Traffic-flow models

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TRAFFIC-FLOW MODELS

State of the Art report

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CONTENTS

FOREWORD

In SWOV, research is divided into Policy-preparing research, Evaluation research and Basic research.
Basic research is indirectly relevant to policy because it gathers knowledge which the first two types of research make use of. In general terms, basic research comprises activities which, without policy measures being directly contemplated, are needing for defining the road-safety problem, making forecasts, setting priorities, improving research methods and theory formulation for the benefit of future research.

One of SWOV's basic-research projects is "Traffic-flow models". It is focused on the interactions between the various driver-vehicle elements as expressed in vehicle movements. The interactions are defined and put in manageable terms by means of traffic-flow models. Vehicle movements, combined in this project into traffic-flow characteristics, depend on the traffic volume wanting to use a given facility at a given moment, characteristics of drivers, vehicles and roads and the circumstances. Countermeasures can be aimed directly at vehicle movements or can influence them via these factors. Traffic-flow characteristics or specific changes in them can also be related to traffic-quality aspects including road safety. In this way, a model is obtained that deals with the relationship between countermeasures and changes in quality aspects via the intermediate stage of vehicle movements.
Vehicle interactions occur when vehicles are in each other's proximity and their importance increases with the traffic volume. This applies to a large part of the Dutch roads system and makes traffic-flow research increasingly relevant.

The literature contains much information on traffic-flow models, but it is not arranged systematically. The few reviews existing on this subject are unsuitable for indicating the importance of this knowledge for road-safety research. It was therefore decided to survey this subject by means of a literature study emphasising as much as possible its relevance to road-safety research. This study resulted in an extensive State of the Art report drawn up by H. Botma (formerly Department of Pre-Crash Research, SWOV, now Delft University of Technology).

This booklet contains the complete text of Part I and X of the State of the Art report; further it also contains an index of all the literature referred to in the report, listed according to subject matter. Complete translations of other parts are not available at present. Should there be interest in one or more other sections, these could be translated as well.

Voorburg, 1980
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1. TRAFFIC-FLOW MODELS PROJECT

1.1. Place and description

Road traffic can be looked at in different ways. An arrangement of subjects which can broadly indicate the place of traffic-flows has been presented by Asmussen (1976), see Figure 1. The following will clarify this diagrammatic representation of the traffic process. Individual social activities bring about a demand for transportation. Whether a demand results in a trip depends on the extent to which the trip is deemed necessary and on the supply of facilities and the limitations. A trip goes together with a number of choices which can be arranged in a four-tier hierarchy. At the first level, the individual selects his destination and time of arrival, at the second the transport mode, at the third the route and timetable and at the fourth the manoeuvre. The behaviour of the individuals together is called the "sum-total" behaviour. In especial at the fourth level carrying out the manoeuvre is expressed in vehicle movements, the "sum-totals" of which are known as traffic-flows.

A variety of characteristics can be distinguished in traffic-flows, such as volume, average speed and speed distributions, headways and travel times. The descriptions of the relationships between the various traffic-flow characteristics are known as "traffic-flow" models. But the "Traffic-flow models" project is not limited to this but is wider in its scope. This can be illustrated with a diagram (See Figure 2), which like the previous one is a specification for this project of a more general diagram of Asmussen's (1976).
The demand for transportation in this diagram is envisaged at the third level of the previous diagram, i.e. as an allocation of sets of trips to road systems. In addition to demand, the factors road characteristics, vehicle characteristics, driver characteristics and the circumstances influence vehicle movements and hence the vehicle-flow characteristics and models as well. Vehicle characteristics for present purposes are defined solely as the permanent ones, such as vehicle type, dimensions and braking capacity, and not the variables reflected in vehicle movements. Countermeasures can influence vehicle movements via the first four factors, and directly as well. An example of the latter is speed limits. Circumstances are factors such as rain, fog and darkness, which on the whole cannot be directly influenced with countermeasures. Yet the adverse effect of some circumstances on vehicle movements can be counteracted by modifying factors that are capable of manipulation. An example is the installation of road lighting, which can be looked upon as a modification of road characteristics.

Demand for transport, facilities and limitations

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Individual traffic behaviour	"Sum-total" behaviour
Choice of destination Choice of arrival time	Journey output, journey attraction, journey distribution
Choice of transport	Model split, i.e. distribution of travellers over different forms of transport
Choice of route Choice of timetable	Allocation of sets of journeys to road systems
Choice of manoeuvre	Traffic-flows

Figure 1. Diagrammatic representation of the traffic process (Source: Asmussen, 1976).

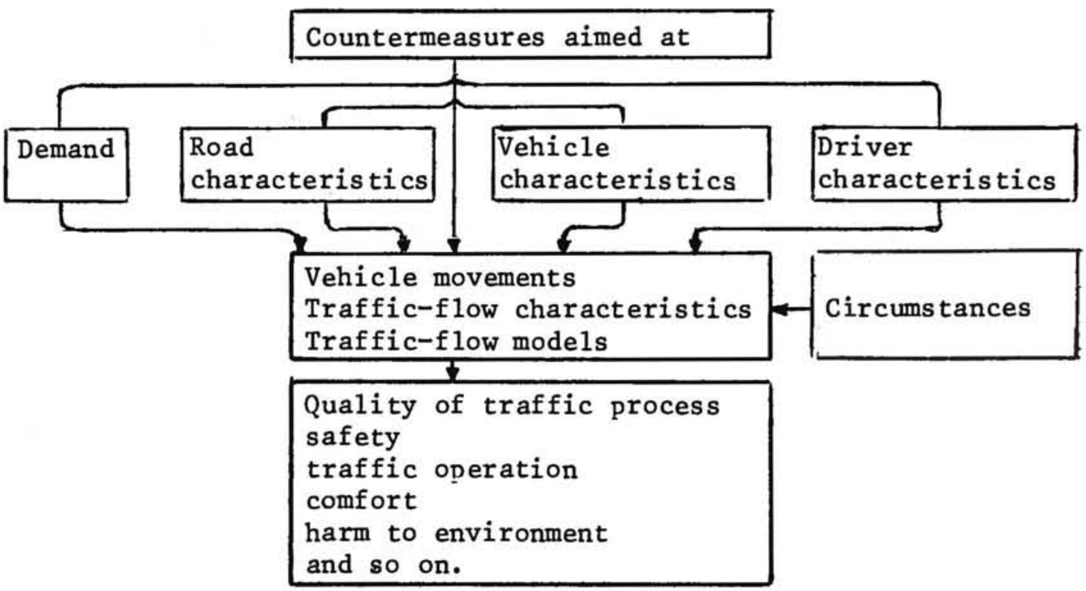

Figure 2. Diagrammatic representation of the "Traffic-flow models" project (Source: Asmussen, 1976).

An important part of the project is also the relationship between traffic-flow characteristics and quality aspects of the traffic process, including the degree of safety. In the final analysis it is a question of the relationship between countermeasures and quality modifications, in order to predict what steps have to be taken to achieve a specific quality. The approach by way of the "Traffic-flow models" project is one means of obtaining a knowledge of the process taking place between countermeasure and quality modification.

