Fast-Time Simulation of Airport Surface Traffic

Memorandum M-798

Arjan Rodenburg

This memorandum has been prepared in the framework of the joint NLR/TUD A-SMGCS project
Title: Fast-Time Simulation of Airport Surface Traffic

Author(s): A. Rodenburg

Abstract: This report describes the continued development of a prototype simulator for airport surface traffic, christened SIMulation of Airport Surface Traffic (SIMAST). Such a simulator is a helpful tool for the development and evaluation of new airport surface movement procedures. These procedures are intended to optimize airport throughput during low-visibility conditions, while at least maintaining the current safety levels. Before continuing the further development of SIMAST, an inventory is presented of several types of airport surface traffic simulators as well as an introduction to the initial version (1.0) of SIMAST and the movement models controlling the behaviour of the surface traffic. The report identifies the possible paths of development for SIMAST and the shortcomings of the prototype version (1.0). The user requirements for the new version (2.0) of SIMAST are described, defining the improvements which need to be made to the simulation software and the movement models. Implementation of these improvements leads to a new version of SIMAST, which enables the simulation of almost every possible aircraft movement on any airport surface (apron movements excluded). SIMAST may now be used for the evaluation of existing taxi-plans, generated manually or by taxi-planning support tools. Furthermore, it enables the user to identify bottlenecks on an airport’s taxiway system.

Keyword(s): Airport surface traffic, movement models, simulation

<table>
<thead>
<tr>
<th>Issue</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>June 1997</td>
</tr>
<tr>
<td>Prepared</td>
<td>A. Rodenburg</td>
</tr>
<tr>
<td>Verified</td>
<td>R.M. van der Haagen</td>
</tr>
<tr>
<td>Approved</td>
<td>H.G. Visser</td>
</tr>
</tbody>
</table>
Summary

Due to the underestimation of the growth of air traffic, when most of today's airports were constructed, many of the worlds' busiest airports are operating at or close to their capacity limits. Construction of new runways and taxiways is often not possible. However, due to the current methods of air traffic handling, the theoretically available capacity of an airports' infrastructure can often not be used. Especially during low-visibility conditions, airport throughput drops dramatically. To optimize airport throughput during low-visibility conditions, while at least maintaining the current safety levels, research is done into Advanced Surface Movement Guidance and Control Systems (A-SMGCS).

Since 1996, the Nationaal Lucht- en Ruimtevaart laboratorium NLR, National Aerospace Laboratory) and the Faculty of Aerospace Engineering of the Delft University of Technology (DUT/FAE) are involved in a joint A-SMGCS research project. Because of the extent of the research project and limited resources, the DUT/FAE activities will be focussed on the development of taxi-planning support tools and airport surface traffic simulation tools.

In this report, the development of the prototype simulator for the SIMulation of Airport Surface Traffic, christened SIMAST, is continued. The simulator is intended to be used for the evaluation of new airport surface movement procedures. Before continuing the development of SIMAST, an inventory is presented of several types of airport surface traffic simulators as well as an introduction to the present version of SIMAST (1.0). After identifying the possible paths of development for SIMAST and SIMASTs' shortcomings, the user requirements for the new version of SIMAST are described. These user requirements define the improvements which need to be made to SIMAST, resulting in a new version of the airport surface traffic simulator.

The new version of SIMAST (2.0) allows for the simulation and control of all possible aircraft movements on any airport surface, excluding movements on the apron area. It can be used for the evaluation of existing taxi-plans, generated manually or by a taxi-planning support tool and the identification of bottlenecks on an airport taxiway system.
Preface

This report details the work carried out as part of my thesis assignment at the Faculty of Aerospace Engineering of the Delft University of Technology. It is the concluding part of the study before graduation. I generally look back upon this period as an interesting and educating part of my study, filled with new experiences, frustrations and fun.

I would like to thank ir. R.M. van der Haagen and dr. ir. H.G. Visser of the Faculty of Aerospace Engineering for their support and advise. Furthermore I would like to thank my parents for their support and motivation, Annelieke for the delicious meals and Erik for his frequent visits and disturbing interruptions, taking my mind of things.

Arjan Rodenburg
Rotterdam, June 1997.
Contents

Summary ........................................................................................................... 3

Preface ........................................................................................................... 4

Abbreviations ................................................................................................. 9

Notations .......................................................................................................... 11

Definitions ....................................................................................................... 15

1 Introduction .................................................................................................. 17

2 Airport Surface Traffic Simulators ............................................................ 21
   2.1 Tower Visual Simulators ........................................................................ 21
   2.2 Real-time Simulation of Airport Surface Traffic ................................. 21
   2.3 Fast-time Simulation of Airport Surface Traffic ................................. 27

3 Previously Developed Movement Models and Simulator ......................... 29
   3.1 Movement Models for Airport Surface Traffic .................................... 29
      3.1.1 The Kinematic Model ................................................................... 29
      3.1.2 The Geographic Airport Model .................................................... 30
      3.1.3 The Control Model ...................................................................... 32
         3.1.3.1 The Traffic Generation Function ....................................... 32
         3.1.3.2 The Sequencing/Scheduling Functions ............................... 32
         3.1.3.3 The Exit Assignment Function ........................................... 33
         3.1.3.4 The Conflict Handling Function ....................................... 33
         3.1.3.5 The Route Generation Function ....................................... 33
   3.2 Original Simulator Design, SIMAST 1.0 ............................................... 33

4 Continued Simulator Development ............................................................. 35

5 Shortcomings of The Present SIMAST Version (1.0) ............................... 37
   5.1 The Geographic Airport Model ............................................................ 37
   5.2 The Kinematic Model .......................................................................... 37
   5.3 The Control Model .............................................................................. 38
      5.3.1 Conflict Prediction and Resolution ............................................ 38
      5.3.2 Sequencing of Arrivals and Departures ..................................... 38
      5.3.3 Traffic Generator ....................................................................... 38
      5.3.4 Exit Assignment ......................................................................... 39
      5.3.5 Taxiroute Generator .................................................................. 39
   5.4 Graphical capabilities .......................................................................... 39
   5.5 Simulation Output Parameters ............................................................. 39
6 Available Commercial Entire Airfield Simulators ........................................ 41
  6.1 The FAA's Airport and Airspace Simulation Model SIMMOD .................. 41
  6.2 The Total Airspace and Airport Modeler TAAM ................................. 42
  6.3 Other Entire Airfield Simulators ..................................................... 43
  6.4 Conclusion ................................................................................. 43

7 User Requirements ............................................................................. 45
  7.1 Requirements for A-SMGCS .......................................................... 45
  7.2 Simulator Requirements ................................................................ 45
  7.3 SIMAST Top-level Design ............................................................. 47

8 Changes in SIMAST's Software and Graphics ....................................... 49
  8.1 Software Changes ..................................................................... 49
  8.2 Graphics Improvements ............................................................... 49

9 The Geographic Airport Model ............................................................ 53
  9.1 Airport Surface Links .................................................................. 53
  9.2 Multiple Runways ....................................................................... 54
  9.3 High-speed Exits ....................................................................... 54
  9.4 Taxiway Turns .......................................................................... 54
  9.5 A Model for Amsterdam Airport .................................................. 55

10 The Kinematic Model .......................................................... ........................ 57
  10.1 The Vehicle model ......................................................................... 57
  10.2 The Kinematic Module .............................................................. 58
      10.2.1 The Deceleration Phase ....................................................... 60
      10.2.2 The Acceleration Phase ...................................................... 61
      10.2.3 The Turn Phase ................................................................ 61
      10.2.4 Runway Turnoffs ................................................................ 61

11 The Control Model ........................................................................ 65
  11.1 The Conflict Prediction and Resolution Function ............................ 65
      11.1.1 Longitudinal Separation Conflict ...................................... 65
      11.1.2 Lateral Separation Conflict ............................................... 67
      11.1.3 Runway Incursion ............................................................... 68
  11.2 The Sequencing and Scheduling Function ....................................... 68
      11.2.1 Parallel Runways ................................................................ 68
      11.2.2 Intersecting Runways ......................................................... 70
      11.2.3 Open-V Runways .............................................................. 70
      11.2.4 Arriving Flights ................................................................. 71
      11.2.5 Departing Flights .............................................................. 72
12 Interface with The Taxi-Planning Support Tool
   12.1 The Taxi Plan ........................................ 73
   12.2 Taxi Display .......................................... 73
   12.3 Aircraft Speed Adjustments ............................ 74
   12.4 Taxi Plan Evaluation .................................. 74

13 Modeling the Stochastic Behaviour of Aircraft
   13.1 Monte Carlo Sampling ................................... 75
      13.1.1 Generating Uniform Independent Deviates .......... 75
      13.1.2 Sampling From the Normal Distribution pdf ... 76
   13.2 Stochastic Modeling of Aircraft Movements ............ 78
      13.2.1 The Landing Phase ................................ 78
      13.2.2 The Takeoff Phase ................................ 80
      13.2.3 The Taxi Phase .................................... 81
      13.2.4 The Accelerating Phase ............................ 81
      13.2.5 The Decelerating Phase ............................ 81
      13.2.6 The Turning Phase ................................ 81
   13.3 Conclusion ............................................. 81

14 Data Output For Simulation Analysis ......................... 83
   14.1 Aircraft Specific Output Parameters .................... 83
   14.2 Link Specific Output Parameters ....................... 85

15 Identification of Aircraft Taxiing Behaviour ............... 87
   15.1 Aircraft Movement Data ................................ 87
   15.2 Data Extracted From the HITT System .................. 88
   15.3 Data Supplied by the LVB ............................. 88
   15.4 Taxi Movement Database ................................ 88

