TNO-report
INRO-VVG 1997-02b

The microscopic traffic simulation model MIXIC 1.3

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Commissioned by the Transport Research Centre,
Ministry of Transport, Public Works and Water Management

Delft, January 1997
97/NV/025

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PREFACE

This document describes the microscopic motorway traffic simulation model MIXIC 1.3. This version of MIXIC was developed during a study commissioned by the Transport Research Centre (AVV) of Rijkswaterstaat, the Netherlands (contract AV-2784). The study was conducted from May 1996-February 1997. The study was undertaken by:

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Coding of the software and the program documentation was done by Gideon Zegwaard of QQQ Software. On behalf of AVV Stef Smulders and Henk Schuurman participated in the project team.

The present study has resulted in five reports. This report describes the current status of MIXIC (version 1.3). A second report focuses on the study of the impact of a special lane for AICC vehicles. The other reports, a programmers manual, a user manual and detailed specifications, together replace the corresponding documentation of MIXIC 1.2.

Delft, 16 October 2001

Bart van Arem

SUMMARY

The microscopic traffic simulation model MIXIC 1.3

B. van Arem, A.P. de Vos & M.J.W.A. Vanderschuren

The model MIXIC described in this report emerged from efforts at both TNO and the Transport Research Centre (AVV) of the Dutch Ministry of Transport, Public Works and Water Management. MIXIC is a microscopic traffic simulation model suitable for the assessment of the impacts of modern telematic technologies in traffic. By means of computer simulation, the consequences for safety, exhaust-gas emission, noise emission, and traffic performance can be weighed in an integrated manner.

One important class of modern telematic technologies are Automated Vehicle Guidance (AVG) systems. Automated vehicle guidance is regarded as a promising tool to improve road network traffic performance and safety. AVG systems can be defined as systems in which the driving task of a driver is taken over partly or entirely by an automated system. Such systems may even involve communication with road-side systems and/or other vehicles.

Autonomous Intelligent Cruise Control (AICC) is a system that automatically maintains a specified speed, taking into account a minimal distance with respect to predecessors. AICC is an autonomous system: it does not communicate with other vehicles or road-side systems. AICC is applicable in mixed traffic flows: vehicles with and without AICC can make use of the same road. AICC is regarded as one of the nearby feasible AVG systems. Its introduction is expected before the end of the 20th century in the higher market segment of passenger cars.

For studying the impacts of AICC on a number of consecutive motorway stretches, the microscopic simulation model MIXIC 1.3 was developed. The model MIXIC 1.3 contains detailed submodels describing drivers, vehicles, assisting systems and their interfaces. The model has been filled for 4 driver and 4 vehicles types. Passenger cars may be equipped with AICC. Drivers of such cars can switch their AICC on or off depending on the prevailing traffic conditions. This interaction model is motivated by the fact that first generation AICC systems are expected to have a limited deceleration range, and must be overruled by the driver if strong decelerations are required, e.g. when approaching a queue. The output of MIXIC ranges from the possibility of recording vehicle/driver combinations, to the measurement of aggregated traffic quantities and the occurrence and severity of shockwaves. The model offers the possibility of narrowing situations and dedicated lanes for AICC vehicles.

In a previous study MIXIC was calibrated using traffic measurements from different motorways in the Netherlands. The calibration took place with respect to traffic performance and shockwaves. For cases in which a detailed calibration was possible, MIXIC corresponded well to real-life situations. In situations where a detailed calibration was not possible, the MIXIC results were

found to be credible.

SAMENVATTING

Het microscopische verkeerssimulatiemodel MIXIC 1.3

B. van Arem, A.P. de Vos & M.J.W.A. Vanderschuren

In dit rapport wordt het microscopisch simulatiemodel MIXIC beschreven. Het model MIXIC is ontwikkeld in het kader van gezamenlijke inspanningen door TNO en de Adviesdienst Verkeer en Vervoer van Rijkswaterstaat. MIXIC is geschikt voor het bepalen van effecten van 'intelligentie' in het verkeer op wegvakniveau. Door middel van simulatie kunnen effecten worden bepaald van op verkeersprestatie, uitstoot (geluid en uitlaatgassen) en veiligheid.

Een vorm van `Intelligente Verkeerssystemen' is Automatische Voertuiggeleiding. Automatische Voertuiggeleiding (AVG) wordt gezien als een veelbelovend middel bij de verbetering van de verkeersprestatie en veiligheid op het Nederlandse wegennet. Systemen voor automatische voertuiggeleiding zijn systemen in de auto die de bestuurder assisteren in (delen van) zijn rijtaak of deze zelfs geheel overnemen. Tevens kan er communicatie plaatsvinden tussen het systeem en apparatuur langs de weg, en/of tussen systemen in verschillende auto's.

Autonomous Intelligent Cruise Control (AICC) is een systeem dat automatisch een ingestelde snelheid handhaaft, echter met inachtneming van een minimale afstand tot eventuele voorliggers. AICC is een autonoom systeem: het communiceert niet met andere voertuigen of met apparatuur langs de weg. AICC is toepasbaar in gemengd verkeer: voertuigen met en zonder AICC kunnen gebruik maken van dezelfde weg. AICC wordt gezien als één van de eerstvolgende praktisch toepasbare AVG systemen. De invoering van AICC systemen wordt voor het eind van de 20ste eeuw verwacht in het marktsegment van de duurdere personenauto's.

Voor het bestuderen van de effecten van AICC op een aantal aansluitende snelwegvakken is het microscopisch simulatiemodel MIXIC ontwikkeld. Het model bevat gedetailleerde deelmodellen voor de bestuurder, het voertuig, de omgeving, de toegepaste vorm van AICC en de interacties hiertussen. Het model is gevuld voor 4 bestuurders- en 4 voertuigtypen. Voertuigen kunnen zijn uitgerust met AICC. Bestuurders van dergelijke voertuigen kunnen hun AICC aan en uitzetten afhankelijk van de verkeerssituatie. Dit overnamemodel is geïmplementeerd aangezien de eerste AICC systemen een beperkt deceleratiebereik zullen hebben. De bestuurder moet de AICC uitzetten door zelf te remmen indien sterke vertragingen nodig zijn, bijvoorbeeld bij het naderen van een file. Binnen het model bestaat de mogelijkheid tot het specificeren van 'afvallende rijstroken' en voor speciale stroken voor AICC voertuigen.

De uitvoer van MIXIC varieert van het registreren van individuele voertuig/bestuurder combinaties tot het meten van geaggregeerde verkeersgrootheden en het optreden van schokgolven en de ernst daarvan.

In eerdere studies is MIXIC gekalibreerd aan de hand van gegevens van verschillende autosnelwegen in Nederland. De kalibratie vond plaats met betrekking tot de verkeersafwikkeling en schokgolven. In gevallen waarin een gedetailleerde kalibratie mogelijk was bleek MIXIC goed overeen te komen met de metingen. In andere gevallen waarin een gedetailleerde kalibratie niet mogelijk was bleken de MIXIC resultaten plausibel.

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1 INTRODUCTION

By the use of new technologies (Advanced Transport Telematics, ATT) Dynamic Traffic Management (DTM) may contribute considerably to a more efficient use of the existing infrastructure for traffic and transportation. Moreover, according to the Second Transport Structure Plan (SVV, 1990), the Dutch Ministry of Transport, Public Works, and Water Management considers the reduction of the environmental effects and improvement of traffic safety as equally important issues. Apart from demand management, DTM is supposed to play an important role in controlling road traffic and increasing road safety in the near future (Rijkswaterstaat, 1994). The use of telematics in DTM may result in 'Intelligent Traffic Systems' that enable the Dutch policy targets to be met. Chances of success in this process strongly depend on the behavioral changes of the road user that are actually achieved.

The product MIXIC described in this report emerged from efforts at both TNO and at the Transport Research Centre (AVV) of the Dutch Ministry of Transport, Public Works and Water Management.

The TNO project Intelligent Traffic Systems (ITS) has been conducted from 1992-1996 and was aimed at the development of an instrument for the assessment of the impacts of ITS applications. By means of computer simulation, the consequences for safety, exhaust-gas emission, noise emission, and traffic performance can be weighed in an integrated manner. The project is sponsored by the Dutch Ministry of Transport, Public Works, and Water Management. Envisaged is the development of both a microscopic and a macroscopic simulation model. The models are linked in such a manner that processes can be modelled on an individual driver and vehicle level, but also that an efficient assessment can be provided on a network level. The ITS project was carried out by four TNO Institutes, each with its own expertise, viz. the TNO Human Factors Research Institute, TNO Inro, the TNO Road-Vehicles Research Institute, and the TNO Institute of Applied Physics.

A series of separate projects were commissioned by the AVV, in which the objectives and results from the ITS project were taken up in their own research programme. These projects had the following successive objectives, leading to successive versions of MIXIC:

- to develop a prototype microscopic traffic simulation model that enables the assessment of an application such as Intelligent Cruise Control (MIXIC 1.0);
- to fill the model with detailed driver, vehicle and ICC models and to calibrate it with respect to traffic performance and safety (MIXIC 1.1);
- to study the impact of AICC using microscopic simulation (MIXIC 1.2)
- to study the impact of a dedicated lane for AICC vehicles (MIXIC 1.3)

During the latter project a number of improvements in MIXIC were made. This document describes the resulting model MIXIC 1.3. The most important improvements are:

- incorporation of the possibility to specify road discontinuities such as lane drops or dedicated lanes;
- incorporation of a mandatory lane change model;
- incorporation of lane change model extension during congestion.

Meanwhile, MIXIC has been applied in a number of other projects:

- In the ITS project MIXIC has been used to study the impact of ICC with an external reference speed depending on the level of service. This has resulted in MIXIC 1.2a.
- MIXIC has been used to assess the impact of fog warning systems. This has resulted in MIXIC 1.2b (van der Voort, 1996).
- MIXIC has been used to assess the impact of 'longer and heavier trucks'. This has resulted in the specification of an additional vehicle type (Hoogvelt et al., 1996).

Future development on MIXIC will take place on the basis of MIXIC 1.3. Versions 1.2a and 1.2b are final versions, which will not be used for further development.

The structure of this document is as follows. Chapter 2 gives the overall structure of the microscopic traffic simulation model MIXIC 1.3, whereas Chapter 3 describes the driver and vehicle model in more detail. Chapter 4 deals with a description and selection of an appropriate ICC application. In Chapter 5 the implementation of MIXIC 1.3 is discussed. Current status and future developments are given in Chapter 6. Appendix A, B and C give detailed descriptions of the driver, vehicle and AICC models. Finally, Appendix D gives a MIXIC bibliography.

This document focuses on traffic modelling aspects. As documentation of MIXIC 1.3, it is supplemented by:
- a detailed specification (Zegwaard, Van Arem & Van Katwijk, 1997),
- a program documentation (Zegwaard & Van Arem, 1997) and
- a user manual of MIXIC 1.3 (Vanderschuren, Zegwaard & Van Arem, 1997).

2 OVERALL STRUCTURE OF MIXIC 1.3

2.1 Requirements of the microscopic traffic model

In the Intelligent Traffic Systems general framework (van der Horst et al., 1993), the microscopic traffic model serves two purposes. First, it is used to accurately describe the vehicle and traffic behaviour on motorway links in an environment where ITS applications are operational. The model will use a vehicle and driver behaviour model as specified in Chapter 3 of this report. The output of the model will be fed into dedicated output modules, resulting in reports for traffic performance, exhaust-gas and noise emission, fuel consumption and safety.

Second, the microscopic traffic model is used to establish an interface with the macroscopic model. By performing suitable experiments and subjecting the results to statistical analyses, the most important impacts are determined. Next, these impacts will be taken into account in the macroscopic model by adapting the link model of the macroscopic model, e.g., by adapting the speed-density relations.

2.2 General outline of the microscopic traffic model: MIXIC 1.3

The requirements imposed upon the microscopic traffic model have been determined in detail in the ITS project. It has turned out that the vehicle and driver model and the output modules impose specific demands upon the microscopic traffic model. Existing microscopic traffic models do not satisfy all these demands.
In the ITS project a special-purpose microscopic traffic simulation model is developed. The model will be tailored to the needs of all the interfacing modules. The present document reports on the development of the model. As a case for guiding the development, ICC with a reference speed issued by a beacon was chosen. The model has been named MIXIC (**Mic**roscopic model for **S**imulation of **I**ntelligent **C**ruise Control).

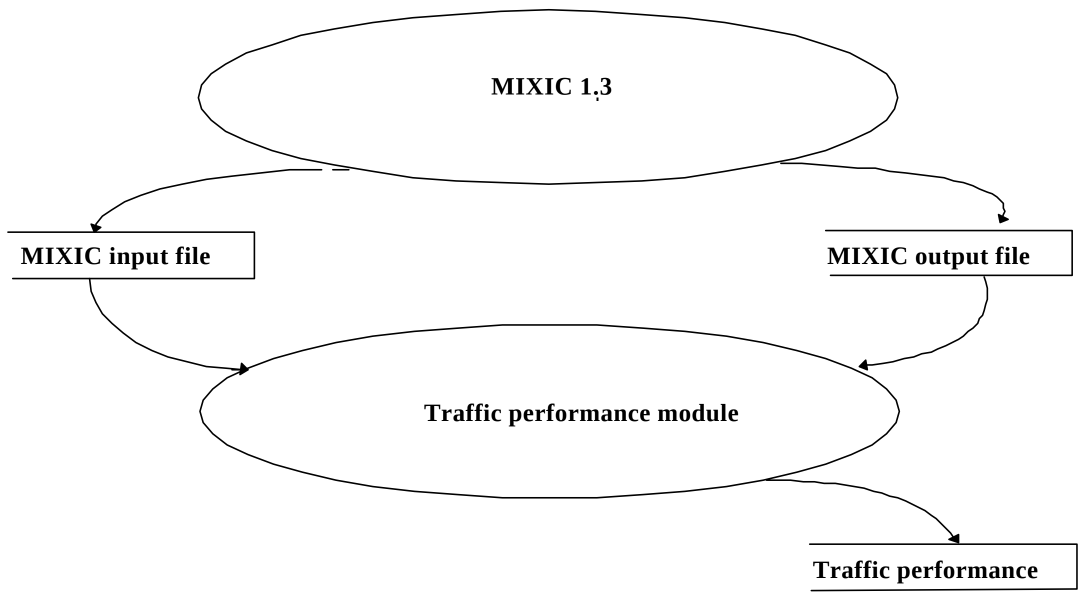

Figure 2.1: Top view of MIXIC 1.3

MIXIC 1.3 operates on a link level in a network. Given an input of traffic flow, it simulates the traffic behaviour in this link and produces traffic statistics. These statistics serve as input to the traffic performance module and the noise module. A traffic safety, exhaust gas emission and fuel consumption and noise emission module are also available.
Also it is important to know how the impacts at a link level may induce impacts at a network level. This will be done as part of the ITS project. The results of the application of MIXIC will be used to establish the interface between the macroscopic and the microscopic traffic model.

The type of road network studied in MIXIC 1.3 is a sequence of homogeneous motorway links, without on- or off-ramps. However, in the future it is anticipated that there will also be a need to study other link types or even small networks. MIXIC 1.3 has been implemented in such a way that this would be possible.

MIXIC 1.3 consists of the following components:
- a traffic generator, generating vehicles at the start of a link
- a link model, which gives the relevant link data and to which vehicle positions can be related; one possible element of the link model could be the presence of an intelligent traffic smoothing beacon, which communicates with the ICC in cases of imminent congestion, by prescribing other headways or intended speeds.
- a traffic evolution model, which describes the movements of the vehicles. This traffic evolution model is induced by the individual vehicle and driver models. At this level the AICC can be switched on or off by the driver. If the AICC is switched on, it fulfils a part of the tasks instead of the driver.
- a data collection component, gathering the microscopic output parameters needed for the safety model, the emission model, the noise model and the macroscopic model.

2.3 The MIXIC 1.3 traffic generator

The traffic generator decides whether to place new vehicles at the start of the first road link or not. In MIXIC 1.3 vehicles are generated from a so-called traffic 'injection' file. Vehicles that are generated, are assigned specific vehicle/driver data and an initial state.

