Evaluation of Travel Time Estimation Techniques

Master Thesis

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Preface

This report presents the master's thesis work I completed at the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering at the Delft University of Technology. The master's thesis study is the final project at the end of the graduate study. Through this study the student should demonstrate that he or she is capable of working as a traffic engineer. This means he must be able to apply skills and knowledge he learned during his education.

The objective of this master's thesis is to analyse, evaluate, and compare travel time estimation techniques developed within the European project DACCORD. The report is self-contained, it can be read independent from the DACCORD deliverables that describe the estimation techniques in detail.

I would like to thank the members of my thesis committee for their suggestions and comments on the preceding versions of this report.

Remmelt Thijs
Summary

The objective of this study is to evaluate travel time estimation techniques. An application area of these techniques is motorway traffic control. Several of such travel time estimation techniques are developed and applied within the DACCORD project of the European Telematics Application Programme (TAP). DACCORD is an acronym for Development and Application of Co-ordinated Control of Corridors. The relative performance of these techniques and their behaviour under different circumstances is unknown.

The evaluation of these estimation techniques is based on two approaches.
- Qualitative analysis of estimation techniques
- Simulation based quantitative analysis of estimation techniques

The functional requirements and user-requirements of travel time estimation techniques in motorway traffic control applications are defined in order to assess on the suitability of the various estimation techniques.

The qualitative analysis involves analysing the various estimation techniques for the way in which these techniques work, and the way in which techniques behave under changing flow conditions.

The simulation based quantitative analysis focuses on the quantitative performance of the techniques under different conditions. The micro-simulation model FOSIM is used to generate traffic data and to simulate various conditions. The estimation techniques are implemented in the mathematical programming language Matlab. The results of the estimation techniques based on the generated traffic data were compared to the simulated travel time by a number of performance indicators. Both the absolute error of estimates compared to the simulated travel time and the relative error related to errors of other techniques give insight into the performance of the estimation techniques and into the effect of various conditions.

Based on the qualitative analysis it is concluded that all estimation techniques are based on the assumption that speed is constant over a section, and that vehicle trajectories are parallel. Moreover, the techniques assume that the arithmetic time-mean speed as computed at induction loop detectors equals the harmonic time-mean speed. This is likely to introduce an bias, especially with changing flow conditions such as congestion building or resolving. The computed travel time underestimates the real travel time.

Based on the qualitative and quantitative analyses the following conclusions are drawn:
- With a constant flow regime all techniques follow the free-flow and congestion situation relatively accurate. However, variations are higher under congestion than under free-flow conditions.
- With a changing flow regime all techniques follow the simulated TT with a lag during congestion building. The techniques follow quite accurately during congestion resolving.
- According to the qualitative analysis the dynamic travel time estimator is superior to the other techniques. Simulation experiments show that this technique displays
the smallest lag and results in the lowest error of estimate. However, the dynamic travel time is an off-line estimation technique and therefore only can be used for off-line tasks such as planning and evaluation.

- The instantaneous network level travel time estimator performs well in the qualitative and quantitative analyses. It can be computed using a simple and direct procedure and is a suitable tool for control applications.
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1. Introduction

The objective of this study is to evaluate travel time estimation techniques. One application area of these techniques is that of motorway traffic control. Several of these techniques are developed and applied within the DACCORD project of the European Telematics Application Programme (TAP). DACCORD is an acronym for Development and Application of Co-ordinated Control of Corridors. However, the 'relative' performance of these techniques is unknown, and little is known about how these techniques behave under different circumstances, such as different time-dependent, and location-dependent conditions.

The subject of this report is the evaluation of these estimation techniques, based on two approaches.
- Qualitative analysis of estimation techniques, in which the strengths and weaknesses of the techniques is identified.
- Simulation based quantitative analysis of estimation techniques, in which the numerical performance based on simulation is assessed.

Chapter 2 discusses the subject, the objective, and the approach of the evaluation study in more detail. The evaluation approach is also considered in chapter two. Chapter three describes the context in which the estimation techniques are used to identify requirements for these techniques. Chapter four and five, uses the two approaches mentioned above to analyse the estimation techniques. Chapter four analyses the techniques based on literature, and only in qualitative terms. Chapter five analyses the techniques by means of simulation exercises. These results also include quantitative terms. Chapter six discusses some results based on analyses with empirical data. Chapter seven summarises the conclusions of the three preceding chapters and presents the final conclusions and recommendations.
2. Subject and approach of the evaluation study

This chapter identifies the objectives of this evaluation study. First, the context of the evaluation of travel time estimation techniques is described in section 2.1, and section 2.2. Then, the subject and objective of the study are defined in detail in the sections 2.3, and 2.4 respectively. Section 2.5 identifies the various estimation techniques within DACCORD, and section 2.6 describes the approach of the evaluation study.

2.1 Context: DACCORD project

DACCORD is a European project, that is part of the Transport Sector of the Telematics Application Research and Development Programme. The DACCORD project is concerned with the development and application of co-ordinated control of corridors and networks.

Design and application of co-ordinated and integrated control tools within the DACCORD project can be seen as a continuation from previous research done in the DRIVE I and DRIVE II programmes. For the practical application-part, the DACCORD project builds upon results of the CHRISTIANE, DYNA (integrated and co-ordinated modelling and forecasting tools) and EUROCOR (integrated and co-ordinated modelling tools and implementation concepts) projects.

The overall objective of the DACCORD project is to design, implement, demonstrate, and evaluate an advanced dynamic traffic management system for integrated (i.e. network-wide) and co-ordinated (co-operative and simultaneous consideration of diverse traffic control measures) control of corridors of interurban motorways. Additionally, an objective is to further develop an open system architecture for interurban traffic management.

In order to validate the measures developed and proposed, the DACCORD project will be verified and demonstrated in three major test-sites:

- the Amsterdam network;
- the Paris network, including the ringroad and the surrounding urban network;
- the Brescia-Venice motorway.

The project has a time horizon of three years. In January 1998 the final year has started. In this year the demonstration of the applications will be performed, and the final evaluation report will be prepared.

An important derived objective of the DACCORD project is the evaluation of different on-line short-term forecasting techniques of flows and speeds in order to predict travel times, by means of comparison between estimated and observed values.

2.2 Dynamic traffic management system

Dynamic Traffic Management Systems (DTMS) are on-line systems that provide support for traffic management, partly by providing support to traffic operators, and partly by carrying out traffic management tasks in an automated manner. The basic functional elements of DTM application distinguished within the DACCORD project are shown in Figure 2.1.
The process consist of the following five main functions:

1. **Data collection**: this function refers to the collection of dynamic data (traffic, road surface and ambient conditions). These data are current measurements provided by induction-loops, video-cameras etc. In the future this data may be provided by probe vehicles;

2. **Data cleaning**: the integrated process of the detection of false and missing data, and the reconstruction and correction of these data if necessary.

3. **Traffic state estimation**: this function refers to the estimation of traffic parameters both on section level as well as network level with respect to the current traffic situation. At section level the estimation of for example in- and outflows, turning fractions, section capacities, speed/density relations, instantaneous travel times, and queue lengths is included. At network level origin-destination-matrices are estimated;

4. **Traffic state prediction**: the purpose of this function is to predict the short-term future traffic state at both section and network level based on the estimated current (section and network) state;

5. **Integrated and co-ordinated control**: this function refers to the integration and co-ordination of the different dynamic traffic management applications based on the predicted traffic state and given control objectives.

### 2.3 Subject of the study

Within the framework of the DACCORD project, different travel time estimation techniques have been developed. These techniques have been developed as a tool within various Dynamic Traffic Management System (DTMS) applications. So far, no evaluation studies have been performed on the comparative performance of these estimation techniques.

The performance of the various estimation techniques is assessed separately. With the assessment the control system is not taken into account: the effect of a delay in time for data collection, travel time computation, and visualising is not part of the evaluation.
The performances of travel time estimation techniques are likely to differ on various time-dependent and location-dependent conditions.

Time-dependent conditions are:
- flow regime (free-flow, near capacity, and congestion),
- ambient conditions (daylight, twilight, and night),
- weather conditions (clear, fog, rain, snow, storm),
- presence of signals of control applications,
- incidents and accidents.

Location-dependent conditions are:
- lengths of section, divided by the induction loop lay-out,
- the extent in which discontinuities in the road layout are present.

A remark has to be made on the flow-regime. Congestion is not only time-dependent, it also depends on the extent to which discontinuities in the road layout are present.

2.4 Objectives of the study

The objectives of the study is to assess the performance of the travel time estimation techniques developed within DACCORD, under different time-dependent and location-dependent conditions.

This study should lead to two types of conclusions:

Conclusions based on qualitative analysis
- Qualitative conclusions on the suitability of the various estimation techniques for control applications.
- Qualitative conclusions on the sensitivity for conditions which could occur within the control systems or within the traffic process.

Conclusions based on quantitative analysis
- Quantitative conclusions on the absolute and relative performance of the estimation techniques under various conditions.

2.5 Categorisation of estimation techniques

In this section the various estimation techniques within the DACCORD project are characterised according to the difference in section level versus network level.

Section level versus network level
The DTMS applications calculate the travel time of a route is calculated. Within the DACCORD project this travel time equals the network-level travel time (NLTT). At first sights the term travel time seems to be well defined by itself, but when used in practise a more detailed definition is required. Here the concept will be explained, and the problem will be specified more clearly.
Definition of Network-Level Travel Time

The Network-Level Travel Time (NLTT) at time moment \( t \) between point A and point B is the expected amount of time required for a traveller departing from point A at time \( t \) to travel to point B, when travelling through the network over a pre-defined path A-B.

Time moment \( t \) may be any time moment, point A and B can be any location in the network, path A-B can be any feasible route through the network leading from point A to point B. By definition account is taken of prevailing traffic conditions and other influences on the travel time.

With the assumption that the traffic conditions (speed, flow and density) are stationary during a time period and homogeneous across a section, time can be discretised in periods, while space is discretised in road-sections. The realism of this approximation depends on the duration of a period and the length of a section and the variability of the traffic conditions. Based on the discretisation in time and space a definition of a section level travel time can be formulated.

Definition of Section-Level Travel Time

The Section-Level Travel Time (SLTT) is defined as the expected time it takes to traverse a road section starting at the beginning of period \( p \).

These definitions will be discussed in more detail in section 4.2.

Categorisation of estimation techniques

The estimation techniques applied in the DACCORD project are categorised in section level and network level. In DACCORD different types of SLTT estimators are applied. An overview is given in Table 2.1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Travel time based on on-line estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLTT</td>
<td></td>
</tr>
<tr>
<td>Short road sections</td>
<td>Instantaneous section-level travel time estimator</td>
</tr>
<tr>
<td></td>
<td>Travel time estimator for short road sections</td>
</tr>
<tr>
<td>Long road sections</td>
<td>Travel time estimator for long road sections (mass balance)</td>
</tr>
</tbody>
</table>

Table 2.1: DACCORD SLTT estimation techniques

NLTT estimators use SLTT estimators as their inputs. These SLTT's can be aggregated to NLTT estimators in different ways. Table 2.2 shows the on-line aggregation techniques that are used for this purpose in DACCORD.

<table>
<thead>
<tr>
<th>Level</th>
<th>Travel time based on on-line estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLTT based on SLTT</td>
<td>Instantaneous travel time estimator based on SLTT</td>
</tr>
<tr>
<td></td>
<td>Weighted instantaneous travel time estimator based on SLTT</td>
</tr>
</tbody>
</table>

Table 2.2: DACCORD NLTT estimation techniques

---

1 This definition was adapted from section 4.1 of Deliverable D05.2 (Grol, 1997)
Combining Table 2.1 and Table 2.2 leads to a matrix of on-line NLTT estimators. Table 2.3 shows which of these techniques are implemented at which site.

The techniques are implemented at the different test sites according to Table 2.3.

<table>
<thead>
<tr>
<th></th>
<th>Instantaneous NLTT</th>
<th>Weighted instantaneous NLTT</th>
<th>Dynamic NLTT¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous SLTT</td>
<td>NL, FR², IT</td>
<td>NL, FR³</td>
<td>NL, FR, IT</td>
</tr>
<tr>
<td>Short SLTT</td>
<td>NL⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long SLTT</td>
<td>NL⁵</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Estimation techniques at DACCORD sites

The abbreviations NL, FR, IT stand for the following test sites:
- NL: The Amsterdam network in the Netherlands,
- FR: The Paris network in France,
- IT: The Brescia-Venice motorway in Italy.

2.6 Approach of the study

To assess the performance of the estimation techniques both qualitatively and quantitatively the master thesis was split up in two parts:
- qualitative analysis and evaluation
- simulation based quantitative analysis and evaluation

Qualitative analysis
The qualitative analysis of estimation techniques is performed by analysing the specifications of the techniques, to identify the way in which techniques work. With this result, the sensitivity for conditions which could occur within the control system or traffic system can be derived.

Quantitative analysis
The quantitative analysis of estimation techniques is performed by analysing the evaluation results of the estimated travel times compared to the computed travel times of a simulation model. Some extra evaluation was performed based on empirical data, but this empirical evaluation was very limited.

¹ The dynamic NLTT estimator is an off-line technique. A definition of the dynamic NLTT will be given in section 4.7.3.
² The instantaneous SLTT estimator is implemented in the Dutch and Italian test site. The French test site estimates the average speed in a similar way out of the density and intensity.
³ The weighted instantaneous NLTT estimator is implemented in the Dutch test site. The French test site estimates the average speed in a similar way out of the density and intensity.
⁴ The short road section travel time is not implemented at one of the test sites. The Dutch test site uses several elements of the short road section travel time for the instantaneous travel time. It is implemented at a Dutch test site, not part of the DACCORD project.
⁵ The long road section travel time is not implemented at one of the test sites. In the Dutch site several elements of the long road section travel time are used.
Evaluation of travel time estimation techniques

Subject and approach of the evaluation study
3. Requirements for travel time estimation techniques

Requirements for travel time estimation techniques are necessary to be able to conclude on the suitability for travel time estimation techniques for control applications, and to be able to conclude on the sensitivity for conditions which occur in traffic control systems. Requirements are assessed based on the functional architecture in section 3.1 and the user-requirements in section 3.2. Section 3.3 presents the conclusions on the requirements for travel time estimation techniques.