16 A Sample Simulation Run and SIMAST’s Limitations ........ 91
   16.1 Sample Simulation run .................................. 91
   16.2 Simulation Limitations .................................. 93
      16.2.1 Limitations of The Geographic Airport Model .... 93
      16.2.2 Limitations of The Kinematic Model ............... 93
      16.2.3 The Limitations of The Control Model ............. 94
      16.2.4 Simulation Output Parameters ....................... 95
      16.2.5 Software Limitations ................................ 95
   16.3 Future Simulator development ............................ 95

17 Conclusions ............................................... 109

18 Literature .................................................. 111

Appendix A Thesis Assignment ................................ 113

Appendix B The Monte Carlo Sampling Algorithm ............... 117
Appendix C The SIMAST (2.0) Software Design ........................................ 119

Appendix D Data Input Parameters ......................................................... 141
  D.1 Geographic Airport Model Input Data Parameters ......................... 141
  D.2 Airport Meteo Input Parameters .................................................. 141
  D.3 Aircraft Type Specific Parameters ............................................ 141
  D.4 Flight Plan Parameters ............................................................ 142
  D.5 Taxiplan Parameters .................................................................. 142
  D.6 Parameters Concerning Air Traffic Control .................................. 142
  D.7 Simulation initialization Parameters .......................................... 142

Appendix E SIMAST User Manual .......................................................... 159
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASDE</td>
<td>Airport Surface Detection Equipment</td>
</tr>
<tr>
<td>A-SMGCS</td>
<td>Advanced Surface Movement Guidance and Control Systems</td>
</tr>
<tr>
<td>AIRPORT-G</td>
<td>Airport Integrated Research and development Project for Operational Regulation of Traffic-Guidance</td>
</tr>
<tr>
<td>ATA</td>
<td>Actual Time of Arrival</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATD</td>
<td>Actual Time of Departure</td>
</tr>
<tr>
<td>ATHOS</td>
<td>Airport Tower Harmonized Controller System</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>AVOL</td>
<td>Aerodrome Visibility Operational Level</td>
</tr>
<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>ETA</td>
<td>Estimated Time of Arrival</td>
</tr>
<tr>
<td>ETD</td>
<td>Estimated Time of Departure</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FAE</td>
<td>Faculty of Aerospace Engineering</td>
</tr>
<tr>
<td>FAR</td>
<td>Federal Aviation Regulations</td>
</tr>
<tr>
<td>HITT</td>
<td>Holland Institute of Traffic Technology B.V.</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>IFR</td>
<td>Instrument Flight Rules</td>
</tr>
<tr>
<td>LVB</td>
<td>LuchtVerkeersBeveiliging (ATC The Netherlands)</td>
</tr>
<tr>
<td>MANTEA</td>
<td>Management of Surface Traffic on European Airports</td>
</tr>
<tr>
<td>MLW</td>
<td>Maximum Landing Weight</td>
</tr>
<tr>
<td>MTOW</td>
<td>Maximum Takeoff Weight</td>
</tr>
<tr>
<td>NLR</td>
<td>Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)</td>
</tr>
<tr>
<td>NM</td>
<td>Nautical Mile</td>
</tr>
<tr>
<td>OEW</td>
<td>Operational Empty Weight</td>
</tr>
<tr>
<td>pdf</td>
<td>probability density function</td>
</tr>
<tr>
<td>ROT</td>
<td>Runway Occupancy Time</td>
</tr>
<tr>
<td>SARP</td>
<td>Signaal Automatic Radar Processing</td>
</tr>
<tr>
<td>SID</td>
<td>Standard Instrument Departure</td>
</tr>
<tr>
<td>SIMAST</td>
<td>SIMulation of Airport Surface Traffic</td>
</tr>
<tr>
<td>SIMMOD</td>
<td>airport and airspace SIMulation MODeI</td>
</tr>
<tr>
<td>SMR</td>
<td>Surface Movement Radar</td>
</tr>
<tr>
<td>STAR</td>
<td>Standard Arrival Route</td>
</tr>
<tr>
<td>TAAM</td>
<td>Total Airport and Airspace Modeller</td>
</tr>
<tr>
<td>TMA</td>
<td>Terminal Manoeuvring Area</td>
</tr>
<tr>
<td>TRS</td>
<td>Tower Research Simulator</td>
</tr>
<tr>
<td>VFR</td>
<td>Visual Flight Rules</td>
</tr>
<tr>
<td>WTC</td>
<td>Wake Turbulence Category</td>
</tr>
</tbody>
</table>
Notations

A  aspect ratio of an aircraft wing or a multiplier
A_1  A(mod 2^{31})
A_2  A-A_1
a  constant rate of acceleration (m/s^2)
a(t)  momentary rate of acceleration
a_a  rate of acceleration of aircraft A
a_{acc}  rate of acceleration
a_b  rate of acceleration of aircraft B
a_{decc}  rate of deceleration
B  engine bypass ratio
C(0,1)  non-central Cauchy distribution
C_{L\text{land}}  maximum coefficient of lift during the landing
C_{L\text{start}}  maximum coefficient of lift during takeoff
cor  air traffic controller reaction time (s)
D  aircraft drag
D_g  frictional force between the aircraft's tires and the surface
D_p  propeller diameter (m)
\mathcal{E}(1)  exponential distribution
\mathcal{E}(0,1)  non-central Cauchy distribution
g  gravitational acceleration (m/s^2)
i  variable
L  length of transition curve (m)
L_r  manufacturers landing run distance (m)
M  a prime number
\mathcal{M}  multinomial
\mathcal{N}(\mu,\sigma^2)  normal distribution with mean \mu and variance \sigma^2
N_e  number of engines
P_f  maximum number of samples that can be drawn before the seed recurs
P_{to}  takeoff power (Nm/s)
P_{tire}  tire pressure (psi)
pir  pilot reaction time (s)
Q  Q-1 is the maximum number of a sequence of non-negative numbers
R(t)  momentary radius of curvature
R_0  radius of curvature
S  area of an aircraft wing (m^2)
S_{ae}  length of the aircraft
S_{brake}  braking distance needed to come to a full stop
S_{jet}  distance behind an aircraft that must be kept clear to avoid jet-blast effects
S_{\text{min}}  the minimum distance that must be maintained between two aircraft at all times
S_{\text{reaction}}  distance traveled by an aircraft whilst the pilot, air traffic controller and the airport radar system in use, react in a time T,
S_t  S_{ae}+S_{brake}+S_{jet}+S_{\text{min}}+S_{\text{reaction}}
S_{to}  takeoff distance (m)
sar  safety reaction time (s)
syr  system reaction time (s)
T    momentary thrust (N)
\( \bar{T} \)  mean thrust during takeoff (N)
\( T_{\text{apron}} \)  time when an aircraft leaves the taxiway system and enters the apron
\( T_{\text{hold}} \)  time spent in hold
\( T_{\text{insim}} \)  time when an aircraft enters the simulation (ATA for arrivals)
\( T_{\text{lineup}} \)  time spent in the lineup for the departure runway
\( T_{\text{takeoff}} \)  time of takeoff (ATD)
\( T_{\text{taxi}} \)  time spent taxiing over the taxiway system
\( T_s \)  total system response time \( \pi r + \cos s + \text{sar} + \text{syr} \) (s)
\( T_{\text{to}} \)  takeoff thrust
\( t \)  point in time (s)
\( U \sim (0,1) \)  uniform distribution on the region (0,1)
\( U_i \)  uniform independent derivative
\( V \)  momentary aircraft/vehicle speed (m/s)
\( V(t) \)  initial aircraft/vehicle speed (m/s)
\( V(t+\Delta t) \)  new aircraft/vehicle speed (m/s)
\( V_A \)  speed of aircraft A
\( V_B \)  speed of aircraft B
\( V_{\text{wish}} \)  desired taxi speed, derived from the assigned taxipland
\( W \)  aircraft weight (N)
\( W_{\text{land}} \)  aircraft landing weight (N)
\( W_{\text{to}} \)  aircraft takeoff weight (N)
\( w_{\text{land}} \)  landing weight factor
\( w_{\text{to}} \)  takeoff weight factor
\( x(t) \)  initial x-position of aircraft/vehicle
\( x(t+\Delta t) \)  new x-position of aircraft/vehicle
\( y(t) \)  initial y-position of aircraft/vehicle
\( y(t+\Delta t) \)  new y-position of aircraft/vehicle
\( Z_0 \)  seed
\( Z_i \)  new random variable
\( Z_{i+1} \)  initial random variable
\( z \)  random variable

\( \gamma_{\text{ap}} \)  flight-path angle during final approach (rad)
\( \gamma_{\text{off}} \)  flight-path angle at the point of lift-off (rad)
\( \Delta t \)  increment in time (s)
\( \Delta t_{\text{allowed}} \)  maximum allowed deviation from the taxiplan (s)
\( \Delta V_{\text{allowed}} \)  maximum allowed deviation from the desired taxi speed derived from the taxiplan (m/s)
\( \mu \)  coefficient of friction
\( \mu_{\text{coll}} \)  coefficient of rolling friction
\( \rho \)  air density (kg/m³)
\( \chi \)  heading (rad)
\( \sigma \)  
standard deviation or  
ratio of air density and the air density at 0m ISA \((\rho/\rho_0)\)  

\( \sigma_{\text{vland}} \)  
standard deviation of the landing weight factor  

\( \sigma_{\text{vto}} \)  
standard deviation of the takeoff weight factor
Definitions

The terms used in this report are explained below.

*Advanced Surface Movement Guidance and Control System (A-SMGCS)*
A system providing surveillance, control, guidance and routing to aircraft and effected vehicles in order to maintain the movement rate under all weather conditions within the Aerodrome Visibility Operational Level (AVOL)

*Aerodrome Visibility Operational Level (AVOL)*
The minimum visibility at or above which the declared movement rate can be sustained by an A-SMGCS.