A traffic injection file consists of recorded real-world data of individual vehicles. Each line in this file represents a vehicle. It gives the arrival time instant of the vehicle at a motorway carriageway and the lane, the speed and the electronic length of the vehicle.
The electronic length of a vehicle is the vehicle length that produces a signal on a loop detector. The relation between physical and electronic length depends on the speed, the vehicle shape, the detector type etc. Experimental research (Donk & Versluis, 1985) has indicated that physical length classes [0.0,5.10[, [5.10,12.50[and [12.50,->[(m) correspond - for the standard Rijkswaterstaat loops - to electronic length classes [0.0, 4.75[, [4.75, 11.12[, [11.12,->[. By matching the interval boundaries an approximate relation is computed relating the physical length to the electronic length, viz.:

$$L_{phys} = 0.9954\ L_{elect} + 0.0116\ L_{elect}^{2} \quad (2.1)$$

By using the physical length, it is checked to which vehicle category the vehicle belongs using the lower and upper bounds of the vehicle type data. If there are more vehicle types based on one vehicle category (e.g. passenger cars with and without ICC equipment are of a different type) then a random generator determines which type is assigned, taking into account the (user-defined) fractions of the involved vehicle types (e.g., fractions of 0.1 and 0.9 of passenger cars with and without ICC equipment, respectively). Further vehicle parameters, such as vehicle, or engine power are either drawn from a distribution or inherited from the vehicle type. MIXIC 1.3 was tested for 4 vehicle categories, see Chapter 3.

Several driver types can be defined. In MIXIC 1.3 there are 4 driver types. The driver type of a vehicle/driver combination is assigned randomly using a matrix giving the occurrence frequencies of the different combinations. Given the type of a driver, further driver specific parameters such as reaction time, are either drawn from a distribution or 'inherited' from the driver type. The intended speed of a driver is first taken as a sample from a normal distribution using the mean and standard deviation of the driver type. Next, the intended speed is taken as the maximum of this sample and the speed in the injection file. Finally, the intended speed is maximized at the physically possible maximum speed of the vehicle in a situation without wind or slope.

The use of an injection file to generate input to a microscopic model, see also van Arem & van der Vlist (1992), offers three advantages. First, given the availability of injection files, it is fast and does not require desk study into realistic vehicle generators. Second, it also puts the traffic evolution model to the test. The traffic evolution model should, in any case be able to process the amount of traffic offered by the injection file, being traffic actually observed in real-life. Third, it allows for calibration and validation by comparing the model with measurements further downstream (van Arem & van der Vlist, 1992). Such an approach was also used in the calibration of MIXIC 1.1 (Van Arem et al., 1994). A disadvantage is that injection files need to be available. Also, an injection file imposes a restriction on the length of a simulation.

2.4 The MIXIC 1.3 link model

A part of the input information for the microscopic traffic model concerns the road network data. These data specify the network to be considered. MIXIC 1.3 supports networks with one type of unidirectional link, viz. a number of homogeneous motorway links without on- and off-ramps. Narrowing or widening scenario's are supported, but testing has only been done for narrowing scenarios. Links are specified in detail. Parameters are specified not only for length, number of lanes, width etc., but also for road and weather conditions and for the computation of noise. Finally, the presence of an ICC beacon is specified. Certain lanes can also be dedicated exclusively for AICC vehicles. On such lanes it can be specified that parameters from the AICC (e.g. following headway) have specific values.

Links are interconnected by nodes. Nodes are origins, destination or just connections between links.

Each node is specified by an incoming link (if any) and/or an outgoing link (if any). If a node marks a motorway discontinuity, i.e., there is a change in the number and/or the accessibility of the lanes change, then a pre-warning distance is specified.

The specification allows that other types of networks and links (e.g., motorway links containing an entry or an exit, or even intersections) may be added in the future.

2.5 The MIXIC 1.3 traffic evolution model

The traffic evolution model is the kernel of MIXIC 1.3. The traffic evolution model continuously updates the traffic state. Given a traffic state at time *t*, it computes the traffic state at time *t+D*. The traffic state consists of the position, speed and acceleration of all vehicle/driver combinations, including all the vehicle and driver states. Some of these variables are kept during a certain history to allow the implementation of driver reaction times and delay of technical systems.

The traffic state is computed for a number of consecutive time instants, until a stopping criterion is satisfied, namely, if:

- the number of completed trips is equal to or larger than the maximal number of completed trips to be simulated, or
- the time simulated is equal to or larger than the maximal simulation time.

Suppose the traffic state at time *t* is known. The traffic evolution model proceeds along the following stages in the evaluation of the state at time t+D.

Stage 1 Compute control

In this stage traffic control signals are computed. The traffic control assumed here is Intelligent Cruise Control (ICC) in combination with a road-side beacon. The beacon supplies a reference speed to the vehicles equipped with ICC.

The stage computes the reference speed provided by the beacon. In MIXIC 1.3, however this stage has not been implemented yet.

Stage 2 Generate new vehicles

This stage decides whether to place new vehicles at an origin node or not. It does so by either applying a random vehicle generator or by applying a traffic injection file. In MIXIC 1.3 vehicles are generated from a traffic injection file, see Section 2.3.

Stage 3 Compute new states and positions

For each vehicle/driver combination the vehicle and driver model is invoked. The vehicle and driver model are described in Chapter 3.

In global outline, the model is as follows. Each driver has an **intended speed** which he aims to maintain or reach. Simultaneously, the driver maintains a **minimum intended headway** to his predecessor. This minimum distance headway is an increasing function of the vehicle speed. If a driver does not drive at his intended speed and is not able to accelerate, he tries to overtake his predecessor. He may do so only if there is sufficient space. A driver goes back to a lane to the right if he will be able to maintain the same speed or acceleration as he would maintain on his current lane.

The result produced by driver and vehicle model consists of an intention to change lane, and an acceleration. The acceleration produced by the driver/vehicle model is such that the vehicle always tries to maintain its minimum distance headway, possibly with very strong decelerations.

Some vehicles are equipped with Autonomous Intelligent Cruise Control (AICC). AICC is capable of measuring distance and speed difference with respect to a predecessor, and automatically adapting the vehicle acceleration. It thus replaces parts of the driver and vehicle model, see Chapter 4. In the future it is intended to also include ICC variants with communication amongst vehicles and amongst road side equipment. It is assumed that drivers use the AICC whenever possible. However, the AICC will be assumed to have a limited deceleration range. Therefore a driver has to intervene and switch the AICC off in situations where strong braking is required. Therefore the driver model also incorporates decisions as to when to switch the AICC on or off.

Stage 4 Move vehicles

In this stage the output of the vehicle and driver model is used to compute and assign the new speeds and positions of all driver/vehicle combinations.

Stage 5 Detect and solve conflicts

Using the procedure described above, two types of inconsistencies can occur. First, two vehicles may overlap by changing to the same lane at the same time from the left and the right lane, respectively (this is not checked in stage 3). If this is the case, the vehicle coming from the left lane is put back into its original lane. This phenomenon can only occur in situations with three or more lanes.

Second, negative distance headways may occur, i.e., vehicles "overlap". This is caused by the fact that the driver/vehicle model is applied for each driver/vehicle combination separately. A specific driver/vehicle combination can therefore not take into account the actions taken by his predecessor during the same time step. It is first attempted to eliminate negative distance headways by adjusting the acceleration. If this does not succeed, the vehicle/driver combination is removed from the simulation and a message is produced to the user.

2.6 Data collection in MIXIC 1.3

Data collection in MIXIC 1.3 is done by keeping statistics for individual vehicles (mean and variance of speed, fuel consumption, etc.), for cross-sections (flow, speed, traffic composition, headways, time-to-collission, etc.), for links (e.g., density) and for a sequence of links (e.g., travel time). Statistics can be collected during a number of time intervals and for all time intervals together. The starting time of the first interval is specified by the user, taking care that the collection of data commences after the road links have 'filled'. At the end of the simulation the statistics are written to an output file in ASCII. This file may be used in combination with the corresponding input file to produce dedicated output.

A special feature is the possibility of measuring shock waves. Each occurrence of a vehicle with a deceleration stronger than a specified threshold indicates a possible involvement in a shockwave. Occurrences are assigned to the same shockwave if they occur within a certain time and space range. A candidate shockwave is considered to be a genuine shockwave if more than a specified number of vehicles is involved. The parameters for measuring shock waves are specified in the input file.

MIXIC 1.3 is accompanied by a number of additional programs.

- The traffic performance module PERFMOD 1.3 reads both the input and (raw) output of a simulation. It produces aggregate statistics and confidence intervals, on e.g., the speed, flow and density per link, the division over lanes, average speed of vehicles, with or without ICC. It also gives aggregate shockwave statistics, such as the number of vehicles involved and the speed of the shockwave.
- In addition, dedicated modules have been developed by TNO to provide output for noise emission, safety, exhaut-gas emission and fuel consumption.
- The program MIXDB32 gives output in a format suitable for spreadsheet processing.

3 DRIVER AND VEHICLE MODEL

3.1 Introduction

Within the microscopic model, new positions and states are calculated in each time step by a driver and vehicle model. The combined driver/vehicle model produces the longitudinal new vehicle acceleration, and a decision to change lane or not. In each iteration, the driver model produces the driver actions, consisting of the lane change action and the new pedal and gear positions. Next, the vehicle model calculates the resulting acceleration of the vehicle.

A general description of the driver and the vehicle model is given in Section 3.2 and 3.3, respectively. Appendices A and B give a further specification of the driver and vehicle model.

3.2 Driver model

The driver model consists of three main components. The first two describe the actual driving behaviour: these are the lane-change model and the longitudinal driver model. In each simulation time step, these sub-models are executed to decide whether or not a driver changes lane and the driver's actions on the vehicle controls, respectively. For vehicles that are equipped with AICC, the third component models the interaction between the driver and the AICC; this part indicates when the AICC is switched on and off..

In MIXIC 1.3, four separate vehicle types are distinguished (see Section 3.3), viz. cars, vans, trucks and very long trucks (road trains). For cars, two different driver types (a slow and a fast one) have been specified. These types differ in the intended speed parameters. For vans there is a separate driver type. The driver type for trucks and 'road trains' are identical. Regardless of the driver type, all driver models have the same structure: they only differ in the parameter settings. Within each driver type, differences that exist between drivers are implemented by means of sampling from (normal) distributions. The parameters of the driver types are given in Appendix A.4. Additionally, a number of parameters that are assumed to be constant for all drivers; these are given in Appendix A.4 as well.

3.2.1 Lane-change model

The lane-change model distinguishes two situations: a mandatory lane-change model and a free lane-change model. The mandatory lane-change model is applied if a driver is aware that the lane he is driving on does not lead to his destination, does not continue on the next link, or is not accessible for the driver. The free-lane change model represents overtaking because a slower lead vehicle is forcing the driver to reduce his speed below his desired speed. During normal operation, the free lane-change model is applied, unless a driver has to make a mandatory lane change. The details of the Lane Change model are given in Appendix A.1.

3.2.1.1 The free lane-change model

The first step of the free lane-change model is to determine whether the modelled driver decides to execute a lane-change manoeuvre to the right or to the left lane. Second, when a lane-change decision has been taken, a simple procedure is used to simulate the actual lane-change execution.

Free lane-change decision

In Appendix A.1 rules are specified for 'want to change' and 'perform change', both to the left and to the right. The rules for 'want to change' include a comparison of the current speed with the desired speed and with the speed of the lead vehicle in the current lane. Also the vehicle's actual acceleration with respect to the maximum comfortable acceleration and deceleration is evaluated. The rules for 'perform change' refer to the safety of the intended manoeuvre, determined by a sufficiently large gap in the target lane.

If a driver is intending to make a lane change, then it is checked whether the target lane will remain to be available if the driver is within a pre-warning distance of a discontinuity point. If the target lane will not be available ahead, then the lane change is not executed.
If an AICC vehicle is in a dedicated lane, the behavioural code to keep to the right is suppressed.

The impact of AICC on free lane changing behaviour

The lane-change model of the driver without AICC takes into account comparisons between the driver's intended speed and the actual speed on the one hand, and between the driver's intended headway and the actual headway on the other. When AICC is controlling speed and headway instead of the driver, these comparisons are no longer meaningful and can even be confusing. Therefore, for vehicles with activated AICC, the lane-change model takes into account a criterion specifying whether the AICC is active and in following mode. If that is the case and the actual speed is below the intended speed (which is an AICC parameter set by the driver), then it is assumed that a driver *wants* to change lane to the left. The decisions to change lane to the right are assumed to be the same for drivers with or without AICC.

Free lane-change execution

Since no lateral control is included in MIXIC, a time delay is used to simulate the actual lane-change execution. When a lane-change decision has been taken, it is executed not immediately, but only after this delay. During this delay time, the lane-change decision is re-evaluated in every time step to allow for the possibility to abort an intended lane-change manoeuvre (for example, if another vehicle suddenly reduces the available space in the target lane). The delay mechanism also prevents the model from executing a lane-change just one time interval after having finished a previous one, which would be unrealistic.

Extension of the free-lane change model in congested traffic

For gaining speed advantage, the free-lane change model only considers lane changes to the left. When a vehicle is below its intended speed and at its maximum acceleration, the vehicle will not intend to go the right. This can lead to situations in which the speed of vehicles on a lane collapses, whilst traffic in one or more lanes to the right is still flowing. Because this situation was considered unrealistic and undesirable, an adaptation in the free lane change model was made, to introduce lane changes to the right in congested traffic to gain speed advantage, i.e. when the lane to the right moves faster than the current lane. This adaptation is applicable as soon as the speed of a vehicle is below a threshold (default 70 km/h). The safety of the manoeuvre is evaluated with respect to the relative speed with respect to the new successor. The criterion is that the new successor should not have to brake to hard. Thus, the gap should be larger than the sum of:

- speed difference times the lane change delay;
- the distance needed to adapt the speed;
- the intended headway.

3.2.1.2 The mandatory lane-change model

The mandatory lane-changing process consists of a number of steps:

– Perception of the forthcoming situation and choice of a destination lane
– Deciding on the intention to change lane
– Scanning for an appropriate gap and controlling relative speed and position
– If the speed difference and position error are small enough the lane change is executed

Perception of the forthcoming situation and choice of a destination lane

At the end of each section there may be a discontinuity point: this may imply that the lane a driver is driving on will not be available to him. For each discontinuity point, there is a pre-warning distance, assigned by default a value of 1350 m (which is based on the Dutch standard distance to announce an exit (1200 m) and a perception distance). As soon as a driver passes the pre-warning distance, the target (or destination) lane is determined. This is done by looking for an appropriate lane starting with the present lane, then looking to the lanes to the right and then looking to the lanes to the left, until he has found a lane that will continue and that will match his type of equipment (or vehicle-type or destination).

Deciding on the intention to change lane

There is a distance at which the driver will start to undertake action to change lane. If a mandatory lane change is needed the intention to change lane is drawn from a normal distribution cut of between the pre-warning distance and some distance before the discontinuity point. The centre of the distribution and the standard deviation depend on the number of lanes that have to be crossed (the more lanes, the earlier the lane change is intended).

Scanning for an appropriate gap and controlling relative speed and position

If the distance of a driver to the next discontinuity point is less then his intention distance, he starts to look for an appropriate gap in the adjacent lane. If the driver has an AICC system which is active, then he first switches it off: gap scanning and controlling relative speed and position are done manually. The 'negotiation' of a mandatory lane-change gives simultaneously results for the desired acceleration and the intended lane change. During this process some special behavioural parameters apply:

– The intended headway a driver maintains to his predecessor is multiplied by a factor, in such a way that from the point where a driver starts to scan for an appropriate gap, he will be gradually accepting shorter headways, until 0.25 (default) his 'normal headway' at the discontinuity.

- The fierceness with which a driver tries to control distance deviations and speed deviation from his intended relative distance or speed, is increasing in a similar way.
- When a driver changes lane, there is a special mandatory lane-change delay, by default 0.5 s.
- In order to perform a mandatory lane change to an adjacent lane, a driver needs a minimum required gap. This minimum required gap is a function of intended headway and decreases with decreasing distance to the discontinuity point.

In order to find a gap he first controls his speed to the speed of the adjacent lane. For this purpose a target vehicle is selected as the predecessor in the target lane, or if there is no predecessor, a successor. It is checked whether the speed matches the relative speed with respect to the target lane sufficiently by: If the relative speed is sufficiently small or if the relative speed is non-perceivable, or if there is no target vehicle, the driver checks whether the nearest gap is larger than min_req_gap. If this is the case, then it is checked whether there is sufficient room at the front and the rear of the vehicle, and fine tuning of the relative position with respect the room is done.

