effected as follows:

- **disturbing points**
  - \( MP_{i} \): moment of passing measure point 1
  - \( MSS \): moment of stopping at disturbing point (stop line, switch, bridge, etc.)
  - \( MPS \): moment of passing disturbing point
  - \( MPM_{2} \): moment of passing measure point 2.

- **stops**
  - \( MHS \): moment of start of stop process i.e. moment doors opened
  - \( MHE \): moment of end of stop process i.e. moment of doors closed or
  - \( MHP \): moment of passing a stop sign, without halting.

The module time is the sum of running time, delay time and stop time

\[ TMA_{i,k} = TRA_{i,k} + TDA_{i,k} + THA_{i,k} \]

A micro processor based DATA COLLECTOR has been developed. Data are stored on magnetic tape and used directly as an input for TRITAPT, the analysis module of TRICOPT.
For the description of a transit line the following convention is used:
- a stop module: is the aggregation of road sections and the following stop
- a section: is the aggregation of stop modules from one passing stop (to which specific operational conditions are applicable) to the next passing stop
- a route (single trip): is the aggregation of stop modules or sections between one terminal A and the other
- a line: is the aggregation of routes from a certain terminal and back to it (so including the intermediate terminal)
- a circuit: is the line plus the initial terminal concerned.

TRITAPT calculates the distribution functions for all sub-processes per stop module, per section, per route, per line and per circuit as well as for the punctuality- and proportional regularity deviations. So complete profiles can be made of transit lines. Table 4.2.1 gives an example of a module profile.

Since there is also automatic measuring of passengers demand the profile is extended with profiles of bus stops (see Table 4.2.2).

This detailed TRITAPT information on the operational processes of the services executed is used as an input for transit flow simulations with the TRIPSIM module.

<table>
<thead>
<tr>
<th>Table 4.2.1 TRITAPT MODULE PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 2019</td>
</tr>
<tr>
<td>Module time</td>
</tr>
<tr>
<td>Running time</td>
</tr>
<tr>
<td>Stop time</td>
</tr>
<tr>
<td>Delay time</td>
</tr>
<tr>
<td>Punct.dev.</td>
</tr>
<tr>
<td>Prop.reg.dev.</td>
</tr>
<tr>
<td>Operational speed</td>
</tr>
<tr>
<td>28.6 km/hr</td>
</tr>
</tbody>
</table>

| Operational speed: based on module time. |
| Transit speed: based on module time minus delay time. |
| Passing speed: based on module time minus stop time. |
| Running speed: based on module time minus delay- and stop time. |

<table>
<thead>
<tr>
<th>Table 4.2.2 TRITAPT BUSSTOP PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 2032</td>
</tr>
<tr>
<td>Passengers in</td>
</tr>
<tr>
<td>Passengers out</td>
</tr>
<tr>
<td>Vehicle load</td>
</tr>
</tbody>
</table>
The input is also extended with the scheduled intervals, the norm- and utmost-capacity of the vehicles, relevant vehicle characteristics, interaction conditions with other transit lines for shared use by passengers, mutual relationships between interval time and stop time, between driver behaviour and stop time, between delay times and running times, between (late) departure moments at terminals and the running speed, also between driver behaviour and running speed, etc.

So all kinds of transit flow can now be imitated and the effects of various control strategies and tactics investigated. Some examples will be presented in the next chapters.

### 4.3 Some effects of irregularity in transit flow

The TRIPSIM module of TRICOPT allows to simulate in detail transit flow based on data, derived from services executed. Together with the characteristics of passenger demand at each stop, the norm-capacity and the utmost-capacity of the applied transit vehicles, the simulation model calculates the maximum admissible interval time as a function of a certain service level. A service level of 85% indicates, that in 85 percent of all cases the actual load of the vehicle does not exceed the norm-capacity. If the actual demand exceeds the utmost-capacity passengers have to wait till the next vehicle arrives.