1.2. Object

The object of SWOV's road-safety research is to gather knowledge useful for road-safety measures, and this applies equally to the "Traffic-flow models" project. The measures relate to improved versions of roads, vehicles, people (by training) and control, while maintaining mobility.
More specifically, the object can be described as:
Investigation of existing, unverified or inadequately verified, and development of new:
- relationships between traffic-flow characteristics (the traffic-flow models);
- relationships between demand (for use of roads), road characteristics, permanent vehicle characteristics, driver characteristics, circumstances and measures on the one hand and traffic-flow characteristics on the other;
- relationships between traffic-flow characteristics and traffic-quality aspects.

All the foregoing as far as relevant to the general objective of road-safety research as mentioned above.

1.3. Background

Road-safety research is ultimately concerned with accidents, but these are comparatively rare and hard to observe. Observation is difficult both in the sense of direct observation of accidents and of post-accident records which are naturally limited and moreover incomplete (see, for example, SWOV, 1978). Moreover, accident statistics are not available when new countermeasures are introduced.

Perhaps a suitable interim criterion is vehicle movements, so that relationships with countermeasures on the one hand and with accidents on the other can in part be investigated separately. As soon as different traffic-flow characteristics are involved the relationship between these as described by traffic-flow models is also important. What matters is that the characteristics of safe and unsafe traffic-flows are established, and next how disturbances or disturbance-sensitive situations can be predicted from preferably simply observable traffic-flow characteristics.
Besides relationships with traffic hazards, there are also more or less direct relationships between vehicle movements and other qual-

ity aspects of traffic such as travel times, comfort and noise. A knowledge of these is useful because countermeasures aimed primarily at improving safety nearly always (this does not apply to crash and post-crash countermeasures) also influence other quality aspects. In the reverse case, i.e. when countermeasures are not aimed primarily at improving safety but, for instance, at cutting travel times, a knowledge of these relationships may also be useful.

1.4. Framework

Road-safety research is classified, inter alia, according to the sequence of events in an accident, into pre-crash, crash and post-crash research. The "Traffic-flow models" project is concerned with the pre-crash stage only, i.e. up to the moment an accident is unavoidable.
SWOV has made a division into basic, policy-preparing and evaluation research. The "Traffic-flow models" project comes under basic research, i.e. it comprises research work not aimed directly at policy measures but needed in order to set priorities, make forecasts, describe road safety problems, improve research methods and theory formulation for the purpose of future research (See, Asmussen, 1976).

As stated earlier, traffic-flow research takes place at the manoeuvre level, within which the following distinctions can be made:
(a) observation, processing of information and decision (by the driver);
(b) vehicle control;
(c) vehicle movements.

In the basic research on "Analysis of the driving task", especially the observational aspects of manoeuvre behaviour are investigated, while in that on "Cybernetic driver - vehicle model" the emphasis is on driver - vehicle interaction. These two projects are concerned with comparatively detailed descriptions of the behaviour of a driver and a driver - vehicle element. Compared with this, behaviour description in terms of vehicle movements in the "Traffic-flow models" project is much less detailed. In a certain sense this applies even more to the approach in the basic-research project on "Road classification", where the basis is the function of the road. Since "sum-total" behaviour is after all determined by the individual, there is a clear relationship between these basic research projects, and the results of one project can be used in another.

2. "STATE OF THE ART" AS THE FIRST STAGE

2.1. Background

The foregoing has shown that traffic-flow models form a fairly extensive subject. To make the proper choice of research it is necessary to have a review of existing knowledge, especially of its relevance to measures influencing traffic flows and road safety. It was therefore decided to survey the overall area by means of a literature study leading to a State of the Art report. In this, the various traffic-flow characteristics and existing models will be discussed and evaluated. Attention is paid to measuring methods and equipment because these partly determine what research is practicable.

2.2. Object

The object of the literature study is:
- to catalogue traffic-flow characteristics;
- to catalogue relationships between traffic-flow characteristics (viz. of the traffic-flow models);
- to verify the validity of the models;
- to catalogue the relationships between demand (for use of roads), road characteristics, permanent vehicle characteristics, driver characteristics, circumstances and countermeasures on the one hand and traffic-flow characteristics on the other;
- to catalogue the relationships between traffic-flow characteristics and traffic qualities;
- to examine the significance of traffic-flow information for indication, design and evaluation of countermeasures influencing the traffic-flow and hence traffic quality;
- to catalogue measuring methods suitable for investigating traffic-flows;
- to catalogue the indicated research.

2.3. Limitations

The rewiew will be confined to motor vehicles. For other road users, such as pedestrians, cyclists and moped riders, hardly any traffic-flow theory has been developed and this approach also seems to be less important for road-safety research.
A second limitation is that traffic flows on arteries will mainly be considered. As to intersections, there is plenty of theory but it relates mainly to waiting-time aspects, and here too a flow approach seems of less importance to road-safety research.
Lastly, the relationships with traffic quality. Various quality as-

pects can be distinguished in road traffic, divided roughly into production aspects (travel time, comfort) and ancilliary effects (hazards, air pollution, noise). The State of the Art report will deal only with hazards, traffic operation (throughput, travel time, and so on) and comfort, because these are closely related, while the others are generally more suitable for consideration in isolation.

2.4. Principle of classification

The principle of classification chosen is the amount of detail in the various descriptions of a traffic flow, in which three levels will be distinguished, i.e. macroscopic, mesoscopic and microscopic. The more detailed the traffic data, the harder they will be to obtain and their analysis will mostly also have to be more detailed. This was the reason for choosing the sequence from macroscopic to microscopic, so that the benefits of the greater effort will become more or less evident step by step. The three levels are described as follows:

1. Macroscopic level: Average traffic-flow characteristics such as volume, density and average speed.
2. Mesoscopic level: Characteristics defined with the aid of collections of individual vehicle characteristics, mainly distributions, for example of speeds and headways.
3. Microscopic level: Characteristics defined with the aid of individual vehicle trajectories, such as journey time and criteria for variability in speed and acceleration.

2.5. Practical classification

Besides classification at the three levels mentioned, traffic-flow characteristics and traffic-flow models are distinguished, the latter at the macro level further still between steady-state and dynamic models. This led to ten special reports, entitled:

I Introduction
II Macroscopic traffic-flow characteristics
III Fundamental diagram
IV Macroscopic dynamic traffic-flow models
V Mesoscopic traffic-flow characteristics
VI Mesoscopic traffic-flow models
VII Microscopic traffic-flow characteristics
VIII Microscopic traffic-flow models
IX Traffic-flow measuring methods
X Conclusions and indicated research.

An idea of the contents is given in the summaries of these individual reports in section 2.7.

2.6. Terminology

A choice had to be made between English and American terminology.

The reasons for choosing the latter were the existence of the world-wide used Highway Capacity Manual and the fact that a great deal of traffic-flow research has been carried out in the U.S.A.

2.7. Summaries of individual reports

Part I. Introduction

The first part describes SWOV's "Traffic-flow models" project by reference to a diagrammatic representation of the traffic process. Next it discusses the object and background of this project and its relations with other basic SWOV research projects. From this are derived the background and object of the literature study which will lead to the "Traffic-flow models" State of the Art report. Lastly, the limitations and the subdivision of the literature study are indicated.