If the nearest gap is too small, the driver evaluates an alternative gap. If his desired speed is above the speed of the target lane and the gap ahead of the nearest gap is large enough and his predecessor in his own lane is not in the way (after an anticipation period) he moves to the gap in front. Otherwise he moves one gap behind.

Changing lane
The mandatory lane change is initiated when:
- the gap is large enough
- the relative position with respect to the gap is right
- the angular speed with respect to the new predecessor and successor are less than a certain threshold (0.021 rad/s by default).

Besides the requirements of a sufficiently large gap and large enough headways with respect to the predecessor and succesor in the target lane, the combination of relative speed and distance is taken into account by means of an angular velocity criterion. The angular velocity is defined as the rate of change of the perceived angle which encompasses the vehicles near the subject. This angular velocity gap acceptance model was proposed by Michaels and Fazio (1989). They reported the threshold to be in the range between 0.01 and 0.001 rad/s with a nominal value of 0.004 rad/s. Analysis of lane change behaviour in the TNO driving simulator showed that the angular velocity threshold depends on traffic density. For high densities the 95%-percentile of the angular velocity was 0.021 rad/s (de Vos & Hoekstra, 1997).

3.2.2 Longitudinal driver model

The longitudinal driver model describes the driver's actions with respect to longitudinal vehicle control. As indicated by Van der Horst et al. (1993), the output of most models from the literature normally consists of the realised acceleration of the vehicle, i.e. those models describe the total of driver plus vehicle, usually without a clear distinction between a driver and a vehicle model. In MIXIC, however, this distinction is explicitly made, and the interface from driver model to vehicle model has been defined at a detailed level (positions of the accelerator pedal, the clutch pedal, and the gear shift, and the force exerted on the brake pedal). Therefore, the following approach is used in MIXIC. The first step in the longitudinal driver model is to calculate the driver's desired acceleration as a result of the current state of the vehicle, and relative position and speed to leading vehicles. Next, this desired acceleration is used together with the current state of the vehicle to determine the vehicle's controls in such a way that the desired acceleration is realised as much as possible. This part of the model represents the 'knowledge' a driver has about the vehicle's reaction to pedal manipulations.

The longitudinal driver model distinguishes free-driving and car-following behaviour. In each iteration, a desired acceleration is calculated for both situations, and the most restrictive one is used as the resulting desired acceleration.

Free driving

In the free-driving situation, the driver only attempts to reach or maintain his intended speed within certain boundaries. This intended speed (assumed constant in time for each driver) indicates the speed that would be maintained in the absence of other traffic. To obtain reasonable parameter settings for MIXIC 1.3, the mean and standard deviation of the free-driving speed have been determined from inductive loop detector measurements, using several input files to represent a reasonable range of traffic conditions. The criterion used for 'free driving' was a time headway of 10 seconds, and the procedure was repeated for each driver type separately. The results are given in the following table.

During the calibration experiments during the development of MIXIC 1.3, positive experiences were gained with the introduction of an additional -more cautious- driver type (mean=100, sd=5). A 50%-50% mixture of these two car driver types led to more variation and a slightly less optimistic flow profile.

Table 3.1: Mean and standard deviation of the free-driving speed for each driver type [km/h].

driver type	mean	sd
car driver	121	12
“cautious car” driver	100	5
van driver	94	15
truck driver	86	6

If the current speed deviates more than a given proportion (set at 3%) from the desired speed, the desired acceleration is made proportional to the speed error, taking into account the reaction time of the driver (see Section 3.2.2). The resulting desired acceleration it is limited within the boundaries for comfortable acceleration and deceleration. Originally, these parameters were set at +1.5 and - 3 m/s^2, respectively, based on data from the Traffic Engineering Handbook (1992). However, initial simulations revealed that these values were too conservative: accelerations reached during overtaking manoeuvres were too low, and lane-changing behaviour was unnecessary precautions. Therefore, the maximum comfortable acceleration and deceleration were set at +3 and -5 m/s^2 respectively. These values are used regardless of the speed and vehicle or driver type.

Car-following

In the car-following situation, the driver has to adjust his speed and/or following distance with respect to traffic ahead. The model implemented in MIXIC is derived from the Optimal Control Model of Burnham, Seo and Bekey (1974). It is based on the assumption that the driver tries to keep the relative speed to the lead car zero, and simultaneously attempts to keep the distance headway at a desired value. The desired headway increases according to a quadratic function of driving speed (Hogema, 1995). Especially at high flow levels the parameters of the intended headway function have a strong effect on the simulation results. In Appendix A.2 the parameter setting of the headway function is discussed. In addition to the original model, also the relative speed to the vehicle ahead of the lead vehicle is taken into account; de Vos (1991) showed that this contributes to the stability of the traffic flow. The desired acceleration from the car-following algorithm is obtained as a linear combination of the relative speeds and the deviation from the intended distance headway. A *perception threshold* for relative speed has been added to this model in a straightforward manner, based on a constant threshold for the detection of changes in the visual angle enclosed by a lead car. This prevents the model from reacting to relative speeds which are far ahead. A more detailed description is given in Appendix A.

In the evaluation of the headway and relative speeds, the *reaction time* of the driver is taken into account. Measurements of driver reaction times have been reported in the literature for a variety of situations, with values ranging from a few hundred milliseconds to several seconds (see for instance Triggs & Harris, 1982). In the context of MIXIC, the driver reaction time represents the delay between a perceived deviation from the desired speed or headway and the (beginning of) the resulting correcting foot movement. Aspects like delays for moving the foot between the accelerator and brake pedal and perception thresholds are modelled separately, so therefore the MIXIC reaction time should be selected smaller than most overall reaction times reported in literature. Furthermore, since each driver's reaction time is assumed to be constant over time, its value should be representative for dense traffic conditions. A mean value of 0.3 s and a standard deviation of 0.05 s have been selected for each driver type.

Calculating pedal and gear positions

Once the desired acceleration is known, it is used to calculate appropriate values for the controls to the vehicle, in such a way that the desired acceleration is realised as well as possible.

The controls to be determined are:
- accelerator pedal position,
- brake pedal force,
- clutch pedal position, and
- gear number,

where the latter two are only relevant when the vehicle model has a manual gear shift. There will generally not be a unique solution for obtaining the desired acceleration. Therefore, gear and clutch position are determined first, and then the accelerator and brake pedal states are computed. Furthermore, for the clutch pedal, only the fully pressed and the fully released positions are used, and it will only be pressed when changing gear or in severe braking manoeuvres. A simple algorithm, based on an upper and a lower limit for the engine rotational speed, is used to determine if a gear shift has to be carried out. For the time needed to change gears for trucks (Elink Schuurman, 1989), a characteristic value of 2.4 s was found in a driving test. However, it is judged that 1.5 seconds may be a more realistic value, especially as switching between high and low gear takes only a very short (about 0.5 s) interruption of the driving torque. In view of this, the gear-shift delay for car drivers was set at 0.5 s.

Then the accelerator and brake pedal states are determined, based on the assumption that the driver will use either the accelerator pedal or the brake pedal, or none (during foot movement from one to the other, which is modelled by a delay). The model first determines which pedal is to be used, and then calculates an appropriate accelerator pedal position or brake pedal force, based on the current vehicle state, the desired acceleration, and a static inverse vehicle model. The time it takes a driver to move his foot from the accelerator pedal to the brake pedal has been reported in several investigations in the literature: see for instance Davies & Watts (1969, 1970) and Snyder (1976). It appears that the mean speeded movement time lies in the range from 150 to 200 ms. Since MIXIC works in multiples of 0.1 s, a value of 0.2 s has been implemented for all driver types.

3.2.3 Driver interaction with the AICC

When a vehicle is equipped with an AICC system, then this system will take over parts over the longitudinal control task. The driver has the liberty to switch the AICC on or off. It will be assumed that the driver has the AICC switched on as much as possible. However, since the AICC has a limited deceleration range, the driver must overrule the AICC in situations where hard braking is required. Therefore, a model is needed which describes the interaction of a driver with the AICC.

Basically, two approaches can be followed to let the driver model take over control from the AICC in situations which require hard braking. Both options occur in reality, and have been implemented in MIXIC.

Driver monitors the car-following situation
The first option is to assume that the driver of a vehicle with active AICC is continuously monitoring the control actions of the AICC in relation to the actual car-following situation. When the driver detects the AICC is braking insufficiently, he takes over control. The problem with this approach is that there is no knowledge available on when and how drivers take over control from AICC's. However, in a driving simulator experiment evidence was found that in the situation of approaching a stationary traffic queue, drivers react later when they have an active AICC compared to the situation without AICC (Hogema, Van der Horst, & Janssen, 1994).

Given the lack of relevant knowledge, the most straightforward monitoring model consists of the existing driver car-following model. The condition for taking over control would then be: the AICC is braking at its highest deceleration capacity, AND the driver would decelerate more strongly in this situation if he was driving himself, see Eq. 3.1.

$$(a == max\_dec)\ \&\&\ (a\ -\ desired\_acc\ >\ t\_o\_acc\_threshold\,) \qquad (3.1)$$

where a is the actual acceleration, max_dec is the AICC's maximum deceleration (specified as a negative number) and desired_acc is the driver's own desired acceleration. The t_o_acc_threshold specifies a threshold by which the driver's desired deceleration must exceed the AICC's braking capability before he takes over control (^{3}0; default value 0).

In cases where an AICC vehicle is approaching a relatively much slower vehicle from an initial large distance, Eq. (3.1) may not produce the appropriate driver action, which in this case would be to switch off the AICC. As long as the slow vehicle is out of the AICC detection range, the AICC does not decelerate, and therefore the first condition in (3.1) is not true. Consequently, based on this equation, the AICC will only be deactivated after the lead car has come in the AICC detection range, which is rather late in situations with large speed differences. A driver, however, can anticipate to slower cars over larger distances than the AICC's detection range, and he can decide to switch the AICC off when necessary. An extra rule was added to Eq. (3.1) to incorporate this behaviour in the model.

ICC warns driver

Since the AICC's sensor is measuring the headway and speed difference to the lead vehicle, it can also determine to a certain extent whether its maximum deceleration is sufficient to avoid a collision. Based on this information, the driver can be warned when necessary. For example, the AICC used in the previously mentioned driving simulator experiment (which was based on the Daimler-Benz prototype) gave the driver an audio warning when necessary. In fact, this adds a Collision Warning functionality to the AICC. Incorporating such a warning system in the MIXIC AICC model allows the driver model to react to a warning signal by taking over control after a reaction time.

In the driving simulator experiment (Hogema, Van der Horst, and Janssen, 1994), the criterion used in approach situations was that the following vehicle had to be able to stay clear of the lead vehicle when braking at the AICC's maximum deceleration, assuming the lead car's speed remained constant. So the warning was given when:

$$[D\ <\ \frac{V_{dif}^{\ 2}}{-2\ max\_dec}\ +\ M]\ \&\&\ [V_{dif}\ \ >\ 0] \qquad (3.2)$$

where D is the actual distance, V_{dif} is the approach speed to the lead vehicle, max_dec is the maximum deceleration and M is a safety margin of 5 m. In the simulator experiment, the AICC's maximum deceleration was -1.8 m/s^2. However, using this value in Eq. (3.2) gave a too precautions criterion. Therefore, the value for max_dec actually used was -3.5 m/s^2. The latter seems a suitable default value for use in MIXIC (this was implemented by adding a correction of -1.5 m/s^2 to the default maximum AICC deceleration specified in MIXIC as -2.0 m/s^2).

MIXIC implementation

In both approaches, there is a decision criterion which tells when the driver initiates an AICC take-over, and furthermore a reaction time which tells how long after the decision is taken the actual reaction starts. The most logical implementation of the actual take-over process seems that after the take-over criterion is met, the drivers starts to move his foot to the brake, where the duration of this movement equals the reaction time. The AICC is deactivated at the moment the driver applies the brake. This would be in correspondence with the functioning of prototype AICC's.

In addition, the AICC is disengaged during a mandatory lane change process.

Due to the nature of the take-over action, larger reaction times can be expected in this process compared to the reaction time during normal car-following. A reasonable default value seems to be 1 s. There may be a difference in the reaction times occurring in the situation where the driver receives an anti-collision warning of the AICC compared to the situation where he monitors the car-following situation himself and decides to take over control. However, at this moment there is no evidence on which separate values can be based and therefore no distinction is made.

Engaging AICC

It is assumed that drivers with equipped vehicles will use the AICC as much as possible. This implies that after a driver has taken over control in a hard-braking situation, it is assumed that he will re-engage the AICC as soon as the situation has been handled. A criterion could be:

$$(-0.5 < \textit{current acceleration} < 0.5) \tag{3.3}$$

However, a near-zero acceleration could also exist when the vehicle is closing in on a lead vehicle. Therefore, in closing-in situations, an extra requirement for re-activation of AICC is:

$$D > \frac{V_{dif}^{\,2}}{-2\, a\_re\_eng} \tag{3.4}$$

where a_re_eng is set at a default value of -1 m/s^2. This ensures that the AICC will only be activated when in the current situation a deceleration of (-) a_re_eng m/s^2 will be sufficient to adjust the speed.

A reaction time could be included similar to the situation where AICC is disengaged, but that seems of minor importance because activating the AICC is not so critical.

In reality, a more adaptive re-activation criterion seems plausible. For example, when a driver has to take over control from the AICC a number of times in rapid succession, this may well decrease his willingness to re-engage the AICC. However, this is a hypothesis for which no empirical evidence exists.

It should be noted that the activation of AICC can cause a new kind of disturbance in a traffic stream (in MIXIC as well as in reality). When it is activated in a situation where the headway is smaller than the AICC's target headway, the vehicle will decelerate.

Some testing results

After incorporating the driver interaction with the AICC two tests were conducted. First, MIXIC was applied to a number of peak periods for a three lane motorway section. In this situation the simulation appeared to proceed without problems. In cases of high traffic demand AICC vehicles were found to gradually switch the AICC on during the course of time.

Second an experiment was conducted with a 'single lane motorway', with a fast vehicle (intended speed 140 km/h) with AICC approaching a slower vehicle with constant speed (47 km/h), see Figure 3.1. Figure 3.1 gives the speed (left vertical axis) and the headway (right vertical axis) for this vehicle as a function of time.

Figure 3.1 Headway and speed of a fast AICC vehicle approaching a slower vehicle

Figure 3.1 is explained using also some data from the vehicle logfile obtained for this case. In the first part is can be seen that the speed is constant and the headway decreases linearly. The AICC is active, and the preceding vehicle is out of the detection range. At this stage the driver has already spotted the predecessor and decides to disengage the AICC off at time 1.1 s. After a delay the AICC is actually disengaged at 1.6 s, followed by a an interval of full deceleration (up to -8m/s^2). After t=3.0 the braking becomes less fierce (around -2 m/s^2). At about t=13.0, the driver decides to re-engage the AICC. The AICC reacts with a deceleration. This is caused by the fact that the AICC headway is larger than the headway in the situation in which it is engaged. The headway in the situation in which the AICC is engaged is based on the driver's minimal headway, which is smaller than the AICC minimal headway at the same speed.

3.3 Vehicle model

The vehicle model describes the dynamic behaviour as a result of the interaction with the driver and the road, taking into account the ambient conditions.
The input variables from the driver model are the position of the accelerator pedal and the force applied on the brake pedal, and for vehicles with a manual gear shift also the gear and clutch position. The microscopic traffic model provides the vehicle model with information on the characteristics of the vehicle, the road geometry, the condition of the road and the wind. The output of the vehicle model to the microscopic traffic model is an updated vehicle acceleration, which is used by the microscopic traffic model to calculate a new vehicle speed and position.