In the model the number of boarding passengers per trip and per stop is calculated as:

\[
in_{n,j} = f(q_n, TIA_{n,j})
\]

\[
TIA_{n,j} = f(TIA_0, j, TTS(0-n), j)
\]

With

- \(i_{n,j}\) : the number of boarding passengers at stop "n" and trip "j"
- \(q_n\) : the random variable for passengers demand at stop "n"
- \(TIA_{n,j}\) : the random variable for the actual interval time for trip "j" at stop "n"
- \(TIA_0, j\) : the stochastic variable for the actual departure interval for trip (j) at the terminal stop "0"
- \(TTS(0-n), j\) : the standard deviation in section times between the terminal "0" to the stop "n" for trip "j".

In the model the number of the alighting passengers is calculated by a stop related percentage of the actual vehicle load.

An example can be given for a transversal transportation line with five sections:

- **section I**: boarding passengers only
- **section II**: twice as many boarding passengers as alighting ones
- **section III**: as many boarding passengers as alighting ones
- **section IV**: three times as many alighting passengers as boarding ones
- **section V**: only alighting passengers.

Average passengers demand: section I-III: 600/hr and section IV: 300/hr.
So hourly volumes are:

Diagram passenger demand/hour

For this study simulations are made for:
* variation coefficients for passenger demand (NPV) of 0, 10, 20, 30, 40, 50 and 60%  
* variation coefficients for departure intervals (TIV) at the terminal of 0, 10, 20, 30, 40, 50 and 60%  
* variation coefficients for the module times (TMV) of 0 and 15%.

Each simulation run consists of:
Norm-capacity of the vehicles: 120 passengers,  
Utmost-capacity of the vehicle: 150 passengers,  
Service level: 85%.
Results are presented for a line, with an 1 hour line time and a terminal time of zero seconds.

a. the effect of fluctuations in passenger demand  
   assumption: an absolute punctuality in transit flow.

Without fluctuations in passenger demand a service with an interval time of 480 sec satisfies the service level (3600(900/120)). Increasing fluctuations require a shorter interval time to fulfill the demand of the 85% service level. For a variation coefficient in passenger demand of 50% an interval time of 390 sec is required. This means an increase of the minimal required fleet size of about 25%.

b. the effect of fluctuations in transit flow  
   assumption: a uniform passenger demand.

The fluctuations are expressed by the mean value of the proportional regularity deviations (PRDM). The actual proportional regularity deviation (PRDA) is the quotient of the absolute value of the difference between the actual interval time (TIA) and the interval time according to the time table (TIT).
So PRDA=|TIA-TIT|/TIT. PRDA is calculated per trip at a stop; PRDM is the mean value for all trips at this stop.
Irregularity has two origins: variations in the departure moments at the terminal stop and variations in the module times. The simulation has been carried out for a variation coefficient of each module time (TMV) of 15% and a varying variation coefficient for the departure intervals at the terminal stop (TIV) from 0-50%. The simulation results show a large effect of irregularity in the transit flow on the minimal required fleet size. For an average proportional regularity deviation of 50%, an interval time of 270 sec is required to obtain the desired service level of 85%.

Without irregularity an interval time of 480 sec suffices, so the extra fleet size is about 75%.

In these calculations the effects have not yet been taken into account of the mutual relationship between interval times and stop times or between vehicle load and stop times.

c. both fluctuations are taken into account.

Simulations have been carried out for a variation coefficient in passenger demand of 40%, a variation coefficient for all module times of 15% and diverse variation coefficients for departure intervals at the terminal stop.

The simulation results show, that the additional contribution of the fluctuation in passenger demand on the effects of irregularity in transit flow is marginal.

To get information on the importance of some control strategies for transit flow, simulations have also been made to calculate the proportional effect of variations in the module times, assuming an uniform passenger demand. The results show that the variations of the departure intervals at the terminal stop have an essential contribution to the increase in the minimal required fleet size.
Finally, an efficient use of the rolling stock is benefitted by an equal vehicle load. As shown irregularities in transit flow (PRDM = varying) contribute much more to the variation coefficient of the vehicle load (BVV), than the fluctuations in the passengers demand (NPV = varying).

**4.4 Principles of operational control in transit flow**

Operational control is directed to the improvement of punctuality or regularity; it deals with minimizing the variations in transit flow. Without operational control, some vehicles are on time, others are late or early.

