Traffic Flow Modeling of Large-Scale Motorway Networks Using the Macroscopic Modeling Tool METANET

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Abstract—This paper employs previously developed modeling, validation, and stimulation tools to address, for the first time, the realistic macroscopic simulation of a real large-scale motorway network. More specifically, the macroscopic simulator METANET, involving a second-order traffic flow model as well as network-relevant extensions, is utilized. A rigorous quantitative validation procedure is applied to individual network links, and subsequently a heuristic qualitative validation procedure is employed at a network level. The large-scale motorway network around Amsterdam, The Netherlands, is considered in this investigation. The main goal of the paper is to describe the application approach and procedures and to demonstrate the accuracy and usefulness of macroscopic modeling tools for large-scale motorway networks.

Index Terms—Modeling, motorway networks, simulation, traffic flow, validation.

I. INTRODUCTION

ONE OF THE major needs in the area of intelligent transportation systems (ITS) is the modeling of the traffic flow process in large-scale motorway networks. The notoriously increasing number of vehicles that use the provided network capacity has lead to severe problems in the form of recurrent and nonrecurrent congestion resulting in serious economic and environmental problems, as well as increased public frustration and discomfort.

Two complementary approaches for solving problems caused by motorway congestion phenomena are possible without diverting demand to other modes of transportation. The first one is to construct new motorways, i.e. address the problem by providing additional capacity to the networks. Land availability issues, especially in and around large metropolitan areas, and environmental considerations render this approach little attractive.

The second approach is based on the fact that the capacity provided by the existing infrastructure is practically underutilized, i.e. it is not fully exploited. Thus, before building new infrastructure, the full exploitation of the already existing infrastructure should be ensured. Recent developments in control, communications, and computer technology has made this task feasible and financially viable. Indeed, in many metropolitan areas Traffic Control Centres (TCC) operate performing a variety of tasks such as traffic monitoring, prediction, and control. It is within this framework that reliable traffic models become important for any of the following tasks:

•*Simulation*. A traffic flow model is needed when the traffic process has to be simulated for a number of different scenarios and conditions. For example, when the impact of adding a new link to a network, thus adding capacity, or performing road works, thus reducing capacity, has to be studied, then simulation of the traffic flow process, under different scenarios, is vital for sound and efficient decision making.

•*Traffic prediction*. The purpose of traffic prediction is to provide reliable forecasts of the traffic conditions that will occur in a network over a predetermined future time horizon. Traffic prediction may be performed on-line so as to enable operators of a TCC to anticipate the impact of various events that take place in the network, such as incidents or high demands at certain locations. The successful performance of this task calls for a realistic traffic flow model able to anticipate the short-term traffic conditions that are likely to prevail.

•*Traffic control*. Traffic control operations in the context of a TCC aim at ameliorating traffic conditions through the systematic use of control measures applied to the traffic process, such as ramp metering, motorway-to-motorway (mtm) control, route recommendation (via Variable Message Signs (VMS) or appropriately equipped vehicles), variable speed limitation, etc. A traffic model is required either for the off-line study of the impact a given control strategy may have on the process, or for the design of the control strategies themselves.

Depending on the view adopted, modeling of the traffic process may be performed at the microscopic, the mesoscopic, or the macroscopic level. In this paper we will confine ourselves within the macroscopic approach toward traffic flow modeling. In this approach, traffic flow is treated as an one-dimensional compressible fluid with specific characteristics. The first macroscopic modeling theory for traffic flow on a highway stretch was reported independently in [1] and [2], where the fundamental laws of kinematic wave theory were established and the background for future macroscopic approaches to

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traffic flow modeling in motorways was laid. A potentially more accurate second-order traffic flow model was proposed in [3] which was extended in [4] and [5] to improve its reliability in merging areas, i.e. around on-ramps or at lane-drop locations. A macroscopic modeling concept that allows traffic flow models to be embedded in a network context, with multiple origins, multiple destinations, and multiple routes for each origin-destination couple was developed in [6]. A number of macroscopic simulators such as METANET [7], METACOR [8], NETCELL [9], STRADA [10] are based on that concept.

An essential issue related to motorway traffic modeling is model validation. Previous validation efforts were based on traffic data from various motorway stretches ([11], [4], [5], [12]) and aimed at optimal estimation of the model parameters so as to maximize the modeling accuracy.

This paper employs previously developed modeling, validation, and simulation tools to address, for the first time, the realistic macroscopic simulation of a real large-scale motorway network. More specifically:

- the macroscopic simulator METANET, involving a second-order traffic flow model as well as network-relevant extensions, is utilized;
- a rigorous quantitative validation procedure is applied to individual network links;
- a heuristic qualitative validation procedure is used at a network level;
- the large-scale motorway network around Amsterdam, The Netherlands, is considered in this investigation.

The main goal of the paper is to describe the application approach and procedures and to demonstrate the accuracy and usefulness of macroscopic modeling tools for large-scale motorway networks.

The rest of this paper is organized as follows. Section II describes in some detail the modeling approach employed. Section III describes the model application to the Amsterdam motorway network while Section IV presents the validation procedure followed along with the obtained results. Finally, Section V discusses the main conclusions drawn from the reported effort as well as future work.

II. Modeling Approach

A. Model Overview

The Amsterdam network was modeled using the modeling tool METANET, see [7]. METANET is a deterministic macroscopic modeling tool for simulating traffic flow phenomena in motorway networks of arbitrary topology and characteristics, including motorway stretches, bifurcations, on-ramps, and off-ramps. This modeling approach allows for simulation of all kinds of traffic conditions (free, dense, congested) and of capacity-reducing events (incidents) with prescribed characteristics (location, intensity, duration). Furthermore METANET allows for taking into account control actions such as ramp metering, route guidance, and mtm control.

METANET has two distinct modes of operation. When traffic assignment (i.e. the drivers' route choice behavior) aspects are not considered, then it operates in the *non destination-oriented*
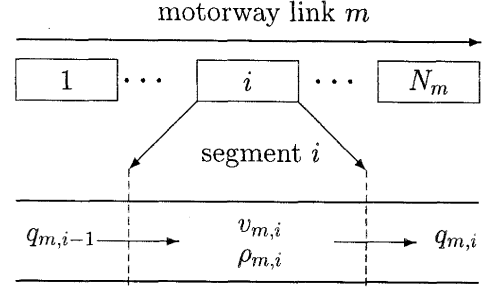

Fig. 1. Discretised motorway link.

mode. When traffic assignment is an issue, it operates in the *destination-oriented mode*.

The motorway network is represented as a directed graph whereby the links of the graph represent homogeneous motorway stretches. Each such motorway stretch has uniform characteristics, i.e., no on/off-ramps and no major changes in geometry. The nodes of the graph are placed at locations where a major change in road geometry occurs, as well as at junctions, on-ramps, and off-ramps.