The vehicle model calculates the vehicle acceleration based on the vehicle inertia and the resultant force of driving resistant forces, traction forces and braking forces. Figure 3.2 outlines the structure in a block diagram. The level of detail at which the dynamics of the vehicle are to be modelled depends on the characteristics of the total controlled system including the driver and the in-vehicle control systems. For the ICC-case that is presently guiding the development of the model, the driver is still kept in the loop, which means that the large time constants characterizing the driver justify a relatively coarse approximation of the vehicle dynamics. However, when a fully automatic system is considered, the driver dynamics are eliminated and thus the vehicle dynamics are more important relative to the fast response of an electronically controlled actuator. When scenarios like following at very small headways are investigated, the more specific dynamics of the vehicle become relevant, for example, tyre lag due to the compliance, inertia and damping in the interaction of vehicle tyres and road, can become a limiting factor in the bandwidth of the system.
In order to keep the present model as lean as possible it is aimed to only model the dynamics necessary for the application under investigation (ICC).

In Figure 3.3 the various forces acting on the vehicle are indicated. In the following, the various elements of the vehicle model are discussed.

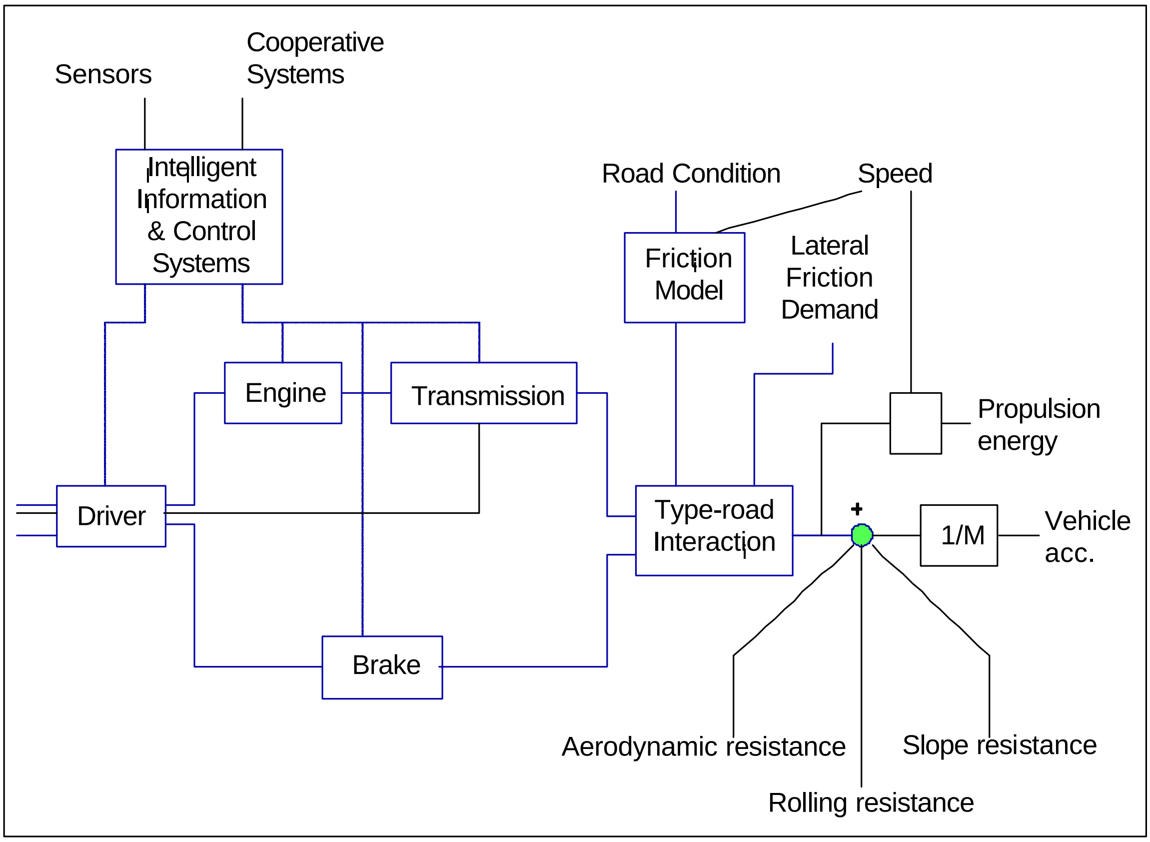

Figure 3.2: Block diagram of the vehicle model and it's environment

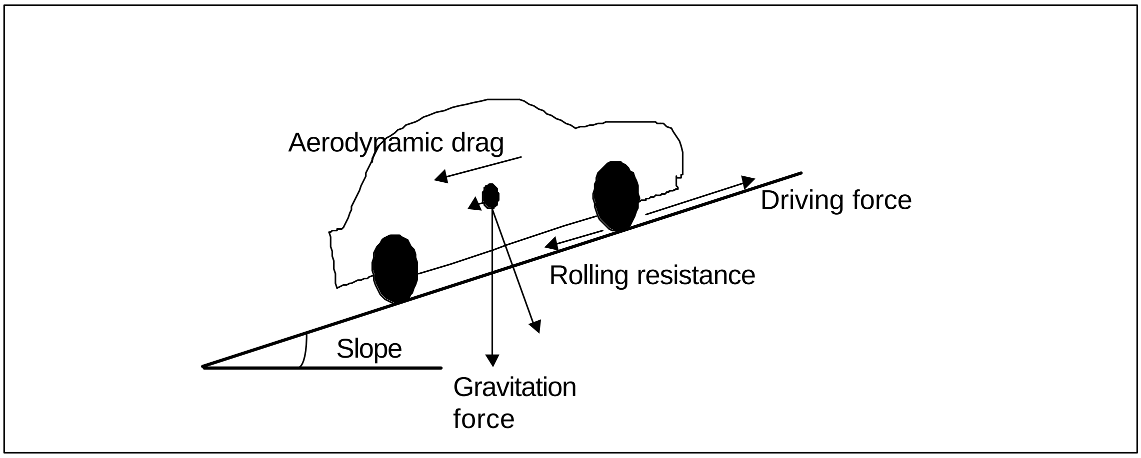

Figure 3.3.: Forces acting on the vehicle

Driving force

The driving force is generated by the engine and transmitted by the transmission and drive shafts to the wheels. The engine translates the control signal provided by the accelerator pedal position into an engine power. The driving force is the quotient of the power and the vehicle speed. The engine power changes are not generated instantaneously but have a dynamic response as result of the fuel system and the ignition system characteristics. The effective dynamics are lumped into a first order response. The static response of the engine is modelled by a limited engine power.

Braking forces

The braking force is a result of the force applied to the brake pedal and the force gain of the mechanics and hydraulics of the braking system. This gain is assumed to be constant, independent of the brake pedal force. The dynamics of the braking system are modelled by a time delay.

Tyre-road interaction

The forces generated in the contact area between the tyres and the roadsurface depend on the longitudinal and lateral slip.

This complicated non linear relationship is taken into account by means of a friction coefficient limiting the tyre forces. The maximum force depends on a number of parameters e.g. tyre type, inflation pressure, vertical tyre load, road surface texture, presence of any 'third body' (water, oil, snow, ice, dirt, etc.). As the surface condition has a predominant effect, this is included in the vehicle model. The friction coefficient is determined based on whether the road is dry, wet, or covered by ice or snow. Due to the hydrodynamic effect the friction coefficient on a wet road is dependent on the thickness of the water layer and the vehicle speed.

Lateral friction demand, e.g. for executing a lane change, is taken into account by effectively reducing the longitudinal friction coefficient.

Resistance forces

The passive forces that act on the vehicle originate from the aerodynamic drag, the rolling losses in the tyres and the longitudinal component of the gravitation force resulting from a non-zero road gradient. Furthermore, the presence of a water layer on the road introduces a hydrodynamic resistance.

The aerodynamic resistance is proportional to the frontal area of the vehicle, and to its aerodynamic drag coefficient; furthermore it increases quadratically with the air speed relative to the vehicle. The longitudinal component of the aerodynamic force determines the aerodynamic resistance.

The rolling resistance is found by multiplying the vertical load by the rolling resistance coefficient.

A road gradient introduces a longitudinal force equal to the gravitation force multiplied by the sinus of the angle of inclination.

Calculation of the propulsion energy

In order to be able to provide input to the 'exhaust-gas and fuel consumption output module', the vehicle model has to calculate the propulsion energy generated by the vehicle engine. The propulsion power results from the driving force and the speed, in each time step, and thus the propulsion energy follows by integration (over time).

Acceleration
The acceleration of the vehicle is calculated by applying Newton's law to the resultant of all forces acting on the vehicle.

A more detailed description of the vehicle model that has been developed is given in Appendix B. This appendix also gives the parameters for the vehicle model.

4 AUTONOMOUS INTELLIGENT CRUISE CONTROL

4.1 General description

This chapter gives an overview of the Autonomous Intelligent Cruise Control (AICC) as it has been implemented in MIXIC 1.3. In addition to the conventional cruise control function of speed control, an AICC is also capable of automatically regulating a vehicle's speed and following distance when following another vehicle. To obtain the additional information needed for this control task, a radar-like sensor is used. The core of the AICC consists of a control algorithm, which influences the vehicle by means of a gas and brake actuator.

Since there is no large-scale practical experience with AICC, the assumptions were made that the AICC will perform as intended, and new hazards that could occur as a result of system failure are not taken into consideration (see also Hitchcock, 1991). Next, all vehicles that are equipped with AICC are assumed to have an automatic transmission, and drivers of AICC vehicles are assumed to have the AICC activated as much as possible.

With respect to the possible driver reaction on the AICC control, there is only little knowledge available (Hogema, Van der Horst, and Janssen, 1994). Therefore, the assumption used as much as possible was that driver behaviour is unaffected by AICC. Some deviations from this assumption had to be made because AICC will be a system that must be overruled by the driver in situations that require hard braking. Therefore, a model was designed indicating when a driver turns the AICC on or off. Furthermore, since a part of the lane-change model is based on driver state variables concerning longitudinal control (which is now taken over by the AICC), it was necessary to redefine the lane changing mechanism.

The AICC implemented in MIXIC 1.3 will be truly autonomous, i.e. function independent from road-side infrastructure or other vehicles being equipped or not. However, the current design allows for a straightforward addition of for instance road-side-to-vehicle communication. This would create the possibility to have a local speed limit automatically being used as the ICC's reference speed.

The main structure of a vehicle equipped with AICC is shown in Figure 4.1. It has to a large extent been based on experience with the implementation of ICC in the TNO driving simulator (Hogema, Van der Horst & Janssen, 1994).

The AICC is equipped with a *sensor* to measure the headway and relative speed with respect to the lead vehicle in the current lane. The sensor is characterised by its delay and by its maximum detection range.

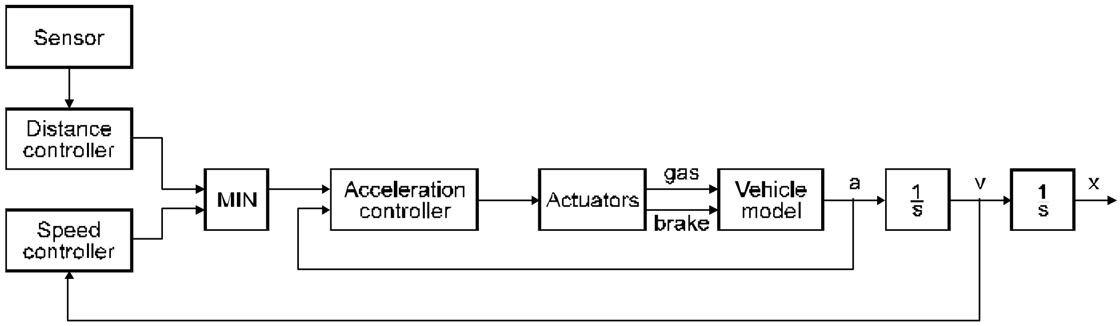

Figure 4.1 Block diagram of AICC in relation to the vehicle model

The AICC has two separate modes, speed control and distance control, which both result in a reference acceleration, i.e. the acceleration the AICC algorithm wants to realize in that mode. The *speed controller* tries to maintain the AICC's reference speed, which is selected equal to the driver's intended speed because of the assumption that driver behaviour is not changed by the AICC. The *distance controller* tries to maintain a reference headway to a lead car. This reference distance has been implemented as a linear function of the current speed, which is defined by a time headway parameter. This approach has also been used by Broqua et al. (1991) and by Müller and Nöcker (1992). In MIXIC, the output of the distance controller is a linear function of the relative speed and of the distance error (i.e. the deviation from the reference headway). This is a slightly different approach than used by Hogema, Van der Horst & Janssen (1994), who used a two-dimensional look-up table to obtain the distance controller output. This table was developed by Müller & Nöcker (1992) by means of fuzzy control techniques, and was made available confidentially for the study in Hogema, Van der Horst & Janssen (1994). Therefore an alternative approach was used in MIXIC.

The outputs of the speed and distance controller are combined into an overall reference acceleration by selecting the most restrictive of the two. This reference acceleration serves as input for the *acceleration controller*, which has the aim of controlling the vehicle's acceleration to its reference value. This is achieved by setting suitable signals to a gas and brake *actuator*, which have as their output the accelerator pedal position and the brake pedal force, respectively. The actuators, which are characterised by a time constant, produce the input to the MIXIC vehicle model.
For a more detailed description of the various sub-systems, the reader is referred to Appendix C.

4.2 Parameter settings of the AICC

After having established the control structure of the AICC, the parameters have to be given suitable values. A distinction must be made in vehicle-dependent and vehicle-independent parameters. Examples of the first group are the gains in the acceleration controller: these have to be tuned to the vehicle's characteristics in order to obtain suitable dynamic behaviour. An example of a parameter which is assumed to be vehicle-independent is the AICC's reference time headway, which is identical for all AICC’s. However, if an AICC vehicle is driving on an AICC lane, then the time headway parameters are overrules by parameters for that lane, allowing AICC vehicles to observe closer following distance on dedicated AICC lanes.

Acceleration controller and actuators

The parameters of the acceleration controller and actuators were tuned first. Apart from the actuator time constants, these are all vehicle-dependent parameters. The following approach has been used. First, the MIXIC vehicle model as specified in Section 3.3 has been implemented in PSI/e, which is a block-oriented simulation program for studying the behaviour of dynamic systems (Van den Bosch, 1990). For this purpose, the vehicle model was slightly simplified: the wind speed and slope of the road were not included as variables (i.e. they were both set at 0). Next, a prototype of each of the three vehicle types was realized in a PSI/e model, using the mean value of all vehicle parameters for which a normal distribution is used. To this vehicle model, the actuators and the acceleration controller were added, using the parameter values that were found by Hogema, Van der Horst, and Janssen (1994) as initial values. Then a number of simulation runs was executed for each vehicle type separately, using a block test signal on the reference acceleration, comparable to the approach of Broqua et al. (1991). The parameters of each vehicle type were tuned with the objective to obtain fast transient responses while avoiding excessive overshoot or oscillatory behaviour. Having found acceptable parameters, vehicle parameters were varied to investigate the sensitivity of the closed-loop behaviour to such changes. It was found that the prototype acceleration controller is sufficiently robust: both for the highest and for the lowest occurring power-weight ratio, the original parameter settings performed well. Consequently, all vehicle-dependent parameters have to be specified for each vehicle type separately, but within each vehicle type, no further differentiation is necessary.

Distance controller

For the distance controller, originally a simple linear feedback law was used, similar to the approach of Broqua et al. (1991):

$$a\_ref\_d = Kd * hw\_err \tag{4.1}$$

where a_ref_d is the reference acceleration as produced by the distance controller, Kd is a constant feedback factor, and hw_err is the headway error, i.e. the deviation of the actual headway from the reference headway. Results from Broqua et al. (1991) showed that a low value of Kd produces platoon instability (since weak feedback allows for large oscillation in distance and speed), whereas a high value of Kd results in platoon stability.

It turned out, however, that this approach did not suffice for the MIXIC vehicles because of the sensor delays that are included in the model. This is illustrated in Figures 4.2, 4.3, and 4.4, which show the results of a simulation of six vehicles in a platoon, the first of which has a stepwise acceleration/deceleration signal as its reference acceleration, and the other five follow the control law of Eq. (4.1). In Figures 4.2 and 4.3, the delays have been set at 0, and the results are comparable to those of Broqua et al. (1991): for small controller gains (Kd=6, Figure 4.2) the control is too weak, resulting in oscillations. For higher controller gains (Kd=20, Figure 4.3), stable control is obtained. However, this approach only works for systems without pure time delay, whereas in MIXIC a sensor delay of 0.1 s is used. Using the same control law, the introduction of this sensor delay results in unstable platoons

(Figure 4.4). Therefore, to obtain better damping, rate feedback was added, resulting in the following control law:

a_ref_d = Kd * hw_err + Kv * rel_speed_sens (4.2)

where rel_speed_sens is the relative speed to the lead vehicle as measured by the sensor, and Kv is a new controller constant. With this approach, it is possible to achieve stable control, which is illustrated in Figure 4.5.