*Aircraft*
Flight vehicle arriving at and departing from the airport over the runway and adhering to the defined path structure.

*Aircraft movement*
The movement of an aircraft on the movement area.

*Airport*
A defined area (including buildings, installations and equipment) intended to be used either wholly or in part for arrival and surface movement of aircraft and operational vehicles.

*Airport surface traffic*
All aircraft, helicopters and vehicles on the movement area.

*Apron*
A defined area on an airport, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fueling, parking or maintenance.

*Conflict*
A situation when there is a possibility of a collision between aircraft and/or vehicles.

*Control*
Application of measures to prevent collisions, runway incursions and to ensure safe, expeditious and efficient movement.

*Gate*
A gate is a designated area on an apron intended to be used for the parking of an aircraft
  *Active gate*
  A gate on which an aircraft is moving or which is being approached by an aircraft.
  *Passive gate*
  A gate which is occupied by a stationary aircraft with non-operating engines.
  *Empty gate*
  A gate which is vacant and which is not being approached by an aircraft.
Guidance
Facilities, information and advice necessary to provide continuous, unambiguous and reliable information to pilots of aircraft and drivers of vehicles to keep their aircraft or vehicles on the surfaces intended for their use.

High-speed exit
A runway exit that can be exited safely at a speed of up to 60 Miles per hour.

Identification
The correlation of a known aircraft movement or vehicle movement callsign with the displayed target of that aircraft or vehicle on the display of the surveillance system.

Manoeuvring area
That part of an airport intended to be used for takeoff, landing and taxiing of aircraft, excluding aprons.

Modularity
Capability to enhance a system by the addition of one or more modules to improve its technical or functional performance.

Movement area
That part of an airport to be used for the takeoff, landing and taxiing of aircraft, consisting of the manoeuvring area and apron(s), excluding: passive gates, empty gates and those areas of the apron(s) which are exclusively designated to vehicle movements.

Route
An assigned track from a defined start point to a defined end point on the movement area.

Routing
The planning and assignment of a route to individual aircraft and vehicles to provide safe, expeditious and efficient movement from their current position to their intended position.

Screen height
The minimum height imposed by airworthiness regulations that has to be reached at the end of the runway length (including the clearway), to ensure an adequate and safe climb-out.

Surveillance
A function which provides identification and accurate positional information on aircraft, vehicles and unauthorised targets within the required area.

Vehicle
Non-flying vehicle operating on the airport surface.

Vehicle movement
The movement of a vehicle on the movement area.
1 Introduction

The air transport industry has roughly doubled its number of passengers in Europe during the last two decades [7]. It is forecast that the passenger traffic will keep growing at this rate during the next two decades. The number of flights continues to grow despite the introduction of larger aircraft. The rate of growth of worldwide passenger traffic has been underestimated in the past and as a result Air Traffic Control (ATC) and airport systems have not kept up with this development. Most of the congestions in the air traffic system are expected in the Terminal Manoeuvring Area (TMA), where several air traffic flows from various directions have to merge. Research shows that during low visibility conditions, flight delays are mostly caused by delays on the airport surface [5].

Due to the underestimation of air traffic growth when today's airports were constructed, many of the world's busiest airports are operating close to or at their capacity limits. Construction of new runways and taxiways is often not possible due to various reasons. However, because of the current methods of air traffic handling the theoretically available capacity of an airport's infrastructure cannot always be used. Especially during low visibility conditions the situation gets only worse. Passengers, airlines, airport authorities and civil aviation authorities have to suffer the losses. Airlines may decide to avoid airports in favor of reliable and well fitted airports to minimize delays and risks. Besides the economical losses, the consequences of an ineffective system with respect to the pollution of the environment and noise production are becoming more important.

The aircraft and vehicles on the airport surface are handled by air traffic controllers by means of visual identification, supplemented by pilot's position reports and Surface Movement Radar (SMR) or Airport Surface Detection Equipment (ASDE), when available. This is a primary radar with only position information and no identification. Especially in low visibility conditions the controller has to build up a picture of the current traffic situation in his mind. This is an extremely demanding task in addition to the planning of the traffic flow. All instructions are transmitted to drivers and pilots via vocal radio telephony. Navigation of aircraft and vehicles is the responsibility of the pilots and vehicle drivers. They have to rely on visual orientation and observation. There is limited support in the form of traffic signs, manually controlled center lights, etc. This results in a considerable workload for both controllers and pilots/drivers. Technical means to support them are only sparsely introduced.

Due to the visual nature of handling airport surface traffic, low visibility conditions have a considerable negative effect on the achievable flow of traffic on an airport. Because identification of aircraft and vehicles is not available, special procedures are applied to safely handle the traffic on the airport surface during low visibility conditions. Under these conditions, usually only one taxiroute is used for arriving aircraft and one for departing aircraft. This establishes and maintains a sequential flow of the traffic, but results in longer taxiroutes and long departure queues at the start of the runway (figure 1.1), with delays as a consequence. When visibility is good, the aircraft are assigned various taxiroutes. Small aircraft may enter the runway somewhere halfway the length of the runway, since they do not need the full length of the runway for takeoff. This leads to more than one, but short departure queues and shorter taxiroutes, since not all aircraft have to taxi to the start of the runway (figure 1.2).
The problem described above, occurring during low visibility, has been recognized worldwide. To optimize airport throughput in low visibility conditions, Advanced Surface Movement Guidance and Control Systems (A-SMGCS) are under investigation in Europe. The purpose of an A-SMGCS is to enhance airport surface movement efficiency while at least maintaining current levels of safety, in all weather conditions.

Since the beginning of 1996 the Nationaal Lucht- en Ruimtevaart laboratorium (NLR, National Aerospace Laboratory) has been involved in a number of EC projects concerned with the research and development of A-SMGCS. Recently, the Faculty of Aerospace Engineering of the Delft University of Technology (DUT/FAE) has joined the A-SMGCS research activities. In view of the broad scale of the research topic and limited resources, the DUT/FAE activities will be focussed on two topics:

- The development of simulation tools for airport surface traffic movements;
- The development of taxi-planning support tools.

The purpose of the taxi-planning support tool is to optimize the sequencing and scheduling of traffic, such as to minimize delays and to reduce the number of stops during taxiing. Initial testing and evaluation of the taxi-planning tool cannot be done on an operational airport. For this reason, simulation programs to evaluate and test the taxi-planning and various other tools developed in the framework of the A-SMGCS research are of paramount importance. A prototype fast-time simulator for airport surface traffic, christened SIMAST (SIMulation of Airport Surface Traffic), has previously been developed in the framework of a thesis assignment [14].

This report deals with the continued development of the SIMAST ground movement simulation tool. Chapter two describes the various types of simulators, which can use previously developed movement models for airport surface traffic [13]. These movement models and the simulator based upon these movement models are described in chapter three. Chapter four identifies the direction of development to be followed for the continued development of SIMAST. The shortcomings of the present version of SIMAST (1.0) are discussed in chapter five. Airfield simulators have also been developed by others and some are available on the market. Chapter six describes a couple of these simulators and checks if it would be beneficial to purchase one of these simulators, instead of continuing the development of SIMAST. Since this is not the case, chapter seven describes the user requirements and gives a top-level design for the new version of SIMAST. Chapter 8 deals with the changes in SIMAST's software architecture made to enable easier implementation of various new features in SIMAST and the enhancements to SIMAST's graphics. The changes made to the movement models on which SIMAST is based, are discussed in chapters 9 through 11. For SIMAST to cooperate with the taxi-planning support tools in development mentioned above, an interface has to be developed. This is done in chapter 12. The movement models need to be adapted to realistically reflect the stochastic behaviour of vehicle movement on airports. A possible approach to this is the use of monte carlo sampling. This is explained in chapter 13. In order to analyse simulation runs, SIMAST produces output. The parameters provided as output are

---

1 European Commission
introduced in chapter 14.

It should be noted that very little information is available about the actual behaviour of vehicles on an airport surface. Recently a number of measurements have been performed on Amsterdam airport, using an A-SMGCS surveillance system developed by the Holland Institute of Traffic Technology B.V. (HITT). Chapter 15 explains what parameters have been measured and how these could be used to acquire more knowledge about the behaviour of aircraft on an airport surface. A sample simulation run is illustrated in chapter 16. Finally on the basis of the user requirements presented in chapter 7, the conclusions and suggestions for further research are presented in chapter 17.

figure 1.1 A sequential traffic flow near the runway during low visibility conditions
figure 1.2 Multiple departure queues during good visibility conditions
2 Airport Surface Traffic Simulators

With the increasing number of flights, airports are reaching their capacity limits. Therefore, several research programmes [4] are aimed at airport related subjects to increase airport capacity, reduce delays, increase the level of safety, provide controllers with decision support tools reducing the workload, reduce delays at airports and operating costs for the users. Simulation is a very useful tool for the evaluation of the effectiveness of new tools developed in the framework of the airport related research projects. Simulators are also needed to teach the air traffic controllers and pilots how to use these new tools. Movement models for taxiing aircraft, such as those developed during a previous thesis assignment [13], can be used for various simulation applications with respect to airport operations. These movement models are described in the next chapter. Three of these applications are:
- tower visual simulators;
- real-time simulation of airport surface traffic;
- fast-time simulation of airport surface traffic.
A basic fast-time aircraft simulator (SIMAST) has already been developed at the DUT/FAE during a thesis assignment [14]. This simulator will be discussed in the next chapter, together with the already mentioned movement models for airport surface traffic developed in the framework of the same thesis assignment. The following paragraphs will address the three simulation applications mentioned above.