B. Definition of Basic Traffic Variables

The macroscopic description of traffic flow implies the definition of adequate variables expressing the average behavior of traffic at certain times and locations. The time and space arguments are discretised. The time discretization is global, but the space discretization is defined for each link separately. The discrete time step is denoted by T. A motorway link m is divided into N_m segments of equal length (Fig. 1). For each segment i of each link m at each time instant $t = k \cdot T, k = 0, 1, \ldots, K$, where K is the time horizon, the following macroscopic variables are defined.

- *Traffic density*: $\rho_{m,i}(k)$ (veh/km/lane) is the number of vehicles in segment i of link m at time $k \cdot T$ divided by the length of the segment L_m and by the number of lanes λ_m.
- *Mean speed*: $v_{m,i}(k)$ (km/h) is the mean speed of the vehicles included in segment i of link m at time $k \cdot T$.
- *Traffic volume or flow*: $q_{m,i}(k)$ (veh/h) is the number of vehicles leaving segment i of link m during the period $[k \cdot T, (k+1) \cdot T]$, divided by T.

Furthermore, for the destination-oriented mode of operation, the following variables are introduced:

- The *partial density* $\rho_{m,i,j}(k)$ is the density of vehicles in segment i of link m at time $k \cdot T$ destined to destination $j \epsilon J_m$, where J_m is the set of destinations reachable via link m.
- The *composition rate* $\gamma_{m,i,j}(k), 0 \leq \gamma_{m,i,j}(k) \leq 1$, is the portion of traffic volume $q_{m,i}(k)$ which is destined to destination $j \epsilon J_m$.

C. Link Model

Five types of links are used when a motorway network is modeled. First, there are the *motorway links* which are used for the representation of homogeneous motorway stretches. Traffic conditions therein are described by the aforementioned basic traffic variables. Second, there are the *origin links* which receive

traffic demand (volume) from outside the network and forward it into the main network. An origin link is characterized by its flow capacity and its queue. Third, there are the destination links which receive traffic flow from inside the network and push it outside. Traffic conditions in *destination links* are influenced by the corresponding downstream traffic conditions. Fourth, there are *store-and-forward* links which are characterized by their queue length, their flow capacity, and their constant travel time. Finally, there are *dummy links*, with zero length, which are used in order to decompose complex network nodes.

1) Motorway Links: The basic equations used to calculate the traffic variables for every segment i of motorway link m are the following:

$$\rho_{m,i}(k+1) = \rho_{m,i}(k) + \frac{T}{L_m \lambda_m} [q_{m,i-1}(k) - q_{m,i}(k)] \quad (1)$$

$$q_{m,i}(k) = \rho_{m,i}(k) \cdot v_{m,i}(k) \cdot \lambda_m \quad (2)$$

$$v_{m,i}(k+1) = v_{m,i}(k) + \frac{T}{\tau} \{V[\rho_{m,i}(k)] - v_{m,i}(k)\}$$
$$+ \frac{T}{L_m} v_{m,i}(k) [v_{m,i-1}(k) - v_{m,i}(k)]$$
$$- \frac{\nu \cdot T}{\tau \cdot L_m} \frac{\rho_{m,i+1}(k) - \rho_{m,i}(k)}{\rho_{m,i}(k) + \kappa} \quad (3)$$

$$V[\rho_{m,i}(k)] = v_{f,m} \cdot \exp\left[-\frac{1}{a_m}\left(\frac{\rho_{m,i}(k)}{\rho_{cr,m}}\right)^{a_m}\right] \quad (4)$$

where $v_{f,m}$ denotes the free-flow speed of link m, $\rho_{cr,m}$ denotes the critical density per lane of link m (the density where the maximum flow in the link occurs), and a_m is a parameter of the fundamental diagram (eqn. (4)) of link m. Furthermore, τ, a time constant, ν, an anticipation constant, and κ, are constant parameters same for all network links. $v_{f,m}$, $\rho_{cr,m}$, a_m, τ, ν, and κ are constant parameters which reflect particular characteristics of a given traffic system and depend upon street geometry, vehicle characteristics, drivers' behavior etc. The parameter values are determined via a quantitative validation procedure such as the one described in Section IV-C.

Additionally, it is assumed that the mean speed resulting from (3) is limited below by the minimum speed in the network $v_{\min}$.

Equation (1) expresses the vehicle conservation principle, while (2) is the flow equation which results directly from the definition of the traffic variables. (3) is the empirical speed equation which describes the dynamic evolution of the mean speed of each segment as an independent variable (hence the model is of second order). Equation (4) is also an empirical equation known as the fundamental diagram and expresses a static relationship of the speed with the traffic density.

Additional terms may be included in (3) for the modeling of lane drops and merging phenomena near on-ramps [5]. In order for the speed calculation to account for the speed decrease caused by merging phenomena, the term $-\delta T q_\mu(k) v_{m,1}(k)/(L_m \lambda_m (\rho_{m,1}(k) + \kappa))$ is added in (3), where δ is a constant parameter determined by the validation process, μ is the merging link and m is the leaving link. In order to consider speed reduction due to weaving phenomena resulting from lane drops in the mainstream, the term $-\phi T \Delta\lambda \rho_{m,N_m}(k) v_{m,N_m}(k)^2/(L_m \lambda_m \rho_{cr,m})$ is added in (3), where $\Delta\lambda$ is the number of lanes being dropped, and ϕ is a

constant parameter estimated from the quantitative validation of the model.

Additionally, in the destination-oriented mode, the partial densities for each reachable destination in every link are calculated from conservation considerations

$$\rho_{m,i,j}(k+1) = \rho_{m,i,j}(k) + \frac{T}{L_m \lambda_m}$$
$$\cdot [\gamma_{m,i-1,j}(k) q_{m,i-1}(k) - \gamma_{m,i,j}(k) q_{m,i}(k)] \quad (5)$$

with

$$\gamma_{m,i,j}(k) = \rho_{m,i,j}(k)/\rho_{m,i}(k). \quad (6)$$

2) Origin and Store-and-Forward Links: For origin links, i.e., links that receive traffic demand and subsequently forward it into the motorway network, a simple queue model is used. Origin links are characterized by their flow capacity and their queue length. The outflow $q_o(k)$ of an origin link o is given by

$$q_o(k) = r_o(k) \cdot \min\left\{d_o(k) + \frac{w_o(k)}{T}, q_{\max,o}(k)\right\} \quad (7)$$

where $d_o(k)$ is the demand flow at time period k at origin o, $w_o(k)$ is the length (in vehicles) of a possibly existing queue at time period k, $q_{\max,o}(k)$ is the flow capacity at the specific period and $r_o(k) \in [r_{\min}, 1]$ is the metering rate for origin link o at period k. If $r_o(k) = 1$, no ramp metering is applied. If $r_o(k) < 1$ then ramp metering becomes active. The flow capacity depends on the density of the primary downstream leaving link μ in the following way:

$$q_{\max,o}(k) = \begin{cases} Q_o & \text{if } \rho_{\mu,1}(k) < \rho_{cr,\mu} \\ Q_o \cdot p(k) & \text{else} \end{cases} \quad (8)$$

where Q_o is the (constant) flow capacity of the origin link and $p(k)$ is the portion of Q_o that can enter link μ, where

$$p(k) = \frac{\rho_{\max} - \rho_{\mu,1}(k)}{\rho_{\max} - \rho_{cr,\mu}} \quad (9)$$

with $\rho_{\max}$ the maximum possible density in the network's links. Thus, eqs. (8), (9) reduce the (geometrical) flow capacity Q_o when traffic conditions on the mainstream become congested.