Figure 4.2 Unstable platoon response because of too weak control (no delays, Kd=6)

Figure 4.3 Stable platoon response because of sufficiently strong control (no delays, Kd=20)

Figure 4.4 Unstable platoon response because of delay (sensor delays 0.1 s, Kd=20)

Figure 4.5 Stable platoon with rate feedback (sensor delays 0.1 s, Kd=0.2, Kv=3)

5 IMPLEMENTATION

5.1 Formal specifications

In Van der Horst et al. (1993) the global design of the microscopic traffic model was reported. Also, a first overview of the information flows was given. Based on this global design the modules were developed in detail. This led to a detailed specification of the operation of the microscopic traffic model and the information flows from, to and inside the microscopic traffic model. Based on the extent of the variables it was anticipated that the program had a risk of being quite demanding with respect to memory and computational requirement. It was decided at that point to focus on functionality rather than memory and computational requirements.

The detailed specification was finally laid down in a formal specification language called 'Vienna Development Method (VDM)'. The formal specifications of MIXIC 1.3 and the traffic performance module are available in Zegwaard & Van Arem (1997a), including an explanation of VDM.

5.2 Programming and platform

The program was implemented in Ansi C. The main reason for choosing Ansi C is that it may be compiled on a large range of platforms. It was developed using the Watcom C Integrated Development Environment. On execution on a Pentium 200 Mhz Personal Computer the simulation of 6.0 km motorway with 4 lanes and 7000 veh/h takes about up to a factor 4 of real time, that is, the simulation of 3 hours of traffic takes 12 hours.

The memory requirements of MIXIC 1.3 are considerable. This is especially due to the large number of variables kept for each driver and vehicle and to the fact that a history of states has to be kept. In order to utilise the full internal PC memory, the program is complied for 32 bit DOS execution.

For demonstration purposes a graphical presentation of the simulation has been added. However, this graphical presentation is not in Ansi C and can not be guaranteed to operate on other computers. It should work on an IBM compatible personal computer with VGA screen.

5.3 Testing results

The earlier version MIXIC 1.0 was subjected to a number of tests in order to check whether it carries out the correct actions. MIXIC 1.0 was tested for endurance (long input files). Next, tests were performed to verify whether the program produces the correct results. This was done by checking the results of a small injection file by manual computation, for a number of variations in the input file, concerning the number of measurement points, the number of vehicle and driver types, the number of links etc. The results were in good agreement. For larger simulations it was checked whether the results are in a reasonable range.

The adaptations incorporated in MIXIC 1.1 were tested in a similar way. In addition, a calibration of the traffic performance and shockwaves took place, for a 3 lane motorway, see Van Arem et al. (1994).

In MIXIC 1.2 the incorporation of AICC and the parameter settings were tested by specifying a number of scenario's in which drivers had to switch on or off the AICC, or had to overtake a lower vehicle. The parameter settings were chosen in such a way that the behaviour of each driver and vehicle was credible. Also in other parts of the program some modifications were made. In Van Arem et al. (1995) a short report of a recalibration is included, in which also attention is devoted to peaks with a very high traffic demand.

MIXIC 1.2 was also used some other studies.
- In Hoogvelt et al. (1996), MIXIC 1.2 was used to study the impact of long and heavy trucks. For this purpose a recalibration for a 2 lane motorway with a large amount of trucks was conducted.
- In Van der Voort (1996) MIXIC 1.2 was used to study the impact of fog warning systems. The study involved a short recalibration at the A59 motorway, which is a 2 lane motorway.

Finally, the current version MIXIC 1.3 was recalibrated using a 4 lane motorway (the A4 near Schiphol). The recalibration address both a homogeneous and a road narrowing situation. The recalibration involved some changes in the driver model, viz.
- the addition of changing lanes to the right during congestion to get speed advantage
- the addition of a mandatory lane change model
- the addition of a 'cautious' car driver type
- the adaptation of the time headway relation: (3, 0.25,0.02) instead of (3, 0.25, 0.01) (Appendix A).

5.4 Documentation

The documentation of the program is included in three reports. It consists of
- a detailed specification in VDM, Zegwaard, Van Arem & Van Katwijk (1997),
- a user manual, Vanderschuren, Zegwaard & Van Arem (1997), and
- a program documentation, Zegwaard & Van Arem (1997).

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APPENDIX A: DRIVER MODEL

The driver model consists of three main elements, viz. the *lane change model*, which determines if a lane change will be carried out, a *longitudinal driver model* which calculates the driver's actions on the pedals and the gear shift, and finally the *driver-AICC interaction model* which indicates when the driver switches the AICC on and off. These sub-models will be described in detail in this appendix.

A.1 LANE-CHANGE MODEL

The lane-change model distinguishes two situations: a mandatory lane-change model and a free lane-change model. The mandatory lane-change model is applied if a driver is aware that the lane he is driving on does not continue on the next link, or is not accessible for the driver. The free-lane change model represents overtaking because a slower lead vehicle is forcing the driver to reduce his speed below his desired speed. During normal operation, the free lane-change model is applied, unless a driver is intending to make a mandatory lane change. The details of the Free Lane Change model are given in A1.1; the Mandatory Lane Change model is described in A1.2.

A1.1 Free lane_change_model

The first step of the lane-change model consists of calculating the target lane, i.e. the lane the driver intends to travel on. If this does not equal the actual lane, a lane-change manoeuvre will be carried out. Since lateral control is not included in the current version MIXIC 1.3, this is simply realised by means of a certain delay, which has been set at 1s. During this delay, the target lane is recalculated in every time step to verify that the driver still wants to continue the manoeuvre. This realises the possibility to abort an intended lane-change manoeuvre, for example, if another vehicle suddenly reduces the available space in the target lane. At the end of the delay, the vehicle will jump to the target lane.

calc_target_lane
This function is the core of the lane-change model: it determines the driver's target lane, i.e. the lane he wants to travel on. Its result will either be the actual lane or, when a lane-change decision has been made, one of the adjacent lanes. Its result will only indicate a lane change if the driver not only wants to carry out a lane change, but also judges it to be safe to do so. First it is determined if the modelled driver wants to make a lane change to the left or to the right. If so, it is judged if this manoeuvre is safe enough.

The rules for wanting to change to the left lane are:
(the vehicle must decelerate to follow a leading vehicle) AND
(the deceleration exceeds the normal comfortable deceleration, OR
the speed of the lead vehicle is less than 95% of the own speed, OR
the own speed is less than 95% of the own desired speed).

For the default driver model (i.e. without active AICC), the first of these conditions is evaluated using a comparisons between the driver's intended speed and the actual speed on the one hand, and between the driver's intended headway and the actual headway on the other. When AICC is controlling speed and headway instead of the driver, these comparisons are no longer meaningful. Therefore, for vehicles with activated AICC, the first of these equations is evaluated by checking whether the AICC is in following mode.

The rules for wanting to change lane to the right are:
(the vehicle has reached, or nearly reached, the intended speed OR
the vehicle has (nearly) reached the maximum comfortable acceleration)
AND
(when speeds are kept constant, there will be no collision with the new lead vehicle in the right lane within 30 s).

The current rules for judging the safety of the intended manoeuvre are simply:
(the distance headway to the new lead vehicle must be at least the own intended distance headway)
AND
(the distance headway of the new following vehicle must be at least the own intended distance headway)

where the own intended distance headway is a quadratic function of the current speed (see A.2, d_ref), and the normal comfortable deceleration is set at 50% of the maximum comfortable deceleration.

Changes to the free lane change decision model induced by mandatory lane changes
In the free lane change model a check is made whether the desired lane change is allowed in view of the equipment of the vehicle and the lane type. Both the present lane type and the lane type ahead (if the *driver is within the pre_warning_distance) are checked. If the target_lane is not available to this* driver/vehicle the free lane change is not executed.

If an AICC vehicle is in a dedicated lane, the behavioural code to keep to the right is suppressed.

Extension of the free-lane change model in congested traffic
For gaining speed advantage, the free-lane change model only considers lane changes to the left. When a vehicle is below its intended speed and below its maximum acceleration, the vehicle will not intend to go the right. This can lead to situations in which the speed of vehicles on the left lane collapses, whilst traffic in the other lanes is still flowing. Because this behaviour was considered unrealistic and un-desirable, an adaptation in the free lane change model was made, to introduce lane changes to the right in congested traffic to gain speed advantage, i.e. when the lane to the right moves faster then the current lane. This adaptation is applicable as soon as the speed of a vehicle is below a threshold (default 70 km/h). The safety of the manoevre is evaluated with respect to the relative speed of the new successor.

Establish whether a lane change to the right is desired
if current_speed =< congestion_lane_change_threshold

and if current speed =< lane_change_right_speed_factor_1 * desired_speed

and (speed_right_pred => lane_change_right_speed_factor_2 * speed_pred, or
right_pred out of visibility range)

target_lane = -1

lane_change_right_threshold == 70 km/h

Check whether a lane change to the right is safely possible.
In case of a lane change to the right in congested traffic it is checked whether the gap relative to the new successor is large enough. The criterion is that the new successor should not have to brake too hard. Thus the gap should be larger than the sum of the speed difference times the lane change delay, the distance needed to adapt the speed and the intended headway:

if((lane_change_delay*right_suc.relative_sp)+
(sign(right_suc.relative_sp)*right_suc.relative_sp*right_suc.relative_sp/
(2*3.6*3.6*ABS(right_suc_max_neg_acc))) + Int_headway(Current_speed(id)) =< right_suc.headway
target_lane = 0

A1.2 The mandatory lane change model

Assumptions for the model are:

- Drivers will not intend a mandatory lane change before a sign is in sight. Anticipation based on familiarity with the local situation is not considered.
- According to the ROA directives a sign which announces the forthcoming divergence is placed at 1300 m in advance of the taper. If the reading distance is assumed to be 50 m, forced lane changes are not expected earlier than 1350 m in advance of the taper.
- Active processes to enlarge or close a gap in order to facilitate or prevent a vehicle from an adjacent lane to merge are not taken into account.
- Lane change strategies may vary among drivers: some may control their position and speed with respect to a predecessor (lead vehicle) in the intended lane, whereas others focus on the vehicle behind (lag vehicle). When searching for an appropriate gap some drivers may prefer to accelerate to scan gaps in front of them whereas others prefer to reduce speed in order to reach an appropriate gap. Not all strategies will be taken into account.
- The mandatory lane changing process consists of a number of steps:
    * Perception of the forthcoming situation and choice of a destination lane
    * Deciding on the intention to change lane
    * Scanning for an appropriate gap and controlling relative speed and position
    * If the speed difference and position error are small enough the lane change is executed

These aspects are described in the following sections. All new variables and parameters are given in *Italic* upon first appearance.

Perception of the forthcoming situation and choice of a destination lane

At the end of each section there may be a discontinuity point: this may imply that a lane a driver is driving on will not be available to him. A drivers perceives the forthcoming situation by the following rules:

- there is a *Pre_warning_distance* for each discontinuity point (specified per link), assigned by default a value of 1350 m;
- as soon as a driver passes the Pre_warning_distance, the target (or destination) lane is determined (*dr_state.target_lane_mlc*). They look for an appropriate lane starting with the present lane, then looking to the lanes to the right and then looking to the lanes to the left, until they have found a lane that will continue and that will match their type of equipment (or vehicle-type or destination).

Deciding on the intention to change lane

- There is a distance at which the driver will start to undertake action to change lane. If a mandatory lane change is needed the intention_distance to change lane is drawn form a normal distribution cut of between the preview warning distance and some distance before the divergence point. The centre of the distribution and the std depends on the number of lanes that have to be crossed (the more lanes, the earlier the lane change is intended). This distance (*dr_state.intention_dist*) is determined using the number of lanes a driver has to change to the left or the right;

$$\text{dr\_state.intention\_dist} = \text{Pre\_warning\_distance} * (\mathit{mlc\_prewarndist\_fix\_1} + \mathit{Random} * \mathit{mlc\_prewarndist\_var\_1})$$

in the case the driver has one lane to change;

$$\text{dr\_state.intention\_dist} = \text{Pre\_warning\_distance} * (\mathit{mlc\_prewarndist\_fix\_2} + \mathit{Random} * \mathit{mlc\_prewarndist\_var\_2})$$

in the case the driver has two or more lanes to change,

where:

Random: a sample from a normal distribution with average 0.5 and a standard deviation of 1/3, truncated at 0 and 1.

mlc_prewarndist_fix_1: by default 0.75

mlc_prewarndist_var_1: by default 0.25

mlc_prewarndist_fix_2: by default 0.9

mlc_prewarndist_var_2:

by default 0.1.

Scanning for an appropriate gap and controlling relative speed and position
The distance of a driver to the next discontinuity point is given by a function *Disc_distance*. As soon as:

Disc_distance <=dr_state.intention_dist

a driver starts to look for an appropriate gap in the adjacent lane. If the driver has an AICC system which is active, then he first switches it off: gap scanning and controlling relative speed and position are done manually. In the case that a driver is 'scanning' or 'negotiating' a mandatory lane change, the normal desired acceleration and lane change model are overruled by a special *MandLaneChangeModel* (mlcmodel). This model gives simultaneously results for the desired acceleration and the intended lane change.

Within the mlcmodel some special behavioural parameters apply, described next:

- the intended headway a driver maintains to his predecessor is multiplied by a factor:

  mlc_headway_fix+*mlc_headway_var**Disc_distance/dr_state.intention_dist

  where mlc_headway_fix and mlc_headway_var are 0.25 and 0.75, respectively. This implies that from the point where a driver starts to scan to an appropriate gap, he will be gradually accepting shorter headways, until 0.25 his 'normal headway' at the discontinuity.

- the fierceness with which a driver tries to control distance deviations (dist_dev_factor_ard) and speed deviation (sp_dev_p_factor_ard) from his intended relative distance or speed, are multiplied by factors:

  mlc_dist_dev_factor_ard = dist_dev_factor_ard*
  (1+ *mlc_dist_dev_factor_ard_alpha**(1-Disc_distance/dr_state.intention_dist))

  and

  mlc_sp_dev_factor_p_ard = sp_dev_factor_p_ard*
  (1+ *mlc_sp_dev_factor_p_ard_alpha**(1-Disc_distance/dr_state.intention_dist))

  respectively, where mlc_dist_dev_factor_ard_alpha and mlc_sp_dev_factor_p_ard_alpha are both 1 by default. Note that dist_dev_factor_ard and sp_dev_p_factor_ard are by default 0.3 and 1.5.

- when a driver changes lane, there is a special *mlc_lane_change_delay*, by default 0.5 s.

In order to perform a mlc to an adjacent lane, a driver needs a minimum required gap (*min_req_gap*). This minimum required gap decreases with decreasing distance to the discontinuity point:

min_req_gap= veh_dr_d.veh_length+ Int_headway(Current_speed)* *(mlc_gap_fix*+*mlc_gap_var**-Disc_distance/dr_state.intention_dist)

where mlc_gap_fix and mlc_gap_var are equal to 0.25 and 0.75 by default, respectively.

While a driver is controlling his relative speed and distance in order to find a suitable gap, he always has to maintain a safe headway to a predecessor in his current lane. The desired acceleration (a_ref_pred) to maintain this safe headway is computed by using the adapted intended headway (see above) but the normal speed and distance deviation factors.

In order to find a gap he first controls his speed to the speed of the adjacent lane. The desired acceleration to reach the speed of the target lane is denoted by *a_ref_tgt_lane*. For this purpose a target vehicle is selected as the predecessor in the target lane, or if there is no predecessor, a successor. It is checked whether the speed matches the relative speed with respect to the target_lane sufficiently by:

abs(relative_speed) <= *mlc_speed_diff_thresh** Current_speed

where mlc_speed_diff_thresh is 0.1 by default. If this is not the case (no sufficient match in speed) and if the relative speed is larger than the perception threshold at the headway to the predecessor (function Calc_v_diff_t), then the intended acceleration is computed by:

a_ref_tgt_lane = -sp_dev_p_factor_ard*relative_speed/3.6

Note, that the 'normal' sp_dev_p_factor is used here. If the relative_speed is sufficiently small or if the relative speed is non-perceivable, or if there is no target vehicle then a_ref_tgt_lane is assigned the value 0.