3.1 Functional requirements

This chapter describes the process within a central traffic management system. A behavioural model is used to split up this complex in smaller functions and processes. Section 3.1.1 describes the overall functional architecture of the Central Traffic Management System of which state estimation is a part. In the sections 3.1.2 to 3.1.6 the functions of the CTMS are described briefly.

3.1.1 Functional architecture

Figure 3.1 describes the CTMS by showing the so-called behavioural model.

![Behavioural model of the CTMS](image)

Each of the functions will be further decomposed into elementary (sub) functions in the ensuing sections. We emphasise that this functional decomposition is restricted to a rather global level.

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1 This section is mainly based on section 7.2 of Deliverable D04.2 (Hoogendoorn-Lanser, 1996)
The function of estimation techniques is to provide, based on cleaned traffic data, the estimated traffic state to the prediction techniques and to the traffic control system.

3.1.2 Data Collection
The first main function in the Functional Architecture is Data Collection. The function Data Collection is referred to as TRAC-monitoring (Traffic, Road and Ambient Conditions) in the CORD function list [CORD, 1996], and comprises:
- Traffic State Monitoring; monitoring and/or computation of traffic flow indicators.
- Road Surface Monitoring; monitoring and provision of the road surface condition.
- Ambient Conditions Monitoring; the monitoring and provision of weather and other ambient condition data.

Some DACCORD estimation techniques should be able to function on data of intensities only, without road surface monitoring or ambient conditions monitoring data, since, these applications are not always implemented.

3.1.3 Data cleaning
The second main decisive function in the functional architecture is data cleaning. The reliability of the final control strategies depends on the level of accuracy of the collected traffic state data (as a part of the TRAC data). One of the objectives in the DACCORD project is the qualification of the collected data (in real time): detection of the missing and false traffic state data and the reconstruction and correction of these data. In currently operational data cleaning systems these three activities do not take place in a consecutive order, but are part of an integrated process.
- Data checking; scanning of the traffic data for missing, and false data.
- Data reconstruction; completing the collected traffic data using e.g. databases or smoothing.
- Data correction; correcting the collected traffic data using e.g. databases or smoothing.

All estimation techniques should be able to keep on performing adequately also if a gap in data occurs.

3.1.4 Traffic state estimation
The third main function in the Functional Architecture of the Central Traffic Management System is the function ‘Traffic State Estimation’. This function takes the output of the previous function, Cleaned TRAC Data, and estimates the current traffic state (e.g. flows, speeds, capacities, performance parameters, congestion) on the road sections of the road network in the area controlled by the CTMS. Furthermore, the function State Estimation requires a (static) description of the road network (called Network Topology Description), current modifications of this static network description (called the Dynamic Network Data), as well as (predicted) information regarding the traffic state in the adjacent road networks (called Predicted Traffic State).

The function Estimate Traffic State produces output, which is referred to as Estimated Traffic State. In the Functional Architecture, a distinction is made between Section State Estimation and Network State Estimation.
The sub-function Estimate Section State comprises a large set of sub-functions. Each of these sub-functions is dedicated to estimate one specific type of (section oriented) traffic state information. Among these are:

- **Estimate Inflow** (this concerns the volume of traffic entering the road network controlled by the CTMS, at all possible entries);
- **Estimate Turning Fractions** (this concerns the fraction of traffic exiting the road network controlled by the CTMS, at all possible exits);
- **Estimate Speed Density Relation** (this concerns the relationship that indicates the traffic performance of a particular road section);
- **Estimate Capacity**;
- **Detect Congestion**;
- **Estimate Queue Length** (whenever congestion has occurred on a road section);
- **Estimate Travel Time**.

This subdivision of the function Estimate Section State into sub-functions is depicted in Figure 3.2.

Some DACCORD estimation techniques should be able to function on cleaned traffic data only, without data from extra sub functions, such as capacity estimator, speed-density relationship estimator, since these applications are not always implemented.

### 3.1.5 Traffic state prediction

The purpose of the sub-function Predict Traffic State is to predict the short-term traffic state at both section and network level based on the estimated (section and network) state, using the cleaned TRAC data. The output of this sub-function is the future state of the traffic on the (sections of the) road network controlled by the CTMS. Several actions are performed in this sub-function:

- prediction of inflows, based on the historic inflows and the estimated inflows;
Evaluation of travel time estimation techniques

- prediction of turning fractions, based on the historic turning fractions and the estimated turning fractions;
- prediction of speeds and flow rates, based on the predicted inflows and turning fractions;
- prediction of travel times, directly derived from the predicted speeds and flows.

3.1.6 Integrated and co-ordinated control

Integrated and coordinated control of motorway traffic is the last function. The control strategies can be grouped under the following headings according to the geographical extent of their application.

- **Point control** strategies address a particular location of the motorway network.
- **Link control** strategies address a motorway stretch that may include several on-ramps and off-ramps.
- **Network control** strategies address a whole (or a part of a) motorway network that includes several motorway stretches.

The point control measure within the DACCORD project is:

- **Motorway-to-motorway control**. Its objectives are to improve traffic conditions at motorway junctions.

The link control measure within the DACCORD project are:

- **Speed recommendation**. Its objective is to improve traffic conditions on motorway stretches via traffic flow homogenisation.
- **Lane use**. Its objective is to improve traffic safety and merging behaviour in case of lane-blocking incidents.
- **Co-ordinated ramp metering**. Its objective is to co-ordinate ramp meters installed along a motorway stretch towards a common objective so as to promote synergetic effects and avoid antagonistic actions.

The motorway network control measure within the DACCORD project are:

- **Network level co-ordinated ramp metering**. Its objective is to improve motorway network traffic conditions via generalised, co-ordinated ramp metering and motorway-to-motorway control actions.
- **Traffic information display**: Its objective is to extend and improve existing real-time traffic information systems to improve motorway network traffic conditions.
- **Advanced routing control**: Its objective is to improve utilisation of motorway network infrastructure via information and route recommendation strategies.
- **Integrated motorway network control**: Its objective is to exploit the synergetic effects from application of various control measures and to avoid antagonistic actions in large-scale motorway networks.

With respect to control the following requirements for estimation techniques can be derived:

- For point control only the estimated state of a small section is needed
- For link control the estimated state of a link is needed
- For network control the estimated state of a several links is needed

---

1 This section is mainly based on section 2.2.1 of Deliverable D06.1 (Kotsiales, 1997)
3.2 User-requirements

This section identifies the user-requirements set to the estimation techniques. First, the users and their requirements are identified, which are translated towards estimation techniques.

3.2.1 Users of DTM applications

This section addresses the different identified user groups based on their area size, and their time horizon of their involvement. The perspective of each user group is described and the main objectives of the user groups are mentioned as far as relevant for state estimation.

Policy makers
Public authorities (either local, regional, national, or inter-national). The objectives of the policy maker have a long-term perspective. The general aim is to provide a cost-effective, safe and efficient transportation system.

Network operators
The network operator is the manager of the network. Their main objective, having a medium term perspective, is to translate the policies into practical plans and study programmes, and thus provide a cost-effective, safe and efficient transportation system.

System operators
The system operators are the crew managing the traffic on a day-to-day basis at the distinct sites. Their objectives are the day-to-day running of a safe and effective system, using the facilities provided by the network operators.

Drivers
The driver is the individual road-users affected by the application. Their objectives are to travel through the network safely, and effectively in time.

Non-users or victims
The non-users or victims of the infrastructural facilities implemented comprise among others the residents living in the vicinity of a road, and the society as a whole. Their objectives are to have a minimum of influence in noise level, and pollution level.

From the perspective of traffic state estimation the system operators and drivers constitute the relevant user groups.

3.2.2 User Requirements of DTMS

All users identified have objectives, and means to reach those objectives. The means to reach the users' objectives range from controlling day-to-day traffic flow using dynamic traffic management measures, (short-term), introduction of dynamic traffic management facilities (medium-term), or the allocation of resources to research and development or drawing up general traffic plans (long-term). Table 3.1 summarises the results of the analysis with respect to user-requirements.

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1 This section is mainly based on section 2.2 of Deliverable D10.2 (Hoogendoorn, 1996)
2 This section is mainly based on section 2.3.1 of Deliverable D10.2 (Hoogendoorn, 1996)
### 3.2.3 Requirements for estimation techniques

The requirements for travel time estimation techniques are identified by a more detailed specification of the requirements for the whole traffic control system with concentration on travel time estimation techniques.

Advanced Transport Telematics applications are designed and implemented in order to achieve some sort of objective. Application objectives range from "improving the safety of the road-users" and "decreasing pollution level and fuel consumption" to "improving the efficient use of the infrastructure" and "providing decision-making assistance to road users".

<table>
<thead>
<tr>
<th>Identified Users (DACCORD independent)</th>
<th>Perspective and Area-Size</th>
<th>General Needs and Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy Makers</td>
<td>long term (years, decades) large area (regional)</td>
<td>• enforcement of co-ordinated control to the extent that it positively influences traffic conditions&lt;br&gt;• serious considerations for the opinion of directly affected users&lt;br&gt;• suitable concertation mechanisms for early resolution of regional or administrative conflicts&lt;br&gt;• insight in various concerns regarding the European Added Value of the DACCORD programme (see notes below), regarding:&lt;br&gt;  • extendibility&lt;br&gt;  • flexibility&lt;br&gt;  • transferability</td>
</tr>
<tr>
<td>Network Operators</td>
<td>Medium term (months, years) Network size area (regional)</td>
<td>• knowledge regarding probable impact of candidate control measures (results of assessment, verification, and demonstration of integrated and co-ordinated control systems)&lt;br&gt;• insight in various technical and organisational aspects of control measures, such as:&lt;br&gt;  • maintenance needs&lt;br&gt;  • reliability and vulnerability of control installations&lt;br&gt;  • system architecture&lt;br&gt;  • qualification of operating staff&lt;br&gt;  • extensibility&lt;br&gt;  • flexibility</td>
</tr>
<tr>
<td>System Operators</td>
<td>short term (days) corridor-size area (local)</td>
<td>• streamlining operations and minimising mutual interference in an automatic, reliable and efficient way&lt;br&gt;• harmonisation of pursued control objectives&lt;br&gt;• higher efficiency in meeting control objectives&lt;br&gt;• ergonomically efficient and flexible Human-Machine Interface, enabling direct intervention whenever necessary&lt;br&gt;• determination of precise set of rules regulating conditions for operator intervention&lt;br&gt;• minimisation of violations or other kinds of incorrect behaviour of drivers</td>
</tr>
<tr>
<td>Drivers</td>
<td>very short-term (a moment) journey-size (route between origin and destination)</td>
<td>• individual efficiency (small travel times), and safety&lt;br&gt;• instruction concerning necessity of DTM applications&lt;br&gt;• information enabling optimisation of individual route and lowering personal stress</td>
</tr>
<tr>
<td>Victims</td>
<td>very short-term (a moment)</td>
<td>• improving environmental conditions (noise- and pollution level)</td>
</tr>
</tbody>
</table>

Table 3.1: Identified Users and User-Needs
In general, application objectives refer to one or more specific user group. In this study, the identified user-groups are the direct users, the system operators at the Traffic Control Centres, and the road-users. Other identified users are not directly involved with the quality of estimation techniques.

<table>
<thead>
<tr>
<th>User</th>
<th>Application Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>System operator</td>
<td>1. provision of reliable measurements for operators or subsystems</td>
</tr>
<tr>
<td></td>
<td>2. improving quality and/or quantity of measurements for operators or subsystems</td>
</tr>
<tr>
<td></td>
<td>3. improving quality of information of current or predicted traffic (network) state for</td>
</tr>
<tr>
<td></td>
<td>operators or subsystems</td>
</tr>
<tr>
<td></td>
<td>4. provision of assistance for decision-making by road-operators</td>
</tr>
<tr>
<td></td>
<td>5. improving effective network-capacity, and the efficient use of infrastructural facilities</td>
</tr>
<tr>
<td>Road-User</td>
<td>6. decreasing travel time losses due to congestion</td>
</tr>
<tr>
<td></td>
<td>7. improvement in assisting road-users (e.g. by means of improved quality and quantity</td>
</tr>
<tr>
<td></td>
<td>of information provision)</td>
</tr>
<tr>
<td></td>
<td>8. improving the safety of the road-users</td>
</tr>
<tr>
<td></td>
<td>9. improving the reliability of the systems (e.g. decreasing the variability of travel-times)</td>
</tr>
</tbody>
</table>

Table 3.2: General Application Objectives and User-Dependencies

All the application objectives set requirements to the estimation techniques concerning the quality of the outcome of the estimation techniques. This means that the following requirements are set to the estimation techniques.

- Provide accurate estimations of travel time under all possible time-dependent and location-dependent conditions. These conditions are:

  **Time-dependent conditions:**
  
  - flow regime (free-flow, near capacity or congested),
  - ambient conditions (daylight, twilight, night),
  - weather conditions (clear, fog, rain, snow, storm),
  - incidents and accidents.

  **Location-dependent conditions**
  
  - road lay-out (1: continuous freeway segment, 2: regular freeway segment, 3: heavily disturbed freeway segment).

- Provide accurate estimations of travel time concerning changes in traffic flow conditions (congestion building, resolving) to improve traffic safety.
- Provide the estimations of travel time fast enough to be useful for both the operator as the road-user.

In the following analyses of the techniques these requirements will be used as evaluation criteria.
3.3 Conclusions on requirements for travel time estimation

The following requirements apply to the estimation techniques:

**Functional requirements**
- Travel time estimation techniques should be able to function only using data of intensities without road surface monitoring or ambient conditions monitoring data, since these applications are not always implemented.
- All estimation techniques should be able to cope with missing and false data.
- Travel time estimation techniques should be able to function using cleaned traffic data without data from extra sub functions, such as capacity estimator, speed-density relationship estimator, since these applications are not always implemented.
- For point control the estimated travel time of a small section is needed
- For link control the estimated travel time of a link is needed
- For network control the estimated travel time of several links is needed

**User-requirements**
- Provide accurate estimations of travel time under all possible time-dependent and location-dependent conditions. These conditions are:
  
  **Time-dependent conditions:**
  - flow regime (free-flow, near capacity or congested),
  - ambient conditions (daylight, twilight, night),
  - weather conditions (clear, fog, rain, snow, storm),
  - incidents and accidents.

  **Location-dependent conditions**
  - road lay-out (1: continuous freeway segment, 2: regular freeway segment, 3: heavily disturbed freeway segment).