2.1 Tower Visual Simulators
Movement models for taxiing operations on airports can be used for synthetic aircraft generation for tower visual simulators. Tower visual simulators simulate in real-time and in a very realistic way, the operational environment of an aerodrome control tower. They can be used for the research and development of new tools, assisting air traffic controllers. Training of air traffic controllers is another application of tower visual simulators. During the simulation, the air traffic controllers are able to control the synthetic traffic present in the simulation. The simulator usually displays a virtual 360° view as seen from an airport control tower in real-time and is often integrated with a realistic radar simulation of the traffic present on the airport. The visual nature of the simulator asks for high fidelity image generation equipment, resulting in high development costs. The NLR is currently in the process of building a visual tower simulator for research purposes, denoted NLR Tower Research Simulator (TRS) [16]. This simulator could be used for Human Machine Interface (HMI) research, with a direct impact on the ATHOS² project. This is a project sponsored by the European Community, partly carried out at the NLR in cooperation with several European partners. The project addresses the development of new tools for the air traffic controllers working position.

2.2 Real-time Simulation of Airport Surface Traffic
If one would like to study the interaction between new systems under development and human operators, a human needs to be included in the process. This implies that simulations set up for this kind of research need to be (near) real-time. An example of such a research project is the

²Airport Tower Harmonized cOntroller System [16]
AIRPORT-G³ project. This is another EC sponsored research project in which the NLR participates with various European partners. The project is aimed at the development of a guidance function for future A-SMGCS. This guidance function guides the pilot over the airport surface, enabling him to safely and expeditiously travel across the airport, independent of the visual conditions. The guidance function provides the pilot with information of his position on the airport and the route to be followed. For the research and development of such a guidance function, it is necessary to include a pilot in the simulation loop, because the interaction between the guidance function and the pilot is very important. One can develop a very sophisticated guidance function, but if the pilot and the guidance function cannot cooperate, another solution has to be found.

Another application of a real-time simulator would be the research into the interaction between a human pilot and a taxi-planning support tool. The taxi-planning support tool should enable the conflict free flow of traffic on the airport surface. Since an on-line as well as an off-line taxi planning support tool are under development at the DUT/FAE[27,20], such a simulator would be very interesting. A proposed top-level design of a real-time simulator is shown in figure 2.1.

The simulator is of a modular design, with different modules for the various functions present in a possible A-SMGCS. The goals for an A-SMGCS are:
- an increase of airport throughput in general, while maintaining at least the present level of safety;
- elimination of airport throughput due to influences of the weather;
- improvement of efficiency by optimum exploitation of available airport capacity;
- reduction of the controller workload;
- reduction of taxi times and prevention of delays during taxing;
- reduction of environmental burden.

With these goals in mind, four functions can be distinguished in an A-SMGCS:
- Planning or routing, the planning and assignment of routes to individual aircraft and vehicles to provide safe, expeditious and efficient movement on the aerodrome;
- Surveillance, this function provides accurate positional information and identification on all aircraft and vehicles which make up the actual traffic situation;
- Monitoring or control, takes care of the prevention of collisions on the taxiway system and unauthorised or inadvertent entry of operational runways;
- Guidance, this function provides pilots of aircraft and drivers of vehicles with information to keep their aircraft or vehicle on the assigned routes.

The advantage of such a modular design is that the various modules can be filled in according to the need and time available for implementation. Once the data transfer between the various modules is defined, the modules inner functioning is totally independent from the other modules. As can be seen from figure 2.1, two positions are needed for human operators to interact with the system. This will result in a complex software design, since communication between at least two stations will have to be incorporated in the simulator.

³ Airport Integrated Research and development Project for Operational Regulation of Traffic-Guidance
The taxi-planning function obviously provides the taxiplans for the aircraft present in the system. If necessary, this function can also provide revised taxiplans if the actual traffic situation deviates from the planned traffic situation. One of the causes for such a situation would be a substantial delay for arriving aircraft. The development of such an on-line taxi-planning support tool is the subject of another thesis assignment at the DUT/FAE [20].

The surveillance function effectively simulates the radar system used in the virtual A-SMGCS. It provides the state (position, speed, heading, ...) of the aircraft present in the system. Figure 2.2 shows a proposal for the design of the surveillance function. The noise generator provides for the simulation of clutter and loss of accuracy due to the radar system.

The monitoring function observes the actual position of the aircraft, supplied by the surveillance function, and compares this with the planned position of the aircraft as defined in the taxi plan. Depending on the magnitude of the deviation of the aircraft position from the planned position, a message is sent to the guidance function to correct the detected deviation, or a request for a new taxiplan is sent to the taxi planning function if the detected deviation can no longer be corrected. The monitoring function should also provide detection of possible conflicts between vehicles. A possible design for the described monitoring function is shown in figure 2.3.
The guidance function (fig 2.4) receives information from the monitoring function about the deviation of the actual position of aircraft from the planned position of aircraft. If needed, the guidance function will generate advisories for the pilot, enabling him to correct the detected deviation.
The guidance function

The pilot's position's function is to include the human operator in the simulation. It brings the human responses of the aircraft pilot into the simulation. A graphical display shows the layout of the airport and the positions of the pilot's vehicle and other vehicles present, informing the pilot about his position and the traffic situation. The pilot is also informed on which taxi route is to be followed. The advisories, generated by the guidance function, to correct for deviations from the taxi plan should also be displayed (figure 2.6). The pilot may control the movement of the aircraft by altering several parameters. During taxi operations, these parameters would be:

- engine thrust and braking force supplying speed control;
- direction of the nosewheel to enable directional control.

To inform the pilot of the consequences of his actions, a display is needed, relating the status (speed, brake setting, thrust level, ...) of the aircraft to the pilot. The design of the pilot position is drawn in figure 2.5.
Figure 2.5 The pilot position

Figure 2.6 An example of a display relating the advisories generated by the guidance function to the pilot
The pilot provides the input for the kinematic model of the aircraft. The brake setting, thrust setting and other pilot control parameters influence the state of the aircraft. How the aircraft state is influenced by these parameters depends on the aircraft model at hand. The new state of the aircraft is calculated and used to obtain the feedback for the pilot. The design is shown in figure 2.7.

![Kinematic aircraft model](image)

figure 2.7 The Kinematic model

The supervisor position is there to provide the parameters to the various functions of the testbed. Taxiplans, guidance advisories and the state of the aircraft in the system are available to the supervisor to enable monitoring of the simulation process.

### 2.3 Fast-time Simulation of Airport Surface Traffic

If it is not necessary to include a human in the simulation, the speed of the simulation is only limited by the computing power of the equipment used. Since the time in the simulation usually passes faster than the time in the real world, such a simulator is said to be fast-time. The movement models developed during another thesis assignment [13] are especially suited for this kind of simulation. A prototype fast-time simulator using the developed movement models, christened SIMulation of Airport Surface Traffic (SIMAST) has already been developed. The movement models and the original design of SIMAST are described in the next chapter.
3 Previously Developed Movement Models and Simulator

During a previous thesis assignment [13], movement models for taxiing aircraft and movement models for other vehicles travelling over the airport surface have been developed. In order to gain insight into the behaviour of aircraft governed by these models, a prototype fast-time batch simulator for airport surface traffic was developed. This simulator was christened SIMAST (SIMulation of Airport Surface Traffic) [14].

3.1 Movement Models for Airport Surface Traffic
The traffic on an airport can be split into aircraft, helicopters and other (non-flying) vehicles such as fuel trucks and baggage carts. A complete model for vehicle movements on an airport surface, can be subdivided in three parts:
- kinematic model;
- airport geographic model;
- control model.

The relationship between these models is shown in figure 3.1. Each of the models will be treated separately in the following paragraphs.

![figure 3.1 Models relationships](image)

3.1.1 The Kinematic Model
The kinematic model, models the different movement phases of aircraft and vehicles on the airport surface [13]. The movement models for helicopters still need to be defined.

The movement phases of aircraft on the airport surface considered are [13, 17]:
- outbound flights:
  - start-up, push-back, taxiing from the parking position to the runway and takeoff;
- inbound flights:
  - landing and taxiing to the apron/gate area.

The taxi movement itself can be split into accelerating, decelerating, turning and taxiing at a constant speed. All of these phases will have to be treated separately. From now on, the taxi phase will be defined as the movement along a straight path with a constant speed. The relationship between the various movement phases is shown in figure 3.2
3.1.2 The Geographic Airport Model
The various movement phases of aircraft and vehicles can be categorized by the area on the airport where these movements take place. The landing and takeoff movement phases for instance take place on the runway, whilst the taxi movement takes place on the taxiway system. The areas present on an airport surface and the order aircraft travel over these areas are described in figure 3.4 [13, 18].
The airport surface is modelled as a number of nodes, joined by links (fig 3.5). The nodes represent the intersections of the taxiway and runway centrelines, gates, holding areas etc. The links connecting the nodes represent path segments. By modeling the airport like this, runways and taxiways can be represented by a series of connecting links. The followed approach results in a modular and generic concept. Any airport can easily be defined by a series of nodes and links.

**Figure 3.5 Modelled single runway airport**
3.1.3 The Control Model
The control model, controls the movement of vehicles over the airport surface. In order to do this, several control functions have to be provided by the control model [14]. The main control functions incorporated in the control model are presented in figure 3.6 below. The various control functions will be discussed briefly below.

![Arrivals Diagram]

![Departures Diagram]

**Figure 3.6** The control model

3.1.3.1 The Traffic Generation Function
The number of inbound and outbound aircraft to be handled, each with its corresponding Estimated Time of Arrival (ETA) or Estimated Time of Departure (ETD), aircraft type and the runway to be used, will be generated by the traffic generation function. The demand is based on one of the following:
- airline schedules (timetables, flight plans);
- aircraft arrival and departure rates.