The conservation equation for an origin link yields

$$w_o(k+1) = w_o(k) + T \cdot [d_o(k) - q_o(k)]. \quad (10)$$

In the destination-oriented model, the notion of *partial queues* is introduced. Partial queues at an origin link evolve according to the relationship

$$w_{o,j}(k+1) = w_{o,j}(k) + T \cdot [\vartheta_{o,j}(k) \cdot d_o(k) - \gamma_{o,j}(k) \cdot q_o(k)] \quad (11)$$

where $w_{o,j}(k)$ is the number of vehicles in the queue of origin link o with destination j, $\gamma_{o,j}(k) = w_{o,j}(k)/w_o(k)$, and $\vartheta_{o,j}(k)$ is the portion of the demand originating in o at period k and having j as its destination.

In order to enable the model to consider mtm control measures and also to approximately consider urban zones, the store-and-forward links are used. These links are characterized

by their flow capacity, their queue length, and their constant travel time. For the determination of their outflow and their queue length, equations similar to (7)–(11) hold.

3) Destination and Dummy Links: Traffic conditions in destination links are influenced by the downstream traffic conditions which may be provided as boundary conditions for the whole time horizon. If no measurements for boundary conditions are available, it is assumed that the downstream traffic conditions are uncongested. Dummy links are auxiliary links of zero length. They do not affect traffic dynamics and they are used to decompose complex network topologies or to represent very short motorway connections.

D. Node Model

Contrary to the link model, the node model does not exhibit any dynamic behavior. Let $Q_n(k)$ be the total traffic volume entering a motorway node n at period k. Then the *turning rate* $\beta_n^m(k)$ is the portion of traffic volume $Q_n(k)$ which leaves node n at period k through link $m \, \epsilon \, O_n$, where O_n is the set of links leaving node n. Let I_n be the set of links entering node n. The following equations hold:

$$Q_n(k) = \sum_{\mu \in I_n} q_{\mu, N_\mu}(k) \quad \forall n \qquad (12)$$

$$q_{m,0}(k) = \beta_n^m(k) \cdot Q_n(k) \quad \forall m \in O_n \qquad (13)$$

where $q_{m,0}(k)$ is the traffic volume that leaves node n via outlink m. Equations (12) and (13) provide $q_{m,0}(k)$ needed in (1) for $i=1$. In the destination-oriented mode, the notion of turning rates is generalized to the notion of *splitting rates*. Let $Q_{n,j}(k)$ be the total traffic volume entering a motorway node n at period k that is destined to destination j. Then, the splitting rate $\beta_{n,j}^m(k)$ is the portion of traffic volume $Q_{n,j}(k)$ which leaves node n at period k through link $m \, \epsilon \, O_n$. In the case where route guidance takes place at node n with respect to destination j (with the use of VMS or other means), $\beta_{n,j}^m$ is used to describe the resulting splitting. In the presence of VMS, an indicating splitting $\beta_{\text{VMS},n,j}^m$ may be defined; if the sign guides drivers toward j via m (the main route), $\beta_{\text{VMS},n,j}^m = 1$, else $\beta_{\text{VMS},n,j}^m = 0$. The relation between $\beta_{\text{VMS,n,j}}^m$ and the resulting splitting rate is modeled by the following equation

$$\beta_{n,j}^m = (1 - \varepsilon)\beta_{\text{N},n,j}^m + \beta_{\text{VMS},n,j}^m \varepsilon \qquad (14)$$

where ε is the compliance rate to the route recommendations ($0 \le \varepsilon \le 1$), and $\beta_{\text{N},n,j}^m$ is the portion of vehicles that take the main route in absence of any route recommendations.

The following equations hold for any network node

$$Q_{n,j}(k) = \sum_{\mu \in I_n} q_{\mu, N_\mu}(k) \cdot \gamma_{\mu, N_\mu, j}(k) \, \forall (n, \, j) \qquad (15)$$

$$q_{m,0}(k) = \sum_{j \in J_m} \beta_{n,j}^m(k) \cdot Q_{n,j}(k) \, \forall m \in O_n \qquad (16)$$

$$\gamma_{m,0,j}(k) = \frac{\beta_{n,j}^m(k) \cdot Q_{n,j}(k)}{q_{m,0}(k)} \, \forall m \in O_n \, \forall j \, \in \, J_m. \qquad (17)$$

Equations (15)–(17) provide $q_{m,0}(k)$ and $\gamma_{m,0,j}(k)$ which are needed in (5) for $i = 1$. When a node n has more than one

leaving links, then the upstream influence of density has to be taken into account in the last segment of the incoming link (see (3)). This is provided via

$$\rho_{m,N_m+1}(k) = \frac{\sum_{\mu \in O_n} \rho_{\mu,1}^2(k)}{\sum_{\mu \in O_n} \rho_{\mu,1}(k)} \qquad (18)$$

where $\rho_{m,N_m+1}(k)$ is the virtual density downstream of the entering link m to be used in eqn. (3) for $i = N_m$, and $\rho_{\mu,1}(k)$ is the density of the first segment of leaving link μ. The quadratic term is used in (18) to account for the fact that one congested leaving link may block the entering link even if there is free flow in the other leaving link.

When a node n has more than one entering links, then the downstream influence of speed has to be taken into account according to (3). The mean speed value is calculated from

$$v_{m,0}(k) = \frac{\sum_{\mu \in O_n} v_{\mu,N_\mu}(k) \cdot q_{\mu,N_\mu}(k)}{\sum_{\mu \in O_n} q_{\mu,N_\mu}(k)} \qquad (19)$$

where $v_{m,0}$ is the virtual speed upstream of the leaving link m that is needed in (3) for $i = 1$.

E. Model Summary

From the previous sections, a nonlinear dynamic model of the form

$$\mathbf{x}(k + 1) = \mathbf{f} [\mathbf{x}(k), \mathbf{c}(k), \mathbf{d}(k)], \, \mathbf{x}(0) = \mathbf{x}_0 \qquad (20)$$

can be obtained for the entire motorway network, where $\mathbf{x}$ is the state vector, $\mathbf{c}$ is the control vector, and $\mathbf{d}$ is the disturbance vector.