Part II. Macroscopic traffic-flow characteristics

The second part deals with macroscopic traffic-flow characteristics, the main ones being volume, density and average speed. These factors are defined in various, mutually consistent ways relating to: a road cross-section and a point of time; a road cross-section and a period; a road section and a point of time; a road section and a period.
The macroscopic characteristics: "total distance travelled", "total time spent", throughput, kinetic energy and occupancy are also defined.
An enumeration is given of available knowledge about the relationship between macroscopic characteristics and traffic hazards defined as the number of accidents per distance covered. Various research projects have shown that on freeways and adjacent road categories both relatively low and high hourly volumes go together with increased hazards.
On two-lane roads the same correlation has been found in one case only. In the Netherlands, the relationship between the representative level of service for a year determined by volume and average speed in the thirtieth but one busiest hour of that year and the hazards has been investigated. On freeways a decreasing level of service, i.e. busier traffic, goes together with increased hazards. On two-lane roads the relationship is not as clear, but it is fairly certain that the two highest levels of service are not the safest.
It was examined what countermeasures are indicated in principle by the relation found between level of service and traffic hazards.

Part III. Fundamental diagram

The fundamental diagram represents the relationship existing in steady state between two out of the three macroscopic traffic-flow characteristics volume, density and average speed. "Steady state" means here that the factors remain constant for some time.
Many theoretical models of the fundamental diagram are discussed. They are based on various assumptions about the behaviour of driver-vehicle elements in the traffic flow or on an analogy between a

traffic flow and a physical flow. Different starting points are sometimes found to lead to the same fundamental diagram.
Next, research aspects are discussed. It is important whether the road section is homogeneous or not, both for representation of the road characteristics and for the choice of measuring method. Appropriate measuring methods are briefly discussed. The main results of the large amount of research are given together with the gaps that still exist in our knowledge.
Lastly, the significance of the fundamental diagram for road design and traffic quality is discussed, including the relationship with level of service. A number of examples of more specific applications are given.

Part IV. Macroscopic dynamic traffic-flow models

The fourth part deals with the behaviour of macroscopic traffic-flow characteristics in dynamic situations. In this case the models are mostly formulated as one, or as a system of partial differential equations.
Firstly, input-output models are discussed. Traffic-flow characteristics at the ramps of a selected part of the road system are related to each other. What happens between the ramps is disregarded in the first instance; it is a black-box model. An important potential application of this type of model is the automatic monitoring of the traffic-flow situation as part of a traffic surveillance and control system.
Secondly, the models are discussed that describe the propagation of a certain traffic-flow situation (kinematic waves) and of a change therein (shock waves) in place and time. These models were drawn up as long ago as the fifties, but have only recently been used rather more. Thus they form an important part of more extensive models describing traffic operation on one carriageway of a freeway with varying geometry and several on-ramps and off-ramps.
Objections to the "wave models" have led to formal extensions, in which is incorporated that drivers on the one hand anticipate the traffic-flow situation ahead and on the other hand react only after a certain response time. A more practical extension in this direction has led to a model useful for traffic operation on the carriageway of a freeway with on-ramps and off-ramps. It was developed for use with a traffic surveillance and control system.
A number of models have been drawn up for lane changing on a one-way carriageway relating the number of lane changes to individual lane densities. Research into this led to a preference for non-linear dependence of densities and density differences. Together with models for kinematic and shock waves the lane-changing models can in principle describe traffic situations occurring for instance near ramps, at a change in the number of lanes and due to a blockage. Applications of these are not yet known.

Part V. Mesoscopic traffic-flow characteristics

Mesoscopic traffic-flow characteristics are collections of local or

instantaneous vehicle-movement characteristics and the characteristics derivable from them. The main ones are the distributions of headways, spacings and speeds. Many suitable mathematical distributions are discussed.
Next, experimental examination of mesoscopic characteristics is dealt with. It was aimed mainly at comparing observed and mathematical distributions, establishing the dependence of successive values and the relationships with mesoscopic traffic-flow characteristics, road characteristics and circumstances.
It is examined what is known about relations between mesoscopic traffic-flow characteristics and hazards. As regards headways and spacings, there has been some research but it produced no results. In this case of speeds, relationships have been found, showing that especially the variability around the average is important to traffic hazards. Combinations of mesoscopic characteristics are rarely related to hazards and this has not led to any results so far.
Lastly, some applications of knowledge of mesoscopic traffic-flow characteristics are given. They relate mainly to measures endeavouring to influence speed behaviour directly.

Part VI. Mesoscopic traffic-flow models
The sixth part deals with mesoscopic traffic-flow models describing the behaviour of mesoscopic traffic-flow characteristics.
Firstly, the platoon models are dealt with - so called because platoons play a central part in them. A distinction is made between platoon models for two-way traffic in two lanes, one-way traffic in one lane and one-way traffic in two or more lanes.
A comparatively large number of models have been drawn up for the first of these cases. They are difficult to evaluate because there has hardly been any comparison as yet with reality. The various model aspects are reviewed.
Models can be distinguished for one-way traffic in one lane which describe the formation of platoons, the dispersal of platoons and the growth and dispersal of a queue. A model is discussed for each case.
Fewer models have been drawn up for one-way traffic in more than one lane. They are usually of the same type as those for two-way traffic in two lanes and are just as difficult to test. In addition, a simpler model has been drawn up which can be investigated with relatively simply observable variables. It appears that changes in the state of vehicles between two road cross-sections, in which the state is determined by driving in platoon or not and the lane, proceed in accordance with a first-order Markov process.
More or less separate are the models describing the behaviour of platoons crossing a number of signalised intersections. The 'diffusion model' drawn up for this seems fairly satisfactory though based on rather unrealistic assumptions.

Secondly, the Boltzmann models are discussed; their name is due to an analogy with statistical-mechanical considerations of particle

systems. In these not the platoons but the speed distributions are the focal point. These models are drawn up solely for one-way traffic in more than one lane, the lanes not being dealt with separately. The model is formulated as an integrodifferential equation in the speed distribution. It must express: that speeds decrease owing to limited passing opportunities; after a decrease in speed the desired speed is gradually reached again; and when traffic is very busy drivers tend to adapt themselves to the average speed.
The model has been tested in a homogeneous and stationary situation with results that are still under discussion. A theoretical analysis indicates that the model is not entirely correct even for low densities. This has prompted the preparation of a still more complex model which will be very difficult to test.

The most important conclusion is that many mesoscopic traffic-flow models have been drawn up which have hardly been tested. Their value is therefore largely unknown at present.