If the relative_speed is sufficiently small or if the relative speed is non-perceivable, or if there is no target vehicle then (a_ref_tgt_lane=0), then the driver checks whether the nearest gap is larger than min_req_gap. If this is the case, then it is checked whether there is sufficient room at the front and the rear of the vehicle. Room at the front is checked whether the new headway would be larger then the (adapted) minimal headway. Room at the rear is checked whether the distance between rear bumper and front bumper of the predecessor is larger than the (adapted) minimal headway. Next, there are 4 possibilities:

- there is enough room at front and rear: no acceleration
- there is not enough room at front and enough at rear: a_ref_tgt_lane is set according to room still needed:

a_ref_tgt_lane = mlc_dist_dev_factor_ard * (new_predecessor -int_headway).

Note that in this relation the adapted mlc_dist_dev_factor is used.

- there is enough room at front but not at rear: a_ref_tgt_lane is computed in a similar way.
- there is not enough room at the front and not enough at rear: the driver will aim at the middle of the gap;

If the gap is smaller than min_req_gap, then the driver will check the forward gap: this is only done when the driver does not have to speed up above his intended speed (or above a certain factor, *mlc_fwd_speed_tresh*, times his intended speed). Furthemore it is checked whether the gap ahead in the target lane is large enough and whether there is a predecessor on the same lane blocking the access to the forward gap. Whether or not the predessesor in the current lane is in the way is determined by predicting the headway within a preview time. This preview time is taken as the time until the discontinuity point is reached minus 2 seconds. The preview time is limited to the interval between 0 and 10 seconds. If the gap ahead is not found suitable, then the driver will aim for the backward gap.

```
if ((speed - new_pred.relative_sp < mlc_fwd_speed_tresh * veh_dr_d.int_speed) &&
        ((new_prepred.headway - new_pred.headway - new_pred.length) > min_req_gap) &&
        ((!pred.veh_dr_comb_id) || (pred.headway - new_pred.headway +
         (pred.relative_sp / 3.6) * min(0, max(10, Disc_distance(id, 1)/(speed/3.6) - 2)) > 
min_req_gap)))
```

'If the nearest gap is too small, the driver evaluates an alternative gap. If his desired speed is above the speed of the target lane and the gap ahead of the nearest gap is large enough and his predecessor in his own lane is not in the way (after an anticipation period) he moves to the gap in front. Otherwise he moves one gap behind.'

Changing lane

The lane change is initiated when:
(1.5*(new_pred.relative_sp/(new_pred.headway)*(new_pred.headway) <= *mlc_angspeed_thresh*) & (1.5*(new_suc.relative_sp/(new_suc.headway)*(new_suc.headway) <= *mlc_angspeed_thresh*) & (new_pred.headway + new_suc.headway) >= min_req_gap & (new_suc.headway>veh_dr_d.-veh_length)

where mlc_angspeed_thresh is 0.021 rad/s by default.

This criterion is based on the angular velocity criterion proposed by Michaels & Fazio (1989):

$$w = k\frac{(V_a - V_{lc})}{l^2}$$

in which:
w = angular velocity
V_a = speed of the vehicle in the adjacent lane
V_{lc} = speed of the vehicle intending a lane change

l = longitudinal separation between the two vehicles
k = lateral offset (1.5 m)

Michaels and Fazio (1989) reported the threshold to be in the range between 0.01 and 0.001 rad/s with a nominal value of 0.004 rad/s. Analysis of lane change behaviour in the TNO driving simulator showed that the angular velocity threshold depends on traffic density. For high densities the 95%-percentile of the angular velocity was 0.021 (de Vos & Hoekstra, 1997)

A.2 LONGITUDINAL DRIVER MODEL

Each time the longitudinal driver model is called, the following functions are executed subsequently:

calc_desired_acc	calculates the desired acceleration
calc_clutch_gear	determines the clutch pedal and the gear positions
calc_gb_pedal_state	determines if the accelerator or the brake pedal will be used
calc_gas_pedal_p	calculates the accelerator pedal position
calculate_brake_pedal_f	calculates the brake pedal force

These functions are detailed below.

calc_desired_acc

This function returns the desired acceleration of the driver model. It calculates two accelerations: one assuming a free-driving situation, and one assuming a car-following situation. The value returned by this function is the most restrictive one.
The free-driving model is described by the following formula:

$$e = v\_ref - v(t-t_r);$$

$$a\_ref\_v = K * e \quad (abs (e/v\_ref) > 0.03) \qquad [A1]$$

$$= 0 \quad (abs (e/v\_ref) \text{ £ } 0.03)$$

where:

a_ref_v	= driver's desired acceleration for free driving (m/s^2)
t_r	= driver reaction time
$v(t-t_r)$	= speed (m/s) at current time minus t_r
e	= the speed error (m/s)
K	= a constant factor, set at 0.4

The resulting a_ref_v is limited between the maximum comfortable acceleration and the maximum comfortable deceleration.

The car-following algorithm takes the following form:

$$d\_ref = c_1 + c_2 * v + c_3 * v^2; \qquad [A2]$$

$$d\_err = d(t-t_r) - d\_ref; \qquad [A3]$$

$$a\_ref\_d = cd * d\_err + \qquad [A4]$$

$cv\_p * v\_dif\_p(t\text{-}t_r) +$
$cv\_pp * v\_dif\_pp(t\text{-}t_r)$

where:

a_ref_d	= driver's intended acceleration for car-following [m/s^2]
d_ref	= the desired distance headway as a function of speed [m]
c_1, c_2, c_3	= constants (set at 3, 0.25, and 0.02, respectively)
d_err	= deviation from desired distance [m]
d(t-t_r)	= distance headway at current time minus t_r [m]
v_dif_p(t-t_r)	= relative speed to predecessor [m/s] at current time minus t_r
v_dif_pp(t-t_r)	= rel. speed to pre-predecessor [m/s] at current time minus t_r
cd	= constant factor for distance deviation
cv_p	= constant factor for speed deviation predecessor
cv_pp	= constant factor for speed deviation pre-predecessor

The values of the three latter car-following parameters have been set at 0.3, 1.5, and 0.2, respectively. Compared with earlier settings for these parameters, emphasis is relatively more on speed difference than on deviation from the intended headway, which has a stabilizing effect on the vehicle/driver transient responses.

Especially at high flow levels the parameters of the intended distance headway function have a strong effect on the simulation results. Similar observations were made for other microscopic traffic simulation models (Grontmij, 1996; Payne, Thompson & Chang, 1997). Starting point in determining these parameters for MIXIC has been to analyze inductive loop detector data, which were gathered for the purpose of the evaluation of the A16 fog warning system (Hogema, Van der Horst & Bakker, 1995). This data set includes passage time, speed and length information of individual vehicles. However the headway as observed by spot measurements may be different from the intended headway in the model for two reasons: On the one hand a spot measurement is only a momentaneous observation of a car-following process, which may deviate from steady state; on the other hand the headways in the simulation are not necessarily equal to the intended headway since they are also affected by the other elements in the longitudinal model i.e. speed control with respect to the intended speed and the feedback of speed differences relative to the preceding vehicle and the vehicle beyond the preceding vehicle. For these reasons the parameters derived from loop detector data were adapted to tune the resulting flow on a homogeneous motorway link to a plausible level. This resulted in c_1 = 3 m, c_2 = 0.25 s and c_3 = 0.01 s^2/m. In the most recent MIXIC study the traffic flow downstream of a lane drop did not collapse at flow levels above the conventional capacity. For this reason the intended headway at higher speed levels was increased by means of increasing the quadratic factor from 0.01 to 0.02, which changed the flow characteristics in the desired direction.

Figure A.1 illustrates how the respective parameters of the intended headway function influence the relationship between speed and headway. The corresponding saturation flows (all vehicles driving at the intended headway and all vehicles having a length of 5 m.) are plotted in Figure A.2.

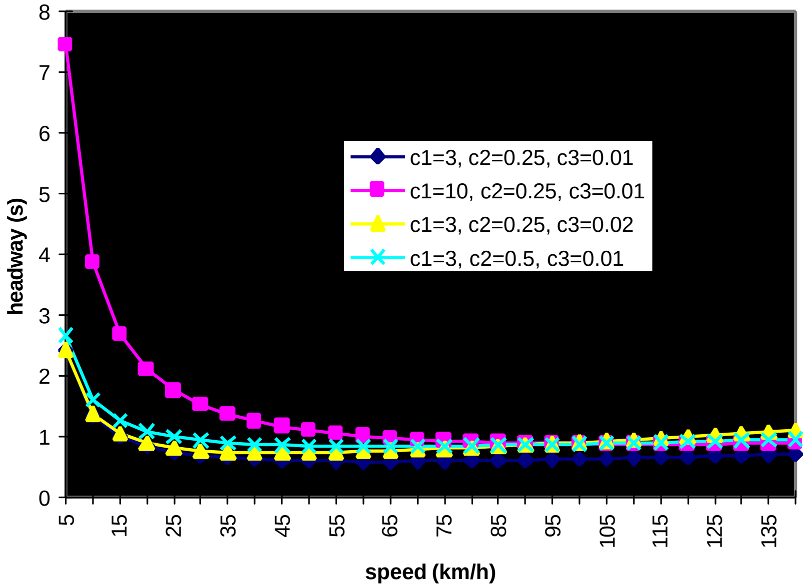

Figure A.1 Intended headway as a function of speed for four parameter settings

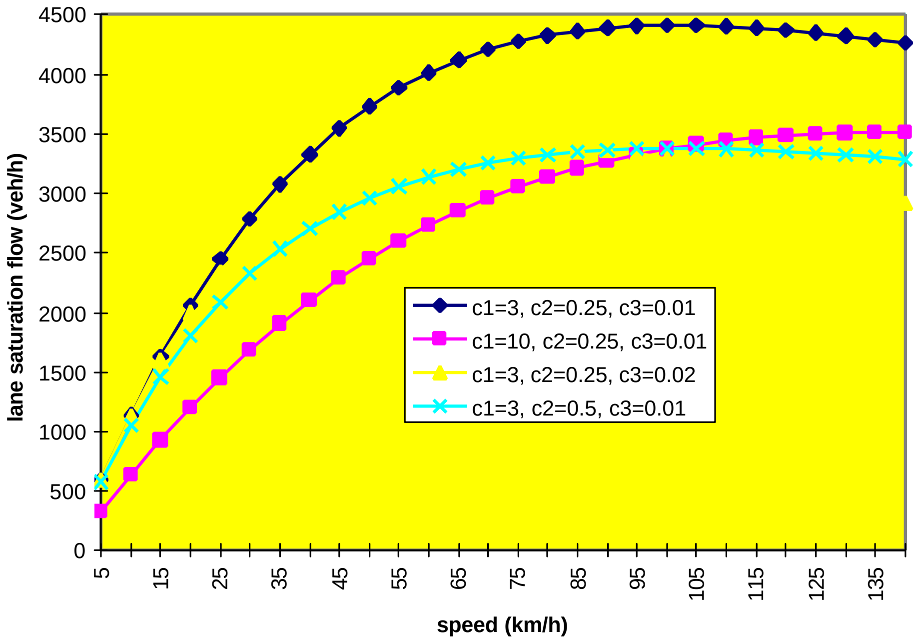

Figure A.2 Saturation flow as a function of speed for four intended headway parameter settings

A perception threshold for speed differences is included as well. The most straightforward model is based on a constant threshold for the perception of the rate of change of the visual angle enclosed by the lead car. This gives:

$$v\_dif\_t = X^2 * w_t / W$$

where

v_dif_t = threshold for perception of difference speed [m/s]
X = net headway [m]
w_t = constant threshold angular velocity [rad/s]
W = width lead vehicle [m]

Using w_t=6E-4 rad/s and W=1.8 m, and converting to km/h this yields:

$$v\_dif\_t = X^2 * 1.20E\text{-}3 \text{ [km/h]} \qquad [A5]$$

When the difference speeds from Eq. [A4] are smaller than v_dif_t, they are ignored, i.e. set to 0 in the calculation of Eq. [A4].

Combining the desired accelerations from the free-driving model and the car-following model is done by selecting the most restrictive one, i.e. the minimum of a_ref_v and a_ref_d. This constitutes the driver's overall intended acceleration.

GearShiftModel

This function it only relevant for vehicles with a manual gear shift. It calculates the gear and the clutch position of the vehicle, and also updates the driver state variables related to gear changing. First, the desired gear position is calculated, based on a comparison of the actual motor rotational speed with an upper and a lower limit, set at 3500 and 1500 revs/s, respectively. When the actual motor rotational speed is above the upper limit or below the lower limit, a gear change is executed in the following steps:

- the clutch is fully pressed,
- a delay is used to represent the actual changing, and
- finally the clutch is fully released.

PedalChangeModel

This function determines which pedal should be used to realize the desired acceleration: the accelerator pedal or the brake pedal. A delay is included to simulate a foot movement from accelerator to brake pedal.

After this, only the accelerator pedal position and the brake pedal force remain to be determined. These are calculated by means of a static inverse vehicle model, the equations of which are derived below.

The acceleration of the vehicle, according to the vehicle model (Appendix B) is given by Eq. A6.

$$a = (-resist\_force - brake\_force + drive\_force) / Mass \qquad [A6]$$

In the case where only the accelerator pedal is used, the brake_force will equal 0. The question is what drive force dr_force_ref, and subsequently accelerator pedal position p_gas, must be applied to arrive at the desired acceleration a_ref. Solving Eq. A6 for dr_force_ref gives Eq. A7,

$$dr\_force\_ref = a\_ref * Mass + resist\_force \qquad [A7]$$

where the value for resist_force can be obtained from the function of the vehicle model (calc_resist_force). When time constants and delays are neglected in the function from the vehicle model which calculates the drive force (CalcDrForce, see Appendix B), Eq. A8 can be derived. It gives the accelerator pedal position needed to produce the drive force dr_force_ref as obtained from Eq. A7.

p_gas = dr_force_ref * act_speed / power [A8]

When using the brake pedal but no accelerator pedal, Eq. 1 can be solved for the required brake force br_force_ref to obtain the required (negative) acceleration a_ref. The result is given in Eq. A9.

br_force_ref = -a_ref * Mass - resist_force [A9]

When neglecting the delay in the model of the brake system, Eq. A10 can be obtained from the function of the vehicle model that calculates the brake force (CalcBrakeForce, see Appendix B). Eq. A10 calculates the pedal force f_brake needed to produce the brake force br_force_ref as obtained from Eq. A9.

f_brake = br_force_ref / gain_brake [A10]

calc_p_gas
This function calculates the accelerator pedal position. When the gb_pedal_state indicates that the driver is using the accelerator pedal, calculations will be carried out according to Eqs. A7 and A8; otherwise, the accelerator pedal position will be made 0. Its result is assigned to veh_state.p_gas.

calc_p_brake
This function calculates the brake pedal force. When the gb_pedal_state indicates that the driver is using the brake pedal, calculations will be carried out according to Eqs. A9 and A10; otherwise, the brake pedal force will be made 0.

A.3 DRIVER-AICC INTERACTION MODEL

This part of the driver model determines when the AICC is switched on or off. It is based on the assumption that the driver will use the AICC as much as possible, which means that the AICC will only be switched off in situations that require hard braking.

Engaging AICC
The actual engaging of AICC has been implemented with a delay. The delay for engaging is given by a constant ICC_engage_rt. If one of the following conditions is fulfilled:

(current_acceleration > min_acc_eng) && (current_acceleration < max_acc_eng)

OR

headway > (relative_sp * relative_sp/ (-2 * a_re_eng)

then a timer for engaging is set to ICC_engage_rt or decremented by a time step. If the timer equals zero, then the AICC is engaged.

The driver state variables AICC_acc_control_i and AICC_acc_control_pi (used in the PI controller of the AICC) are reset to zero.

At the start of the simulation each driver with AICC is generated with the AICC switched off. In the first time step the driver engages the AICC if the above condition is satisfied without a time delay.