In the non destination-oriented mode, (20) is obtained by substituting (2), (12), (13) into (1); (4), (18), (19) into (3); and (7), (8), (9) into (10). In this case, the state vector consists of the densities $\rho_{m,i}$ and mean speeds $v_{m,i}$ of every segment i of every link m, and the queues w_o of every origin and store-and-forward link o. The control vector consists of the ramp metering rates r_o of every on-ramp and store-and-forward link metered. The disturbance vector consists of the demands d_o at every origin link o and the turning rates β_n^m at every bifurcation node n. In the destination-oriented mode, eq. (20) is obtained by substituting (2), (15)–(17) into (5); (4), (18), (19) into (3); and (7)–(9) into (11). In this case, the state vector consists of the partial densities $\rho_{m,i,j}$ of every segment i and reachable destination j from link m, the mean speed $v_{m,i}$ of every segment i of every link m, and the partial queues $w_{o,j}$ of every origin and store-and-forward link o. The control vector consists of the ramp metering rates r_o of every on-ramp and store-and-forward link o, and of the splitting rates $\beta_{n,j}^m$ for every bifurcation n where route guidance with respect to destination j takes place. The disturbance vector consists of the demands d_o at every origin link o, the composition rates of the demand $\vartheta_{o,j}$ (OD matrix), the splitting rates $\beta_{n,j}^m$ at every bifurcation node n where no route guidance is applied, and the drivers' compliance rates.

The state space formulation described is very usuful since it allows for the use of well known methods from the automatic control theory to the problem of motorway network traffic control, see [13].
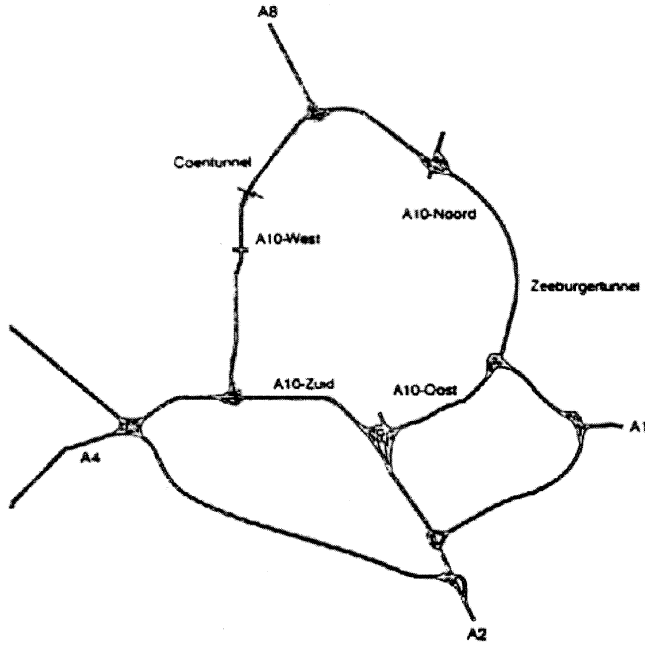
Fig. 2.   Amsterdam motorway network.

III. MODEL APPLICATION TO THE AMSTERDAM NETWORK

A. Description of the Amsterdam Motorway Network

The objective of this section is to describe the Amsterdam test site consisting of the Amsterdam Orbital Motorway (A10) and certain parts of the regional motorway network. An overview of the Amsterdam test site is shown in Fig. 2.

The central feature of the site is the Amsterdam Orbital Motorway (the A10). The A10 simultaneously serves local, regional, and inter-regional traffic and acts as a hub for traffic entering and exiting North Holland. To the North, the A8 motorway feeds into it, carrying a large amount of commuting traffic to Amsterdam. To the Southwest, the A4 carries most of the traffic between the North of the country and attractors in the South such as Schiphol Airport, The Hague, and Rotterdam. South of the A10, the A9 forms a bypass for traffic between the North-east on the one hand and the Centre of the country as well as the region between Amsterdam and The Hague (including Schiphol airport) on the other. A2 connects the A10 to the A9 bypass and connects the A10 with the Centre of the country. Finally, to the South-east, the A1 connects to the A10, and serves traffic between the North and Centre of the country.

The A10 contains two tunnels, the Coen Tunnel at the North-west of A10 and the Zeeburg Tunnel at the North-east, which effectively divide the orbital motorway into two sections: the "North Ring" and the "Ring West/South/East".

The network is subject to considerable recurrent congestion. Congestion is especially heavy on the north-western and southern parts of the A10, but less so on the north-eastern part. Due to the network structure and the current network load, route choice is a factor of influence on this network, which presents a potential for dynamic traffic management.

TABLE I
MODELED MOTORWAYS

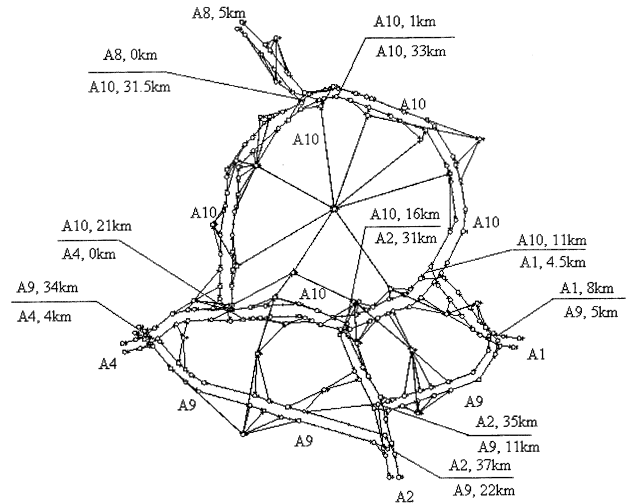| Motorway	From (km)	To (km)	Length (km)
A10	1	33	32×2
A8	0	5	5×2
A4	0	5	5×2
A2	31	37	6×2
A1	4.5	8.5	4×2
A9	5	12	7×2
A9	22	34.5	12.5×2

Fig. 3.   Amsterdam network representation.

B. Model of the Amsterdam Motorway Network

Each motorway of the Amsterdam network was modeled in both directions. Table I shows the limits of the motorways that were considered. The total length of the network is 143 km (both directions), and its main part is the A10 ring road which engulfs Amsterdam. The total number of links that was used to model the motorway network is 654 (all types of links). This number includes 249 motorway links, 231 store-and-forward links, and 174 dummy links. The motorway links were divided into a total of 291 segments. The length of each segment ranges from 400 to 800 m. Taking into account the total motorway length considered and the number of segments used, the average segment length is 491.4 m. Fig. 3 depicts the resulting modeled network, along with the kilometer numbers at the points where the motorways are connected.

At the North, the 5-km section of the A8 considered may be seen. The ring road A10 is the dominant (and most important) motorway. Connected with A10 to the South are (from left to right) the A4, the A2, and the A1 motorways. The A9 further to the South connects these four motorways thereby forming two secondary rings.

Adjacent to the motorways and in the center of the three rings, virtual origins and destinations are placed, each representing an urban zone. These virtual nodes are used in order to model the influence of the corresponding urban zones on motorway traffic, particularly with regard to route choices of drivers. Origins and destinations in the modeled area may be connected via a purely motorway or mixed path. In order to take into account the urban

connections in a simplified way, virtual links and nodes are suitably introduced. The links that are used are of store-and-forward type. Each such link is attached to a virtual node and has the task of either receiving flow from the network and pushing it out of it, into the urban area, or receiving flow from the urban area and then pushing it into the network. From a specific stretch and a given direction of the motorway, the on- and off-ramps are modeled as store-and-forward links which start/end from/at a virtual urban origin/destination. This is the reason for the large number of store-and-forward links used.