3.1.3.2 The Sequencing/Scheduling Functions
The sequencing and scheduling functions are there to make sure that the required separation between two subsequent aircraft is maintained at all times. Departing aircraft are not allowed to takeoff as long as any of the separation requirements are violated, or if an arrival is on final approach for the same runway. Arriving aircraft are not allowed to land as long as the runway is being occupied by other aircraft. Distinction is made between Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) flights with respect to the separation procedures. For runways operated in mixed mode, full preference is given to arriving flights.
3.1.3.3 The Exit Assignment Function
After touchdown and braking, arriving aircraft will vacate the runway via an exit. To assign an exit to an arriving aircraft, all exits along the runway are scanned and checked for availability and suitability. The first suitable and available exit is assigned to the aircraft in order to vacate the runway as quickly as possible.

3.1.3.4 The Conflict Handling Function
During taxiing, conflicts may arise. In order to meet the required separation criteria on the taxiway system, predetermined longitudinal spacing (fig. 3.7) between aircraft has to be achieved, taking aircraft speeds, relative directions, aircraft sizes, jet blast effects, total system response time and aircraft braking performance into account.

Lateral separation conflicts may arise when two aircraft simultaneously approach a taxiway intersection. If this occurs, it is checked which aircraft is closest to the intersection. This aircraft will be given permission to cross the intersection first. The other aircraft will be held short of the intersection. Lateral separation conflicts might also occur when two aircraft pass each other on a two-way taxiway.

Conflict resolution can be achieved by re-routing, stopping or decreasing the speed of (one of) the aircraft involved. For the time being, one of the aircraft involved will be stopped.

![figure 3.7 lateral and longitudinal separation](image)

3.1.3.5 The Route Generation Function
If an origin point (for example a gate) and a destination point (for example a runway entry point) of a flight is known, a taxi route can be generated. First it is checked whether there are any known standard taxi routes available. If not, a shortest path algorithm is used to find an appropriate taxi route.

3.2 Original Simulator Design, SIMAST 1.0
The movement models described above, have been used for the development of a basic prototype simulator for the SIMulation of Airport Surface Traffic (SIMAST). An overall movement model enables the simulation of all possible aircraft movements on the airport surface (fig. 3.8). The overall movement model SIMAST has been based upon, consists of several submodels. These submodels are the control model, the aircraft kinematic model and the geographic airport model. These three models are simplified prototype implementations of the three previously developed models [13,14] discussed above. Chapter 5 will discuss the simplifications in the design of SIMAST with respect to the developed movement models.
figure 3.8 The overall movement model
4 Continued Simulator Development

As can be gathered from the previous chapters, research into A-SMGCS has a very broad scale. The four distinct functions of an A-SMGCS (surveillance, planning, monitoring and guidance) each present its own research topic. Besides these research activities, simulators need to be developed to analyse the effectiveness of new A-SMGCS concepts. Thus, in view of the broad scale of the joint NLR-DUT/FAE A-SMGCS research project and limited resources, the TUD/FAE activities will not concern every aspect of A-SMGCS, but will be focussed on two topics:

- the development of simulation tools for surface traffic movement;
- the development of taxi-planning support tools.

At present, work is in progress on the development of two taxi-planning tools [20, 27]. The purpose of the taxi-planning support tools is to optimize the sequencing and scheduling of traffic, such as to minimize delays and to reduce the number of stops during taxiing.

In the envisioned concept, the movement of ground traffic should be planned in a conflict-free fashion, some 20 minutes before the involved vehicles/aircraft actually enter the system. This will be referred to as off-line planning. In contrast, on-line planning concerns an activity primarily based upon observations of the current state of the system. It is performed in a relatively short period of time to allow interventions on the controlled traffic. At present, thesis assignments are aimed at both the development of an off-line tool [27] and an on-line tool [20]. The taxiplans produced by the planning support tools may serve as an input for an airport surface traffic simulator.

As was discussed in chapter two, different sorts of simulation tools for airport surface traffic are possible (TRS, real-time, fast-time). The movement models for airport surface traffic developed during a previous thesis assignment [13] could in principle be used for the generation of synthetic autonomous aircraft within each of these simulators. However, it is important to realize that each of these simulators bring about different requirements. A prototype fast-time simulator, named SIMAST, has been developed at the TUD/FAE [14]. The development of SIMAST was aimed at creating a fast-time simulation package for the evaluation and testing of various tools developed in the framework of the joint NLR/DUT A-SMGCS research project.

In its present state of development, SIMAST is better equipped to be further developed to facilitate the testing of A-SMGCS functions, such as the planning tools [20, 27], rather than to serve as a synthetic traffic generator for a tower visual simulator. This is for two reasons:

- SIMAST is configured as a fast-time batch simulator. All aircraft are processed according to their predefined flight/taxi plans. When separation conflicts arise, these are automatically detected and resolved. In other words, SIMAST operates autonomously, essentially responding on the basis of the "see-and-avoid principle". For the tower visual simulation function it is required that SIMAST can be operated in a real-time mode, with the human-in-the-loop (i.e., controllers and pilots) providing and/or executing taxiing directives;
- SIMAST has a limited graphical (animation) capability. Although a very useful prototype traffic display has been developed for SIMAST, which can potentially serve as a basis for future (moving) map displays in the tower and/or cockpit, the overall required graphical capabilities go well beyond this particular device.
The testing and evaluation of the taxi-planning support and various other tools do not call for the need of a human operator to be included in the simulation. Therefore, SIMAST does not have to be configured as a real-time simulator. In view of these considerations it has been chosen to pursue the further development of SIMAST as a fast-time simulator aimed at the evaluation and testing of various tools developed in the framework of the joint NLR/DUT ASSMGCS research activities. Due to the limited timespan of the present thesis assignment, an intermediate goal is to develop SIMAST as a testbed for the off-line and on-line taxi-planning functions developed in the framework of other thesis assignments.

To support the development of SIMAST, a similar simulation package, named SIMMOD (developed by the Federal Aviation Administration, FAA), was recently acquired by the TUD/FAE. The suggestion is to use SIMMOD as a reference tool, in the sense that SIMAST should eventually be equipped with at least the same capabilities as SIMMOD.
5 Shortcomings of The Present SIMAST Version (1.0)

In its current state of development, SIMAST can only handle very simple airfields and traffic situations and it is not suited for evaluation and testing of various tools developed for an A-SMGCS. The several movement models (kinematic, geographic airport, control), which make up SIMAST need work in order to be able to do so and simulate airport surface traffic more realistically.

5.1 The Geographic Airport Model

The airport is modelled as a series of nodes representing the centrelines of both taxiway and runway intersections, connected by links or path segments (figure 3.5). Runways and taxiways can be designated as a series of links.

At present, SIMAST can only handle single runway airports. For single runway airports the taxiway system is usually situated between the apron area and the runway, thus cancelling the need for runway crossings. Another implication of a single runway airport is that the traffic flows of departures and arrivals are almost automatically separated. Due to this effect SIMAST 1.0 cannot handle intersections of these traffic flows. This greatly limits the use of the simulator since most busy airports have multiple runways, taxiroutes and traffic flow intersections.

Two common features that almost all airports have but the airport model does not are taxiway turns and high-speed exits. High-speed exits are very useful for quickly vacating the runway and thus increasing its capacity. Taxiway turns have a negative effect on the capacity of the taxiway system since aircraft will traverse these at a lower speed (depending on the radius of curvature) than straight taxiways. In order to be able to realistically simulate airport surface traffic, both high-speed exits and turns will have to be included in the airport model.

Standard Instrument Departures (SID's) are not incorporated in the airport model. In reality departing flights usually follow one of several predefined SID's upon leaving an airport. Which SID is used, depends on the current runway configuration and the destination of the flight. If two departures from the same runway use different diverging SID's, the trailing aircraft might takeoff sooner than otherwise would be the case due to separation considerations. Therefore the use of SID's can increase the capacity of the runway, resulting in shorter departure queues.

5.2 The Kinematic Model

The kinematic model contains the various models for the different movement phases of vehicles on the airport surface (fig 3.2) [13, 17]. Only movement models for the different movement phases of aircraft on the airport surface have been developed. All vehicles other than aircraft (helicopters, ground vehicles) and movements around the airport (fly by, missed approach) are not considered. Simulation of the airport surface traffic is restricted to the runway and taxiway system. Movements on the apron area are not yet considered due to the lack of accurate input data and the "erratic" behaviour of the traffic on the apron area. This cancels the need for the push-back and start-up modules in the kinematic aircraft model. The movement model for taxiway turns has not been implemented in SIMAST.
The acceleration and deceleration of aircraft on the taxiway system are calculated using a number of basic aircraft parameters (thrust, weight and runway friction). Inspection showed that this led to inaccurate numbers (values of up to $\pm 8.0$ m/s$^2$) and thus inaccurate behaviour of the aircraft during acceleration and braking on the taxiway system. More detailed information will have to be gathered to obtain a realistic value for these parameters.

The average taxiing speeds and the corresponding standard deviation are the same for all airport surface links and aircraft types. This is not very realistic. High-speed exits for instance can be traversed at up to 60 knots, which is not common practice for most of the taxiway system. More detailed information has to be collected yet.

5.3 The Control Model
The control model controls the behaviour of the aircraft on the airport surface. The various control functions incorporated in the originally designed model [14] are shown in figure 3.6. Their shortcomings will be discussed in the following paragraphs.

5.3.1 Conflict Prediction and Resolution
On the taxiway system, the taxiways are used for one-way traffic only. Using taxiways for 2-way traffic could have a positive effect on the capacity of the taxiway system. Before considering this course of action, the support of a reliable taxi-planning tool is needed to ensure the overall safety of aircraft and other vehicles on the taxiway system.