- Provide accurate estimations of travel time concerning changes in traffic flow conditions (congestion building, resolving) to improve traffic safety.
- Provide the estimations of travel time fast enough to be useful for both the operator as the road-user.
4. **Qualitative analysis**

This chapter presents a qualitative analysis for the estimation techniques developed during the DACCORD project. This qualitative analysis aims to clarify the interdependencies between travel time and observed traffic data, the way estimation techniques work, and their behaviour under different flow conditions. Section 4.1 describes the approach of the qualitative analysis. Section 4.2 defines the network-level travel time, and analyses how it can be approximated based on observed traffic data. The following sections deal with one section-level estimation technique each, and section 4.6 analyses the way the section-level techniques behave under various flow conditions. Section 4.7 analyses the various network-level travel time techniques. Section 4.8 concludes on the sensitivities, and the suitability for control application of the various techniques.

4.1 **Approach qualitative analysis**

The qualitative analysis approach consists of first analysing the interdependencies between travel time and observed traffic data. Then the section level travel time estimators, and next the network level travel time estimation techniques are analysed.

The analysis is performed based on two methods.

- Identification of the way techniques work in order to identify any biases in and the sensitivity of the techniques in control processes.
- Identification of the way in which techniques behave in order to identify the sensitivity under different flow conditions.
- Identify strengths and weaknesses.

**The way in which techniques work**

To identify the way in which techniques work some graphical tools are used:

- Analysis based on a time-distance diagram.
- Analysis based on a cumulative flow diagram.

A time-distance diagram represents the movement of individual vehicles as a curve in time and space. These movements are graphically represented in this diagram by increasing curves so-called vehicle trajectories. Each point along the trajectory depicts the location of a vehicle at a specific time instant. The individual speed of the vehicle can be derived from the time distance diagram as the angle of a tangent along the line as shown in Figure 4.1 (see Daganzo, 1997).
A cumulative flow diagram represents the cumulative number of vehicles that have passed a point in a network. Each instant a vehicle passes this point, the total number of vehicles having passed is increased by one. Because the number of vehicles is large, the curve is smoothed. The cumulative flow at a certain point is represented by an increasing curve over time. The angle of a tangent along this curve represents the flow at a moment in time (see Daganzo, 1997).

The cumulative flow diagram can be determined for a number of locations. Each location is presented by a curve in the diagram. From the start of a time period the cumulative flow increases. For a second location the cumulative flow equals zero at a later time period, as the first vehicles have to travel along the section provided vehicles leave the corridor in the same order as they enter (FIFO). The horizontal distance indicates the travel time between the two locations at a certain time instant. The vertical distance represents the number of vehicles present on the section between A and B as shown in Figure 4.2.
The way in which techniques behave
The way in which techniques behave is assessed by a comparison of travel time estimates under different flow conditions. This analysis is performed in section 4.6.

Time lags
In practice travel time estimations are based on data from a few minutes back in time. The data is collected over a time period, and then it takes some time to compute the travel time from this data, which can be shown on VMS-signs. This study evaluates the performance of the techniques and therefore focuses on the performance of the techniques based on the data of the current time period. In reality the estimations are known for the end-users in a few minutes time, and are therefore less accurate than the results found in this study. The estimation techniques are considered to function within a real-time control application. The performance of the techniques should be seen in the context of the sensitivity of these control applications with respect to the accuracy of these estimations.

4.2 Definitions of speed and travel time
This section analyses the interdependencies between network-level travel time and observed traffic data.

Introduction
The objective of travel time estimation techniques is to estimate NLTT according to the definition in section 2.5.

The NLTT can not (yet) be observed directly in a sufficient automated manner to be used for on-line application. To estimate NLTT we therefore rely on data that can be collected and processed on-line. For the moment inductive loops are the main source of such data. Using inductive loops one can observe intensities and occupancies at a specific location. If a double inductive loop is applied, also vehicle speeds can be observed.

Decomposing NLTT
We assume a distribution of travel time for each location for each time instant corresponding to the travel times of vehicles nearby present at a road stretch for a small time period. The travel time of a hypothetical vehicle from A at time instant $t$ is defined as the expected travel time from this distribution (see Figure 4.3). In this evaluation study we define the $\text{NLTT}_{A,B}(t)$, as the expected travel time experienced by this hypothetical vehicle that departs on route $A-B$ at time instant $t$. 

Figure 4.3: Time distance diagram with hypothetical vehicle

If the travel time is defined in this way the NLTT_{A,B}(t), can be decomposed as follows:

$$NLTT_{A,B}(t) = \sum_{k=1}^{K} NLTT_k^*(t_k, t, A)$$  \hspace{1cm} (4.1)

Where $k$ denotes the components (subsection) of route $A-B$ and $t_k$ denotes the expected departing time at each component. Note that the indices $t$ and $A$ on the right hand side indicate that the $NLTT_k^*(t)$ at section $k$ refers to the distribution of vehicles departing at $A$ at time instant $t$.

Decomposing the NLTT is necessary because observations relate to short route sections. Because equation (4.1) is not very practical we approximate this equation by:

$$NLTT_{A,B}(t) \approx \sum_{k=1}^{K} NLTT_k^*(t_k)$$  \hspace{1cm} (4.2)

The question whether or not this introduces a bias will not be investigated in this evaluation study.

Discretisation in time and space

Until now we assumed that time and space are continuous variables. However, the available data of induction loop detectors is aggregated in time periods and apply to specific road sections. A typical length of such periods is 60 seconds. A typical length of a road section is 500 meter.

We will assume that vehicle trajectories corresponding to a specific section and time period, are parallel. The travel time that applies to these vehicles is defined as follows:

$$NLTT_{A,B}(t) \approx \sum_{k=1}^{K} \sum_{p=1}^{P} \omega_{k,p} SLTT_k^*(p)$$  \hspace{1cm} (4.3)

Where $\omega_{k,p}$ is the relative distances travelled per section $k$ in period $p$. $\sum_p \omega_{k,p} = 1$ and the $SLTT_k^*(p)$ is the SLTT over section $k$ for period $p$ (see definition in section 2.5).
In equation (4.3) \( \omega_{k,p} \) denotes the weight with which \( SLTT_k(p) \) contributes to the \( NLTT_{A,B}(t) \). In other words, the \( NLTT_{A,B}(t) \) is approximated as a weighted sum of \( SLTT_k(p) \) for specific periods and sections, where \( SLTT_k(p) \) is discretized over time and space. In the following paragraph we will discuss the following subjects:
- how to compute \( SLTT_k(p) \) from traffic observations,
- how to combine \( SLTT_k(p) \) to NLTT (i.e. which weights for \( \omega_{k,p} \) are used).

**Comparing SLTT**

We did not yet specify in which way the SLTT is to be computed. Consider the vehicle trajectories on section \( k \) in period \( p \) (see Figure 4.4).

![Figure 4.4: Time distance diagram with vehicle trajectories on section k in period p](image)

For this region the time-space mean speed \( v^*(k,p) \) can be defined as the total distance travelled over the section \( k \) in period \( p \) divided by the total vehicle time spend on section \( k \) during period \( p \) (see Botma, 1998).

In this evaluation study one way to define \( SLTT_k(p) \) is to derive it from the definition of the time-space mean speed i.e.

\[
SLTT_k(p) = \frac{L}{v^*(k,p)}
\]  

(4.4)

Where \( L \) denotes the length of section \( k \), and where \( v^*(k,p) \) denotes the time-space mean speed on section \( k \) during period \( p \).

Unfortunately, there are no means to observe time-space mean speeds directly. Instead, vehicles are observed at a fixed location. In absence of information on vehicle speeds in between detection positions we will assume that vehicles will move with a constant speed over a section and that the time-space mean speed can hence be reconstructed from the detector data. In the following we will discuss how this can be done.
Evaluation of travel time estimation techniques

Suppose during period $p$ an average of $I$ vehicles traverse section $k$. Assuming these vehicles move with constant speed $v_i$, the average travel time for these vehicles on section $k$ is:

$$SLTT_k(p) = \frac{L}{v_k(p)}$$

(4.5)

$$v_k(p) = \frac{I}{\sum_{i=1}^{I} v_i}$$

(4.6)

$v_k(p)$ thus equals the harmonic mean of the vehicle speeds.

Suppose a detector is present at the beginning of section $k$, then the harmonic mean of the speeds observed during period $p$ at this detector $\bar{v}_{i} \,(p)$ is the best available approximation for $v_k(p)$. We will use the following approximation:

$$SLTT_k(p) = \frac{L}{\bar{v}_i \,(p)}$$

(4.7)

Where $\bar{v}_i \,(p)$ is the harmonic time-mean speed during period $p$ at the detector at the beginning of section $k$.

Although in theory the harmonic mean speed can be observed with road side detectors, in practise the data is aggregated in a manner that prohibits the computation of harmonic means. Instead, all practical data collection systems considered in this evaluation study unfortunately store the arithmetic means of detected speeds.

$$\bar{v}_i \,(p) = \frac{1}{I} \sum_{i=1}^{I} v_i$$

(4.8)

For the remaining of the evaluation we introduce $V_{s,k}(p)$ and $V_{e,k}(p)$ as the arithmetic time-mean speed at the start respectively end of section $k$ in period $p$.

For any sequence of data the harmonic time-mean speed can be approximated by the following equation:

$$\bar{v}_i \,(p) \approx \bar{v}_i \,(p) - \frac{\sigma_i(p)^2}{\bar{v}_i \,(p)}$$

(4.9)

Where $\bar{v}_i \,(p)^2$ denotes the variance of the detected local speeds.

From this formula it can be concluded that the arithmetic time-mean speed is usually larger than the harmonic time-mean speed unless no variation in speed exists. Variations in travel time occur when the speed variation is high, such as during congestion building. The harmonic mean speed is a better approximation for the time-space mean speed of a section than the arithmetic time-mean speed;

- If the harmonic time-mean speed is used to represent the average speed at a section than the estimate of the section level travel time has no substantial bias.
**Qualitative analysis**

- If the arithmetic time-mean speed is used to represent the average speed at a section, than the estimate of the section level travel time has a bias: the average travel time is underestimated.

Figure 4.5 shows the difference between the harmonic time-mean speed and the arithmetic time-mean speed for a traffic situation described as the 'standard condition' in section 5.1.3.

![Figure 4.5: arithmetic and harmonic time-mean speeds of several detectors](image)

It can be concluded that the difference between the harmonic and arithmetic time-mean speed is no larger than a few percent. Only when the variation in travel time is high, as in congestion building or congestion resolving, the bias between harmonic and arithmetic time-mean speed is substantial.

### 4.3 Instantaneous section-level travel time estimator

This section analyses the instantaneous section-level travel time estimator in qualitative terms. Section 4.3.1 describes the general approach. Section 4.3.2 analyses the way in which the techniques work, and section 4.3.3 remarks on the suitability of the model for control applications.

#### 4.3.1 General approach instantaneous SLTT estimator

The instantaneous section-level travel time estimator computes the time needed to traverse the first half of the section using the arithmetic time-mean speed at the start of the section, and the second half of the section with the arithmetic time-mean speed at the end of the section, both for the same period.

---

1 The instantaneous SLTT as specified in this section is implemented in the Dutch and Italian test site. The French test site estimates an average speed by using of the density and intensity.
4.3.2 Analysis of the instantaneous SLTT estimator

The basis for the calculation of the instantaneous SLTT is the assumption that all vehicles drive half of the section with the time-mean speed detected at the downstream end of the section, and half of the section with the time-mean speed at the upstream end of the section. This is expressed in the equation (4.10). The principle of this equation is shown in Figure 4.6. With this principle the time period duration should be long enough to ensure a large enough sample.

\[
T_{i\text{inst}}^* (p) = \frac{L_s}{2V_{A,A} (p)} + \frac{L_s}{2V_{B,B} (p)}
\]

(4.10)

Figure 4.6: Time distance diagram with the principle of the instantaneous SLTT

The time-mean speeds at the start and the end of a section are weighted equally. With an arithmetic average of the arithmetic weighted time-mean speeds at the start and end of the section this is not the case, as is shown in the example below:

Input: \( V_{A,A} (t) = 10 \text{ m/s} \) \( V_{B,B} (t) = 40 \text{ m/s} \) \( L_s = 500 \text{ m} \)

Model: arithmetic weighted mean of the arithmetic time-mean speeds Space-based weighted mean of the arithmetic time-mean speeds

Applied formula: \( 500/((10+40)/2) \) \( 500/(2*10)+500/(2*40) \)

Result: 20 31.25

The space-based weighted mean of the speeds is more correct to use, since the average of the travel times of the two vehicles is exact 31.25. The variation is larger with a large difference in speed at the start and end of the section.

4.3.3 Remarks

The following remarks apply to the instantaneous section-level travel time technique.
Remarks on the implementation

- The technique uses the arithmetic time-mean speed at the start and end of each section for the same period. According to theory this leads to an under estimation of travel time.
- The technique functions well for sections shorter than 1000 meters according to the specifications (see Hadj-Salem, 1997).

Remarks on the methodology

- The technique computes a space-based weighted mean of the arithmetic time-mean speed on a section, which is a better estimate of the SLTT than the arithmetic weighted time-mean speeds.
- The technique assesses the speed at a detector for each time period separately without averaging using earlier time periods. This results in some sensitivity for measurement errors, but more accurate estimations under changing flow conditions.

4.4 Short road section travel time estimator

This section analyses the short road section travel time estimator in qualitative terms. This estimator was specially developed for short road sections. Section 4.4.1 describes the general approach. Section 4.4.2 analyses the way in which the technique works, and section 4.4.3 remarks on the suitability of the model for control applications.

4.4.1 General approach short road section travel time estimator

The travel time estimator for short road sections is subdivided into a number of modules.

Estimate travel time according to the ‘speed algorithm’

The ‘speed algorithm’ is the same algorithm as the instantaneous SLTT.

Estimate travel time according to the ‘intensity algorithm’

The ‘intensity algorithm’ estimates the travel time as the time needed for all vehicles present on the section to leave the section with the current outflow. To estimate the number of vehicles on the section two algorithms have been developed. First, the ‘density method’, which combines the average density with the length of the section. Secondly, the ‘intensity method’ which counts the number of entering and exiting vehicles. These methods are both part of the ‘intensity algorithm’.

Combine estimated road section travel times

Both travel time estimates are combined to form a final estimate of the SLTT during a time interval. The SLTT estimates per road section are then checked between an upper and lower limit.

Appendix B ‘Travel time estimator for short road sections’ describes the technique in more detail.