Urban origins/destinations are placed in the network where there is a high concentration of on-ramps or off-ramps. An urban origin node concentrates all the demand originating from the corresponding urban zone and distributes it to several adjacent motorway on-ramps based on suitable dynamic traffic assignment considerations. Similarly, a destination node collects the outflow of several adjacent motorway off-ramps that is destined to the corresponding urban zone. This approach has the advantage that there is no need to model in detail the urban network, which would result in a significantly more complicated system. Moreover the aggregation that is performed this way at the on-/off-ramps results in the significant reduction of the required origin-destination matrix dimension. In Fig. 3, the virtual urban nodes are placed within the loops, i.e. in the urban areas. This feature of the model is not utilized in the present application. It is part of future work that will be conducted for the study of traffic assignment and route recommendation (via VMS or equipped vehicles) control measures. Nevertheless, the network's model remains unaffected from this fact since it operates in the non destination-oriented mode for the validation and the internal urban routes are not considered.

Additionally, store-and-forward links are used to model the interaction between two or more merging motorways. In this case store-and-forward links are placed as connection links at motorway junctions. The queuing model of store-and-forward links provides a sufficient approximation for the traffic process at these points, and also facilitates the modeling of motorway-to-motorway control measures.

IV. MODEL VALIDATION

The model validation procedure aims at enabling the whole motorway network model to represent traffic conditions with sufficient accuracy. The methods used to this end are quantitative and qualitative in nature, and both procedures are presented in this section.

A. Model Validation Overview

The macroscopic model presented in Section II includes a number of parameters which have to be estimated in order to accurately model the traffic flow of a particular network. The model validation for this particular case was performed in two successive phases, the quantitative and the qualitative.

• *Quantitative model validation* aims essentially at estimating model parameters through a well-defined straightforward procedure, and is carried out in two stages. In the first stage a group of parameters that reflect particular characteristics of a given motorway stretch and depend upon highway geometry, vehicle

characteristics, drivers' behavior, etc., is calibrated so as to fit a representative set of real data with the maximum possible accuracy (parameter estimation). In the second stage, the developed model is applied with the estimated parameter values and the results are compared with sets of traffic data different from those used in the parameter estimation stage (model verification).

• *Qualitative model validation* aims to represent traffic conditions not for isolated motorway stretches, as in the case of the quantitative validation, but for the entire motorway network. The goal is for the model to capture the network-wide dynamics of traffic congestion, i.e. to be able to predict the location, duration, and propagation of congestion. While in the quantitative validation only isolated motorway stretches are considered, the qualitative validation aims at enabling the network model to consider the interactions between the motorway stretches. The process of qualitatively validating the model consists of manually calibrating a number of parameters (i.e., turning rates, and store-and-forward links' capacities and travel times) via repeated computer simulations. After each simulation the results are compared against real data from locations around the network, particularly those where congestion appears, and a suitable manual adjustment of a number of (or a single) parameters is performed based on the observation of whether or not congestion is predicted sufficiently accurately. Because neither a quantitative measure nor a rigorous optimization is used during this procedure, the results are qualitative in nature (hence the term qualitative validation).

B. Available Data

For the model validation procedure, data from loop detectors for four consecutive days (June 3–6, 1996) were available. These data consisted of one-minute measurements of flow and speed for the whole day. They were used in order to determine the disturbancies to the traffic system, and to provide the necessary boundary data. As boundary data, the traffic flow, the mean speed, and the traffic density were used in the quantitative validation, while only the traffic flow was provided to the model, in the qualitative validation.

C. Quantitative Model Validation

The quantitative validation aims at estimating model parameters through a well-defined straightforward optimization procedure. The detailed results of this effort are reported in [14].

1) Parameter Estimation Procedure: From the motorway traffic flow process model described in Section II, a nonlinear dynamic model of the form

$$\mathbf{x}(k+1) = \mathbf{f}\left[\mathbf{x}(k), \mathbf{u}(k), \mathbf{z}\right], \ \mathbf{x}(0) = \mathbf{x}_0 \qquad (21)$$

can also be obtained for individual motorway stretches, where $\mathbf{x}$ is the state vector, $\mathbf{u}$ is the boundary-conditions vector, and $\mathbf{z}$ is the parameter vector. This can be done by substituting (2), (12), and (13) into (1); (4), (18), (19) into (3); (7), (8), and (9) into (10), for the non destination-oriented mode of operation.

The estimation of the unknown parameters for a motorway traffic system is a nontrivial task, since system equations are highly nonlinear in both the parameters and the state variables. The most common approach for the identification of nonlinear

systems is the minimization of the discrepancy between the model calculations and the real process in the sense of a quadratic output error functional.

Let $\mathbf{y}$ be the output vector of the nonlinear system (21), with

$$\mathbf{y}(k) = \mathbf{g}\left[\mathbf{x}(k), \mathbf{z}\right]. \tag{22}$$

Then the parameter estimation problem may be formulated as the following least-squares output error problem:

Given the time sequences of measured data $\mathbf{h}^m(k)$ (measured boundary conditions), $\mathbf{y}^m(k)$ (measured process output), $k = 0, 1, \ldots, K$, and the initial state $\mathbf{x}_0$, find the set of parameters $\mathbf{z}$ minimizing the cost functional

$$J(\mathbf{z}) = \sum_{k=1}^{K} \parallel \mathbf{y}(k) - \mathbf{y}^m(k) \parallel_{\mathbf{Q}}^2 \tag{23}$$

subject to (21) with $\mathbf{h}(k) = \mathbf{h}^m(k)$, and (22).

The model parameters $\mathbf{z}^T = [v_f, \rho_{cr}, a_f, \phi, v, \delta, \phi, \kappa, v_{\min}]$ (when a unique fundamental diagram is used for all segments) are selected from a closed admissible region of the parameter space which may be defined on the basis of physical considerations. $\mathbf{Q}$ is a positive definite, diagonal matrix. When measurements are taken from $e4$ locations in the motorway stretch, then $\mathbf{y}^T = [q_1 v_1 \ldots q_e v_e]$.

The determination of the optimal parameter set must be performed by means of a nonlinear programming routine whereby for each choice of a new parameter vector $\mathbf{z}$ the value of the performance criterion (23) is computed by a simulation run of the model equations driven by the measured inputs according to Fig. 4.

An approach to the solution of the formulated optimization problem is via application of the Complex algorithm of Box [15]. The advantages of this algorithm are summarized as follows.

- The algorithm does not require the calculation of the derivatives of the cost functional like competitive gradient-based methods.
- The algorithm has grater chances of finding the global (or at least a "good" local) minimum than gradient-based methods.

The algorithm starts with an initial complex (group) of points $\mathbf{z}$ which are randomly scattered throughout the admissible region in the parameter space. Then, at each iteration step, the parameter set with the worst value of the cost functional is replaced by a new parameter set which is chosen appropriately. The procedure is terminated when the complex points $\mathbf{z}$ reach a sufficiently small region around the optimum so that no further improvement of the performance criterion can be achieved by further iterations. Even with this algorithm, however, it is not easy to decide whether the global optimum has actually been reached. For this reason it is useful to repeat the procedure with different sets of starting points.