There is a mutual relationship; a vehicle, running behind schedule, has a big chance to handle more passengers than the average number, so it meets longer stopping times and it becomes slower and slower. Its successor gets less passengers, short stopping times and gains on the schedule until it clusters. As a result the following vehicle will probably also get more passengers and longer stopping times, so it runs behind schedule. And so on; irregularity in transit flow has been born. For the sake of regularity the services executed should be homogeneous.

As trams and buses operate amongst other traffic control, control measures should not jeopardize traffic safety conditions. So transit drivers cannot be rushed. If time tables are based on the average trip times, fifty percent of the vehicles run behind schedule and operational control is out of order.

So the primary control condition is a relevant feasibility level of the time tables, to enable most of the drivers to execute their services from terminal to terminal within the schedules route times (TST); the terminal time should be primarily regarded as a resting time for the drivers and can be used for absorbing flow variations in exceptional cases only.

Within a feasibility level of 85-90% almost any transit vehicle can be on time. Operational control has to provide that they do not run too early.

For this the line or route is divided into sections, with punctuality conditions for the boundary stops.

Two tactics can be distinguished: absolute punctuality control (APC), in which the vehicles are just in time at the section stops, and conditioned punctuality control (CPC), in which the vehicles are within a limited interval at the section stops.

For the APC tactic all sections have to be regarded independently; the scheduled route time must be calculated as the sum of the individual (85-90%) excess values of the section times. For reasonable variation coefficients of these section times the route times will increase considerably. So with the APC tactic punctuality is reached at the cost of the operational speed.
This disadvantage can be prevented with the CPC tactic; the control moments for the section stops are now a function of the 85-90% excess value of the route time and the feasibility condition for the following sections. For each section stop the 85-90% excess time value is calculated for the supplementary part of the route and this value is subtracted from the scheduled route time. These moments are called the passing moments. Transit vehicles, controlled by the passing moments have a likelihood of 85-90% to reach the terminal stop in time without a decreased operational speed.

Passing moments are directed to drivers, who run faster than scheduled. They slow down the fast transit vehicles to prevent the threatening longer interval times to its successor. Drivers should not pass a section stop before the passing moment concerned has expired. They will not be too late if they pass some time later! So for each section stop a certain limited time interval exists for the operational control, which depends on the fluctuations in transit flow at the following sections.

The difference between the CPC tactic and the APC tactic effects also the required fleet size; this difference is determined by the number of sections, into which the routes are divided and the variation coefficients of the respective section times. It can be stated that for increasing variation coefficients more controlled section stops are needed.

This difference (DNV) is:

\[
DNV = \frac{TST_{APC}}{TST_{CPC}}
\]

For \( n \) independent section times, with equal mean values (TTM) and standard deviations (TTS):

\[
DNV = \frac{TSM+u*TSS*n}{TSM+u*TTS*sqr(n)}
\]

TSS = TTS*sqr(n)

So: TTS = TSS/sqr(n)

\[
DNV = \frac{TSM+u*TSS*sqr(n)}{TSM+u*TSS}
\]

Say: TSS = c*TSM

Then: DNV = \frac{TSM(1+u*c*sqr(n))}{TSM(1+u*c)}

Say: \( u_{85} = 1.0 \)

Then: DNV = \frac{1+c*sqr(n)}{1+c}
With TST: scheduled route time
TSM: mean route time
TTM: mean section time
TSS: standard deviation of route times
TTS: standard deviation of section times.

TRICOPT works with the tactic of conditioned priority control (CPC) to reach the highest operational speed. So the concept of operational can be summarized with:
* detailed data collection of all sub-processes in the services executed.
* calculation of route times (from initial- to end terminal), with a feasibility level of 85%.
* the calculation of passing moments for section stops, based on the concept of supplementary sections; passing moments are derived from the scheduled route times minus the 85%-time-value for the total of the following sections.
* information to the drivers at section stops about their position to the passing moments, so that they can slow down if they run ahead of schedule.