---

1 The short road section travel time as specified is not implemented at one of the test sites. The Dutch test site uses several elements of the short road section travel time for the instantaneous travel time.
2 This section is mainly based on the text of section 3.3.1 of Deliverable D05.1 (Hadj-Salem, 1997)
4.4.2 Analysis of the short road section travel time estimator

The analyses of the road section travel time estimator concentrates on the calculation of the SLTT using the 'speed algorithm' and the 'intensity algorithm' respectively.

'Speed algorithm'

The 'speed algorithm' equals the instantaneous SLTT, which was analysed in section 4.3.

'Intensity algorithm'

To assess the travel time according to the 'intensity algorithm' the number of vehicles on the section must be known. For this problem two algorithm have been developed:

- 'density method',
- 'intensity method'.

'Density method'

The 'density method' computes the number of vehicles on a section as the average density of the start and the end of the section multiplied with the length of the section as in equation (4.11). The density is computed by applying the formula \( q = k \cdot v \).

\[
N_k^{\text{density}}(p) = \frac{L_k}{2} \left( \frac{J_{A_k}(p)}{V_{A_k}(p)} + \frac{J_{B_k}(p)}{V_{B_k}(p)} \right) 
\]  

(4.11)

With

\( N_k^{\text{density}}(p) \) = The number of vehicles according to the 'density method'

note that the formula \( q = k \cdot v \) is valid for the generalized definitions of flow, density and speed (see Botma, 1998) e.g. Let \( S \) be a surface in the time-distance diagram that we wish to analyse as in Figure 4.7. Let \( A^S \) be the area of this surface then the generalized flow, density and speed for \( S \) are given by:

- \( q = \) total distance travelled / \( A^S \)
- \( k = \) total vehicle time spent / \( A^S \)
- \( v = \) total distance travelled on \( S \) / total time spent on \( S \)

![Figure 4.7: Definitions of generalised flow, speed, and density for any surface in a time-distance diagram](image)

The definitions of \( J_{A_k}(p) \) and \( V_{A_k}(p) \) in equation (4.11) do not correspond exactly with the generalised flow and speed, but with observations of flows and speeds at a specific location. In this way, some error is introduced. The extent of this error was not investigated.
‘Intensity method’

The intensity method computes the number of vehicles at a section by counting the number of vehicles entering and exiting the section as in equation (4.12).

\[
N_k^{\text{int \_ density}}(p) = N_k^{\text{int \_ density}}(p-1) + I_{A,k}(p) - I_{B,k}(p)
\]

With

\[N_k^{\text{int \_ density}}(p) = \text{The number of vehicles according to the 'intensity method'}\]

Combining ‘intensity and density methods’

The outcomes of the density and intensity method are combined to reach a final result as in equation (4.13). The outcomes are combined with a weighing factor \(\gamma\) depending on the speed \((0 \leq \gamma \leq 1)\) as in Table 4.1. \(\gamma_{\text{max}}\) is specified for each separate road section depending on the configuration \((\gamma_{\text{max}} \leq 1)\).

\[
N_k(p) = \gamma \cdot N_k^{\text{density}}(p) + (1 - \gamma) \cdot N_k^{\text{int \_ density}}(p)
\]

With

\[N_k(p) = \text{The number of vehicles according to 'density' and 'intensity method'}\]

<table>
<thead>
<tr>
<th>Min (V_{A,k}(t)), and (V_{B,k}(t))</th>
<th>(\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\geq 85 \text{ km/h})</td>
<td>1</td>
</tr>
<tr>
<td>(\geq 35 \text{ km/h}, \leq 85 \text{ km/h})</td>
<td>(\gamma_{\text{max}})</td>
</tr>
<tr>
<td>(\geq 20 \text{ km/h}, &lt; 35 \text{ km/h})</td>
<td>(2/3 \gamma_{\text{max}})</td>
</tr>
<tr>
<td>(&lt; 20 \text{ km/h})</td>
<td>(1/3 \gamma_{\text{max}})</td>
</tr>
</tbody>
</table>

Table 4.1: Decision table weighing factor \(\gamma\)

The ‘intensity algorithm’ computes the travel time as the time that is needed for all vehicles present on the section to leave the section, under the assumption that the intensity equals the average intensity a number of time periods. The number of the time periods \(N\) can be varied, the value in the specifications (see Hadj-Salem, 1997) is 3 for one minute periods.

\[
T_k^{\text{int \_ density}}(p) = T_k^{\text{int \_ density}}(p) = N_k(p) \left/ \sum_{m=0}^{N-1} I_{B,k}(p-m) \right.
\]

With

\[T_k^{\text{int \_ density}}(p) = \text{The SLTT according to the 'intensity algorithm'}\]

\[N_k(p) = \text{The number of vehicles on the section k at the start of period p}\]

Figure 4.8 shows the cumulative flow of the start and the end of the section. The vertical distance between the two lines represents the number of vehicles present on the section. The ‘intensity algorithm’ determines the time needed to process this number of vehicles with the average outflow of the last 3 time periods.
Combining ‘speed algorithm’ and ‘intensity algorithm’

With relatively high speeds the reliability of the ‘speed algorithm’ was found to be high, and for lower speeds the intensity algorithm is more reliable as stated in the specifications (see Hadj-Salem, 1997). The estimates are weighed with each other depending on the measured speed with a factor \( \alpha \) and \( \beta \). The factor \( \alpha \) is not determined as it is tested. The factor \( \beta \) is determined out of the minimum speed measured at begin and end of the section as in Table 4.2. \( \beta_{\text{max}} \) is specified per road section.

\[
T_k^{\text{short}}(p) = \alpha \cdot T_k^{\text{short}}(p-1) + \beta \cdot T_k^{\text{speed}}(p) + (1 - \alpha - \beta) \cdot T_k^{\text{intensity}}(p)
\]

With

\[
T_k^{\text{short}}(p) = \text{The SLTT according to the 'short road section algorithm'}
\]

\( 0 \leq \alpha, \beta \leq 1 \) & \( \alpha + \beta \leq 1 \)

<table>
<thead>
<tr>
<th>Min ( V_{A,k} ) ((t)), and ( V_{B,k} ) ((t))</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 60 \text{ km/h} )</td>
<td>( \beta_{\text{max}} )</td>
</tr>
<tr>
<td>( \geq 35 \text{ km/h}, \leq 60 \text{ km/h} )</td>
<td>( 2/3 \beta_{\text{max}} )</td>
</tr>
<tr>
<td>( \geq 20 \text{ km/h}, &lt; 35 \text{ km/h} )</td>
<td>( 1/3 \beta_{\text{max}} )</td>
</tr>
<tr>
<td>&lt; 20 \text{ km/h}</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2: Decision table weighing factor \( \beta \)

4.4.3 Remarks

The following remarks are made concerning the instantaneous section-level travel time estimation technique.

**Remarks on the implementation**

- The technique uses the arithmetic time-mean speed and intensity at the start and end of each section
- The technique functions well for sections smaller than 1000 meters according to the specifications (see Hadj-Salem, 1997).
Remarks on the methodology
- The technique computes a space-based weighted mean of the arithmetic time-mean speed on a section, which is a better estimate of the SLTT than the time-based weighted time-mean speed.
- The 'intensity algorithm' computes the time needed for all vehicles present on the section to leave the section. This principle assumes the first-in-first-out principle (FIFO) and therefore, a small number of overtaking operations.
- The number of vehicles on a section is estimated based on the average density, or based on a counting principle.
- The intensity algorithm and speed algorithms are combined based on the speed.

Remarks on the behaviour
- The technique assesses the speed at a detector for each time period separately without averaging with earlier time periods. This results in sensitivity for measurement errors, but more accurate estimations under changing flow conditions.
- The algorithm based on the counting principle is more sensitive for measurement errors than the algorithm based on the average density, since errors accumulate.
- The 'intensity algorithm' is based on the time needed for all sections to leave the section is sensitive for a high variation in the speed. But, this algorithm is only used for low speeds when the variability is low.

4.5 Long road section travel time estimator¹

This section analyses the long road section travel time estimator in qualitative terms. Section 4.5.1 describes the general approach. Section 4.5.2 analyses the way in which the techniques work, and section 4.5.3 remarks on the suitability of the model for control applications.

4.5.1 General approach long road section travel time estimator²

The travel time estimator for long road sections is subdivided into a number of separate modules. The function of each module is described briefly.

'Travel time based on speeds'
The 'travel time based on speeds' equals the instantaneous SLTT, which was analysed in section 4.3.

'Travel time based on comparison of flow patterns'
The 'travel time based on comparison of flow patterns' algorithm consists of two modules. The first module has a congestion monitoring function. It has two possible output signals: normal traffic flow and congestion. The congestion detection is based on the comparison of the in- and outflow of a section as impulses. The impulse of the inflow is compared to the impulse of the outflow of a free-flow time period later.

¹ The long road section travel time as specified is not implemented at one of the test sites. In the Dutch site several elements of the long road section travel time are used. Here, only the 'delay time and travel time' algorithm is used.
² This section is partly based on the text of section 5.1 of the appendix E of Deliverable D05.1 (Hadj-Salem, 1997)
Depending on the output of the congestion detection, the second module has two levels of operation. With no congestion, the SLTT equals the free-flow travel time. With congestion the travel time is computed based on flow comparison. When the outflow is found to be smaller than the inflow, there will be 'too many' vehicles on the road section, which might indicate the presence of congestion. Two methods for computing travel times and delay times are elaborated.

The 'delay time and travel time' algorithm first computes the delay time, which is added to the free-flow travel time to compute the travel time. The delay time is defined as the time that is needed for the number of vehicles too many to leave the road section at a rate that is equal to the effective outflow.

The 'travel time and delay time' algorithm computes the travel time directly. The travel time is defined as the time that is needed for all vehicles that are currently on the section to leave the section.

**Combine estimates of road section travel time**

Depending on the minimum time-mean speed at the start and end of a section, and the length of the road section, an indicator is calculated signifying the reliability of the travel time estimate based on speeds. For the travel times estimate based on comparison of flow patterns also reliability indicator has been included. Depending on these reliability factors the final road section travel time estimate is a combination.

Appendix C 'travel time estimator for long road sections' describes the techniques in more detail.

**4.5.2 Analysis of the long road section travel time estimator**

This section analysis the modules needed for the computation of travel times. The queue length estimate is not analysed, as it has no direct influence on the travel time computation.

'Travel time based on comparison of flow patterns'

The travel time based on comparison of flow patterns is a complex algorithm, which is divided in several sub-modules according to Figure 4.9.

![Figure 4.9: Subdivision in sub-modules of the algorithm for estimation travel times using comparison of flow patterns](image-url)
Congestion detection

The impulses of a platoon of traffic of the start and end of the section are compared to each other with a shift in time equal to the free-flow travel time. Because of this time difference not all observations can be used. The eldest observations at the end of the section are not used, because of the lack of observations of the same traffic platoon at the start at the section, and the most recent observations at the start of the section are not used for the same reason.

If the impulses deviate too much congestion is indicated. Then the SLTT is computed as described in the rest of the section. If no congestion is detected the SLTT equals the free-flow travel time.

\[ \text{Congestion detection} \]

\[ \begin{align*}
    I_{AK}(p) &= I_{AK}(p), I_{BK}(p) = c_k(p) * I_{BK}(p) \\
    c_k(p) &= I_{AK}(p) / I_{BK}(p)
\end{align*} \]

The ‘correction function’

The ‘correction function’ computes a correction factor for \( c_k(p) \) on- and off-ramps, which are not monitored. The computation is only performed under free flow conditions, and held constant during congestion.

Three different situations could occur:

- The inflow is lower than the outflow.
  \[ I_{AK}(p) = I_{AK}(p), I_{BK}(p) = c_k(p) * I_{BK}(p) \]  \[ c_k(p) = I_{AK}(p) / I_{BK}(p) \]  \[ (4.16) \]

- The inflow is about equal to the outflow; no corrections are made.
  \[ I_{AK}(p) = I_{AK}(p), I_{BK}(p) = I_{BK}(p) \]  \[ (4.17) \]

- The inflow is higher than the outflow.
  \[ I_{AK}(p) = I_{AK}(p) / c_k(p), I_{BK}(p) = I_{BK}(p) \]  \[ (4.18) \]

Vehicles ‘too many’

With congestion building the outflow of the section is lower than the inflow of the section. Therefore, the number of vehicles ‘too many’ \( N \) is an indication for the level of congestion.

The number of vehicles entering the section is measured during a period back in time equal to the free-flow travel time as depicted in Figure 4.11.
Evaluation of travel time estimation techniques

\[ N_k(p) = N_k(p-1) + I_{\text{free}}(p - t_{\text{free}}) - I_{\text{eff}}(p) \]  
(4.19)

With

\[ N_k(p) = \text{vehicles 'too many' on section } k \text{ in period } p \]

\[ \text{numveh}_k(p) = \sum_{m=p-1}^{p-\text{free}} I_{\text{eff}}(m) + N_k(p) \]  
(4.20)

With

\[ \text{numveh}_k(p) = \text{number of vehicles on section } k \text{ at the start of period } p \]

Figure 4.11: Impulses of passing vehicles at the start and end of a section

**Number of vehicles**

The number of vehicles on the section ‘numveh’ is estimated as the corrected entering flow over a period equal to the free-flow travel time combined with the vehicle ‘too many’.

For the calculation of the travel time and the delay time over the section two alternative calculation methods have been developed.