Part VII. Microscopic traffic-flow characteristics

Microscopic traffic-flow characteristics are based on individual vehicle trajectories. Many characteristics are discussed. They are subdivided according to the amount of detail and are based on the vehicle trajectory itself, the time history of speed and the time history of acceleration respectively. Examples of characteristics at the three levels are trip time, standard deviation of the time history of speed and the spectral density of the time history of acceleration.
Two kinds of relations between microscopic traffic-flow characteristics are dealt with: those that can be derived directly from the definitions and those apparently following from the nature of the traffic process. Little research has, in fact, been carried out into the latter type of relation.
Microscopic traffic-flow characteristics are usually drawn up with the object of representing traffic-flow quality aspects. This applies to traffic operation, because characteristics such as trip time, stopping time and delay are operationalisations of traffic-operation aspects. As to hazards, no clear relationship with the characteristics has yet been demonstrated, but appears to be rather reasonable. Relationships with comfort are difficult to establish, because there is no suitable operational definition of this.
Instrumented vehicles with test subjects and measuring systems observing random vehicles are suitable for collecting the characteristics. Both methods are briefly discussed and compared on a number of aspects.

Part VIII. Microscopic traffic-flow models

The eighth part deals with microscopic traffic-flow models, i.e. the manoeuvre models for following, lane changing and passing, and the more complete simulation models of a traffic flow embodying various manoeuvre models.

Of the many car-following models, the most important ones are discussed, the evolution being followed from simple and very mechanistic models to those embodying the limitations of drivers and vehicles. Investigation of car-following models is broken down into determining drivers' possibilities of perception, examination of following behaviour in laboratories and ordinary traffic. Some applications of the following models are given with the indication, development and evaluation of aids to driving.
Lane changing and passing are analysed in terms of the space needed and available for these manoeuvres. This part discusses what is known of drivers' possibilities of perception relevant to these manoeuvres and what space is needed by reference to vehicle characteristics. Research in actual traffic mostly boils down to determining the gap-acceptance function indicating the chance of a driver starting the manoeuvre dependent upon certain conditions.

More complete descriptions of the traffic-flow on a microscopic scale can be achieved only with the aid of simulation models. In these, vehicle movements are simulated with a digital computer on the basis of deterministic and chance-related rules. Besides the general aspects of these advancing models, a number of recent examples are discussed. The main applications are in the area of traffic operation. In addition, the possible relationship with road-safety research is gone into.

Part IX. Traffic-flow measuring methods
The ninth part deals with measuring methods suitable for collecting traffic-flow data. They are subdivided primarily according to the subject of measurement. The starting point is the collection of all vehicle trajectories over a given road section and within a given period.
Firstly, measuring methods are dealt with which are suitable for collecting all these trajectories. These are aerial photography methods and measuring systems in which a system of detectors is applied to the road at comparatively short distances apart.
Secondly, measuring methods are discussed which take a sample in the vehicle trajectories, i.e. several isolated or a limited number of adjacent trajectories are observed. Instrumented vehicles are mainly used for this.
Thirdly, the sample in space is discussed, with which the traffic flow is observed on one or more road cross-sections. This is the most widely used measuring method but will be dealt with only briefly.
Fourthly, the sample in time is discussed, the traffic flow being observed at a number of moments. This can almost only be done with an aerial photography method.
Lastly, a number of methods that do not fit in with the classification are discussed.
A number of aspects are mentioned which are important in evaluating a measuring method. In discussing the various methods, evaluation

is made by reference to this list. Details of equipment are not gone into.

Part X. Conclusions and indicated research

The tenth and last part again briefly describes the entire subject matter by reference to the objects of this literature study mentioned in the first part. This is mainly a matter of the conclusions and the indication of research linking up with existing knowledge and apparently applicable.
Firstly, the traffic-flow qualities needed for description, i.e. the traffic-flow characteristics, are discussed. It is important that when the characteristics are used they should be clearly defined and that attention is paid to any differences between formal definition and operationalisation.
The entire collection of traffic-flow models, i.e. the descriptions of interactions between traffic-flow characteristics, is discussed again in brief. Much of the required research consists of determining the validity of the models with the aid of actual traffic data. Promising types are the macroscopic dynamic models, because of their importance to dynamic traffic surveillance and control systems, and the microscopic simulation models, because these allow a more realistic description of vehicle movements than the less detailed models.
The extraneous factors influencing the traffic flow are the demand for use of roads, road characteristics, permanent vehicle characteristics, circumstances and countermeasures directly influencing vehicle movements. A brief sketch is given of the expected influence of each individual factor and which has also been partly confirmed in research.
Lastly, knowledge of relationship between traffic-flow characteristics and traffic-flow quality aspects is discussed, limited to traffic operation and safety. The main results are the relationships demonstrated between level of service, hourly volume and speed distribution and number of accidents per distance covered.

3. INTRODUCTION TO CONCLUSIONS AND INDICATED RESEARCH

The following chapters, being the full text of Part X, will consider the entire subject matter once again. Emphasis will be upon the conclusions and the indicated research, i.e. research linking up with existing knowledge and expected to produce useful results. It is not, therefore, everything as yet unknown, but only a part of this. For clarity, the conclusions and the indicated research are preceded by a brief review of the state of the art in the area concerned. More details and backgrounds are to be found in the individual reports mentioned above. The overall notion behind the "Traffic-flow models" project, of which this literature study forms part, is illustrated in Figure 1 (see page 9). This shows that vehicle movements, described with traffic-flow characteristics and traffic-flow models, are a link as it were between the partly manipulable extraneous factors and quality aspects of the traffic process.

The subdivision of the material largely corresponds to the objects of the literature study mentioned in section 2.2., which were formulated as:
- to catalogue traffic-flow characteristics;
- to catalogue relationships between traffic-flow characteristics (viz. of the traffic-flow models);
- to verify the validity of the models;
- to catalogue the relationships between demand (for use of roads), road characteristics, permanent vehicle characteristics, driver characteristics, circumstances and countermeasures on the one hand and traffic-flow characteristics on the other;
- to catalogue the relationships between traffic-flow characteristics and traffic qualities
- to examine the significance of traffic-flow information for indication, design and evaluation of measures influencing the traffic flow and hence traffic quality;
- to catalogue measuring methods suitable for investigating traffic flows;
- to catalogue the indicated research.

Firstly, Chapter 4 deals with traffic-flow characteristics, subdivided like the models into macro-, meso- and microscopic. It may be added that present literature usually distinguishes only macroscopic and microscopic levels. The mesoscopic in the present report is there usually counted as macroscopic.
Chapter 5 deals with the traffic-flow models including the aspect of validity indicated separately in the objects.
Next, Chapter 6 deals with the relationship between extraneous fac-

tors such as road characteristics and circumstances, and traffic-flow characteristics. In this, the subdivison follows the extraneous factors themselves.
Chapter 7, finally, deals with relationships between traffic-flow characteristics and quality aspects of traffic, limited to traffic operation and safety, again arranged according to macro-, meso-, and microscopic.

The significance of traffic-flow information for indication, design and evaluation of countermeasures and the indicated research is not dealt with separately, but with the individual aspects.
The measuring methods suitable for investigating traffic flows have not been dealt with again. For this, reference is made to Part IX of the Report.

4. TRAFFIC-FLOW CHARACTERISTICS

4.1. Macroscopic traffic-flow characteristics

State of the Art

The principal macroscopic traffic-flow characteristics are volume, density and average speed. Volume relates mostly to a road cross-section and a period, density to a road section and a time, while the average speed may relate to both. The three characteristics can be consistently defined for: a road cross-section and a point of time, a road cross-section and a period, a road section and a point of time, a road section and a period. In the last of these, volume and density are by definition linked respectively to total distance covered and total time spent, for all vehicles on the road section during the relevant period.
A comparatively new characteristic is the occupancy, indicating what fraction of the time a road cross-section is occupied by a vehicle and related to the density.