### 4.5 Some applications

**The Rotterdam experiment**
The TRICOPT-concept was tested out in cooperation with the RET Transportation Company in Rotterdam. It concerned a tram line 5, with a length of 16 kilometers, 41 stops and a scheduled interval time of 5 minutes during peak hours; average route time 56 minutes, a feasibility level of the time table about 60%, and a proportional regularity deviation in the services executed of 40-70%.

Before situation

![Before situation](image)

Section stops with passing moments feasibility level = 60%

![Section stops with passing moments](image)

Passing moments at each stop feasibility level = 85%

![Passing moments at each stop](image)

Regularity deviations Simulation results

TRIPSIM simulations showed that within the existing time table a reduction of the regularity deviation could be reduced to 20-40% by dividing the route into 8 sections. For a situation with a time table, adjusted to a feasibility level of 85% and passing moments for each stop, a further reduction of the proportional regularity deviation could be possible to under 20%.
For a proper execution of the transit services each driver needs detailed information about the moment of departure from the terminal stop as well as about the passing moments at the section stops. Since there was no infrastructure available to transmit the passing moment information to the drivers, an interim solution is found by means of the passing disc. On this low cost device the passing moments of all trips of one vehicle are stored.

The driver adjusts the passing disc to the trip concerned by turning the inside disc. Special passing discs have been made for working days, for Saturdays and for Sundays. Also for summer and for winter periods. They have been in use since September 1981.

Before and after studies have been carried out to investigate the effects of the operational transit control.

### Proportional regularity deviations

**Discussion:**

The results of the Rotterdam experiment has proved to be satisfactory. The drivers reacted positively and sometimes gave their own interpretation to operational control. See for instance the increased irregularity during the evening peak at the end of the route. They were right, because during that period there is mainly outbound passengers demand, with hardly any boardings at the stops. So then the speed-strategy must have priority above regularity. Recent investigations have shown, that due to operational control the variation coefficient of the vehicle load decreased about 30-50%. The transportation company has adopted the TRICOPT-conception; because of the usefulness of the passing disc and the low costs of this device, the RET company decided to continue with this concept. Now the RET is introducing the passing disc on other transit lines, light rail as well as buses. This is a success on the one hand, but it has some disadvantages on the other hand. Being a one-way communication system, there is no (continuous) judgement, if drivers obey the passing moments.
And this has proved to be essential. Especially the supervision of the departure moments from the terminal stops is necessary, since drivers do not start exactly on the scheduled departing moments. So further research has been carried out to develop a management information system to supervise the daily performance of the transit system.

The Amsterdam experiment

In cooperation with the GVB transportation company of Amsterdam a management information system has been developed for the supervision of the operational transit qualities of a tram line. It concerns tram line 1, about 10 kilometers long, handling more than 50,000 passengers a day. During peak hours a tram departs from terminal Dijkstraapleyn (DCP) to Central Station (CST) every 4 minutes, and vice versa.

The last couple of years all tram cars are provided with VETAC-identification equipment, and at 10 section stops per route specific detectors and detector stations are installed, which pass the collected data about arrival- and departure moments to a central processor via transmission cables. The out-stations are provided with a processor, which receives the passing moments for the operational control from the central processor.

Passing moments are calculated for each day separately, split up into 18 different periods a day, according to the characteristics of transit flow and of passenger demand. Each controlled stop has a roadside display; a so called five-eye. The combinations of the burning lights indicates to the driver his position to the passing moments.

The collected data are daily processed by the TRIEVAL module of TRICOPT. This results in a quality review of all services executed per controlled stop. The review can be given for all trips during the whole day (see Table 4.5.1), for the trips per period of the day, for the trips per driver and for the individual trips.

This quality review is summarized in the quality index. It gives information to line managers at a glance. This index is a mark, indicating if the operational quality was satisfactory (> 6) or not (< 6).

The index is the average of the scores for punctuality of the departure moments at the terminal stops, the punctuality and regularity en-route and the operational style of the driver (slow/fast driving). A standard is formulated for each of these factors; the standard scores 6 pnts.