**'Delay time and travel time’**

The first method is based on the delay time induced by the vehicles ‘too many’. This delay time is summed to the free-flow travel time to estimate the experienced travel time as in equation (4.21). Figure 4.12 shows the principles of the algorithm. The effective flow during congestion equals the outflow at the end of the section. The effective flow for freeflow is a predefined value equal to the capacity.

\[ T_{\text{eff}}(p) = \text{freeflow}_k + \frac{N_k(p)}{C_{\text{eff}}(p)} \]  
(4.21)

\[ C_{\text{eff}}(p) = \frac{1}{m} \sum_{n=0}^{m} I_{\text{eff}}(p-n) \]  
(4.22)

With

\[ T_{\text{eff}}(p) = \text{SLTT according to the 'delay time and travel time' algorithm} \]

\[ C_{\text{eff}}(p) = \text{effective outflow out of section } k \text{ in period } p \]
‘Travel time and delay time’

The second method estimates the travel time based on the number of vehicles present on the section. The delay time is derived as the free-flow travel time minus the calculated travel time. The travel time is computed as the time that is needed for the vehicles present on the section to leave the section with the effective outflow as in equation (4.23). Figure 4.13 shows the principle of the method.

\[
T_k^{\text{ delay}}(p) = \frac{\text{numveh}_k(p)}{C_{\text{ef},k}(p)} \tag{4.23}
\]

With

\[
T_k^{\text{ delay}}(p) = \text{travel time according to the ‘travel time and delay time’ algorithm}
\]
Combining travel time from measured speeds and from comparison of flow patterns

The travel time is computed as a combination of the estimation based on speeds and based on comparison of flow patterns depending on the reliability of the estimates as in equation (4.24). The calculation of the travel time from direct speeds is unreliable if one of the speeds at the start of the end of the section is smaller than 30 kilometres or the section is longer than 1000 metres. For the calculation of the travel time from flow patterns no averaging factor has been agreed upon (default value 0.5, see Hadj-Salem, 1997). The travel time from comparison of flow patterns is one of the two 'delay time and travel time' or 'travel time and delay time' algorithms.

\[ T_{k}^{\text{long}} (p) = \beta * T_{k}^{\text{speed}} (p) + (1 - \beta) * T_{k}^{\text{flow}} (p) \] (4.24)

With

\[ T_{k}^{\text{long}} (p) = \] travel time according to the long section algorithm

4.5.3 Remarks

The following remarks are made concerning the long section travel time estimation technique.

Remarks on the implementation
- The technique uses the speed and intensity at the start and end of each section
- The technique functions well for sections longer than 1000 meters according to the specifications.

Remarks on the methodology
- The method 'delay time and travel time' uses the number of vehicles 'too many' on a section to compute delay time on top of the free-flow travel time.
- The vehicles 'too many' is computed as the deviation on the number of vehicles at the end of a section compared to the impulse of traffic at the start of the section a free-flow travel time ago.
Evaluation of travel time estimation techniques

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Qualitative analysis

- The method ‘travel time and delay time’ computes the total number of vehicles present on a section to compute the travel time.
- The number of vehicles on a section is computed as the inflow at the section for a time period equal to the free-flow travel time combined with the vehicles ‘too many’, which is computed similarly to the preceding method.
- The technique takes into account the presence of unmeasured on- and off-ramps.

Remarks on the behaviour
- The technique assesses the speed at a detector for each time period separately without averaging with earlier time periods. This results in some sensitivity for measurement errors, but more accurate estimations under changing flow conditions.
- The technique ‘delay time and travel time’ is more sensitive to measurement errors then the technique ‘travel time and delay time’, as the total number of vehicles on the section is computed while with the ‘travel time and delay time’ technique only the vehicles ‘too many’ is computed.

4.6 Sensitivity under various traffic flow conditions

This section focuses on the behaviour of travel time estimation techniques under various traffic flow conditions.

4.6.1 Traffic flow conditions

The speed, density and intensity are the three major properties describing the state of traffic on a road section. Equation (4.25) follows from the definitions of these properties at a particular location.

\[ q = k^* v \]  

(4.25)

To evaluate the behaviour of estimation techniques, the fundamental diagram is used to identify different flow conditions. The fundamental diagram has one special point representing the capacity of the road section, and two characteristic branches representing congestion and non-congestion.

To evaluate estimation techniques three points are chosen from the fundamental diagram to present three characteristic traffic flow conditions. First, the point representing capacity, then a point along the non-congested branch, and then one along the congested branch. Traffic flow conditions at a particular location can shift from one traffic condition to another as is shown in Figure 4.14.

![Figure 4.14: Intensity versus density diagram with shifts](image)
The different transitions occur on motorway's in relation to other vehicles and the surroundings. An example of such interaction is given in Figure 4.15 where three transitions take place.

Figure 4.15: Time distance diagram with different transitions

The three points and six transitions of Figure 4.14 can be visualised in time-distance diagrams as is shown in Figure 4.16. These diagrams are enlargements of the parts of the traffic flow as the boxes in Figure 4.15.

Figure 4.16: Time distance diagrams for nine different traffic state transitions
Evaluation of travel time estimation techniques

The evaluation of the behaviour of the techniques under different changing traffic flow conditions are performed by computing the travel time using the estimation techniques, and subsequently comparing this travel time with the estimated travel time.

4.6.2 Experimental set-up

To gain some insight into this subject some (limited) experiments were carried out. For all nine transitions in Figure 4.16, data were synthesised with a spreadsheet program (see appendix A ‘Travel time with transitions’. The following techniques were implemented.

- Instantaneous travel time estimator, see for specifications section 4.3;
- Travel time estimator for short road sections, see for specifications section 4.4; the following parameter values were used: \( n=3, \gamma_{\text{max}} = 0.6, \beta_{\text{max}} = 0.3; \)
- Travel time estimator for long road sections, see for specifications section 4.5 the following parameter values were used: \( c_k = 1, t_{\text{freeflow}} = L/v_{\text{free}}, m=t_{\text{freeflow}}, n=3; \)

These techniques are compared to an estimate approximating the real travel time. This estimate is computed based on the assumption that the average travel time in such traffic flow transitions has a large variance. Therefore only a rough estimate of the travel time is made. The travel time for the different traffic flow transitions can be estimated according to the following principle:

*If the time-distance interval is divided into areas of equal size, the total average travel time equals the sum of the weighted average travel times of each area. The average travel time of a section can be computed as the angle of a straight line presenting the average angle in the area. The length of trajectories within an area represents the weight of that area in the average for the total travel time as presented in Figure 4.17.*

![Figure 4.17: Computation method for estimated realistic travel time](image)

The computation of the travel time was performed by hand on three slightly different situations for each transition. The trajectories for each transition are slightly moved compared to the transitions presented in Figure 4.16. The results are averaged and rounded.
4.6.3 Experimental results

The travel time is computed according the different techniques and an approximation of the realistic travel time. The results are shown in Table 4.3.

![Travel time with various flow conditions](image)

Table 4.3: Results of travel time computation for nine transitions for different SLTT estimation techniques

<table>
<thead>
<tr>
<th></th>
<th>free-free</th>
<th>free-cap</th>
<th>free-cong</th>
<th>cap-free</th>
<th>cap-cap</th>
<th>cap-cong</th>
<th>cong-free</th>
<th>cong-cap</th>
<th>cong-cong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous TT</td>
<td>33.33</td>
<td>38.18</td>
<td>57.14</td>
<td>38.18</td>
<td>45.00</td>
<td>63.53</td>
<td>49.52</td>
<td>63.53</td>
<td>128.57</td>
</tr>
<tr>
<td>Short section TT</td>
<td>33.33</td>
<td>38.81</td>
<td>45.69</td>
<td>38.81</td>
<td>47.18</td>
<td>62.84</td>
<td>48.18</td>
<td>62.84</td>
<td>105.58</td>
</tr>
<tr>
<td>Long section TT</td>
<td>33.00</td>
<td>36.88</td>
<td>52.05</td>
<td>35.88</td>
<td>42.33</td>
<td>57.33</td>
<td>46.78</td>
<td>57.33</td>
<td>110.90</td>
</tr>
</tbody>
</table>

The following remarks are made on the behaviour of travel time estimation techniques under different flow conditions.

- The results of the instantaneous travel time estimator are relatively good compared to the other techniques towards the realistic travel time.
- The short and long section travel time estimation techniques perform worse with congestion building and with congestion.

4.7 Network-level travel time

For the combining of SLTT towards a NLTT basically three methods were developed:

- Instantaneous network-level travel time estimator
- Weighted instantaneous network-level travel time estimator
- Dynamic network-level travel time estimator

4.7.1 Instantaneous network-level travel time estimator

The instantaneous network-level travel time estimator based on section-level travel time computes the travel time that would be experienced if all considered sections were to be traversed in the current time period. The method does not take into account that traffic conditions vary over time.

The method uses the SLTT estimation techniques to calculate the instantaneous NLTT. The SLTT that is calculated is summed over all sections of the route as in Figure 4.18.

\[
NLTT^{\text{inst}}(p) = \sum_{k=1}^{K} \left( \frac{L_k}{2V_{A,k}(p)} + \frac{L_k}{2V_{B,k}(p)} \right)
\]

(4.26)
The following remarks are made:

- The instantaneous NLTT estimator does not take into account that flow conditions may change on a route in time. This may result in inaccurate estimations, especially during congestion building or resolving.
- The instantaneous NLTT estimator divides space and time in sections and time periods. This assumes homogeneous traffic flow conditions. The lengths of sections as well as the duration of time periods should be small enough to justify this assumption.
- The instantaneous NLTT estimator exposes a higher variability towards the dynamic travel time. This is due to extrapolation in time upon which the instantaneous travel time estimator is based and which also causes the FIFO-principle to be violated.

4.7.2 Weighted instantaneous network-level travel time estimator

The weighted instantaneous network-level travel time estimator is an instantaneous NLTT estimator based on the instantaneous SLTT of section 4.3. The general approach of the weighted instantaneous NLTT estimator is to add a section-specific weighting factor to the SLTT's. The weighting factor is a factor for the total distance driven by all vehicles present on that section compared to the total distance driven of all vehicles at the total route.

\[
NLTT^{\text{weighted}}(p) = \frac{\sum_{i=0}^{k} L_i * I_i(p) v_i(p)}{\sum_{i=0}^{k} L_i * I_i(p)}
\]  

The bold arrow in the corner of each area represents the average speed of that area. The other arrows represent the number of observations for each area.

The weighted instantaneous NLTT as specified in this section is implemented in the Dutch test site. The French test site estimates an average speed out of the density and intensity.

1 The bold arrow in the corner of each area represents the average speed of that area. The other arrows represent the number of observations for each area.

2 The weighted instantaneous NLTT as specified in this section is implemented in the Dutch test site. The French test site estimates an average speed out of the density and intensity.
Evaluation of travel time estimation techniques

\[ v_k(p) = I_k \left( \frac{L_k}{2V_{A_k}(p)} + \frac{L_k}{2V_{B_k}(p)} \right) \quad (4.28) \]

\[ I_k(p) = I_{A_k}(p) \quad (4.29) \]

Figure 4.19: Computation of the weighted instantaneous NLTT from SLTT's

The following remarks are made:

- The weighted instantaneous NLTT does not take into account that flow conditions may change on a route in time. This may result in inaccurate estimations, especially during congestion building or resolving.
- The weighted instantaneous NLTT divides space and time in sections and time periods. This assumes homogeneous traffic flow conditions. The lengths of sections as well as the duration of time periods should be small enough to justify this assumption.
- The weighted instantaneous travel time estimator exposes a higher variability related to the dynamic travel time. This is due to extrapolation in time upon which the instantaneous travel time is based and which also causes the FIFO-principle to be violated.

### 4.7.3 Dynamic network-level travel time estimator

The dynamic NLTT estimator is based on the instantaneous section-level travel time estimator. The section-level travel time is calculated for each section and for each time period. Next, the dynamic travel time is calculated according to the principle shown in Figure 4.20.

---

1. The bold arrow in the corner of each area represents the average speed of that area. The other arrows represent the number of observations for each area.
2. \( \alpha_1 + \alpha_2 + \alpha_3 = 1 \)
Figure 4.20: Computation of the dynamic NLTT from SLTT’s

Given a certain start moment \( t \) and start position \( x \) in a start section \( s \) and start period \( p \) the following travel time is computed:

\[
T_{s,s+1}^{\text{stretch}} = \frac{f_s(x) - x}{V_{s,p}}
\]

With

\[
T_{s,s+1}^{\text{stretch}} = \text{travel time towards the end of the section } s \text{ starting at } x \text{ in section } s
\]

\[
f_s(i) = \text{position of the start of section } i
\]

If this travel time is smaller than the time left in the current time period, the following applies:

\[
T_i^{\text{total}} = T_i^{\text{total}} + \frac{f_s(x) - x}{V_{s,p}}
\]

\[
t_i = t_i + \frac{f_s(x) - x}{V_{s,p}}
\]

\[
x_i = f_s(x + 1)
\]

Else the following applies:

\[
T_i^{\text{total}} = T_i^{\text{total}} + f_i(p + 1) - t
\]

\[
x_i = x_i + (f_i(p + 1) - t) * V_{s,p}
\]

\[
t_i = f_i(p + 1)
\]

With

\[
f_i(i) = \text{time instant of the start of time period } i
\]

---

\(^1\) The bold arrow in the corner of each area represents the average speed of that area. The other arrows represent the number of observations for each area.
The following remarks are made:

- The dynamic NLTT takes into account that flow conditions may change on a route in time. This result in more accurate estimations than the instantaneous NLTT, especially during congestion building or resolving.
- The dynamic NLTT divides space and time in sections and time periods. This assumes homogeneous traffic flow conditions. The lengths of sections as well as the duration of time periods should be small enough to justify this assumption.

### 4.8 Conclusions on the qualitative analysis

The conclusions on the qualitative analysis are divided in general conclusions, conclusions on each section-level estimation technique, and the network-level estimation techniques.

**General conclusions**

- NLTT can only be composed from SLTT’s if the following assumptions apply:
  - the distribution of vehicles is the same along a route;
  - trajectories of vehicles in a specific section and time period are parallel;
  - vehicles travel over a section with a constant speed
  - the arithmetic time-mean speed approximates the harmonic time-mean speed with enough accuracy.
- The last assumption is the most hazardous. The arithmetic time-mean speed over estimates the harmonic time-mean speed, and therefore under estimates the travel time.

**Conclusions on the instantaneous section-level travel time estimator**

- The technique computes a space-based weighted mean of the arithmetic time-mean speed on a section, which is a better estimate of the SLTT than the arithmetic weighted time-mean speed.
- The technique assesses the speed at a detector for each time period separately without averaging using earlier time periods. This results in some sensitivity for measurement errors, but more accurate estimations under changing flow conditions.
- The results of the instantaneous travel time are relatively good compared to the realistic travel time.

**Conclusions on the short road section travel time estimator**

- The technique computes a space-based weighted mean of the arithmetic time-mean speed on a section, which is a better estimate of the SLTT than the time-based weighted time-mean speed.
- The ‘intensity algorithm’ computes the time needed for all vehicles present on the section to leave the section. This principle assumes the first-in-first-out principle (FIFO) and therefore, a small number of overtaking operations.
- The technique assesses the speed at a detector for each time period separately without averaging with earlier time periods. This results in sensitivity for measurement errors, but more accurate estimations under changing flow conditions.
- The algorithm based on the counting principle is more sensitive for measurement errors than the algorithm based on the average density, since, errors do not accumulate.
- The ‘intensity algorithm’ to assess the travel time based on the time needed for all sections to leave the section is sensitive for a high variation in the speed. But, this algorithm is only used for low speeds when the variability is low.
• The short road section travel time estimation technique performs less good with congestion building and with congestion as with congestion resolving.