2) Results and Model Verification: For the identification procedure, four measurement sets (corresponding to four consecutive days) were available from the A10 ringroad of Amsterdam. These data provided flow and speed measurements on a minute-by-minute basis. Four motorway stretches were
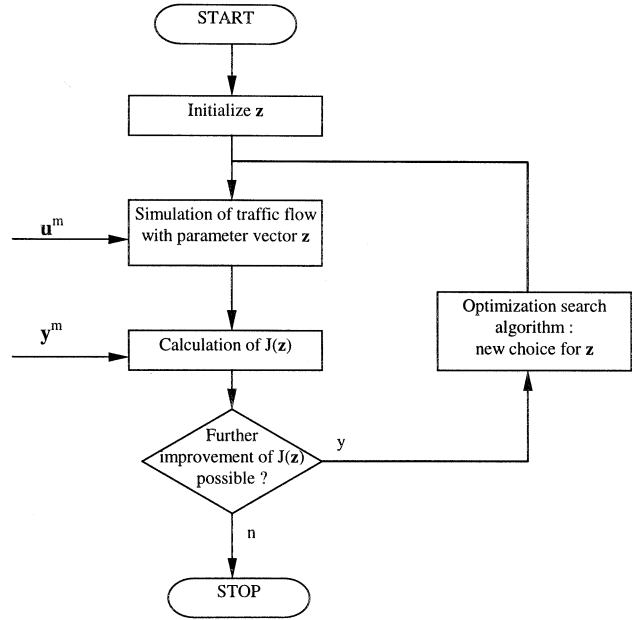

Fig. 4.   Functional sketch of the parameter estimation procedure.

TABLE II
PARAMETER SETS FOR THE A10 MOTORWAY

	Motorway Stretches			
	1	**2**	**3**	**4**
From (km)	10.7	22.0	28.1	13.5
To (km)	19.7	33.0	16.7	3.4
Parameters				
$\rho_{cr,m}$ (veh/km/lane)	35.93	28.75	33.25	27.65
	Common values for all stretches			
a_m	2.34			
$v_{f,m}$ (km/h)	102			
τ (seconds)	18			
δ	0.012			
ν (km²/h)	60			
ϕ	2.2			
$v_{\min}$ (km/h)	7.4			
κ (veh/km)	40			

selected from the ringroad and for each one of them a set of optimal parameters was established. The summarized outcome of this effort is presented in Table II. The first two rows indicate where each particular stretch starts and ends. In the ringroad, the kilometers increase clockwise, with zero placed just after the A8.

From Table II it can be seen that the critical density is a crucial parameter of the model. For the four motorway stretches the parameter set is identical save for the critical density. Based on the sets of parameters shown in Table II, examples of the model output for a single location can be seen in Figs. 5 and 6. More precisely, Fig. 5 depicts the volume trajectory determined by the model as compared with the flow measurements for the same location in the second motorway stretch. For this particular location, Fig. 6 depicts the speed trajectory determined by the model and compared with the actual speed measurements. Both figures are indicative of the model's ability to represent
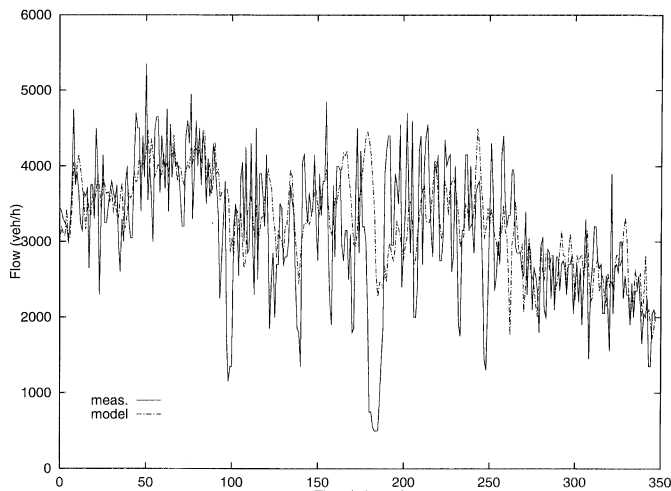
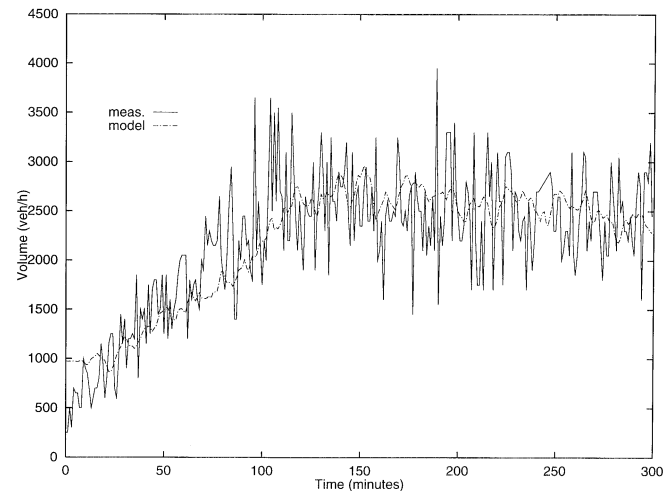Fig. 5. Stretch 2, measured versus predicted flow, quantitative validation.

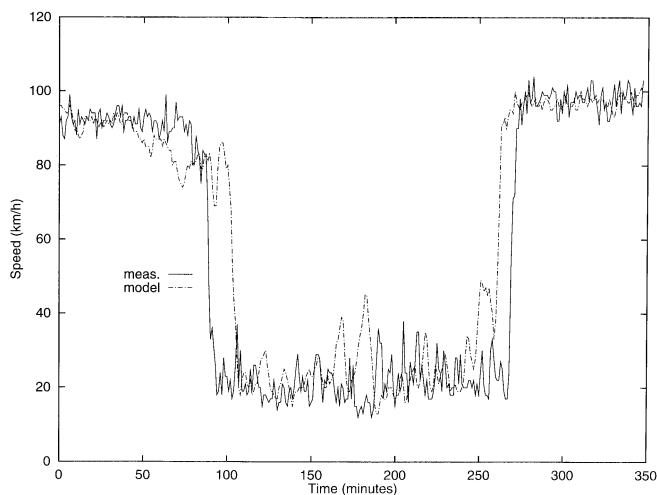Fig. 7. L26, measured versus predicted flow, qualitative validation.

Fig. 6. Stretch 2, measured versus predictive speed, quantitative validation.

traffic conditions in each of the motorway stretches based on the estimated parameters.