In its present state of development SIMAST can only handle single runway airports. Only longitudinal separation between flights on the taxiway system is considered. Since there usually are no taxiway or runway crossings at a single runway airport there was no need to consider lateral separation and runway incursions. This greatly limits the use of the simulator.

If a conflict is detected, it is resolved by decelerating/stopping the trailing aircraft until the separation criterion is no longer violated. Conflict resolution by re-routing flights is not considered, because it is usually not an option on single runway airports. Re-routing flights to resolve or prevent conflict situations could however have a positive effect on the capacity of the taxiway system.

5.3.2 Sequencing of Arrivals and Departures
Inbound traffic is assumed to be sequenced and scheduled before entering the simulation. The module for sequencing arrivals has therefore not been developed. No check is performed to see whether or not the runway is clear for landing. Departing flights will try to fit in the slots between arrivals on runways operated in mixed mode. Departures are sequenced on a first come first serve basis. The departure which reaches the runway first will be the first to receive takeoff clearance.

5.3.3 Traffic Generator
A module for traffic generation has not been constructed yet. All traffic has to be defined before the simulation starts. In its current state of development this is not a problem. However, for the envisioned concept of SIMAST as a testbed for new A-SMGCS tools, a traffic generator could be very useful. For the function as a testbed for the taxi-planning support tool a traffic generator is not needed. The off-line planning tool will provide input for SIMAST.
consisting of the traffic present in the simulation and the routes to be followed by the flights.

5.3.4 Exit Assignment
All flights within the simulation have a predefined taxiplan. This taxiplan defines the route to be followed from the runway threshold (aircraft is still airborne) up to the apron entry and vice versa for departures. In doing so there is no need for an exit assignment module in the simulation. For future use as an evaluation tool for A-SMGCS features an exit assignment module in coalition with a traffic generation module could be useful. For the time being both modules won’t be necessary. A check is performed to see whether the distance between the touchdown point and the runway exit is enough to provide for braking up to the desired exit-speed.

5.3.5 Taxiroute Generator
A taxiroute generating module is not present. All possible taxiroutes have to be defined within the airport model and all flights have to have a taxi route assigned to them at the start of the simulation. For the envisioned concept of a simulator as a testbed for new A-SMGCS tools, a taxiroute generator could prove to be beneficial. However work is in progress on both an offline and an on-line taxi-planning tool. The off-line planning tool will generate an inputfile for SIMAST whilst the on-line planning tool can serve as a plug-in to SIMAST, dealing with the re-routing of flights. These two planning tools may serve as the taxi-route generator.

5.4 Graphical capabilities
Simast’s graphical capabilities are rather limited (fig 5.1). The maximum resolution is 640x480 pixels. Furthermore, no zooming function is provided, which can be a real hindrance if a large airport has to be displayed on a small monitor. During the simulation, relevant information about the aircraft present on the simulated airport is presented on the screen. When a lot of aircraft are simulated, not all of the pertaining information can be displayed due to lack of enough space to do so. An option to scroll through the flight information or flip through various pages is not present.

5.5 Simulation Output Parameters
After a simulation run, an outputfile is created with information about the various aircraft present in the simulation. Table 5.1 is a sample of such an outputfile. The data present in the output is not very structured, nor suited for the evaluation of the simulation run. Dependent on the application of future versions of SIMAST, the data to be saved needs to be specified.

<table>
<thead>
<tr>
<th>Callsign</th>
<th>A/D</th>
<th>type</th>
<th>route</th>
<th>t_{min} (s)</th>
<th>ETA/ETD</th>
<th>t_{start} (s)</th>
<th>W (kg)</th>
<th>S_{c}/S_{c,ref}</th>
<th>ROT (s)</th>
<th>t_{c} (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL123</td>
<td>A</td>
<td>3</td>
<td>3</td>
<td>30</td>
<td>30</td>
<td>-</td>
<td>33614</td>
<td>1483</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>NW456</td>
<td>D</td>
<td>4</td>
<td>9</td>
<td>34</td>
<td>195</td>
<td>276</td>
<td>51438</td>
<td>978</td>
<td>28</td>
<td>241</td>
</tr>
<tr>
<td>BA789</td>
<td>D</td>
<td>10</td>
<td>10</td>
<td>11</td>
<td>190</td>
<td>209</td>
<td>52305</td>
<td>1088</td>
<td>32</td>
<td>195</td>
</tr>
<tr>
<td>IB312</td>
<td>D</td>
<td>7</td>
<td>9</td>
<td>89</td>
<td>250</td>
<td>344</td>
<td>87688</td>
<td>1092</td>
<td>27</td>
<td>253</td>
</tr>
<tr>
<td>PA456</td>
<td>A</td>
<td>4</td>
<td>150</td>
<td>150</td>
<td>-</td>
<td>126246</td>
<td>1974</td>
<td>52</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

39
figure 5.1 A screen dump of a SIMAST (version 1.0) simulation run
6 Available Commercial Entire Airfield Simulators

Before continuing the further development of SIMAST it is wise to check whether there are any commercial airfield simulators available on the market, suited for the evaluation and testing of various tools that will be developed in view of A-SMGCS research.

6.1 The FAA's Airport and Airspace Simulation Model SIMMOD

The TUD/FAE acquired the PC-version of SIMMOD release 1.2 as a reference tool, with respect to the simulation of airport operations, for the development of its own prototype airport surface traffic simulation tool SIMAST. The acquired version of SIMMOD is not as comprehensive as the more widely used workstation versions which the TUD/FAE cannot afford. The following is a short description of the SIMMOD airport and airspace simulation tool, used during the course of this thesis assignment.

SIMMOD, the FAA airport and airspace simulation model is a comprehensive planning tool for airport designers and managers, air-traffic planners, and airlines. Analysts use SIMMOD to study and improve en route and terminal-area air traffic, as well as airport and airline ground operations. SIMMOD addresses both the design and procedural aspects of all air traffic operations, and produces measures of airport capacity and aircraft travel time, delay, and fuel consumption [3].

SIMMOD's modeling and simulation capabilities provide answers to "What if..." questions at every level of air traffic operations, from major air route networks, including the interactions of airports sharing common airspace, to individual terminal gate operations. SIMMOD simulates the movement of all aircraft, step by step, resolving conflicts and keeping track of the time and fuel consumed along each flight and taxi segment. Users can import CAD layouts of existing airport/airspace features, input existing layout using a digitizer or build their own using SIMMOD's Network Builder. The airport/airspace is build up of nodes, connected by links. Simulation results can be viewed in an animated display of the network, or in detailed graph and tabular data reports.

Once a standard scenario has been developed (based on data from existing or proposed operations), users can change the input to develop and evaluate new alternatives. Because SIMMOD is "data-driven", such changes do not require programming. Procedures, schedules, and physical layouts can be modeled and remodeled to evaluate many combinations of options.

Since SIMMOD's inception, the FAA has developed logic modules that cover a wide variety of airport and airspace design and management issues. The following is a partial list of SIMMOD's feature set, with respect to airport operations:
- gate-taxiway-runway management;
- traffic demands and fleet mix;
- air carrier scheduling;
- hub and spoke operations;
- air traffic control separation rules;
- controller decision logic;
- airport expansion;
- support for input from the AEE's Integrated Noise Model, for noise calculations;
- de-icing logic;
- slot window logic;
- runway crossing logic;
- single direction path;
- complex runway dependencies are catered for;
- several reports for analysis of the simulation.

Both PC and workstation versions of SIMMOD provides utilities to help users build data sets. SIMMOD offers several options for displaying results. For each simulation, SIMMOD's animated graphics show all aircraft moving through the modeled airport and/or airspace. Detailed airport maps typically include runways, taxiways, individual gates, and surrounding aprons. This infinitely scalable, two-dimensional graphic display presents the results of the simulation in a readily comprehensible format that facilitates the analytical process. In addition to animated displays, SIMMOD produces printed reports and graphics. These reports provide statistics on airport capacity, delay, and fuel consumption.

As can be seen from the text above, SIMMOD is a very extensive simulation tool. The model does not only incorporate airport surface traffic, but also the complete airspace. The extensiveness of SIMMOD is also one of its disadvantages. The costs of learning how to operate SIMMOD are high. Every new application takes a lot of time and expertise to implement. Other disadvantages of SIMMOD are:
- the source code of the simulation package is not available. This means that one will not be able to tailor the simulator to one's wishes. This is not acceptable if one intends to use the simulator as an evaluation tool for A-SMGS functions which still have to be developed;
- SIMMOD is not suited to cooperate with the taxi-planning support tools in development at the TUD/FAE;
- the kinematic model of the aircraft is rather simple. Speeds of the aircraft change abruptly (from 136 knots to 15 knots, within the blink of an eye) at the nodes. The movement of the aircraft along the links is strictly linear and uniform. Taxiway turns and the effect of these on the taxiing speed of the aircraft are not taken into account;
- the PC-version owned by the TUD/FAE offers only poor graphical capabilities.

6.2 The Total Airspace and Airport Modeler TAAM
TAAM is a workstation based computer program for the fast or real-time simulation of airspace and airport operations. It can be used to assist with the design of airspace and airport systems and facilities as well as operational planning activities of airlines. TAAM provides a detailed simulation of aircraft movements visualized through a multicolor three-dimensional display. Subsequent analysis of the simulation can take place using the numerical data generated during simulation and the standard reports. Just as SIMMOD, TAAM is a what-if tool, highlighting problem areas such as air traffic system bottle necks. However, TAAM is even more sophisticated than SIMMOD and thus shares a common disadvantage with SIMMOD. Learning and training costs are very high and the implementation of a new application takes a lot of time and expertise. Other disadvantages of TAAM are:
- the source code of the simulation package is not available. This means that one will not be able to tailor the simulator to one's wishes. This is not acceptable if one intends to use the simulator as an evaluation tool for A-SMGS functions which still have to be developed;
TAAM is not suited to cooperate with the taxi-planning support tools in development at the TUD/FAE;

the significant license fee. The TUD/FAE simply cannot afford TAAM.