Indicated research and applications

The relationship between occupancy and density must be investigated further with the object of ascertaining whether density can be estimated from occupancy. This is important because density, unlike occupancy is comparatively difficult to observe. If a reliable relation is found it can be used in any project in which density plays a part and has to be measured.

4.2. Mesoscopic traffic-flow characteristics

State of the Art

The principal mesoscopic traffic-flow characteristics are headways, spacings, speeds and speed differences (between two successive vehicles) and the distribution of these factors. A characteristic derivable from these is the degree and nature of platooning in a traffic flow, a platoon consisting of a number of successive vehicles in one lane which influence one another to a certain extent.

Conclusions

Of the mesoscopic traffic-flow characteristics, mainly the distributions are used. Characteristics in which sequence in time or place plays a part are not used much as yet.

Headways and spacings

- Many mathematical distributions have been suggested for headways and spacings. At low volumes the exponential distribution is found to be a good description; at greater volumes the log-normal distribution seems suitable because it is flexible and comparatively simple to use. The combinations of various distributions have theoretically attractive properties; but in practice they are difficult to use owing to the many parameters and the necessary breakdown of the traffic flow into parts.
- Successive headways and spacings are found to be entirely or more or less independent on freeways; on rural undivided roads the research results are contradictory.

Speeds

- Speeds are mostly assumed to be distributed normally, and this indeed often proves to be the case. Where there are pronounced differences, there are a number of alternatives, between which no definite preference can yet be stated.
- Successive speeds are very dependent if the corresponding headways are lower than a given threshold value.

Platoon

- Much attention has been paid to making a suitable platoon definition, but this had not yet produced any clear results.

Indicated research and application

- Check whether the capacity of arteries can be predicted from headway distributions, perhaps combined with speeds measured at volumes below capacity. This is important because in many cases capacity is often not known precisely enough, though it is a major parameter in road design.
- Study of distributions and interdependences of headways, spacings, speeds and speed differences. Knowledge of these can be used especially for microscopic simulation models.

4.3. Microscopic traffic-flow characteristics

State of the Art

Microscopic traffic-flow characteristics are based on the trajectories on individual vehicles and the time history of speed and acceleration derivable from these. Examples are respectively, the trip time (related to the trip distance), the standard deviation of the time history of speed and the (energy-density) spectrum of acceleration. Some characteristics also embody aspects of lateral vehicle movements and simple aspects of vehicle control. The characteristics are mostly established with the object of representing traffic-flow quality aspects.

Conclusions

- Most characteristics relate solely to longitudinal vehicle movements.
- There is no need to embody vehicle-control aspects in the characteristics, especially in the arbitrary way this has been done so far.
- Some characteristics are operationalisations that differ considerably from the magnitudes it is really desired to determine. This is presumably due to the limitations of the available measuring and recording equipment and non-automatised processing. Operationalisations on these grounds are now hardly needed any more with the means at present available.

Indicated research and application

- It is important to establish the connection between the characteristics because this may lead to greater understanding of the traffic process and more efficient data collection. So far, any linear dependence of the various characteristics has only been investigated to a limited extent.
- Investigation of newly established characteristics dealing more equally with aspects of longitudinal and lateral vehicle movements, for example a combination of longitudinal and lateral acceleration instead of longitudinal acceleration and angular speed.
- Applications of existing and future knowledge depend on the relationships to be dealt with in Chapter 6 and 7 between extraneous factors, traffic-flow characteristics and traffic qualities.

5. TRAFFIC-FLOW MODELS

5.1. General

5.1.1. The fundamental diagram

Description

This model describes the relations existing in steady-state between two of the three macroscopic traffic-flow characteristics: volume, density and average speed. Very many models have been drawn up for the fundamental diagram; they are based on various assumptions of the behaviour of driver-vehicle elements in the traffic flow or on an analogy between a traffic flow and a physical flow.

Conclusions

- The overall form of the fundamental diagram is known.
- A fairly large amount of quantitive knowledge of the fundamental diagram has been collected for the area where density is less than the critical value (the capacity value) on high-category roads (freeways and so on).
- Less is known for the area where densities are greater than the critical value on all road categories.
- Too little information has been gathered for a definitive opinion about occurrence or non-occurrence of a discontinuity in relations in the region of the capacity situation.
- The effect of conditions such as rain, dusk and darkness on the relationships is practically unknown.

Indicated research

It is necessary to establish the fundamental diagram for all road categories that are heavily loaded regularly. The relevant aspects within this framework are:
- the effect of road characteristics within a category, including discontinuities such as narrowing of the cross section and steep grades;
- the effect of conditions such as rain, darkness and road lighting;
- the effect of the traffic composition;
- the effect of operational measures such as influencing speeds.

Research of a more theoretical nature at present is that:
- regarding the occurrence of a discontinuity in the fundamental diagram;
- the useful extension of the fundamental diagram to a network,

i.e. to find relations between the quantity and the speed of traffic on a network.

Applications

- In road design, knowledge of the fundamental diagram, related to road characteristics, is of value in achieving the contemplated traffic behaviour.
- The fundamental diagrams for the relevant arteries are needed in devising traffic-control countermeasures.
- In evaluating countermeasures, a change or changes in the fundamental diagram are often a suitable characterisation or characterisations of effects on the traffic flow.

5.2. Macroscopic dynamic traffic-flow models

5.2.1. Input-output models

Description

An input-output model relates traffic-flow characteristics at two or more places in the roads system, the traffic-flow process being put as it were in a black box. So far, only the relationship between input and output variables has been determined on the assumption that a linear system description is suitable.

Conclusions

This viewpoint has not yet been widely used, but would seem to be a fruitful approach.

Indicated research and applications

Further research into this approach is advisable, extending to a fuller description of input and output and abandonment of the assumption of a linear system. Moreover, integration with existing traffic-flow theory is needed. If this method can indeed be used for making reliable short-term forecasts, the potential applications include: traffic-dependent control with traffic lights and design and operation of automatic incident detection.
As compared with other methods, it is comparatively simple with the model in its present form to determine travel-time distributions of vehicles over a road section. There is of course the major limitation that traffic must be freely flowing, i.e. vehicles must not influence one another.

5.2.2. Kinematic waves and shock waves

Description

This theory, one of the oldest in the subject of traffic flows, describes the propagation of states (kinematic waves) and changes in states (shock waves) in the traffic flow.

Conclusions

- This is a useful theory for qualitative description of a number of traffic-flow phenomena.
- The theory is also suitable for quantitative description, but not for phenomena involving comparatively few vehicles and/or where the time for changes in speed is not slight as compared with the time under consideration.
- It is not yet known what value there is in an extension of the theory with which anticipation and response properties of driver-vehicle elements are modelled.

Indicated research

- Further investigation of the wave models can best be carried out as part of the extended macroscopic dynamic models dealt with under section 4.3.

Applications

- In designing automatic incident-detection systems.
- In estimating travel times when traffic operation is disturbed.
- As part of a more extensive model.