The indices for the aspects concerned are calculated as follows:

Punctuality: standard for TPDM is 1.5 min.

\[
Q_{IP} = 10 - \frac{TPDM - 0.5}{0.25}
\]

The same standard for punctuality deviations in the departure moments as en-route at the stops.
Regularity: standard for PRDM is 25%

\[ Q_{IR} = 10 - \frac{PRDM - 5}{5} \]

Driving time: standard = 1.5 min. deviation from the scheduled time

\[ Q_{ID} = 10 - \frac{TTMT - 0.5}{0.25} \]

So the quality review of 1987-04-06 of tram line 1 in Amsterdam is summarized with:

<table>
<thead>
<tr>
<th>Table 4.5.2 TRIEVAL QUALITY REVIEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram-line 1 Amsterdam. Date: 1987-04-06</td>
</tr>
<tr>
<td>Quality indices. Period: 05.44 - 24.08</td>
</tr>
<tr>
<td>aspect:</td>
</tr>
<tr>
<td>punct. deviations departure moments:</td>
</tr>
<tr>
<td>punct. deviations en route:</td>
</tr>
<tr>
<td>regularity deviations:</td>
</tr>
<tr>
<td>driving style (&lt; 0: too fast)</td>
</tr>
<tr>
<td>QUALITY INDEX TOTAL:</td>
</tr>
</tbody>
</table>

To analyse the origins of a low quality index the line manager has detailed information at his disposal about all relevant operational aspects of each trip. An example is presented in Table 4.5.3. The tables show that the operational qualities are as yet far from satisfactory.

However improvements have been recorded since the management information system has been put into action (see Table 4.5.4). Before it started in 1986 the mean punctuality deviation in the departure moments (TPDM) was about 2.50 min. and the mean proportional irregularity en-route about 50%.

Many factors play an important role in quality management, particularly the factors at a non-technical level (man-power management). This is beyond the reach of the traffic control engineer. The management information system however has proved to be a powerful tool for a continuous judgement of the operational transit qualities.
### Table 4.5.1 TRIEVAL QUALITY REVIEW

<table>
<thead>
<tr>
<th>Tram-line</th>
<th>Amsterdam.</th>
<th>Date: 1987-04-06</th>
<th>Total of all trips.</th>
<th>Period: 05.44 - 24.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop</td>
<td>PROM</td>
<td>TPDN</td>
<td>TPDS</td>
<td>TTN</td>
</tr>
<tr>
<td></td>
<td>centi-minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DGP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OVS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KPL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MGT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CST</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.5.3 TRIEVAL QUALITY REVIEW

<table>
<thead>
<tr>
<th>Tram-line</th>
<th>Amsterdam.</th>
<th>Date: 1987-04-06</th>
<th>Individual trips.</th>
<th>Period: 05.44 - 24.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip nr</td>
<td>PROM</td>
<td>TPD (min.)</td>
<td>Too fast</td>
<td>Quality index</td>
</tr>
<tr>
<td></td>
<td>en route</td>
<td>dep.</td>
<td>en route</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>35</td>
<td>1.18</td>
<td>0.89</td>
<td>0.35</td>
</tr>
<tr>
<td>103</td>
<td>56</td>
<td>1.15</td>
<td>1.65</td>
<td>2.17</td>
</tr>
<tr>
<td>105</td>
<td>37</td>
<td>1.18</td>
<td>1.59</td>
<td>2.92</td>
</tr>
<tr>
<td>106</td>
<td>15</td>
<td>0.59</td>
<td>1.99</td>
<td>4.58</td>
</tr>
<tr>
<td>107</td>
<td>53</td>
<td>0.64</td>
<td>1.09</td>
<td>1.91</td>
</tr>
<tr>
<td>108</td>
<td>20</td>
<td>1.01</td>
<td>2.83</td>
<td>4.74</td>
</tr>
<tr>
<td>111</td>
<td>51</td>
<td>1.82</td>
<td>2.83</td>
<td>10.1</td>
</tr>
<tr>
<td>113</td>
<td>39</td>
<td>0.81</td>
<td>1.76</td>
<td>2.63</td>
</tr>
<tr>
<td>117</td>
<td>28</td>
<td>1.35</td>
<td>1.32</td>
<td>2.84</td>
</tr>
<tr>
<td>119</td>
<td>51</td>
<td>1.37</td>
<td>1.83</td>
<td>8.70</td>
</tr>
<tr>
<td>120</td>
<td>31</td>
<td>1.49</td>
<td>1.90</td>
<td>3.88</td>
</tr>
<tr>
<td>121</td>
<td>36</td>
<td>1.26</td>
<td>1.17</td>
<td>1.17</td>
</tr>
<tr>
<td>122</td>
<td>25</td>
<td>1.12</td>
<td>1.24</td>
<td>2.84</td>
</tr>
<tr>
<td>123</td>
<td>48</td>
<td>1.89</td>
<td>1.67</td>
<td>3.58</td>
</tr>
<tr>
<td>127</td>
<td>42</td>
<td>1.32</td>
<td>1.66</td>
<td>1.84</td>
</tr>
</tbody>
</table>