Conclusions on the long road section travel time estimator
• The technique takes into account the presence of unmeasured on- and off-ramps.
• The technique assesses the speed at a detector for each time period separately without averaging with earlier time periods. This results in some sensitivity for measurement errors, but more accurate estimations under changing flow conditions.
• The technique ‘delay time and travel time’ is more sensitive to measurement errors then the technique ‘travel time and delay time’, as the total number of vehicles on the section is computed while with the ‘travel time and delay time’ technique only the vehicles ‘too many’ is computed.
• The long road section travel time estimation technique performs less good with congestion building and with congestion as with congestion resolving.

Conclusions on the network-level travel time estimators
• The instantaneous and weighted instantaneous NLTT estimators do not take into account that flow conditions may change on a route in time. This result in inaccurate estimations, especially during congestion building or resolving.
• The dynamic NLTT estimator does take into account that flow conditions may change on a route in time. This result in more accurate estimations than the instantaneous NLTT, especially during congestion building or resolving.
• The instantaneous, weighted instantaneous and dynamic NLTT estimators divides space and time in sections and time periods. This assumes homogeneous traffic flow conditions. The lengths of sections as well as the duration of time periods should be small enough to justify this assumption.
Evaluation of travel time estimation techniques

Qualitative analysis
5. **Simulation based quantitative analysis**

This chapter presents a quantitative study for the performance of the estimation techniques under different time- and location-dependent conditions. Section 5.1 describes the approach of the simulation study. Section 5.3 presents the results, and section 5.4 concludes on the performance of the various estimation techniques.

5.1 **Simulation study approach**

This section describes the approach for simulation-based analysis, and evaluation of the estimation techniques developed in the DACCORD project. Unlike the experiments described in the previous chapter, this study is based on data generated with a realistic behavioural simulation model. Data were generated for various conditions. Section 5.1.1 describes the simulation study objective in more detail. Section 5.1.2 indicates the general approach of this study in three modules, which are described in the following sections. Section 5.1.3 describes the traffic generator model used for the traffic simulation. Section 5.1.4 describes the implementation of the techniques in a model. Section 5.1.5 describes the used indicators to measure the performance of the techniques.

5.1.1 **Subject of the simulation study**

This section describes the simulation study objective, the techniques that are analysed, and the different conditions under which the techniques are evaluated.

*Simulation study objective*

The objective of the simulation based quantitative analysis is to:

1. evaluate the performance of different techniques based on simulated data,
2. compare the performance of the different techniques, and
3. compare the performance of these techniques under different conditions.

The performance of the estimation techniques is measured as the mean error and mean squared error of the results compared to the simulated observations.

The performance is measured both in absolute terms to the simulated data and in relative terms compared to the other techniques under different conditions.

*Conditions*

The evaluation of the techniques is performed for a limited number of conditions since a number of conditions is not taken into account in the simulation model. For example the simulation model was not designed to cope with different weather and ambient conditions. The different techniques are evaluated under the following conditions:

1. The effect of the length of road sections.
2. The effect of the length of time periods.
3. The effect of the flow regime.
5. The effect of road works

With all these conditions no data errors or gaps are present, while in practice these errors do occur. The results of the simulation study have to be seen with this limitation. Research based on empirical data is recommended for extra insight in the effect of such errors.
In the evaluation of DACCORD the effect of the percentage of slow traffic (trucks) is not evaluated since this percentage is not recorded. A simulation tool can be capable of recording and changing the percentage of slow traffic. It is therefore that this percentage is also taken into account.

- The effect of the percentage of slow traffic.

**DACCORD techniques**

Since the prediction techniques are too large and too complex to implement. Only, the estimation techniques are included in the simulation study as they are relatively simple to implement in a simulation model. The on-line estimation techniques developed within the DACCORD project are:

- Instantaneous travel time estimator (FR, IT, NL)
- Weighted instantaneous travel time estimator (FR, NL)
- Short road section travel time estimator (NL, but not at the Dutch DACCORD site)
- Long road section travel time estimator (NL)

In the DACCORD project the evaluation of the estimation and prediction models is based on the comparison with observations and comparison with the performance of simple naive reference models used as base-line models. The number of observations is relatively small for the three test sites. To be able to perform statistically correct evaluations for all conditions more observations would be required. Alternatively, the number of observations can be extended using an off-line travel time estimator. The dynamic network level travel time estimator is an example of such an off-line estimator.

The simulation study evaluates the performance of the dynamic network-level travel time estimation compared to the simulated data. If the dynamic NLTT performs well, chances are high that the dynamic NLTT is good enough to use for interpolating observations to extend the total number of 'observations'. An evaluation of the dynamic NLTT based on real observations should point out if this is really the case.

The dynamic travel time estimator was chosen because this off-line technique is theoretically the best estimation technique to approximate the experienced travel time. This conclusion was based on the qualitative analysis in section 4.7.

Figure 5.1 presents the approach of the quantitative evaluation of estimation and prediction techniques within the DACCORD project.

![Figure 5.1: Evaluation of estimation and prediction techniques](image-url)
5.1.2 Simulation approach

The objective of this section is to describe the approach for the simulation based quantitative analysis, and to identify the different modules necessary for this approach with demands set to them.

Analysis approach

The evaluation of the estimation techniques under different conditions is performed by a comparison of the outcomes of the technique in a ‘standard’ situation, to the outcomes of the technique under various deviating conditions. For some conditions multiple runs are simulated to evaluate the effect of the condition at an interval between realistic values, such as the condition “percentage of slow traffic”. Other conditions are only varied in discrete steps, such as with the condition “disturbed motorway layout”, in which an extra lane is included.

Two analyses are performed for each condition and technique:
1. a comparison of the average of the simulated travel time to the estimated travel time to identify any biases,
2. a comparison of the single observations of the simulated travel time to the estimated travel time of the nearest minute, to identify the effect of variation in observations.

Table 5.1 indicates the different groups of conditions involved in the evaluation. The table indicates in what way conditions are varied compared relative to the standard condition. This standard condition functions as a reference for the effect of a condition, and is defined as the most usual conditions.

<table>
<thead>
<tr>
<th>Scenario’s of conditions</th>
<th>Condition</th>
<th>Flow regime</th>
<th>Percentage slow traffic</th>
<th>Motorway layout</th>
<th>Time periods</th>
<th>Road sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Varying percentage</td>
<td>Low</td>
<td>Standard</td>
<td>Extra block</td>
<td>Standard</td>
<td>Standard</td>
<td></td>
</tr>
<tr>
<td>4 Varying motorway layout</td>
<td>Standard</td>
<td>Standard</td>
<td>Extra block</td>
<td>Standard</td>
<td>Standard</td>
<td></td>
</tr>
<tr>
<td>5 Varying time period</td>
<td>standard</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Varying road sections</td>
<td>standard</td>
<td>Standard</td>
<td>Standard</td>
<td>Short</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Varying multiple</td>
<td>Cong building</td>
<td>Standard</td>
<td>Long</td>
<td>Standard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: combinations of the standard conditions with variations in conditions
Experimental set-up
The experimental set-up consists of the following elements:
1. a traffic generator model, which generates traffic for obtaining experienced travel times, and inductive loop data;
2. implemented techniques, in which the estimated travel time is calculated;
3. an evaluation module, in which estimations are compared with the simulated observations.

Figure 5.2 illustrates the experimental set-up, in which both the developed DACCORD techniques, and as an extra model the dynamic travel time are evaluated.

Requirements for the traffic generator module
A traffic generator is basically a program that tracks vehicles along their route on a motorway. Different conditions can be simulated. The use of an existing program should guarantee that the traffic generator is sufficiently tested and realistic. The following requirements are defined for the traffic generator:
1. The model should at least have two vehicle types presenting fast and slow vehicles.
2. The model should be a microscopic model and be calibrated to the reality.
3. The user of the model should be able to specify the intensity at the start of the road stretch over time.
4. The input of the model should have the possibility to specify the percentage of slow traffic.
5. The input of the model should have the possibility to specify the road layout of the stretch.
6. The output of the model should have the possibility to calculate the travel time of individual vehicles, and the speed and intensity over any cross section at any time period.

Requirements on the implementation of the techniques
The techniques should be implemented in such a way that travel times for any time period can be calculated based on data from the traffic generator model. The following requirements are defined to the implementation of the techniques:
1. All estimation techniques of DACCORD should be implemented.
2. The techniques should be the exact implementations of the specifications of the techniques.
3. The travel time calculation should be based on the output of the traffic generator model.
4. The output of the travel time calculation should be travel time related to a start time.

Requirements for the evaluation module
The evaluation module compares data sets of travel times of an estimation technique to simulated travel times and expresses their differences in a performance indicators or visual illustration. The evaluation module should meet the following requirements:
1. The evaluation module should have the possibility to compare the simulated travel time with the travel time of any estimation technique.
2. The evaluation module should compute a limited number of indicators for the comparison of a technique to the simulated travel time, providing a maximum level of insight.
3. The results should be presented visually to identify the behaviour of the techniques under different conditions, and for the possibility to validate the results.

5.1.3 Traffic generator module (FOSIM)
This section specifies the different runs to be used with the traffic generator module, and to calculate the input needed for this module.
As traffic generator the probe version of the simulation model FOSIM 3.1 is used to generate vehicle trajectories.

Simulation model FOSIM
The simulation model FOSIM is a microscopic traffic flow model. The model calculates the position of each vehicle for each time step. The positions are first calculated downstream, because speed and distances are determined based on the position and speed of vehicles and the infrastructure ahead. In the calculations, random generators are used to model stochastic characteristics.
In FOSIM multiple vehicle types are implemented with different driving characteristics, such as the desired speed, mass, maximum acceleration etc. Intensities can be varied for each lane. Also the origin destination matrix of the vehicles for a lane can be varied. The maximum stretch for simulation is 8 lanes over 10 km. On- and off-ramps, maximum speeds, mandatory lane use, or traffic lights can be simulated as well.

Simulation runs
In section 5.1.2 the different simulation runs are defined. The simulation runs vary upon a simulation run of the standard condition, which is defined by Figure 5.3, and the remarks 1-6 with this table.
The following variables for the simulations are used as the standard situation:

1. The travel time for half the stretch for the congested case is about 8 minutes, the free-flow travel time is about 3 minutes. The total simulation duration is set to 2100 seconds starting collecting data at 300 seconds to obtain a stable initial traffic condition. The time step for the calculation of the position of the vehicles is 1 second.

2. Within FOSIM five vehicle types are defined from slow trucks to fast persons cars, with different desired speed, acceleration etc. For the standard situation a percentage of trucks of 10% is used.

3. The time periods for data collection are set to 60 seconds, as this is the median of the time periods at the sites (Fr: 30; NL: 60; IT: 300).

4. The average section length is set to 500 as this is representative for the sites (Fr: 500; NL: 300; IT: 1000). The section length is not constant but is varied between 200 and 750 m. The total length of the simulation stretch is 5000 m.

5. Identical intensities for the three lanes vary over time to obtain different flow regimes during the simulation. The performance indicators are not calculated for each flow regime separate, but with graphs the effect between estimated and observed travel times should be visible. Separate runs were performed for the individual flow regimes to get insight in the behaviour under a specific flow regime.

6. The micro simulation model FOSIM needs single lanes at the start of the section, because otherwise the generation of vehicles is not performed as specified. The length of the single lane section is set to 300 meter based on the graph in appendix E ‘FOSIM generator’.

Based on the description of the different conditions in section 5.1.2 the following runs are specified as in Table 5.2.
Evaluation of travel time estimation techniques

### Simulation based quantitative analysis

#### Scenario's of conditions

<table>
<thead>
<tr>
<th>Scenario's of conditions</th>
<th>Road layout</th>
<th>Section lengths (m)</th>
<th>Time periods (s)</th>
<th>Percentage slow traffic (%)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Standard</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>2 Free-flow</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Low 2</td>
</tr>
<tr>
<td>3 Cong. Building</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Rising 1</td>
</tr>
<tr>
<td>4 Congestion</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>High 1,2</td>
</tr>
<tr>
<td>5 Cong. Resolving</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Lowering 1,2</td>
</tr>
<tr>
<td>6 Road work / incident</td>
<td>Extra block</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>7 Road layout</td>
<td>Extra ramp</td>
<td>500</td>
<td>60</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>8 Section length 1</td>
<td>Standard</td>
<td>1000</td>
<td>60</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>9 Section length 2</td>
<td>Standard</td>
<td>200</td>
<td>60</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>10 Length time period 1</td>
<td>Standard</td>
<td>500</td>
<td>120</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>11 Length time period 2</td>
<td>Standard</td>
<td>500</td>
<td>300</td>
<td>10</td>
<td>Standard</td>
</tr>
<tr>
<td>12 Perc. slow traffic 1</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>5</td>
<td>Standard</td>
</tr>
<tr>
<td>13 Perc. slow traffic 2</td>
<td>Standard</td>
<td>500</td>
<td>60</td>
<td>25</td>
<td>Standard</td>
</tr>
<tr>
<td>14 Cong. build + section</td>
<td>Standard</td>
<td>1000</td>
<td>60</td>
<td>10</td>
<td>Rising</td>
</tr>
<tr>
<td>15 Cong. build + time</td>
<td>Standard</td>
<td>500</td>
<td>300</td>
<td>10</td>
<td>Rising</td>
</tr>
<tr>
<td>16 Section + time</td>
<td>Standard</td>
<td>1000</td>
<td>300</td>
<td>10</td>
<td>Standard</td>
</tr>
</tbody>
</table>

Table 5.2: Specification simulation runs

1) The values for the intensities for the different flow regimes were found by experiment.
2) The data collection with the flow regimes congestion, and congestion resolving starts at 600 in stead of 300 to obtain an initial congestion level.
3) The ramp is placed on an extra lane. The total flow is kept equal by using half the intensity of the most left lane to the onramp. The percentage of trucks is kept the same for the onramp.
4) The inductive loops are placed on the following co-ordinates: 500, 1250, 2600, 3400, 4000, 4999.
5) The inductive loops are placed on the following co-ordinates: 300, 500, 900, 1250, 1500, 1700, 1900, 2200, 2300, 2600, 2800, 3000, 3150, 3400, 3700, 4000, 4500, 4700, 4999.
6) An incident is simulated as a extra lane blockage. This is also used to simulate road works.