D. Qualitative Model Validation

The scope adopted in the qualitative model validation extends from individual network parts (motorway stretches in quantitative validation) toward the entire network. The goal of this phase is, by manually calibrating a number of parameters, to enable the model of the whole network (Section III-B) to sufficiently represent the network-wide dynamics of traffic congestion. The manually calibrated parameters include turning rates at bifurcation junctions, and capacities and travel times of store-and-forward links. The calibration was performed through repeated simulations via trial-and-error until the appropriate parameter values were obtained. The parameter values were deemed as appropriate when the model was able to reproduce with sufficient accuracy the time and location of recurrent congestion, its duration and propagation. Particular attention was paid to the main junctions of motorways, e.g. A8 with A10, as quantitative validation did not focus on motorway interactions at major motorway intersections. When a real congestion, that occurs at a certain lo-

cation of a motorway, spills back into another motorway, then the model should be able to reproduce this propagation.

In order to make the network-wide traffic flow model to comply with this requirement, all the cases of recurrent congestion observed in the motorway network were recorded and for each one of them the location and time of its creation, as well as the its duration and propagation to other motorways was noted. Three main cases of recurrent congestion were identified. Some of them were strongly related due to their geographic proximity, while others were independent from each other. One of the major origins of congestion on the A10 ringroad is the spillback of congestion created at off-ramps (either due to existence of traffic lights at the end of the off-ramp or due to restricted outflow capacity).

The most severe congestion of all appears upstream of the Coen Tunnel at the 30th km of the A10 ringroad in the counter-clockwise direction of the A10 (the *l*-direction as opposed to the clockwise *r*-direction). Congestion at the Coen Tunnel begins at the 30th km and propagates backward on the A10 to the 32nd km and to the A8 up to 3.3 km. This area is congested from 6:20 A.M. until 10:00 A.M.

The second main congestion appears at the southern part of the A10. It begins at 17.6 km at 8:00 A.M., in the *r*-direction, and propagates backward until 13.6 km of A10 until 10.25 A.M. It must be noted that in this highway stretch spillback phenomena take place causing the congestion that appears at 8:00 A.M. at the specific location. A bit later, severe congestion due to limited capacity appears at the 2.4 km of A4 in the direction of flow that leaves Amsterdam. This congestion propagates backward to the A10, it catches up with the previously mentioned congestion, and combined they create a severe congestion that begins from the A4 and propagates up to the A10, reaches the A2 and propagates into it until the 31.5 km.

Another congestion that appears in the southern part of A10, but this time in the *l*-direction, begins at the 18th km at 8:00 A.M. and propagates backward up until the 24.2 km of A10. This congestion propagates to A4 in direction where the flow enters the A10, and propagates in the A4 up to the 4th km.

After manually calibrating the model parameters, the model was able to predict the network traffic conditions (free, critical,
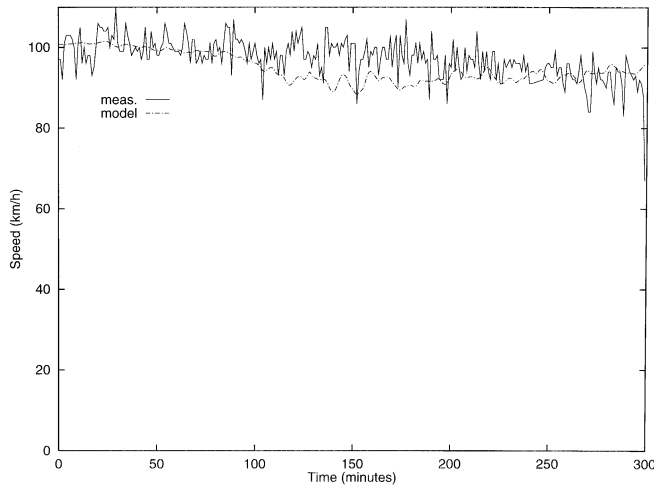
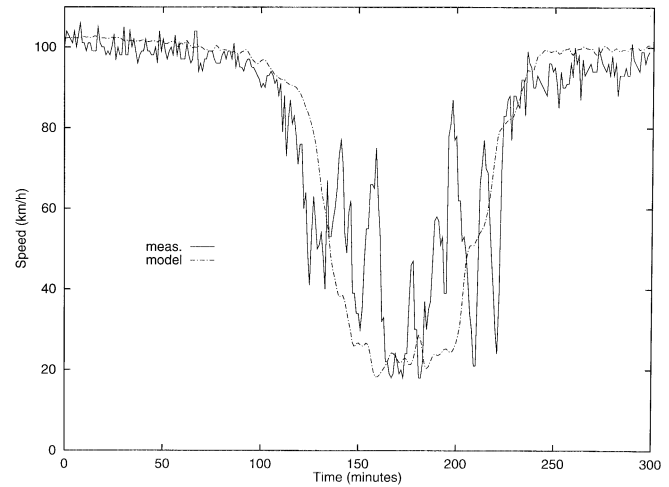Fig. 8. L26, measured versus predicted speed, qualitative validation.

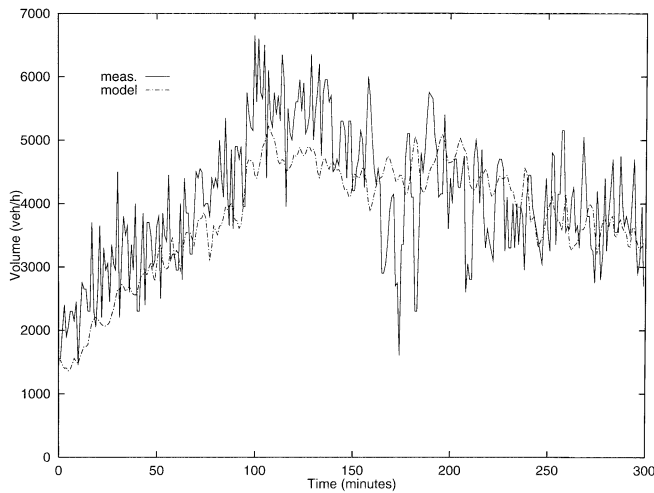Fig. 9. L11, measured versus predicted flow, qualitative validation.

Fig. 10. L11, measured versus predicted speed, qualitative validation.

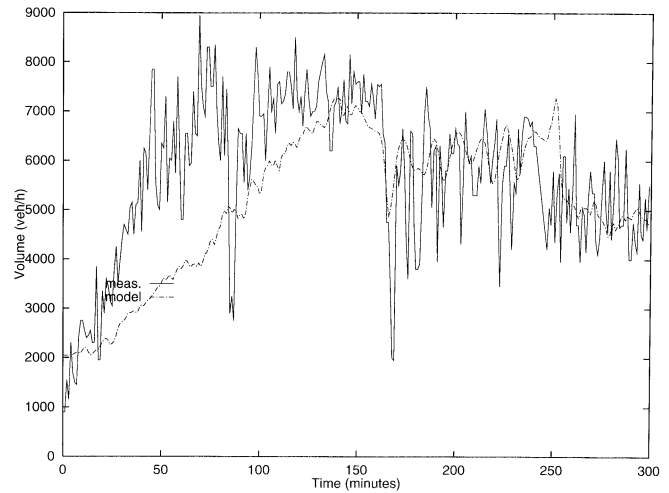Fig. 11. L72, measured versus predicted flow, qualitative validation.