5.2.3. Extended macroscopic dynamic models

Description

A number of models have been drawn up describing the entire traffic operation on a roadway of a freeway, including the effects of on-ramps and off-ramps. They use the wave theory and other individual models. The most important model would appear to be May's which has been extended with a procedure for calculating fuel consumption and emission of exhaust gases. A model not developed as far as this is Payne's, which has the same potential possibilities as May's.

Conclusions

- May's model would appear to be a suitable description of traffic operation on a roadway on a freeway, with many off-ramps and a variable geometry.
- The same applies to Payne's model, but to a less extent.

Indicated research

- In view of the potential applications it seems important to examine and develop these models further. For European conditions, a more detailed description of the traffic flow may be needed, especially a distinction between private cars and trucks and separate modelling of lanes and the number of lane changes.

Applications

- Indication and prediction of the effect of road extensions on traffic operation.
- Design and operation of traffic surveillance and control systems, especially systems with on-ramp metering.
- Prediction on the effect of countermeasures on fuel consumption and emission of exhaust fumes.

5.2.4. Models for number of lane changes

Description

- A number of models have been drawn up and partly tested, which in various ways relate the intensity of lane changing, which one-way traffic on a multi-lane roadway, to lane densities. A development has also been started in which the theory of kinematic and shock waves is combined with a lane-changing model.

Conclusions

- Too little verifying research of the various lane-changing hypotheses has been carried out for an opinion to be given.
- It seems rather restrictive to take only density as the "explanatory" factor for the number of lane changes.

Indicated research and applications

- The lane-changing models must be developed further; for instance, with the effect of greater deviations from the steady-state situation and the inclusion of more explanatory factors than density alone. The potential applications of these models are their use as parts of a more extensive model.

5.2.5. General conclusions

- There is a fairly small number of models describing the behaviour of traffic-flow characteristics at the macroscopic level in dynamic situations.
- So far, verification of these models has been too superficial in many cases.
- Developments in this field have started speeding up, for one

thing because of the need for greater control of traffic, and for another owing to the development of measuring, recording and processing equipment.
- The models are useful mainly for designing and operating traffic surveillance and control systems, both in distributing over a network, metering and controlling, and in aspects thereof such as automatic incident detection, but also for some countermeasures affecting road geometry.
- In view of the heavy load on part of the freeway network, the reluctance to build new roads and the potentially favourable effects of traffic surveillance and control systems, the macroscopic dynamic traffic-flow models would also appear to be important for the Netherlands.

5.3. Mesoscopic traffic-flow models

5.3.1. Cluster models

Descriptions

In these models, platoons play an important part. They describe the size of the platoons expressed as number of vehicles and their speed, and changes in these "external" platoon characteristics. A distinction can be made between platoon models for one-way traffic in one lane, one-way traffic in two or more lanes and two-way traffic in two lanes.

In one-way traffic in one lane the situation is comparatively simple. Nevertheless the few existing models schematise vehicle behaviour rather strongly. The question is, therefore, how a comparison with reality, not made as yet, will affect the models.
For one-way traffic in more than one lane, lane changing also has to be modelled. The model takes the form of a system of differential equation describing the distribution of platoons by size, speed and lane, and development in space and time. Only the homogeneous and stationary situations have been described so far, with reasonable results, as limited verification has shown.
Rørbech has drawn up a Markow model for the same traffic situation describing the changes that occur between two road cross-sections fairly close together. The state of a vehicle is defined as driving in a platoon or not, and the lane. A first-order Markov process is found to be a realistic description.

A comparatively large number of platoon models have been drawn up for two-way traffic in two lanes. They are difficult to compare because they often emphasise different aspects of the overall phenomenon and one does not follow upon another. They describe only homogeneous and stationary situations.

Conclusions

- Either platoon models are still very limited, or have not been verified at all, and on these grounds cannot be regarded as good.
- Comparison on other grounds is difficult because the models are often focused on different aspects of the overall phenomenon.

Indicated research and applications

- Before the platoon models can be used they will have to be tested much more extensively than so far. The most promising way would appear to be further development of Rørbech's Markov model. Potentially, the models can be used for designing and evaluating measures such as speed limits, no-passing zones and geometric modifications of the road. The question is, however, whether development of the microscopic simulation models discussed in section 6.2. will not be more fruitful.

5.3.2. Boltzmann models

Description

This type of model, drawn up for one-way traffic in two or more lanes, is focused on speed distribution. The model is formulated as a integrodifferential equation for speed distribution, which must express that: speeds are reduced owing to limited passing possibilities after a reduction in speed the desired speed is gradually reached again; and when traffic is very busy drivers tend to adapt themselves to the average speed. The model has been tested in homogeneous and stationary situations, with results that are still under discussion. A theoretical analysis shows that the model is not entirely correct, even for low densities. This has prompted the production of a still more complex model, which it will be very difficult to verify.

Conclusions

Both the limited tests and a theoretical evaluation work out adversely for this model.

Indicated research

In view of the state of the art, further development of this type of model is not indicated.

5.4. Microscopic traffic-flow models

5.4.1. Manoeuvre models

Description

A distinction is made between the manoeuvres "following", including "overtaking" and "passing". In the passing manoeuvre it is important to know whether oncoming vehicles have to be allowed for; if not, it is better to regard lane changing as a separate manoeuvre. A following model describes how a driver-vehicle element follows a vehicle ahead; a part is played by perception, decision and vehicle-control aspects. Many models have been drawn up for the "car-following" manoeuvre and a clear development can be shown from very simple to complex models, the latter embodying the limitations of vehicle and driver. Research into following models is split into ascertainment of drivers' perceptive capacities and research into following behaviour in laboratories and ordinary traffic.
For lane-changing and passing models the description is limited to perception and decision aspects, and driving during the manoeuvre is (as yet) left out of account. Research concentrates on human perception and the result of the decision process, i.e. when does a driver decide to begin or not to begin the manoeuvre.

Conclusions

On the whole the manoeuvre models have not yet been (sufficiently) tested. One reason is the expensive instrumentation that is needed, especially for field research in actual traffic.

Indicated research

- Research into drivers' perceptive capacities must be continued for all kinds of traffic situations.
- More information on manoeuvring behaviour in actual traffic is needed for testing the models.

Applications

- The most important application of the manoeuvring models is to fit them into a more extensive traffic-flow model.
- The models are also useful for indication, development and evaluation of aids to drivers.

5.4.2. Simulation models

Description

Fuller descriptions of the traffic flow on a microscopic scale which includes manoeuvring models are possible only with simulation models. In these, vehicle movements are simulated with the aid of a digital computer based on deterministic and chance-related rules. Development of these models is still fairly recent and has become possible only because big, fast computers have become available.

Conlusions

With the present state of the art no clear conclusions can be drawn yet about the value of the models. There is a great variety of models and specific applications, and on the whole their validity has not been adequately investigated. It is possible to speak of a very promising development and of a potentially large area of application.
In principle, the models can generate accidents in the sense of impacts between vehicles. It cannot be assumed at present that this has any real value; the models do not appear to be detailed enough for this. But it is conceivable that they can realistically generate conflicts, i.e. events requiring definition which are assumed to be accident-related.
The major step that then remains is to relate conflicts to accidents.