### Travel time computation

An output file of FOSIM is a list of vehicles present at the stretch with probe number and position for each second. If a vehicle is present for the first time also the time step of generation is included.

A Matlab program was developed that computes the number of times a vehicle is in the list and combines this with initial generation period. Then each observation consists of the start time and the travel time which has a two second maximum error. For a minimum travel time of 144 seconds this is an acceptable error.

This Matlab program also extracts the time-mean speed per period at prespecified detector locations and time periods. The speed computed with this procedure corresponds with the arithmetic average of the individual vehicle speeds over a detector. Also the intensity per period is filtered by the Matlab program. The listing of the Matlab program is included in appendix F ‘Speed and travel time computation’. The main program is included in appendix L ‘Main evaluation program’.

#### 5.1.4 Implementation of techniques

Before, the techniques can be implemented in a simulation model some choices have to be made on the exact specifications, because not all elements were specified. The exact specifications of the various techniques are described in this section based on the
specifications in the appendixes (see appendix B and C). For the formulae of the various techniques there is referred to chapter 4 'qualitative analysis'.

The following remarks are made concerning all techniques:
• \( L_{k}, V_{A,k}(p), V_{B,k}(p), I_{A,k}(p), I_{B,k}(p) \) are known for all sections for all time periods.

**Instantaneous travel time estimator**
No extra specifications were made.

The simulation program is included in appendix G ‘Instantaneous travel time program’.

**Weighted instantaneous travel time estimator**
The following extra specifications were made:
• For \( k \) the value 3 is used.
• For the flow on a section the outflow for the section is implemented.

The simulation program is included in appendix H ‘Weighted instantaneous travel time program’.

**Short road section travel time estimator**
The following extra specifications were made:
• Since \( \beta_{\text{max}} \) was not specified, the value 0.3 is used (\( 0 < \beta_{\text{max}} < 0.5 \)).
• Since \( \gamma_{\text{max}} \) was not specified, the value 0.6 is used (\( 0 < \gamma_{\text{max}} < 1 \)).
• For the first time period the \( N_{\text{density}} \) was used for the \( N_{\text{density}} \).

The simulation program is included in appendix I ‘Short road section-level travel time program’.

**Long road section travel time estimator**
The following extra specifications were made:
• If no congestion is detected the long road section travel time estimator defines the travel time as the free-flow travel time. As this travel time is constant and therefore inaccurate, the travel times estimator is combined with the instantaneous travel time estimator with a factor \( \alpha \), depending on the speed.
• To be able to implement \( T_{\text{flow}} \) for long sections on the used stretch the stretch must be split up in equal sections close to the travel time of whole minutes as the free-flow travel time is used in the algorithm in whole minutes. The stretch was split up in three equal sections of about 1700 m (0, 1700, 3400, 4999), which is the average distance travelled for one minute under free-flow conditions.
Evaluation of travel time estimation techniques

- No correction function is needed for this situation in which all vehicles are counted, including on on-ramps.
- For the first time period the number of vehicles on the section 'numveh' is assumed to be equal to the inflow of the first minute.
- Since, only three sections with 60 seconds interval are implemented for the long road section travel time estimator the conditions for different section lengths and time periods lengths are not applicable.

The simulation program is included in appendix J ‘Long road section-level travel time program’.

Dynamic travel time estimator
No extra specifications were made:

The simulation program is included in appendix K ‘Dynamic travel time program’.

5.1.5 Evaluation module
This section identifies the performance indicators and visualising techniques for the evaluation of the estimation techniques compared to the observations. The indicators and visualisation techniques should give information on the bias and lag of estimation of the techniques under different conditions. The evaluation is performed for sets of the simulated travel time with the estimated travel time.

Visualising technique
The travel time versus time is used as a visualisation method, with the travel time of various techniques and the simulated TT in one graph. With this approach the behaviour of various techniques can be compared to the simulated travel time, and to each other.

Scatter plots of the estimated travel time versus the observed travel time are also used to identify the behaviour of the various techniques. The scatter plots show a line under 45 degrees which presents the perfect estimate. A circular cloud around this line indicates a lag (see Hoogendoorn, 1997).

Because, the simulated travel time, and the dynamic travel time can not be calculated for the last few time periods, the plots ends at different moments for different techniques. The performance indicators are only calculated for the complete set of simulated travel time and estimated travel time by a technique.

Performance indicators
Performance indicators describe the quality of the estimation. They are determined from the differences between estimations and simulated travel times. Two classes of performance indicators are used:

- those computed for each time period comparing the estimated travel time relative to the average simulated travel time,
- those computed for each individual simulated vehicles comparing the estimated travel time relative to the simulated travel time.

---

1 This section is based on the note assessment of travel time estimations and predictions (Hoogendoorn, 1997).
An important difference between these classes is that the second class emphasizes on periods in which many vehicles depart.

For all performance indicators the following statements are used:
- Averaging by the length improves the potential to compare between roads of different section lengths. The absolute performance of the techniques is expressed in deviations per meter instead of per trip.
- Averaging by the number of time periods enables comparing performances with different number of time periods.

Definitions
The following definitions are used:
- \( T^{\text{mod}}(p) \) estimated travel time for period \( p \)
- \( T^{\text{sim}}(p) \) averaged simulated travel time for cars departing in period \( p \)
- \( t^{\text{sim}}(k) \) simulated travel for vehicle \( k \)
- \( L \) length of the route
- \( P \) number of periods
- \( K \) number of observations of simulated travel time
- \( p(k) \) period in which vehicle \( k \) departs

The following performance indicators are proposed:
- An indicator conveying the mean error of the travel time estimate:
  \[
  \text{ME}_{\text{average}} = \frac{1}{L \times P} \sum_{j=0}^{p} \left( T^{\text{mod}}(p) - T^{\text{sim}}(p) \right) \] s/m (5.1)
  \[
  \text{ME}_{\text{single}} = \frac{1}{L \times K} \sum_{k=0}^{K} \left( T^{\text{mod}}(p(k)) - t^{\text{sim}}(k) \right) \] s/m (5.2)
  Note that the mean error may be zero, while the estimates show large fluctuations around the reference travel times. The ME indicates the average bias over one meter.
- To provide means for comparative analysis the mean error, proportional to the reference travel time is introduced:
  \[
  \text{MEP}_{\text{average}} = \frac{1}{L \times P} \sum_{j=0}^{p} \left( \frac{T^{\text{mod}}(p) - T^{\text{sim}}(p)}{T^{\text{sim}}(p)} \right) \] 1/m (5.3)
  \[
  \text{MEP}_{\text{single}} = \frac{1}{L \times K} \sum_{k=0}^{K} \left( \frac{T^{\text{mod}}(p(k)) - t^{\text{sim}}(k)}{t^{\text{sim}}(k)} \right) \] 1/m (5.4)
- To study the average fluctuations of the travel time, the mean squared error per kilometre per minute is determined:
  \[
  \text{MSE}_{\text{average}} = \frac{1}{L \times P} \sum_{j=0}^{p} \left( T^{\text{mod}}(p) - T^{\text{sim}}(p) \right)^2 \] s²/m (5.5)
  \[
  \text{MSE}_{\text{single}} = \frac{1}{L \times K} \sum_{k=0}^{K} \left( T^{\text{mod}}(p(k)) - t^{\text{sim}}(k) \right)^2 \] s²/m (5.6)
- Finally, the mean absolute error per kilometre minute and the mean proportional absolute error are determined:
  \[
  \text{MAE}_{\text{average}} = \frac{1}{L \times P} \sum_{j=0}^{p} \left| T^{\text{mod}}(p) - T^{\text{sim}}(p) \right| \] s/m (5.7)
Evaluation of travel time estimation techniques

5.1 Simulation based quantitative analysis

The MAE indicates the average deviation in the travel time over one meter.

The Evaluation module is included in appendix M ‘Evaluation module’.

Some experiments were performed to get insight in the size of these indicators. To identify the deviations the 95% upper and lower limits were computed by a spreadsheet program. Figure 6.9 shows each observation of travel time within the simulation study. Both a line presenting the 95% upper and lower limit were added by a lines computed as 1.96 times the variation compared to the moving average over 20 observations. These limits are represented by a continues thin line. The upper and lower limit are smoothed by a moving average over 40 observations, represented by a thick line.

![Figure 5.4: Travel time of all observations with 95% upper and lower limit](image)

The variation of the observations is large with a small number of vehicles or during congestion building. It is small with a large number of observations or during congestion resolving. With the evaluation of travel time with real observations this effect has to be taken into account.

5.2 Validation of the simulation model

The objective of the validation is to check if the results of the simulation model are realistic. For certain circumstances the estimated travel time should be equal to the average of the observed experienced travel time. For homogeneous circumstances, this should be the case for all techniques. For inhomogeneous conditions deviations can occur between the

\[
MAE_{\text{single}} = \frac{1}{L \cdot K} \sum_{k=0}^{K} \left| T_{\text{mod}}(p(k)) - T_{\text{sim}}(k) \right| \quad \text{s/m} \quad (5.8)
\]

\[
MAE_{\text{average}} = \frac{1}{L \cdot P} \sum_{j=0}^{P} \frac{\left| T_{\text{mod}}(p) - T_{\text{sim}}(p) \right|}{T_{\text{sim}}(p)} \quad \text{l/m} \quad (5.9)
\]

\[
MAE_{\text{single}} = \frac{1}{L \cdot K} \sum_{k=0}^{K} \left| T_{\text{mod}}(p(k)) - T_{\text{sim}}(k) \right| \quad \text{l/m} \quad (5.10)
\]
techniques, but the dynamic travel time should be very close to the averaged observations under all circumstances.

The findings in the simulation study for congestion building stated that also the dynamic travel time has a lag compared to the observed travel time.

If the dynamic travel time corresponds to the observations, it is proven that the simulation model functions well, and it can be assumed that the other techniques are correctly implemented as well. The following analysis are performed to cover the most important reasons for possible deviations:

1. An analysis of the method of computation of both the dynamic travel time and observations, including the analysis of the origin of the used data (section 5.2.1).
2. An analysis on the effect of different section lengths and time interval duration (section 5.2.2)
3. An analysis of the typical limitations of data gathering based on detectors (section 5.2.3).

One other important reason for invalid results is the use of the harmonic mean speed instead of an arithmetic mean speed. This reason for invalid results was not analysed.

5.2.1 Computation procedures

To validate the computation procedures first the origin of the data is analysed. Figure 5.5 shows which data is used for a detector for a time interval. The various techniques use the data of the two detectors at the start and the end of a section differently.

![Time distance diagram with origin detector data](image)

The arithmetic time-mean speed is computed as the arithmetic mean of the individual speeds at the start of the section over a time period. This speed is used to represent the speed of this time period for the section around the detector. The available information is therefore used correctly within the calculations.

To validate the computation procedures of the techniques and the simulated travel time, two methods (the dynamic TT, simulated TT) were implemented based on another programming procedure. The results based on the same input are exactly the same for the two programs. The listing of this second techniques is included in the appendix N ‘Alternative travel time computation program’. The two methods are either both correctly implemented or both wrongly implemented.
The average of the experienced travel time is calculated within the travel time computation program and is validated by a centred moving average over 20 time steps by a spreadsheet program, as shown in Figure 5.6.

The calculated average is very close to the moving average of the observations. Only with fast changes, and with a low number of observations the moving average shows a lag, which can be expected. The calculated average is a good approximation of the average of the simulated travel time.

The dynamic travel time is also calculated based on another procedure. The listing is included in 'Alternative dynamic travel time program'. The results of the two independently implemented dynamic travel time computation programs are identical, and therefore it is very likely that the dynamic travel time program is correct.

5.2.2 Section length and time period duration

A reason for the lag compared to the observations could be a too large average section length or too long time period duration. Figure 6.5 shows the dynamic travel time for decreasing section length and time period durations.
5.2.3 Average speed of detectors and time moments

Measurements of the traffic are based on the data collected by detectors, which results in data on the speed and intensity for a location, and time interval. It is not possible to measure traffic data for a time moment for a specific space interval. The information for a section for a time interval is not optimal as is shown in the example in Figure 5.8.

Figure 5.7: Travel time dynamic TT for different section lengths and time period lengths

The bias between the dynamic travel time even with small section lengths and time periods duration is still present. Further decreasing the section length and time period duration would lead to unreliable results because of decreasing sample size.
Approximating the time-space-mean speed with a combination of both the space-mean and time-mean speed would be the most accurate way to compute the average time-space mean speed for a section in a time interval. This is one of the conclusions of the qualitative analysis in chapter four. In reality only traffic data from the detectors are available, but with a simulation program it is also possible to extract the average speed at a time moment. This makes it possible to compute an average based on the speeds at detectors and the speeds at time moments as shown in Figure 5.9.

\[ T = \frac{V_{A_1,A_2} \cdot N_{A_1,A_2} + V_{B_1,B_2} \cdot N_{B_1,B_2} + V_{A-B,1} \cdot N_{A-B,1} + V_{A-B,2} \cdot N_{A-B,2}}{N_{A_1,A_2} + N_{B_1,B_2} + N_{A-B,1} + N_{A-B,2}} \]  

This algorithm could not be implemented and equation (5.12) was used instead.

\[ T = \frac{\frac{1}{2} \cdot L + \frac{1}{3} \cdot L + \frac{1}{4} \cdot L}{V_{A_1,A_2} + V_{B_1,B_2} + V_{A-B,1} + V_{A-B,2}} \]  

Figure 5.10 shows the results of the standard dynamic travel time compared to the simulated travel time, and the results of the special dynamic travel time, which was calculated based on equation (5.12) based on both data of detectors and of time moments.
The results of the dynamic TT based on both detector information and time moments is better with long sections and time periods. The effect of the extra input is marginal. With small time periods and sections the two methods converge to each other. The expected improvements towards the simulated travel time are not present.

5.2.4 Conclusions on the validation of the simulation model

The following statements conclude on the validation of the simulation programs.