Disengaging AICC
The actual disengaging of AICC is also implemented with a time delay, ICC_disengage_rt. The conditions for starting to disengage are:

(acceleration < Current_ICC_max_dec+curdec_tresh_diseng &&
desired_acc < acceleration-desdec_tresh_diseng)

OR

(desired_acc < Current_ICC_max_dec && headway > Current_ICC_det_range)

OR

(headway < relative_sp * pred.relative_sp /
(-2 *(Current_ICC_max_dec+curaiccmaxdecalarmcorr)) &&
pred.relative_sp > 0)

After disengaging the gb_pedal_state of the driver is set to on_gas if the desired acceleration is larger than zero. Otherwise it is set to on_brake.

A.4 PARAMETERS OF THE DRIVER MODEL

Parameter	Value	Comment
norm_max_dec_perc	0.5	fraction normal comfortable deceleration of

		max. comfortable deceleration
int_sp_error_threshold_da	0.03	threshold for correction of deviations from intended speed
int_sp_error_factor_da	0.4	reaction to deviations from intended speed
dist_dev_factor_ard	0.3	reaction to deviation intended headway
sp_dev_p_factor_ard	1.5	reaction to speed deviation to predecessor
sp_dev_pp_factor_ard	0.1	reaction to speed deviation to pre-pre-decessor
v_dif_factor_vdt	0.0012	perception threshold speed difference factor
int_hw_c1	3	intended headway: constant term
int_hw_c2	0.25	intended headway: linear factor
int_hw_c3	0.02	intended headway: quadratic factor
engine_rot_speed_high	3500	upper threshold for gear shifting (revs/s)
engine_rot_speed_low	1500	lower threshold for gear shifting (revs/s)

Driver type 1 "passenger car"

Parameter	Value	Comment
dr_type_nr	1	passenger car
mean_int_speed	121.0	
stdev_int_sp	12.0	
pref_lane[1]	1	not used
pref_lane[2]	1	not used
pref_lane[3]	2	not used
pref_lane[4]	2	not used
mean_reac_time	0.3	
stdev_reac_time	0.05	
max_comf_dec	-5.0	
max_comf_acc	3.0	
gear_shift_delay	0.5	
lane_change_delay	1.0	
pedal_change_delay	0.2	

Driver type 2 "mini bus"

Parameter	Value	Comment
dr_type_nr	2	mini bus
mean_int_speed	94.0	
stdev_int_sp	15.0	
pref_lane[1]	1	not used
pref_lane[2]	1	not used
pref_lane[3]	2	not used
pref_lane[4]	2	not used
mean_reac_time	0.3	
stdev_reac_time	0.05	
max_comf_dec	-5.0	
max_comf_acc	3.0	
gear_shift_delay	0.5	
lane_change_delay	1.0	
pedal_change_delay	0.2	

Driver type 3 "truck/bus"

Parameter	Value	Comment
dr_type_nr	3	truck/bus
mean_int_speed	86.0	
stdev_int_sp	6.0	
pref_lane[1]	1	not used
pref_lane[2]	1	not used
pref_lane[3]	2	not used
pref_lane[4]	2	not used
mean_reac_time	0.3	
stdev_reac_time	0.05	
max_comf_dec	-5.0	
max_comf_acc	3.0	
gear_shift_delay	1.5	
lane_change_delay	1.0	
pedal_change_delay	0.2	

Driver type 4 "cautious passenger car"

Parameter	Value	Comment
dr_type_nr	4	passenger car
mean_int_speed	100.0	
stdev_int_sp	5.0	
pref_lane[1]	1	not used
pref_lane[2]	1	not used
pref_lane[3]	2	not used
pref_lane[4]	2	not used
mean_reac_time	0.3	
stdev_reac_time	0.05	
max_comf_dec	-5.0	
max_comf_acc	3.0	
gear_shift_delay	0.5	
lane_change_delay	1.0	
pedal_change_delay	0.2	

APPENDIX B: VEHICLE MODEL

B.1 DESCRIPTION OF THE VEHICLE MODEL

Part B1 of this appendix specifies the prototype implementation of the vehicle model that has been developed for inclusion in the microscopic traffic simulation model MIXIC. The choice of parameters is explained in part B2, while the resulting list of vehicle parameters for each vehicle type is given in part B3.

In the vehicle model the following functions are executed subsequently:

CalcFricCoeff	calculates the current friction level
CalcResistForce	calculates the resistance forces as experienced by the vehicle
CalcDrForce	calculates the driving force of the vehicle
CalcBrakeForce	calculates the braking force
CalcBrakeLights	determines the state of the brake lights
CalcAcceleration	calculates the vehicle acceleration
CalcSumPropulsionEnergy	calculates the propulsion energy

These functions are described in more detail in this appendix (the definition of the parameters is given in the program documentation of MIXIC 1.3):

CalcFricCoeff

CalcFricCoeff calculates the friction coefficient, fric_coeff, based on the road condition, rd_condition, and vehicle speed:

```
if rd_condition == dry
    fric_coeff = fric_coeff_dry

if rd_condition == wet
    fric_coeff = fric_coeff_dry - (fric_coeff_wet_depth * water_depth + fric_coeff_wet_speed *
    speed)

if rd_condition == ice
    fric_coeff = fric_coeff_ice

if rd_condition == snow
    fric_coeff = fric_coeff_snow
```

The longitudinal friction potential is corrected for lateral friction use needed in case of a lane change:

```
if lane_change == 1
    fric_coeff = fric_coeff - lateral_fric_use
```

CalcResistForce
CalcResistForce calculates the present resistence force, resist_force, opposing the vehicle motions:

resist_force = mass * g * sin(slope) + f_r * mass + aer_coeff * long_rel_wind_speed * long_rel_wind_speed;

The longitudinal component of the relative wind speed is calculated by:
long_rel_wind_speed = speed + wind_speed * cos(wind_angle)

The influence of the wake of a preceding vehicle when following at a short headway can be included by a correction of the aerodynamic coefficient:

aer_coeff_corr = f(aer_coeff, predecessor_headway)

CalcDrForce
CalcDrForce first calculates the driving force without taking into account the dynamic response of the driveline:
dr_force_uncorr = (p_gas * power) / speed

The driveline dynamics are taken into account by a first order response:
dr_force[current] = dr_force[past] * exp(- t / time_const_drive_line) + (1-exp(- t / time_const_drive_line) * dr_force_uncorr

The limitations of road friction and engine power are taken into account:
dr_force[current] = min(dr.force[current], dr_force_max)

in which:
dr_force_fric_max = fric_coeff * mass * g * load_ratio_dr_wheels
dr_force_engine_max = power / speed
dr_force_max = min(dr_force_fric_max, dr_force_engine_max)

CalcBrakeForce
CalcBrakeForce calculates the current braking force taking into account the limited road friction:
brake_force = gain_brake * p_brake
brake_force_fric_max = fric_coeff * mass * g
brake_force = min(brake_force, brake_force_fric_max)
CalcBrakeLightState
CalcBrakeLightState determines whether the brake lights are on or off:
if brake_force => 0
    veh_state.brake_lights = on
else veh_state.brake_lights = off

CalcAcceleration

CalcAcceleration calculates the vehicle acceleration, acc:
acc = (1/mass) * (-1 * resist_force - brake_force + dr_force[current])

CalcSumPropulsionEnergy
CalcSumPropulsionEnergy calculates the cumulative propulsion energy used by the vehicle, to be used as input to the output-module for emission and fuel consumption

B.2 DESCRIPTION OF THE VEHICLE PARAMETERS

For the calibration of the MIXIC model, the input file and the parameter definitions have to be filled with realistic data.
The vehicle type data are filled for the following three vehicle types:
- an average passenger car;
- a small bus / delivery van;
- a truck;
- very long truck (road train).

Future extensions of the number of vehicle types could be:
- Differentiation between different types of passenger cars, e.g. small, medium and top model cars';
- Motorcycle;
- Car with trailer or caravan;
- Truck, truck - trailer, tractor semi-trailer, bus.

For each of the three vehicle types a driver type has been specified, so there is a one to one relationship between vehicle type and driver type. In future a differentiation between drivers with different capabilities and driving style could be made.

The parameterset for the passenger car is based on the Opel Kadett E, which has been in production from 1984 to 1991 [Autotechnisch handboek].
With 475917 vehicles of this type on the road, which is equal to 8.3% of all passenger cars, this was by far the most popular passenger car in 1993 [CBS, 1993].
For the mini bus / delivery van category, a Volkswagen Transporter has been taken as example to fill the parameterset.

In the truck category the parameters of a Volvo F16 have been used. This truck is one of the biggest and most powerful types of trucks and therefore typically used for international transport. Depending on the type of road that is being considered the parameters of a more modest truck can be taken. As an intermediate solution some parameters (especially engine power and the aerodynamic coefficient) can be adapted.

Driveline data

To determine the engine speed [rev/min] from the vehicle speed [km/h], the MIXIC Vehicle-Driver model uses the effective transmission ratio in which the end reduction i_{end} and the wheel radius r_w have been incorporated:

$$transm\_ratio = \frac{2p\ r_w}{60\, i_{gear,n}\, i_{end}}$$

The transmission parameters for the three vehicles are as follows:
Passenger car: i_{end} = 3.94, r_w = 0.28 m

gear	i_{gear}	transmission ratio
1	3.55	2.10 e-3
2	1.96	3.80 e-3
3	1.3	5.72 e-3
4	0.89	8.36 e-3

Mini bus: i_{end} = 4.56, r_w = 0.327 m

gear	i_{gear}	transmission ratio
1	3.78	1.99 e-3
2	2.06	3.65 e-3
3	1.35	5.56 e-3
4	0.97	7.74 e-3
5	0.77	9.75 e-3

Truck: i_{end} = 3.1, r_w = 0.526 m

gear	i_{gear}	transmission ratio
1	14.98	1.19 e-3
2	12.06	1.47 e-3
3	10.07	1.77 e-3
4	8.1	2.19 e-3
5	6.63	2.68 e-3
6	5.33	3.33 e-3
7	4.44	4.00 e-3
8	3.57	4.98 e-3
9	2.82	6.30 e-3
10	2.27	7.83 e-3
11	1.86	9.55 e-3
12	1.49	11.93 e-3
13	1.24	14.33 e-3
14	1	17.77 e-3

A truck driver does not necessarily use all gears. The gear shift pattern depends on the road gradient and the vehicle load. A normal gear shift pattern to accelerate from standstill can be:
2_low
3_low
4_low
5_low
6_low
6_high
7_low
7_high
In the input file, the other transmission rates have been omitted to prevent excessive gear shifting.

In a driving test a characteristic value of 2.4 s was found for the time needed to change gear [Elink Schuurman, 1989]. It is judged that 1.5 seconds may be a more realistic value, especially as switching between high and low gear takes only a very short (about 0.5 s) interruption of the driving torque.

The engine power for each vehicle type is:

Vehicle type	Engine power [kW]
Passenger car	44
Mini bus	60
Truck	340

An average minibus has a relatively low power engine and as a result the maximum speed of these mini busses is close to the normal desired speed of the drivers. In case of strong resistance forces (strong headwind or uphill driving) the minibuses can not achieve the speed that is desired by the driver. The average power of the various models of the VW Transporter is 50 kW, however we assume that the models with a more powerful engine will be more popular and therefore a vehicle power of 60 kW is used.

A statistical distribution of the engine power is used to model the differences between various vehicles of the same vehicle category. The values for the standard deviation are chosen as follows:

Vehicle type	Standard deviation engine power [kW]
Passenger car	2
Mini bus	2
Truck	15

Resistance coefficients

The aerodynamic coefficient in the Vehicle-Driver model is an effective value resulting from the aero-dynamic drag coefficient C_w and the frontal area A:

$$Aer\text{-}coeff = 0.5\, r A C_w$$

Vehicle type	C_w	A [m^2]	aerodynamic coefficient
Passenger car	0.32	1.85	0.37
Mini bus	0.36	2.62	0.94
Truck	0.7	9	3.94

Based on a literature survey about the rolling resistance coefficient of vehicle tyres [De Sitter] the following characteristic values can be used:

Vehicle type	Rolling resistance coefficient	Standard deviation
Passenger car / mini bus	0.011	3 e-4
Truck	0.006	3 e-4

Vehicle mass

The masses of the passenger car and the mini bus are found by adding 1.5 times the weight of a person to the bare vehicle weight.

The mean value and standard deviation of the truck mass are chosen in such a way that the maximum mass (mean + 3 stdev) equals the maximum allowed total weight (50 tons), while the minimum weight (mean - 3 stdev) reflects the mass of an unladen truck.

Vehicle type	Mean mass	Standard deviation
Passenger car	1000	100
Mini bus	1600	100
Truck	35000	5000

Vehicle length

The vehicle categories are characterised by a length interval, which is used to determine to which category a vehicle is belonging. A specific length is attributed to each individual vehicle. The thresholds between the vehicle categories (NOB Wegtransport, 1992) and the statistical distribution data are listed in the table underneath:

Vehicle type	Length lower threshold	Length upper threshold	Mean length	Standard devi-ation
Passenger car	1	4.7	4	0.1
Mini bus	4.7	12	5	0.1
Truck	12	20	15	1

Friction coefficient

The friction coefficient between vehicle tyre and road surface is incorporated in the first 5 vehicle dynamics parameters veh_dyn[1..5].

In general a linear relationship between friction and speed can be applied:

$$m = A + B\,h + C\,v$$

in which:

A = veh_dyn[1] = the friction coefficient near speed zero at a dry road surface
B = veh_dyn[2] = dm/dh
C = veh_dyn[3] = dm/dv
v = average traffic speed
h = waterlayer

These parameters can be fitted based on measurement data available in literature. Often used are the data from the measurement programme that was performed by Gengenbach (1968) on an inner drum facility (only on an inner drum it is possible to maintain a waterlayer on the drum surface), however these measurements are quite old and the tyres used for these measurements do not reflect the characteristics of modern tyres.
Much more up-to-date are the results of the tyre measurement programme within the DRIVE II project ROSES, which has recently been completed. An algorithm to translate the roadstatus into friction data has been proposed (De Vos, 1994) and in ROSES Workpackage A5 matrices of the algorithm parameters for different road type and road condition have been filled (Hogt & Rooney, 1994).

Depending on the vehicle, different friction values can be used e.g.:
m_lock_average is the friction coefficient at wheel lock for an average vehicle tyre
m_lock_lower is the friction coefficient at wheel lock for a bad tyre
m_max_upper is the maximum friction coefficient for a good tyre, this value could be exploited by an anti lock braking system or a very good driver.

In view of the limited penetration rate of ABS systems, it is realistic to use the m_lock_average, while, if in future ABS becomes a standard (mandatory) device, the definition may be adapted into m_max.

The ROSES measurements are translated into a linear relationship between friction and speed. This yields the following parameters for MIXIC:

m_lock_average

	Porous Asphalt (ZOAB)	Asphalt (DAB)	Concrete
Dry	veh_dyn[1]=0.76 veh_dyn[3]=0	veh_dyn[1]=0.88 veh_dyn[3]=1.62e-3	veh_dyn[1]=0.90 veh_dyn[3]=0
Wet	veh_dyn[1]=0.55 veh_dyn[3]=-4.71e-4	veh_dyn[1]=0.66 veh_dyn[3]=-1.87e-3	veh_dyn[1]=0.57 veh_dyn[3]=0

These data are based on measurements of passenger car tyres. The lower performance of truck tyres has not been taken into account.

Type of fuel

For the calculation of the fuel consumption and the emission quantities, the type of fuel has to be known. For each vehicle category the distribution of fuel types is used in the model.

These distributions between different fuel types are determined based on the status in the Netherlands per August 1st 1993 (CBS, 1993):

Vehicle type	Fuel Type		Number of vehicles	Percentage of vehicles
Passenger cars	Petrol		4608492	80.1%
	Diesel		622899	10.8%
	LPG		523739	9.1%
Delivery vans	Petrol		145101	28.3%
	Diesel		344867	67.4%
	LPG		21991	4.3%
Trucks, etc.	Petrol	trucks	1326	4.3%
		tractors	17	
		special vehicles	5773	
		busses	27	
	Diesel	trucks	86545	95.5%
		tractors	41477	
		special vehicles	19479	
		busses	12120	
	LPG	trucks	52	0.2%
		tractors	5	
		special vehicles	327	
		busses	24	

Besides the fuel type, also the presence of catalytic converters has an influence on the exhaust emission. The following Table gives the status for the passenger vehicles on the road at august 1 1993 as well as the distribution for the vehicles with construction date in 1993.