Indicated research and applications

Further development and validation of simulation models is advisable, with the objects (inter alia) of:
- predicting the effects on traffic flow of changes in extraneous factors;
- predicting conflicts and relating conflicts to other traffic-flow characteristics (a necessary addition to this is relating conflicts to hazards);
- support or derivation of the less detailed mesoscopic and macroscopic traffic-flow models.

6. RELATIONS BETWEEN EXTRAENOUS FACTORS AND TRAFFIC-FLOW CHARACTERISTICS

6.1. State of the Art

Extraenous factors are here definded as the demand (for the use of roads), road characteristics, permanent vehicle characteristics, driver characteristics, circumstances and measures directly (intended to) influence vehicle movements; see also Figure 2 (page 9). This subject is so extensive in itself that it has received relatively little attention in the report. Moreover, it is difficult to examine the effects of a single factor in isolation, and every factor influences practically all traffic-flow characteristics. An effort will be made in the following to outline the influence of each individual factor as expected, and also as partly confirmed by research.

The demand, i.e. the quantity of traffic wanting to use a road, determines traffic volume. As long as the capacity of the road is sufficient, demand can be described by volume, and the effect on other traffic-flow characteristics can be investigated "via" the volume. If the capacity of the road is insufficient, the situation becomes more complex and there is no longer a simple relation between demand and the traffic-flow situation. Description of the traffic flow then at least needs a macroscopic dynamic traffic-flow model. The effects on more detailed traffic-flow characteristics can then be investigated "via" density.

The effects of road characteristics, from road type to details of geometry, have been investigated mainly as regards speed behaviour of freely moving vehicles, and there is a fairly large amount of information on this. In addition, research has been carried out into the effect on average speed in combination with volume, and this in fact relates to the fundamental diagram; see also Chapter 3.

Permanent vehicle characteristics relate mainly to dimensions, power-to-weight ratio and maximum speed. The effects of these characteristics, mostly reduced to a subdivision into vehicle types, on speed and the time history of speed (for instance on grades and when driving off) are known to some extent. Research into the ratio between maximum speed of cars and following behaviour is comparatively new.

The relationship between driver characteristics and traffic-flow characteristics is as yet practically virgin territory.

Circumstances may relate to the weather, lighting, season, time of day and the like. The relationship between these factors and traffic-flow characteristics has hardly been investigated yet.

As regards measures aimed at vehicle movements, much research has been done mainly into the effects of speed limits on speeds travelled, sometimes plus headways. It has not produced any clear results; sometimes the average speed is influenced (temporarily), and independently of this the variance in speeds often decreases. Research into the effects of measures aimed at influencing vehicle movements as part of a dynamic traffic surveillance and control system is still in its infancy.

6.2. Indicated research and applications

Research into the relationships between details and combinations of road characteristics and speeds must be extended further, especially with the objective of controlling speeds by means of road design.
Research into the relations between the driver characteristic "driving experience" and microscopic traffic-flow characteristics may be relevant in view of the comparatively great accident involvement of inexperienced drivers.
The relationship between weather conditions (wet/dry) and lighting (daytime/nighttime/road lighting) and traffic-flow characteristics require attention for "explaining" the effect of these factors on road safety and the indication of countermeasures.
As regards countermeasures, research into the effects of dynamic traffic surveillance and control systems on traffic-flow characteristics is necessary for good indication, design and operation of such systems.

7. RELATIONS BETWEEN TRAFFIC-FLOW CHARACTERISTICS AND TRAFFIC-FLOW QUALITY ASPECTS

7.1. Introduction

As to quality aspects, only traffic operation, hazards and safety, and to a limited extent comfort, have been dealt with. Traffic operation itself is an undefined concept and on the whole is better translated into terms of travel times. Hazards in this context can nearly always be characterised best as the number of accidents per distance covered, a form of the "accident rate".
The relations between traffic-flow characteristics and traffic operation are sometimes trivial, and there is then no need to mention them. This applies, for example, to the microscopic traffic-flow characteristic "trip time" which can be regarded as an operationalised traffic operation.
It should be added that it is no easy matter to establish a relationship between a (combination of) traffic-flow characteristic(s) and a quality aspect of the traffic flow, especially where it is a question of hazards. All other influencing factors would, in principle, have to be constant or display a normal variability. These conditions are rarely satisfied, and on the whole not enough is known in order to take the effect of the disturbing factors into account. The sequence of treatment, as usual, is macro-, meso- and microscopic. The idea is that quality aspects of the traffic flow are to be described with data as simple as possible because these are relatively easier to observe and, if need be, to influence. But this is not necessarily always so.

7.2. Macroscopic traffic-flow characteristics

Conclusions

- Various projects have shown that on freeways and related road categories both comparatively low and high hourly volumes occurring at levels of service A, B, C and D go together with an increased accident rate. On two-lane roads the same kind of relationship has been established in only one project.
- In the Netherlands the relation between the representative level of service for a year determined by volume and average speed in the thirtieth but one busiest hour of that year, and road hazards, has been investigated. On freeways a decreasing level of service, i.e. a greater traffic density, goes together with greater hazards. On two-lane roads the relationship is not as clear, though it is fairly certain that the two highest levels are not the safest.
- The supposition that the traffic composition expressed as the fraction of the volume consisting of trucks, is related to the

accident rate has not yet been clearly confirmed by research.
- No research is known of regarding the relation between density and hazards.
- The supposition that the average speed in itself is closely related to the accident rate has not been generally confirmed in spite of much research.

Indicated research

It is advisable to establish the relationships between a (combination of) macroscopic traffic-flow characteristic(s) and the accident rate for road types regularly heavily loaded.
The suitable traffic-flow characteristics are: volume/capacity ratio (provided level of service F does not occur), density, occupancy, level of service, plus traffic composition where appropriate. The characteristic must be observed in detail, i.e. not a 24-hour value but, for instance, the value per hour or even per quarter hour. Furthermore, it must not only be a good predictor for the accident rate but must also be suitable for routine observation.
The following research phases can be distinguished:
- establishment of relationship;
- explanation of the relationship, perhaps requiring, inter alia, mesoscopic and microscopic traffic-flow models;
- ascertaining how the relationship can be improved.

Applications

The relationship found between traffic volume and accident rate means that there is a range in loading an artery which is more or less the optimum for road safety. Loadings under this range are difficult to prevent, and moreover low loadings often go together with factors such as darkness and drinking, which are more likely causes of greater hazards. For loadings above the optimum range two kinds of countermeasures are indicated in principle. Firstly, to avoid the high loading. This can be done by reducing the demand, either absolutely or by more even distribution over time and roads, and by increasing the capacity by road extensions. Secondly, an effort can be made to vary the relationships favourably by influencing vehicle movements on the arteries, for instance by regulating lane usage and speeds. Countermeasures of both kinds form part of the traffic surveillance and control systems being vigorously developed and aiming at better use of existing road facilities.