- The speed for a time moment for a detector is the average of the speeds at the detector from that time moment until the following time moment. This average speed is used to represent the speed of this time period for the section around the detector. The available information is therefore used correctly within the calculations.
- The bias between the dynamic travel time even with small section lengths and time intervals is still present. With even smaller sections and time intervals the number of observations will be that small that a high variation can be expected, which results in inaccurate estimates.
- The results of the dynamic TT based on both detector information and time moments is better with long sections and time periods. The effect of the extra input is marginal. With small time periods and sections the two methods converge to each other. The expected improvements towards the simulated travel time are not present.
The difference in dynamic travel time and simulated travel time could be explained by the difference in use of the harmonic and arithmetic mean of the observed speeds at a detector. It is recommended that this is subject for further research. When variations become high the dynamic travel time shows a bias towards the simulated travel time as in Figure 5.6. It is reasonable to believe this is caused by the difference in the harmonic and arithmetic mean. If further research should learn that the use of harmonic average speed leads to a substantial decrease of the difference between dynamic travel time and simulated travel time the following conclusions can be drawn.

- The simulation model, the implementation of the techniques, and the evaluation module function all as specified.
- The difference in using the harmonic or arithmetic mean is substantial, especially under changing flow conditions. The travel time computed with the use of the arithmetic mean-speed under estimates the realistic travel time.

Last remark is that the congestion building is unrealistically high with a change in intensity from 500 to 2000 vehicles per hour in 5 minutes. In reality this increase is much smaller and the deviations will be much smaller as well.

5.3 Experimental results

The objective of this section is to evaluate the performance of the estimation techniques. This evaluation is based on the performance indicators compared to the simulated travel time for each technique for each condition. In addition to the performance indicators, graphs with the travel time of multiple techniques clarify the performance of the techniques under different conditions. Also the effect of changes in the conditions are taken into account. Based on the performance indicators and the graphs, conclusions can be drawn on the absolute and relative performance of the techniques. The techniques are evaluated per condition, because this enables assessing the relative performance. The dynamic travel time is also included in the evaluation. This technique is considered as a possible basis for extending the measured observations based on the results of the qualitative analysis in chapter 4.

5.3.1 General remarks on evaluation results

With the presentation of the results basically three graphical means are used:

- Travel times as a function of time with estimated results of the various techniques,
- Scatter plots of the estimated travel time versus observed travel time.
- Tables with performance indicators for the various techniques.

Travel time as a function of time

The graphs present the estimated travel time for a time interval for various techniques. A dot in the graph means the estimated travel time for a vehicle departing on that particular time moment according to one specific technique. Lines connect the dots to identify the behaviour of the technique over time. The conclusions, which can be drawn from the graph, concern the relative performance of the various techniques towards the simulated travel time.
Estimated travel time versus observed travel time

The graphs present points with the ratio between estimated travel time and the observed travel time. This ratio should be one for a perfect estimate. So, the perfect estimate is indicated by a line in the graph from the origin under 45 degrees. If a techniques has a bias the points form a circular cloud around this line.

Table with performance indicators

The tables present the computed performance indicators for the various techniques for one specific condition. Both the performance indicators relative to the averaged observations (equations (5.1), (5.3), (5.5), (5.7), and (5.9)) as to the single observations (equations (5.2), (5.4), (5.6), (5.8), and (5.10)) are included.

For each performance indicator, columns present the calculated values for each technique. Each indicator is accompanied by a value displaying the multiplying factor towards the absolute value. This absolute value can be used to express the bias or variation in meters.

5.3.2 Evaluation of the standard condition

Evaluation of the standard condition indicates the relative performance of the techniques under common conditions. The standard situation is used as a baseline for the evaluation of the effect of different conditions. The following tables show the performance indicators of the different techniques compared to the simulated travel time.

![Figure 5.11: Travel times of the standard condition](image-url)
Evaluation of travel time estimation techniques

Standard condition

![Graph showing performance indicators of the standard condition](image)

**Table 5.3: Performance indicators of the standard condition**

![Graph showing scatter plot of observed versus estimated travel time of the standard condition](image)

**Figure 5.12: Scatter plot of observed versus estimated travel time of the standard condition**
The scatter plot indicates that the dynamic travel time is a very good estimate as it is close to the line. The instantaneous and weighted instantaneous travel time both show a circular cloud around the line starting from the free-flow travel time, which corresponds with a lag.

Table 5.4 presents the main remarks related to the ‘standard condition’.

<table>
<thead>
<tr>
<th>Condition:</th>
<th>standard condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>General remarks</td>
<td>Except for the dynamic travel time estimator all techniques follow the simulated TT with a delay when the travel time increases. The techniques react differently when the travel time decreases.</td>
</tr>
<tr>
<td>Remarks on absolute performance</td>
<td>All techniques, except for the dynamic travel time estimator, estimate the travel time both above and below the simulated travel time, as the ME is smaller than the MAE. But, all techniques under estimate the simulated travel time during most periods, as the ME is negative.</td>
</tr>
</tbody>
</table>
| Remarks on relative performance | In terms of MSE and MAE the dynamic TT performs as best techniques with a small MSE, even though there is a relative high ME.  
| | The weighted instantaneous TT performs worst of the techniques. It has the highest MSE, and MAE. |
| Sensitivity to evaluation criteria | When the performance is measured using single observations (see Table 5.3), the relative performance does not change.  
| | As expected the absolute performance volume of all error indicators increase if single observations are used. |

The following conclusions can be drawn on the performance related to single observations:
- The performance indicators for all techniques are much alike if related to single observations.
- The relative performance of the techniques is very similar from with the averaged observations.

### 5.3.3 Evaluation of constant flow regimes

Evaluation under constant flow regime enables the comparison of the performance of the techniques under different flow conditions. The following tables show the performance indicators of the different techniques compared to the simulated travel time (watch for the scale).
Evaluation of travel time estimation techniques

Simulation based quantitative analysis

Free-flow condition

Figure 5.13: Travel times of the freeflow condition

Scatter diagram with freeflow

Figure 5.14: Scatter diagram with the freeflow condition
Evaluation of travel time estimation techniques

Simulation based quantitative analysis

Figure 5.15: Travel times of the congestion condition

Figure 5.16: Scatter diagram with the congestion condition
Evaluation of travel time estimation techniques

Simulation based quantitative analysis

Freeflow and congestion

Table 5.5: Performance indicators of the free-flow and congestion conditions

<table>
<thead>
<tr>
<th>Condition:</th>
<th>Constant flow regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>General remarks</td>
<td>• All techniques follow the free-flow and congestion situation relatively accurate. Variations are higher under congestion than under free-flow.</td>
</tr>
<tr>
<td>Remarks on absolute performance</td>
<td>• All techniques estimate the travel time very accurate during free-flow conditions. Under congestion the performance is somewhat worse.</td>
</tr>
</tbody>
</table>
| Remarks on relative performance | • The dynamic TT performs worst of all techniques under free-flow, although still with a very small deviation.
• The long section TT performs worst under congestion. The deviation is relative high compared to the other techniques. The travel time is estimated below the simulated TT. |

Table 5.6: Remarks on the condition 'constant flow regime'

The following remark is made on the performance related to single observations:
• The performance indicators for all techniques are comparable to the indicators of the averaged observations. This means that the variation of the observed travel times was small.

5.3.4 Evaluation of changing flow regimes

Evaluation under varying flow regimes indicates the performance of the techniques under different flow conditions. The following tables show the performance indicators of the different techniques compared to the simulated travel time.
Figure 5.17: Travel times of the congestion building condition

Figure 5.18: Scatter diagram with the congestion building condition
Evaluation of travel time estimation techniques

Simulation based quantitative analysis

Congestion resolving

Figure 5.19: Travel times of the congestion resolving condition

Table 5.7: Performance indicators of the congestion resolving condition

Table 5.8 presents the main remarks related to the 'constant flow condition'.
Evaluation of travel time estimation techniques

Table 5.8: Remarks on the condition 'changing flow regime'

<table>
<thead>
<tr>
<th>Condition:</th>
<th>Changing flow regimes</th>
</tr>
</thead>
</table>
| General remarks | • All techniques follow the simulated TT with a lag during congestion building. The techniques follow quite accurate during congestion resolving.  
• Differences based on single and averaged observations are small. |
| Remarks on absolute performance | • All techniques estimate the travel time below the travel time during congestion building, as the ME is negative, and equal to the MAE.  
• All techniques, except for the long section TT, estimate the travel time accurate to the simulated TT during congestion resolving, as the MAE, and MSE are relatively small. |
| Remarks on relative performance | • The dynamic TT performs as the best of the techniques under congestion building with a small MSE, and MAE. The long section TT performs as the worst.  
• Under congestion resolving differences are small, except for the log section TT, which has a relatively bad performance. |

5.3.5 Evaluation of the road layout

Evaluation of the road layout regime indicates the performance of the techniques under a different road layout, and road works/incidents. The following tables show the performance indicators of the different techniques compared to the simulated travel time.

Figure 5.20: Travel times of the motorway layout condition
"Standard" road layout, disturbed road layout, and road works/incidents

Table 5.9: Performance indicators with road works

<table>
<thead>
<tr>
<th>Condition:</th>
<th>Road layout</th>
</tr>
</thead>
</table>
| General remarks           | • The impact of the road works is very high on the travel time, specially compared with the effect of a disturbed motorway layout, which has a small impact. The impact on the performance of the estimation techniques is high if the deviation in travel time is high.  
• Differences based on single and averaged observations are small. |
| Remarks on absolute       | • All techniques estimate the travel time under the disturbed motorway layout comparable accurate as with the standard condition.  
• The deviations are much higher with the road works condition, in which the travel time rises to very high levels. Under this conditions the performance is very bad as well. |
| performance               |                                                                           |
| Remarks on relative       | • Under a disturbed motorway layout the performance of the techniques is comparable to the performance of the standard condition.  
• The weighted instantaneous TT performs as the worst of the techniques under the condition road. |
| performance               |                                                                           |

Table 5.10: Remarks on the condition 'changing flow regime'
5.3.6 Evaluation of the percentage of slow traffic

Evaluation of the percentage slow traffic indicates the performance of the techniques under different percentages slow traffic. The following tables show the performance indicators of the different techniques compared to the simulated travel time.

Percentages of slow traffic

<table>
<thead>
<tr>
<th>Percentage of slow traffic</th>
<th>ME average</th>
<th>MAE average</th>
<th>MSE average</th>
<th>MAPE average</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.21: Travel times of the percentages of slow traffic condition

Table 5.11: Performance indicators with various percentages of slow traffic

Table 5.12 presents the main remarks related to the 'percentage of slow traffic'.
Evaluation of travel time estimation techniques

<table>
<thead>
<tr>
<th>Condition:</th>
<th>Percentage of slow traffic</th>
</tr>
</thead>
</table>
| General remarks            | • The impact of the percentage of slow traffic on the travel time is quite high. With the growing variation in travel time, there is also a worsening of the performance of the techniques  
• Differences based on single and averaged observations are small. |
| Remarks on absolute       | • All techniques perform worse with a higher percentage of slow traffic.                   |
| performance                |                                                                                           |
| Remarks on relative       | • The techniques perform differently to each other with different percentages of slow traffic.  
• With a low percentage of slow traffic the long section TT performs very good to the dynamic TT, which performs as the best for all percentages.  
• With a high percentage of slow traffic the instantaneous TT and the long section TT perform comparable to each other and better than the short and long section TT |
| performance                |                                                                                           |

Table 5.12: Remarks on the condition 'percentage of slow traffic'

5.3.7 Evaluation of the section length

Evaluation of the section length indicates the performance of the techniques with different distances between the inductive loops. The following tables show the performance indicators of the different techniques compared to the simulated travel time. The technique long road section travel time is not included, because this has a constant number of sections necessary for the implementation of this technique.

Figure 5.22: Travel times of the section length condition
Table 5.13: Performance indicators with various average section lengths

Table 5.14: Performance indicators of averages and single observations with average section length of 1000 meters
Table 5.15 presents the main remarks related to the ‘section length’.

<table>
<thead>
<tr>
<th>Condition:</th>
<th>section length</th>
</tr>
</thead>
<tbody>
<tr>
<td>General remarks</td>
<td>• The impact of the section length is very small and is even a little better with larger sections.</td>
</tr>
<tr>
<td>Remarks on absolute performance</td>
<td>• All techniques estimate comparable under different section lengths. The performance of the estimations under different section lengths is comparable to the performance of the standard condition.</td>
</tr>
<tr>
<td>Remarks on relative performance</td>
<td>• All techniques perform comparable to each other with different section lengths. The performance of the estimations techniques to each other is comparable to the performance of the techniques to each other under standard conditions</td>
</tr>
</tbody>
</table>

Table 5.15: Remarks on the condition ‘section length’

The following conclusions can be drawn on the performance related to single observations:
• The performance indicators for all techniques have a lower ME with the single observations compared to the averaged observations as shown in Table 5.14. This means that there are some very small travel times.

5.3.8 Evaluation of the time period duration
Evaluation of the time period duration indicates the performance of the techniques with different time periods for data collection. The following tables show the performance indicators of the different techniques compared to the simulated travel time. The technique short road section travel time is not included, because there is a standard number of time periods to be able to implement this technique.

![Figure 5.23: Travel times of the time period length condition](image)
Table 5.16: Performance indicators with various time period lengths

Table 5.12 presents the main remarks related to the ‘time period duration’.

<table>
<thead>
<tr>
<th>Condition:</th>
<th>Time period duration</th>
</tr>
</thead>
</table>
| General remarks | - The impact of the length of the time period is not very high. The performance is a little better with small time intervals.  
- Differences based on single and averaged observations are small. |
| Remarks on absolute performance | - All techniques estimate a lower travel time compared to the simulated TT with an increasing length of the time period. The MAE stays about constant, or becomes smaller for the instantaneous TT and weighted instantaneous TT, while the ME becomes larger |
| Remarks on relative performance | - The techniques perform differently to each other with different time period lengths. With small time period lengths the dynamic TT performs as the best. With larger time period lengths the instantaneous and weighted instantaneous TT perform as the best. |

Table 5.17: Remarks on the condition ‘time period duration’

5.3.9 Evaluation of combined conditions

Evaluation of the combined conditions indicates the performance of the techniques with some combined conditions. The following tables show the performance indicators of the different techniques compared to the simulated travel time. The technique short road section
travel time is not included, because there is a standard number of sections and time periods to be able to implement this technique.

Figure 5.24: Travel times of the combined section length and time period length

Table 5.18: Performance indicators of the combined section length and time period length
Evaluation of travel time estimation techniques

Simulation based quantitative analysis

Figure 5.25: Travel times of the combined flow condition with section length or time period length

Table 5.19: Performance indicators of the combined flow condition and section length or time period length