**etc.**

| PROM en route | mean value over all stops. |
| TPD dep. | punctuality deviation terminal stop. |
| TPD en route | mean value over all stops. |

### Table 4.5.4 TRIEVAL QUALITY REVIEW

<table>
<thead>
<tr>
<th>Tram-line</th>
<th>Amsterdam.</th>
<th>Date: June 1986-June 1987</th>
<th>Comparison operational qualities.</th>
<th>average values/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPD departure</td>
<td>PROM en-route</td>
<td>QUALITY INDEX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>moments (min.)</td>
<td>(%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MON</td>
<td>1.55</td>
<td>1.35</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>TUE</td>
<td>1.62</td>
<td>1.35</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>WED</td>
<td>1.56</td>
<td>1.31</td>
<td>41</td>
<td>32</td>
</tr>
<tr>
<td>THU</td>
<td>1.70</td>
<td>1.33</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>FRI</td>
<td>1.77</td>
<td>1.27</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>M-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAT</td>
<td>1.68</td>
<td>1.48</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>SUN</td>
<td>1.67</td>
<td>1.39</td>
<td>23</td>
<td>19</td>
</tr>
</tbody>
</table>

**Table**

| PROM : Proportional Regularity Deviation Mean. |
| TPDN : Time Punctuality Deviation Mean. |
| TPDS : Time Punctuality Deviation Standard-deviation. |
| TTN : Time Section Mean. |
| TTS : Time Section Standard-deviation. |
| TTNT : Totalized Mean Section Times. |
| TTST : Standard-deviation Totalized Section Times. |
4.6 Further research

a. Integration of a tram line into the metro system

Transportation policies in Amsterdam are formulated to improve the tram services. One of the options is a shared use of parts of the metro tube by a (new) express tram line: the double rail project. Because of alterations in the master plan for the metro system, the tube has much unused capacity; so it is very attractive to use it for the light rail system. On the other hand the metro exploitation may not be disturbed by the tram.

<table>
<thead>
<tr>
<th>section</th>
<th>length (km)</th>
<th>nr. of stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>tram</td>
<td>13</td>
</tr>
<tr>
<td>II</td>
<td>metro</td>
<td>6</td>
</tr>
<tr>
<td>III</td>
<td>metro</td>
<td>6</td>
</tr>
<tr>
<td>IV</td>
<td>metro (2 x)</td>
<td>2</td>
</tr>
<tr>
<td>V</td>
<td>tram + metro</td>
<td>5</td>
</tr>
</tbody>
</table>

During peak hours both the metro lines and the tram line have a scheduled interval time of 450 seconds. So at section V three vehicles will pass within a cycle of 450 seconds. The capacity of the tram cars is half that of the metro cars. To avoid overloading, tram cars should run with the shortest possible interval behind a metro car. The minimum interval corresponds with the block time, which is 50 seconds at the insertion point increasing to 110 seconds at the end of section V. So there is a time range of 60 seconds. By an optimal positioning of the insertion moment of the trams, there is also a small time range of 20 seconds for late vehicles. Hence, the trams should start just before the insertion point within an interval of maximum 80 seconds around the scheduled insertion moment.