7.3. Mesoscopic traffic-flow characteristics

Conclusions

- Research into the relation between speeds and road hazards has produced two important results. Vehicles diverging greatly from the average speed are involved relatively more in accidents; a great variability in speed is therefore a symptom of a comparatively dangerous traffic flow. The severity of accidents increases with pre-crash speeds.

- A possible relationship between headways and spacings itself and traffic hazards has only been investigated to a limited extent, without any results.
- Incidentally, a close correlation was found between the accident rate in horizontal curves on two-lane roads and a function of variances of lateral positions and average speeds at the beginning and middle of the curve.
- The assessment of combinations of speeds and spacings of successive vehicles in terms of potential rear-end collisions is theoretically and practically possible, but no relationship with accidents has yet been demonstrated.

Indicated research

It is advisable to investigate further the relationships between a (combination of) mesoscopic traffic-flow characteristic(s) and traffic hazards. This can be linked up with the relations already known. The objects of this research include "explaining" the relations between macroscopic characteristics and road hazards.

Applications

- Together with other considerations, the relationship found between the variability of speeds and traffic hazards has led to a fairly general endeavour to achieve traffic flows in which there are only slight differences in vehicle speeds; this is known as making traffic flows more homogeneous or smoothing traffic.
- The relationship between the accident rate in horizontal curves and speeds and lateral positions may be useful for evaluating markings and signalling in curves.

7.4. Microscopic traffic-flow models

Conclusions

- Microscopic traffic-flow characteristics are partly direct operationalisations of traffic operation and therefore related by definition.
- There are indications of a relationship between "acceleration noise" or related characteristics expressing the irregularity of time histories of speed and traffic hazards.
- Relations with comfort are difficult to establish because a suitable operational definition of this quality aspect is lacking. Of traffic-flow characteristics, the microscopic ones seem in principle most suitable for a relationship with or operationalisation of "comfort".

Indicated research

Further research is advisable into the relationship between microscopic traffic-flow characteristics and traffic hazards. Historically, "acceleration noise" has received most attention. But it is worthwhile, and with present recording and analysis methods also possible, to determine the optimum relationship from an extensive collection of microscopic characteristics and accident data. That is to say, to examine what function of one or more microscopic characteristics best predicts the accident rate. One of the objects is to "explain" the relationships between macroscopic and microscopic traffic-flow characteristics and traffic hazards.

Applications

As long as the relationships between microscopic traffic-flow characteristics and traffic hazards have not been adequately demonstrated, it is only possible to speak of potential applications. These might be the replacement of accident statistics by microscopic characteristics, a change for which there is a very great need in view of the scarcity and difficult observability of accidents. Moreover, such relationships may give indications for safety measures.

8. FINAL REMARKS

8.1. Relevance of traffic-flow knowledge to road safety

The purpose of this State of the Art report has been to make an orderly arrangement of the great mass of information on traffic flows and traffic-flow models existing in the literature, and in particular to indicate their relevance to road-safety research. Partly because of this latter aspect, this report differs from other reviews such as the monogram on "Traffic-flow theory" by Gerlough & Huber (1975) and the part on "Flow theories" in the book "Traffic science" by Gazis (1974).

As regards the relevance of traffic-flow knowledge to road-safety research, the following general observations:
Per vehicle distance travelled, the risk of an accident has decreased in the course of time to a relatively low level. As the overall damage due to traffic accidents is still considerable, a need remains for a further reduction in traffic hazards. This will have to be achieved partly with newly devised measures, for which more thorough knowledge of the overall traffic process is needed than is at present available. The traffic-flow approach, i.e. description of the traffic process in terms of vehicle movements, is only one approach and its results will generally have to be considered together with those of other approaches.

In general, it can be said that the traffic-flow approach becomes more relevant the greater the volume of traffic is, because vehicle interactions then become more frequent and more intensive. The latter will apply increasingly in the Netherlands because road construction is lagging behind the growth of traffic. The endeavour to create more clearly defined traffic and residential areas or, to put it otherwise, to separate through and local traffic more, in both urban and rural areas, will bring an extra increase in the traffic volume on main arteries.

8.2. Importance of traffic-flow knowledge for countermeasures

Many countermeasures for improving some quality aspect of traffic have a direct or indirect influence on vehicle movements, and traffic-flow knowledge is therefore always relevant in principle, but to a varying degree in practice. In the following enumeration of a number of types of countermeasures, their relevance generally declines in the order given.

Firstly, measures aimed directly at vehicle movements. Examples are

traffic dependent route choice control, ramp metering, speed limits, no-passing zones and rules for following. The first two of these lead to a different traffic distribution in place and time, and knowledge of traffic flows has implications for travel operation and traffic hazards. For the control system itself, a macroscopic dynamic traffic-flow model can be used, and a microscopic simulation model for details. Speed control has direct implications in terms of travel times and partly known implications in terms of safety because of the relationship between speed distribution and the accident rate. In the case of no-passing rules and rules relating to following, the implications can be determined in terms of traffic operation, and those in terms of safety can be explored, with a microscopic simulation model.
In countermeasures relating to road characteristics, a general distinction can be made between design of networks and the actual road design relating primarily to the geometry. In the former, a role is played by road function, predicted traffic volume, requirements in terms of traffic operation and the implications (not yet requirements) in terms of hazards. Knowledge of the fundamental diagram and the relationship between hazards and level of service are useful for this. In geometric road design the relationships between road characteristics and the fundamental diagram and microscopic simulation models can be used.
An example of a measure changing permanent vehicle characteristics is increasing the power-to-weight of trucks. The implications of traffic operation of the overall traffic-flow can be determined, and those for traffic hazards explored, with the aid of a microscopic simulation model.

As regards the above examples it must be borne in mind that with present knowledge of traffic flow the effects of countermeasures can only be predicted to a limited extent. Measures must therefore often be considered from different viewpoints, for instance from a knowledge of drivers' perceptive and controlling abilities as elements in a man/machine system. Knowledge of these areas has so far only been embodied in traffic-flow models to a very limited extent.

8.3. Main conclusions and indications

It is important in connection with traffic-flow characteristics for these to be clearly defined, and for sufficient attention to be paid to any differences between formal definition and operationalisation.

As regards traffic-flow models, the following:
- The validity of many models has hardly been verified, if at all, with actual traffic data, though this is an essential step that must precede the use of the model.
- Most models have been developed for one-way traffic; more attention is needed for development of models for two-lane roads, which

are important from the aspect of vehicle kilometers and traffic hazards.

- Promising types of models are the macroscopic dynamic models and the microscopic simulation models. The former because of their application in dynamic traffic surveillance and control systems and the latter because they make possible a more realistic description of the behaviour of driver-vehicle elements. Simulation models are expected to be the most relevant for road-safety research.

As to the effects of extraenous factors on traffic flow, the relationships between road characteristics and speeds and those between the countermeasure, dynamic traffic surveillance and control systems and traffic-flow characteristics are most important.

Comparatively little research has been carried out as yet into relationships between traffic-flow characteristics and traffic hazards. The principal results to date are the relationships demonstrated between level of service, hourly volume and speed distribution and accident rate.
Traffic-flow measuring methods have been greatly improved in recent years, especially by better adjustment of measuring, recording and processing to one another. This has considerably widened the scope for traffic-flow research.

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