	Catalytic conv.: all passenger cars per 1/8/93			Catalytic conv. Passenger car built in 1993		
	number	%		number	%	
Controlled catalytic converter	1462941	25.4	34.0	217460	83.4	84.2
Uncontrolled catalytic converter	497604	8.6		1976	0.8	
Rest	3794831	65.9		41436	15.9	

B.3 VEHICLE PARAMETERS FOR EACH CATEGORY

Vehicle type 1 "passenger car"

Parameter	Value	Comment
v_type_nr	1	passenger car
v_cat	2	passenger car and van (light)
aut_transm_fr	0.2	
n_gears	4	
transm_ratio[1]	0.00210	
transm_ratio[2]	0.00380	
transm_ratio[3]	0.00572	
transm_ratio[4]	0.00836	
mean_power	44	
stdev_power	2	
aer_coeff	0.37	
mean_mass	1050	
stdev_mass	100	
mean_f_r	0.011	
stdev_f_r	0.00033	
veh_dyn[1]	0.76	
veh_dyn[2]	0	
veh_dyn[3]	0	
veh_dyn[4]	0.2	
veh_dyn[5]	0.2	
veh_dyn[6]	0.5	load driven wheels
veh_dyn[7]	0.05	time constant drive line

Parameter	Value	Comment
veh_dyn[8]	500	gain brake
veh_dyn[9]	0	
veh_dyn[10]	0	
veh_dyn[11]	0	
veh_dyn[12]	0	
veh_dyn[13]	0	
veh_dyn[14]	0	
veh_dyn[15]	0	
veh_dyn[16]	0	
veh_dyn[17]	0	
veh_dyn[18]	0	
veh_dyn[19]	0	
veh_dyn[20]	0	
veh_length_upper	4.7	
cat_conv_fr	0.34	
fuel_fr[1]	0.801	petrol
fuel_fr[2]	0.108	diesel
fuel_fr[3]	0.091	LPG
equipment_fr	0	

Vehicle type 2 "mini bus"

Parameter	Value	Comment
v_type_nr	2	mini bus
v_cat	3	light trucks and buses (medium)
aut_transm_fr	0	
n_gears	5	
transm_ratio[1]	1.99 e-3	
transm_ratio[2]	3.65 e-3	
transm_ratio[4]	7.74 e-3	
transm_ratio[5]	9.75 e-3	
mean_power	60	
stdev_power	2	
aer_coeff	0.94	
mean_mass	1600	
stdev_mass	100	

Parameter	Value	Comment
mean_f_r	0.011	
stdev_f_r	3 e-4	
veh_dyn[1]	0.76	
veh_dyn[2]	0	
veh_dyn[3]	0	
veh_dyn[4]	0.2	
veh_dyn[5]	0.2	
veh_dyn[6]	0.5	
veh_dyn[7]	0.05	
veh_dyn[8]	500	
veh_dyn[9]	0	
veh_dyn[10]	0	
veh_dyn[11]	0	
veh_dyn[12]	0	
veh_dyn[13]	0	
veh_dyn[14]	0	
veh_dyn[15]	0	
veh_dyn[16]	0	
veh_dyn[17]	0	
veh_dyn[18]	0	
veh_dyn[19]	0	
veh_dyn[20]	0	
veh_length_upper	12	
veh_length_lower	4.7	
mean_veh_length	5	
stdev_veh_length	0.1	
cat_conv_fr	0	
fuel_fr[1]	0.283	
fuel_fr[2]	0.764	
fuel_fr[3]	0.043	
equipment_fr	0	

Vehicle type 3 "truck / bus"

Parameter	Value	Comment
v_type_nr	3	truck / bus
v_cat	4	heavy trucks (heavy)

Parameter	Value	Comment
aut_transm_fr	0	
n_gears	8	
transm_ratio[1]	1.77 e-3	
transm_ratio[2]	2.68 e-3	
transm_ratio[3]	4.0 e-3	
transm_ratio[4]	6.30 e-3	
transm_ratio[5]	9.55 e-3	
transm_ratio[6]	11.93 e-3	
transm_ratio[7]	14.33 e-3	
transm_ratio[8]	17.77 e-3	
mean_power	340	
stdev_power	15	
aer_coeff	3.94	
mean_mass	35000	
stdev_mass	5000	
mean_f_r	0.006	
stdev_f_r	0.00033	
veh_dyn[1]	0.76	
veh_dyn[2]	0	
veh_dyn[3]	0	
veh_dyn[4]	0.2	
veh_dyn[5]	0.2	
veh_dyn[6]	0.3	
veh_dyn[7]	0.05	
veh_dyn[8]	500	
veh_dyn[9]	0	
veh_dyn[10]	0	
veh_dyn[11]	0	
veh_dyn[12]	0	
veh_dyn[13]	0	
veh_dyn[14]	0	
veh_dyn[15]	0	
veh_dyn[16]	0	
veh_dyn[17]	0	
veh_dyn[18]	0	
veh_dyn[19]	0	
veh_dyn[20]	0	
veh_length_upper	20	
veh_length_lower	12	

Parameter	Value	Comment
mean_veh_length	15	
stdev_veh_length	1	
cat_conv_fr	0	
fuel_fr[1]	0.043	Petrol
fuel_fr[2]	0.955	Diesel
fuel_fr[3]	0.002	LPG
equipment_fr	0	

Vehicle type 4 "road train"

PARAMETER	VALUE	COMMENT
v_type_nr	4	truck / bus
v_cat	4	heavy trucks (heavy)
aut_transm_fr	0	
n_gears	8	
transm_ratio[1]	1.77 e-3	
transm_ratio[2]	2.68 e-3	
transm_ratio[3]	4.0 e-3	
transm_ratio[4]	6.30 e-3	
ransm_ratio[5]	9.55 e-3	
transm_ratio[6]	11.93 e-3	
transm_ratio[7]	14.33 e-3	
transm_ratio[8]	17.77 e-3	
mean_power	340	
stdev_power	15	
aer_coeff	3.94	
mean_mass	70000	
stdev_mass	5000	
mean_f_r	0.006	
stdev_f_r	0.00033	
veh_dyn[1]	0.9	
veh_dyn[2]	0.0112	
veh_dyn[3]	0.0043	
veh_dyn[4]	0.2	
veh_dyn[5]	0.2	
veh_dyn[6]	0.26	
veh_dyn[7]	0.05	

PARAMETER	VALUE	COMMENT
veh_dyn[8]	500	
veh_dyn[9]	0	
veh_dyn[10]	0	
veh_dyn[11]	0	
veh_dyn[12]	0	
veh_dyn[13]	0	
veh_dyn[14]	0	
veh_dyn[15]	0	
veh_dyn[16]	0	
veh_dyn[17]	0	
veh_dyn[18]	0	
veh_dyn[19]	0	
veh_dyn[20]	0	
veh_length_upper	31	
veh_length_lower	20.5	
mean_veh_length	24	
stdev_veh_length	0.5	
cat_conv_fr	0	
fuel_fr[1]	0	Petrol
fuel_fr[2]	1	Diesel
fuel_fr[3]	0	LPG
equipment_fr	0	

APPENDIX C: AUTONOMOUS INTELLIGENT CRUISE CONTROL

This appendix gives a description of the functions that are a part of the AICC. The main structure of the AICC and its interface to the vehicle model has already been shown in Fig. 4.1. The values of the various parameters are listed at the end of this appendix.

For vehicles with AICC, the following functions are subsequently executed in each iteration:
- Calc_hw_sens,
- Calc_ref_acc,
- Calc_icc_acc_control,
- Calc_icc_gas_act, and
- Calc_icc_brake_act.

Calc_hw_sens
This function calculates the outputs of the AICC's sensor, taking into account a sensor delay and a maximum detection range. The outputs of the sensor are:
- the headway to the lead vehicle at time = current time minus sensor delay
- the relative speed to the lead vehicle at time = current time minus sensor delay.

If no lead vehicle is detected within the detection range, this is indicated by a special output value. Based on the assumption that all equipment will work as intended (see Section 4.1), the sensor implemented has been made ideal in the sense that it will always correctly detect a lead vehicle in the same lane as long as it is within the detection range. In reality, a sensor may miss a lead vehicle, for instance in a curve.

Calc_ref_acc
This function calculates the reference acceleration of the AICC algorithm. It consists of a speed controller and a distance controller.

The speed controller is a simple P-type controller: it first calculates the speed error, defined as the deviation of the vehicle's actual speed from the AICC's reference speed. This speed error is multiplied with a constant gain factor to produce the speed controller's output.

The distance controller starts by calculating the reference headway, which is defined by Equation C1:

hw_ref = M_aicc + v * tau_aicc (C1)

where

v	= current speed (m/s)
M_aicc	= a constant offset, or safety margin (m)
tau_aicc	= time-headway setting (s)

In Figure C.1 the reference headway is given for three situations:

- a driver according to eq. A2;
- an AICC vehicle with M_aicc=10 and tau_aicc=0.64 (corresponding to a 1.0 s time headway at 100 km/h);
- an AICC vehicle with M_aicc=10 and tau_aicc=1.14 (corresponding to a 1.5 s time headway at 100 km/h);

Figure C.1 Reference headways as a function of speed

An error term for distance control is defined as:

hw_err = hw_ref - hw_sens (C2)

where hw_sens is the headway as measured by the sensor [m].
The reference acceleration for distance control is:

a_ref_d = Kd * hw_err + Kv * rel_speed_sens (C3)

where rel_speed_sens is the relative speed measured by the sensor, and Kd and Kv are constants, identical for all vehicles.

The overall reference acceleration determined by taking the most restrictive of the speed and the distance acceleration references. Finally, this value is limited between the maximum acceleration and deceleration of the AICC.

Calc_icc_acc_control

The acceleration control loop tries to realize the actual reference acceleration by means of setting appropriate reference values for the gas and brake actuator. A block diagram of a continuous realization of the acceleration controller is given in Figure C.2. It consists of a PI-controller with a gain K_a and a time constant t_a. The controller output u is normalized between -1 and +1. The PI controller is equipped with Anti-Reset Windup (ARW) to prevent excessive overshoot after periods of continued controller saturation. The ARW logic halts the I-action of the controller when the combination of the signals u_pi and a_{err} indicates that the controller has just begun to saturate.

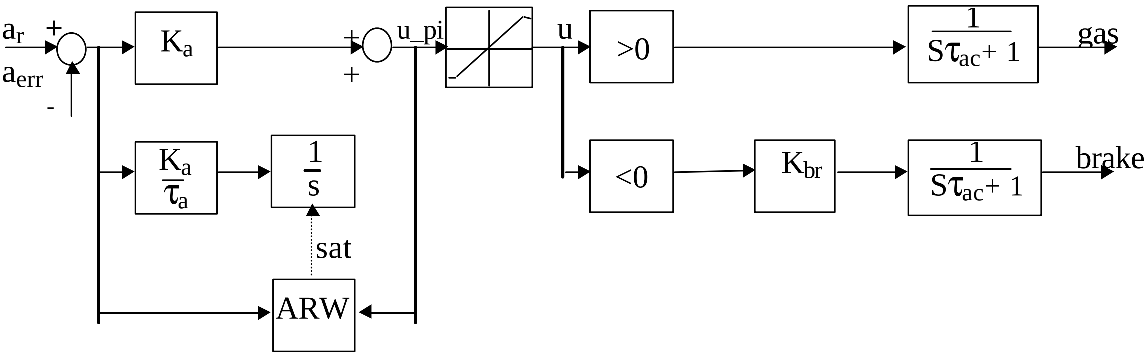

Figure C.2 Block diagram of continuous acceleration controller and actuators.

Calc_icc_gas_act,
Calc_icc_brake_act.
For positive values of the controller signal u, the gas actuator is used (see Fig. C1). Since both the controller signal u and the accelerator pedal position are normalized between 0 and 1, no additional scaling is necessary. For negative values of u, the brake actuator is applied. An additional, vehicle-type dependent gain K_{br} is necessary to scale the normalized control variable to a sufficient braking force. Both actuators are characterized by a first-order time constant.

Parameter settings
The AICC parameter settings are given in the following Tables. Table C1 gives the vehicle independent parameter settings, whereas the vehicle-dependent parameter settings for cars, vans, and trucks are given in Table C2, C3, and C4, respectively.

Table C1: AICC vehicle-independent parameters

Parameter	Value	Comment
Det_delay	0.1	sensor delay (s)
det_range	150	maximum detection range sensor (m)
K_aicc	0.1	Gain of P-type speed controller $(m/s^2)/(km/h)$
Kd	0.2	distance controller distance error factor
Kv	3.0	distance controller speed error factor
inter_pl_hw	1.5	s, not used
intra_pl_hw	1.0	s, not used
platoon_size	10	not used

ICC_ref_lower	50	km/h, not used
ICC_ref_upper	140	km/h, not used
curdec_thresh_diseng	0.1	AICC disengage threshold
desdec_thresh_diseng	0.5	
curaiccmaxdecalarmcorr	-1.5	m/(s*s)
min_acc_eng	-0.5	m/(s*s)
max_acc_eng	0.5	
a_re_eng	-1.0	m/(s*s)

Table C2:AICC vehicle-dependent parameters for Vehicle Type 1 (passenger car)

Parameter	Value	Comment
ICC_max_acc	-2	m/(s*), maximal acceleration
ICC_max_dec	2	m/(s*s), minimal acceleration
ICC_em_dec	-5	m/(s*s), emergency deceleration, not used
ICC_det_range	135	m, sensor range
ICC_det_delay	0.1	s, detection delay
ICC_act_delay	0.1	s, actuator delay
ICC_tau	0.64 or 1.14	s, time headway setting, resulting in 1.0 and 1.5 s headway at 100 km/h for ICC_M=10
ICC_M	10	m, safety margin
ICC_engage_rt	0.5	s, reaction time for engaging ICC
ICC_disengage_rt	1.0	s, reaction time for disengaging ICC
pi_gain	0.08	gain acceleration (PI) controller
pi_time_const	0.04	time constant acceleration (PI) controller (s)
Brake_actuator_gain	6.0	gain of brake actuator

Table C3: AICC vehicle-dependent parameters for Vehicle Type 2 (vans); parameters not used, AICC is only studied and tested on passenger cars

Parameter	Value	Comment
ICC_max_acc	-2	m/(s*), maximal acceleration
ICC_max_dec	2	m/(s*s), minimal acceleration
ICC_em_dec	-5	m/(s*s), emergency deceleration, not used
ICC_det_range	135	m, sensor range
ICC_det_delay	0.1	s, detection delay
ICC_act_delay	0.1	s, actuator delay
ICC_tau	0.64 or 1.14	s, time headway setting, resulting in 1.0 and 1.5 s headway at 100 km/h for ICC_M=10
ICC_M	10	m, safety margin
ICC_engage_rt	0.5	s, reaction time for engaging ICC
ICC_disengage_rt	1.0	s, reaction time for disengaging ICC
pi_gain	0.08	gain acceleration (PI) controller
pi_time_const	0.03	time constant acceleration (PI) controller (s)
Brake_actuator_gain	10.0	gain of brake actuator

Table C4: AICC vehicle-dependent parameters for Vehicle Type 3 (bus/truck); parameters not used, AICC is only studied and tested on passenger cars

Parameter	Value	Comment
ICC_max_acc	-2	m/(s*), maximal acceleration
ICC_max_dec	2	m/(s*s), minimal acceleration
ICC_em_dec	-5	m/(s*s), emergency deceleration, not used
ICC_det_range	135	m, sensor range
ICC_det_delay	0.1	s, detection delay
ICC_act_delay	0.1	s, actuator delay
ICC_tau	0.64 or 1.14	s, time headway setting, resulting in 1.0 and 1.5 s headway at 100 km/h for ICC_M=10
ICC_M	10	m, safety margin
ICC_engage_rt	0.5	s, reaction time for engaging ICC
ICC_disengage_rt	1.0	s, reaction time for disengaging ICC
pi_gain	0.04	gain acceleration (PI) controller
pi_time_const	0.025	time constant acceleration (PI) controller (s)
Brake_actuator_gain	300	gain of brake actuator

APPENDIX D: MIXIC BIBLIOGRAPHY

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