In principle there is a simple solution by considering the last section stop before the insertion point as a kind of a terminal and a scheduling of the tram line in such a way, that all vehicles arrive before the insertion moment. However it should be an express tram line, so waiting times at that section stop should not be too long. Thus the first question was the prediction of these waiting times.
The future express tram line is modelled by corresponding sections of existing tram lines, of which data are collected of the services executed; together with the expected passenger demand, TRIPSIM simulations have been carried out.

![Graph showing variations in departure moments at section stops.](image)

Variations in departure moments at section stops.

![Probability distributions of arrival moments at insertion point.](image)

Probability distributions of arrival moments at insertion point.

The results show that without operational control (see variant 1) only a third of the vehicles are expected to arrive within the given time range, another third would be too early, and a third too late. The last about 13% of the vehicles are so late that the other 20% are able to continue before the consecutive metro car but are expected to become overloaded and hinder the metro exploitation.
To avoid this by a further repositioning of the tram schedule results in still longer waiting times for the other vehicles. This was not acceptable, so the next research question was, what will be the effect of operational control.

Variant 3 represents the strategy of departure moment control at the initial tram terminal (all vehicles start exactly on time), together with operational control at the section stops, slowing down vehicles running ahead of schedule; variant 2 is the strategy of departure moment control only, and variant 4 the strategy of operational control and a standard deviation in the departure moments, in conformity with the existing metro operation in Amsterdam.

The results show that due to the operational control almost all vehicles will arrive within the time range available. Further arrangements will be made to solve also the problems at a non-technical level (man-power management).

b. Public transport as a quality product

If public transport is to play a role of importance (again) it has to compete with private transport. So transportation companies begin to understand that they no longer operate in a sellers market, with a take-it-or-leave-it mentality, but a buyers market, in which the quality demands of the consumers are decisive.

In cooperation with the GVU-transportation company of Utrecht (300,000 inh.) a research project has started for a comprehensive improvement of the operational transit qualities.

The objective is to introduce and maintain regularity and punctuality in all the services executed in such a way that the transportation company can face the nineties with the motto "Public transport is a quality product!"

The transport system should be so reliable that this can be used in advertising campaigns and give guarantees to the customers. The device should be:

"If you use the bus system in Utrecht and you arrive at the scheduled time at our bus stops then:
* you will never miss the bus
* your bus will usually arrive within one minute, and
* you will not have to wait more than three minutes
* if not ... money back".

or:

* "during off-peak hours you will always have a seat, and
* in the peak hours the bus will not be overloaded,
* at transfer stops, your consecutive bus is usually waiting
* if not ... please phone us!"

For this challenging perspective a lot of research is needed to develop an adequate management- and information system, to control all quality aspects in transit flow day by day.

Relevant data should be collected to predict very accurately by means of simulations, what type of measures should be taken and what kind of control strategies should be put into effect.

The GVU-transportation company has already taken the decision for a step by step approach.

Counting systems are already introduced, so it is possible to determine per route or section the passenger load of the vehicles and the number of passengers boarding or alighting per stop.
The next step will be a vehicle based communication system, which provides the options for the various types of data to be collected and delivered to other parts of the system. Based on their experience with VETAG Philips designed a new inductive communication system: VECOM, which allows for transfer of a vast amount of data from vehicle to road side and vice versa.

So new possibilities for the operational control come within reach. The traffic control engineers can use that to investigate various characteristics to improve (simulation) models, to integrate the operation control with traffic control and contribute to the success of operational qualities in transit flow.

Acknowledgements:
TRICOPT has been developed in close cooperation with Ir.Th.H.J. Muller of the Transportation Research Laboratory of the Delft University of Technology. He is responsible for the whole software package, and without his knowledge the ideas of TRICOPT could not have been put into effect.
The researchers are grateful to the transportation companies of Rotterdam (RET), Amsterdam (GVB), Westnederland, Gent (MIVG), Utrecht (GVU) and Brussels (MIVB) for the possibility to put into operation the various aspects of the TRICOPT concept.
Verwijderd uit catalogus
TU Delft Library