Fig. 12. L72, measured versus predicted speed, qualitative validation.

and congested) for the period from 6:00 A.M. to 11 A.M. For the motorway parts without any congestion there was no problem for the model to reproduce the traffic conditions. Figs. 7 and 8 show, respectively, the flow and speed trajectories of link L26 (28.489–28.911 km) of A10 r-direction compared with the real measurements from the same location. For the congested motorway parts that do not exhibit spillback phenomena from off-ramps, the model is able to predict the location and duration of congestion with sufficient accuracy. Figs. 9 and 10 depict the flow and speed trajectories, respectively, for link L11 (22.950–23.721 km) of A10 l-direction, compared with real measurements taken from the same location.

For the congested motorway parts that do exhibit congestion coupled with spillback from off-ramps, the model is not very accurate in predicting traffic conditions. Figs. 11 and 12 show, respectively, the flow and speed trajectories of link L72 (18.2–19.5 km) of A10 r-direction where spillback from an off-ramp occurs. Notice that in reality congestion appears much earlier than the model anticipates because spillback limits the available capacity sooner than in normal conditions. It appears difficult to provide a theoretical basis for the description of the impact of off-ramp spillback on the mainstream traffic. Drivers
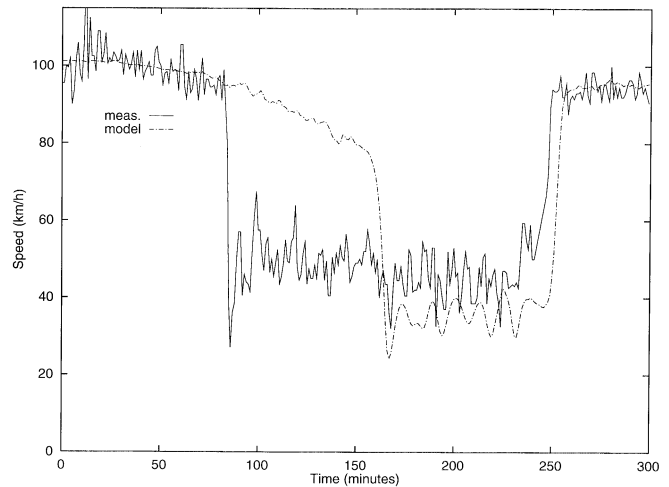
wishing to exit, may occupy the outmost right lane of the mainstream throughput. However, if the queue grows further, some exiting drivers may also attempt to use further mainstream lanes which may lead to a breakdown of the mainstream traffic flow.
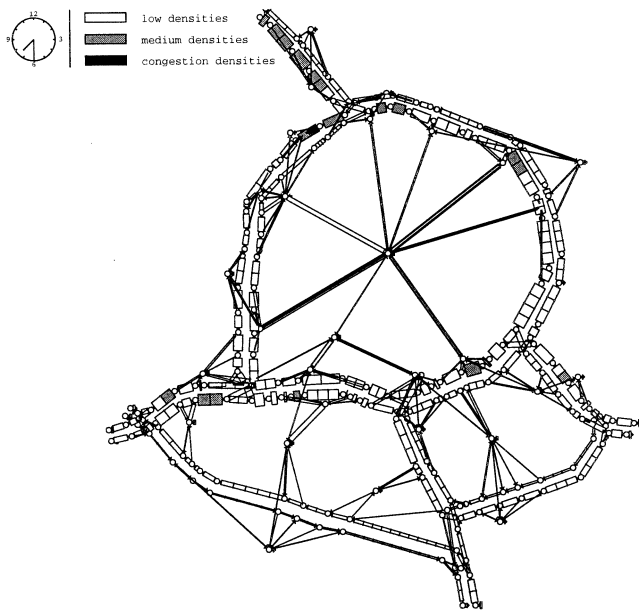
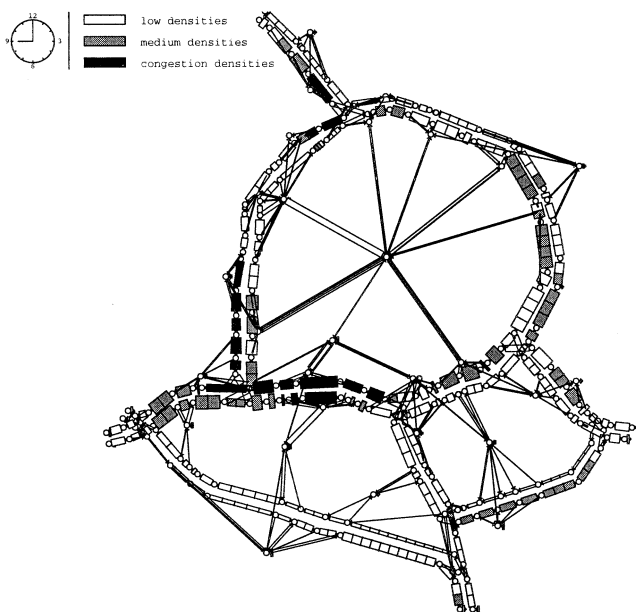Fig. 13.   Simulated traffic conditions in the network, 7:30 A.M.

Fig. 14.   Simulated traffic conditions in the network, 9:00 A.M.

These phenomena are probably of a strong probabilistic character and there is hardly any possibility to describe them accurately in a deterministic framework.

Figs. 7–12 give an idea of the model's performance only at the local level. As was mentioned before, the qualitative validation aims to enable the network model to capture the network-wide dynamics of congestion. Figs. 13 and 14 present the picture of the traffic conditions for the whole network at certain time instants. Free, dense, and congested conditions are present, and each segment is filled with the appropriate pattern to indicate them. The links' segment width is proportional to the traffic flow passing through them. Fig. 13 depicts the Amsterdam motorway network at 7:30 A.M. in the morning. The model predicts that congestion should appear only upstream the Coen Tunnel

and nowhere else in the network, which is in accordance with the data observations. Fig. 14 shows the model's prediction of traffic conditions at 9:00 A.M. From this figure it can been seen that the model reproduces the previously described recurrent congestions sufficiently, thus making it a suitable tool for evaluating the impact of various traffic control measures on the traffic flow process.

V. CONCLUSIONS AND FUTURE WORK

This paper presented the modeling of the large-scale motorway network around Amsterdam, The Netherlands, and its validation against real measurements. The macroscopic modeling tool METANET was used for this purpose. In order to validate the model, a two-phase validation process was followed. The first phase, called quantitative validation, employed a rigorous method in order to determine the model's parameters for a selected number of motorway stretches from the network. For each motorway stretch, an optimal parameter set was determined. Based on the results obtained by the quantitative validation, the second phase, called qualitative validation, aimed at enabling the motorway network model to capture the network-wide dynamics of congestion. The results obtained from this approach demonstrate that METANET is able to reproduce traffic congestion built in reality with considerable accuracy, thus making it suitable for evaluating various control strategies and performing further modeling and simulation tasks. The off-line evaluation of motorway control measures such as ramp metering, motorway-to-motorway control, and route guidance will be the subject of further work for this network.

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