6.3 Other Entire Airfield Simulators
Besides the already mentioned SIMMOD and TAAM simulation packages, other entire airfield simulators have been/are being developed. HERMES and The Airport Machine are examples of such simulators. HERMES is still under development and cannot yet be considered as a realistic option for the evaluation and testing of A-SMGCS tools. Very little information has been found about The Airport Machine. However, it is safe to say that this simulator will not be able to cooperate with the taxi-planning support tools in development. The license fee ($50,000) is also a major consideration. As usual the source code is not available to the user.

6.4 Conclusion
The question posed at the start of this chapter was whether it would be worth the time and energy to continue the development of the airport surface traffic simulation tool SIMAST. The previous paragraphs showed that on top of the significant license fees involved, other airport simulation tools available on the market are not suited for use as an evaluation tool for newly developed A-SMGCS tools. This provides enough motivation to continue the development of SIMAST as a fast-time simulator for the testing and evaluation of new A-SMGCS features and the mentioned taxi-planning support tools especially.
7 User Requirements

The simulator SIMAST is intended to be used as an evaluation tool for future A-SMGCS tools. Therefore, the user requirements of the simulator can be formulated by considering the operational requirements of A-SMGCS.

7.1 Requirements for A-SMGCS
A-SMGCS is a Air Traffic Management (ATM) system. Just like other ATM systems, the main goals of A-SMGCS are to ensure the safety of airport surface traffic under all weather conditions (this includes conditions under which the pilot or vehicle driver would not be able to taxi by visual reference) and to improve efficiency of airport operations in order to increase the traffic throughput of the airport. In specific, the goals for an A-SMGCS are [2]:

- an increase of airport throughput in general, while maintaining at least the present level of safety;
- eliminate the reduction in airport throughput due to influences of the weather;
- improvement of efficiency by optimum exploitation of available airport capacity;
- reduction of the controller workload;
- reduction of taxi times and prevention of delays during taxiing;
- reduction of environmental burden.

With these goals in mind, four functions can be distinguished within an A-SMGCS [2]:

- Planning or routing, the planning and assignment of routes to individual aircraft and vehicles to provide safe, expeditious and efficient movement on the aerodrome;
- Surveillance, this function provides accurate positional information and identification on all aircraft and vehicles which make up the actual traffic situation;
- Monitoring or control, takes care of the prevention of collisions on the taxiway system and unauthorised or inadvertent entry of operational runways;
- Guidance, this function provides pilots of aircraft and drivers of vehicles with information to keep their aircraft or vehicle on the assigned routes.

Another requirement for an A-SMGCS is that the system should be modular in design, so that it is adaptable to any airport surface and any traffic situation.

7.2 Simulator Requirements
In compliance with what has been stated in the previous paragraph, the user requirements of the simulator to be developed can be formulated as follows:

- the simulator should provide the same four basic functions as a real A-SMGCS (surveillance, routing, control and guidance);
- the simulator will have to be modular in design so that it can be adapted to any airport structure, traffic situation and new A-SMGCS features to be developed;
- the simulator should provide the usual airport operations, such as air carrier scheduling and hub–spoke operations
- all possible aircraft and vehicle movements around and on the airport surface have to be accounted for;
- for the purpose of planning, the models developed for the movement of aircraft and vehicles will have to allow for trajectory prediction;
the simulation of movements on and around the airport need to be realistic. This requires that the movement models include a realistic spread in performance characteristics depending for example on aircraft type, airline operations and weather conditions;

- due to the fast-time nature of the simulation, the movement models need to be efficient;

- the simulator will need to generate output, enabling the analysis and evaluation of the simulated A-SMGCS.

These user requirements reflect the ultimate goal for SIMAST to be used as an evaluation and testing tool for various A-SMGCS tools developed in the framework of the joint NLR-DUT/FAE A-SMGCS research activities. However, due to the limited timespan of the present thesis assignment, it is not possible to implement all these features in SIMAST.

An intermediate goal is to develop SIMAST as a testbed for the off-line taxi-planning support tool under development at the DUT/FAE [27]. The purpose of this tool is to optimize the sequencing and scheduling of traffic, such as to minimize delays and to reduce the number of stops during taxiing. The planning is restricted to aircraft on the taxiway system. Movements on the apron and the movements of other types of vehicles are not considered. With this in mind, the following requirements can be formulated for the intermediate version of SIMAST:

- the simulator will have to be modular in design so that it can be adapted to any airport structure and traffic situation;

- all possible aircraft movements on the taxiway system have to be accounted for;

- for the purpose of planning, the models developed for the movement of aircraft and vehicles will have to allow for trajectory prediction;

- the simulation of movements on and around the airport need to be realistic. This requires that the movement models include a realistic spread in performance characteristics depending for example on aircraft type, airline operations and weather conditions;

- due to the fast-time nature of the simulation, the movement models need to be efficient;

- the taxi-planning support tool has to be able to interface with the simulator;

- the simulator will need to generate output, enabling the analysis and evaluation of the taxi-planning support tool during execution and after completion of a simulation run.

These user requirements define the improvements that need to be made to SIMAST:

- improve the flexibility of the SIMAST software, so that it can simulate any airport and any volume of traffic;

- improve the graphical output of SIMAST to supply the user with a good overview of the simulation run;

- upgrade the geographic airport model so that it can be used to represent any airport;

- expand the kinematic model to include models for the movement phases for high-speed exits and taxiway turns;

- adapt the control model to enable it to control traffic on a complex multiple runway airport with taxiway/taxiway and taxiway/runway crossings;

- devise an interface with the taxi-planning support tool;

- adapt the movement models to include a realistic spread in performance characteristics;

- create an output report, with which the user can analyse the completed simulation run and the taxi-planning support tool.
7.3 SIMAST Top-level Design

With the requirements in mind, a top-level design for the new version of SIMAST would be as follows:

![Diagram of SIMAST top-level design]

**Figure 7.1 SIMAST top-level design**

This top-level design is basically the same as for a real-time simulator (chapter 2). The difference is that the pilot position has been eliminated. For reasons of clarity, the supervisor position is not shown in this figure. This position should at least receive and display information about the current state of the aircraft, the current taxi plans, deviations from the taxi plans and the actions undertaken to correct these. The aircraft are directly controlled via the guidance function. The design for the control (monitoring), surveillance and guidance functions do not need to be changed with respect to the design proposed in chapter two. However, due to the removal of the pilot position, the kinematic model design will have to be changed into the following:

![Diagram of the kinematic model]

**Figure 7.2 The kinematic model**

For the time being, the surveillance function and datalink will not be implemented. The kinematic model will directly provide the new state of the aircraft. In the future, the routing function will be performed by the on-line taxi-planning support tool [20]. For now, the taxi plans will be generated either manually or with the off-line taxi-planning support tool under
development [27]. The taxiplans will not be updated during simulation. This will be the task of the on-line planning tool.

The design also shows the three models which have been incorporated in SIMAST. The airport layout is synonymous to the geographic airport model and the kinematic model is obvious. The control and guidance functions will be incorporated in the control model. This results in figure 7.3.

![Diagram](image)

**figure 7.3**

The following chapters deal with the improvements to the airport surface traffic simulator SIMAST. Chapter eight describes the basic changes made to SIMAST’s software and the implemented improvements to the graphics produced by SIMAST. The improvements to the geographic airport model are covered in chapter nine, whilst chapter ten deals with the improvements made to SIMAST’s kinematic model. How the control model has been adjusted to enable it to control the traffic on more complex airports, than the original single runway airport is discussed in chapter eleven. The interface with the off-line taxi-planning support tool and how to get the aircraft to follow their assigned taxiplan will be introduced in chapter twelve. In order to simulate a realistic spread in aircraft performance, monte carlo sampling may be used. How to use this technique will be explained in chapter thirteen. The output parameters, which are available to analyse the performance of the off-line taxi-planning support tool and the simulation run are introduced in the fourteenth chapter.
8 Changes in SIMAST's Software and Graphics

Next to all the necessary changes in the movement models of SIMAST, changes were also made to the software of SIMAST to enhance flexibility. The graphics have also been improved, to provide the user with a better overview of the simulation.

8.1 Software Changes
Before starting to work on the further development of SIMAST, the software of the simulator itself was reconstructed to provide more flexibility and easier implementation of new features and improvements. Several bugs were removed in the process. SIMAST had a fixed limit for the number of flights, airport nodes, airport links, etc. it could handle. By applying dynamic memory allocation, SIMAST is now versatile enough to cope with any number of flights and any airport, dependent upon the available computer memory. This has significantly increased the flexibility of the simulator.

Data management has been improved by grouping related variables together. This object oriented like approach enables to show the correlation between variables. For example, all variables with respect to the airport are put in a variables group named "airport". This structure itself is subdivided into several other structures with respect to the nodes, links, runways, etc. (fig 8.1). Representing the variables in this way improves the readability of the code, making it easier to keep track of the variables. Implementation of improvements and new features is simplified in this way.

After reconstruction, the operation of SIMAST was verified to ensure that the simulation had not been affected by all the architectural changes in the software.

8.2 Graphics Improvements
During simulation, the airport and all the aircraft present in the situation can be presented on the screen (fig 8.2). The screen has been divided in two, the bottom part presents the flight information, while the upper part animates the movement of the aircraft on the airport surface. The total airport has to be represented on a rather small area. This makes it difficult to see details of the simulation animation. To overcome this problem, a zooming option has been added to zoom in on specific areas of the airport surface, enhancing the detail of the animation. When conflicts occur, the aircraft receiving orders to halt until the conflict is resolved, are shown in red for easy identification of problems.

The flight information presented on the bottom part of the screen has been divided in flight information of arrivals and departures. The information offered here comprises of the following parameters: callsign of the flight, aircraft type, ETA or ETD and the state of the aircraft. The state of the aircraft reflects the movement phase the aircraft is currently in (e.g. deceleration, taxiing, takeoff, landing,...). Since usually not all the information can be presented on one screen, the option exists to flip through various pages with flight information. When an aircraft has completed its flightplan, the information relating to that particular flight is removed from the screen.
Figure 8.1 Variable relationships for the airport model
figure 8.2 A sample of SIMAST's new graphics screen.
9 The Geographic Airport Model

The original geographic airport model [13], models the airport as a series of nodes, joined by links. The nodes represent the intersections of the taxiway and runway centerlines, gates and holding area's. The links connecting the nodes represent path segments. By modeling the airport like this, the runway and the taxiways can be defined by a series of connecting links. However, the present airport model can only handle single runway airports, because it makes no distinction between different runways and it lacks high-speed exits and taxiway turns. As a matter of fact there isn't made any distinction whatsoever between different sorts of links such as straight taxiway, high-speed exit and runway. In the first four paragraphs of this chapter, these problems will be tackled.

The original version of SIMAST (1.0) uses a model of Rotterdam Airport. This is a single runway airport (fig 3.5). Since SIMAST will be developed into a simulator which can also cope with multiple runway airports, another airport with more than 1 runway needs to be modelled. The last paragraph of this chapter deals with the implementation of a new geographic airport model for Amsterdam Airport.

9.1 Airport Surface Links

Originally the path segments on the airport surface or links were modelled as a simple connection between two nodes. No distinction between the various types of links with their specific characteristics (e.g. maximum speed) could be made. To differentiate between the different types of links, a type identifier is added to the links. For the time being, three different types of links will be used:
- RWY for runway segments;
- TXI for the normal taxiways;
- HSX for high-speed exits.

This can easily be expanded, but for now these three types will do. Taxiway turns are not actually present in the airport model, but will be emulated. This is explained in paragraph 9.4.

The model for the links has also been expanded with a number of link specific parameters. These parameters are:
- length of the link;
- orientation of the link or heading;
- maximum speed limit.

Links now contain the following information (fig 8.1):
- startnode;
- endnode;
- type (RWY, TXI or HSX);
- length;
- heading;
- maximum speed limit.
9.2 Multiple Runways
Runways are commonly identified by their heading and, if there are 2 parallel runways, a L or R extra to identify the left or right runway. This same kind of identification can be used for SIMAST to differentiate between runways. The modelled runways thus consist of a number of connected links, forming the runway, and an identification. The links which make up the runway are given the type identification RWX, so it is clear that they are part of a runway. The runway identification can also be used in the flight plans. It is now possible to identify the runway an aircraft is occupying or crossing at a given moment. If necessary, use of the same runway can be denied to other flights.

9.3 High-speed Exits
The model for a high-speed exit does not differ from the previously expanded model for normal taxiways. The high-speed exit consists of just one link. This link can be identified as being a high-speed exit by the type identification HSX. Arriving aircraft will enter these high-speed exits at the approximate maximum speed for the exit used. Upon entering the high-speed exit the aircraft will start to decelerate up to the desired taxi speed.

9.4 Taxiway Turns
The idea was to model taxiway turns as a series of short links with slight increments in heading and a low maximum speed to allow for the slower speeds at which aircraft travel through a turn compared to straight taxiways. However short links proved to create problems for the offline planning support tool and a different approach was chosen.

The nodes defined in the airport model (fig. 8.1) are modified to include information with respect to the radius of curvature present at that location. The information available for each node is now:

- x-position;
- y-position;
- radius of curvature.

The begin and endpoint of a turn can than be calculated with the known radius of curvature and the begin and endpoint of the links considered (fig 9.1). This is all done automatically during program execution [11]. The aircraft will however not really make a turn. The aircraft continues along the straight taxiway link, defined by the nodes. The turns are emulated by adjusting the speed of the aircraft in accordance with the defined radius at a node. The maximum speed at which aircraft can travel through a taxiway turn is dependent upon the radius of curvature (table 9.1).
figure 9.1 Start and endpoint of taxiway turns

<table>
<thead>
<tr>
<th>Radius of curve (m)</th>
<th>Taxiing speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>60</td>
<td>32</td>
</tr>
<tr>
<td>135</td>
<td>48</td>
</tr>
<tr>
<td>240</td>
<td>64</td>
</tr>
<tr>
<td>375</td>
<td>80</td>
</tr>
<tr>
<td>540</td>
<td>96</td>
</tr>
</tbody>
</table>

9.5 A Model for Amsterdam Airport

The airport used by the simulator can easily be changed. Due to its generic design, SIMAST is completely data driven with respect to the airport. The input data defines the airport for which operations will be simulated. The new geographic airport model discussed above will now be applied to another airport than the single runway airport that was used for SIMAST 1.0.

The model to be used for the further development of SIMAST, will be a model of Amsterdam Airport in The Netherlands. A model of this airport has been obtained from the NLR with permission of the Luchtverkeers Beveiliging (LVB, the Dutch ATC authority). The model is not up to date. Since it was constructed, a number of new exits and some new taxiways have been created at the real airport. The model obtained from the NLR was meant for use with
SIMMOD, another airport simulator (section 6.1). This SIMMOD model for Amsterdam Airport specifies the coordinates of the nodes and information about the connecting links. With some modifications and conversion from longitude and latitude to Cartesian coordinates, the model may now be used by SIMAST. The conversion is not an integral part of SIMAST 2.0. The conversion will have to be performed separately.

Some of the missing exits in the SIMMOD model of Amsterdam Airport, which have been realized on the actual airport, have been added as well. The used model is not completely in accordance with the actual airport. For instance, runway 04/22 is present, but cannot be used. There are no taxiways leading to this part of the airport. For the purpose of validating the simulation concept, these slight shortcomings are not deemed relevant. The resulting airport model is shown in figure 9.1.

figure 9.1 Model for Amsterdam Airport
10 The Kinematic Model

The kinematic model is of a modular design, such that it cannot only be used by aircraft, but can also be used to simulate the movement of ground based vehicles such as fuel trucks and follow-me cars. The behaviour of the vehicles and aircraft is dictated by the control variables, which depend upon the movement phase, the vehicle model, the piloting technique (characteristics of the vehicle driver) and meteo data. The movement phase of the vehicle is dictated by the control model, which will be discussed in the next chapter. The implemented kinematic model is shown in figure 10.1. The different components of the kinematic model are discussed in the following paragraphs.

figure 10.1 The kinematic model

10.1 The Vehicle model

For the time being there is only one type of vehicle present in the simulation, namely aircraft. Other vehicles are not simulated. The aircraft model describes aircraft type specific parameters, which are used to determine the control variables. An example of different aircraft types and their specific parameters are shown in table 10.1.

The aircraft model can easily be expanded with more aircraft types. The aircraft types and their specific parameters are described in an inputfile, which is read at the start of the simulation. Adding aircraft types to this inputfile automatically adds them to the vehicle model. SIMAST is data driven in this aspect.
<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Engine Type</th>
<th>T0 (lb)</th>
<th>B</th>
<th>OEW (kg)</th>
<th>MLW (kg)</th>
<th>MTOW (kg)</th>
<th>A</th>
<th>S (m2)</th>
<th>Lr (m)</th>
<th>StO (m)</th>
<th>Stp (psi)</th>
<th>Cl Start</th>
<th>Cl Land</th>
<th>a accel (m/s²)</th>
<th>a decel (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-300-600</td>
<td>CF6-80C2A3</td>
<td>2</td>
<td>60200</td>
<td>5</td>
<td>90339</td>
<td>140000</td>
<td>170500</td>
<td>8</td>
<td>260</td>
<td>1555</td>
<td>2290</td>
<td>180</td>
<td>2.58</td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td>A-310-300</td>
<td>CF6-80C2A2</td>
<td>2</td>
<td>53500</td>
<td>5</td>
<td>80344</td>
<td>123000</td>
<td>150000</td>
<td>9</td>
<td>219</td>
<td>1479</td>
<td>2408</td>
<td>217</td>
<td>2.81</td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td>A-320-200</td>
<td>V2527-A5</td>
<td>2</td>
<td>26500</td>
<td>5</td>
<td>41782</td>
<td>64500</td>
<td>73500</td>
<td>9</td>
<td>122</td>
<td>1540</td>
<td>2336</td>
<td>163</td>
<td>2.29</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Fokker100</td>
<td>Tay650-15</td>
<td>2</td>
<td>15100</td>
<td>3</td>
<td>24375</td>
<td>39915</td>
<td>43090</td>
<td>8</td>
<td>93.5</td>
<td>1360</td>
<td>1840</td>
<td>124</td>
<td>2.01</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>B-737-300</td>
<td>CFM56-3C1</td>
<td>2</td>
<td>22500</td>
<td>5</td>
<td>31895</td>
<td>51719</td>
<td>56472</td>
<td>8</td>
<td>105</td>
<td>1393</td>
<td>2027</td>
<td>200</td>
<td>2.38</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>B-737-400</td>
<td>CFM56-3C1</td>
<td>2</td>
<td>22500</td>
<td>5</td>
<td>33434</td>
<td>54885</td>
<td>62822</td>
<td>8</td>
<td>105</td>
<td>1497</td>
<td>2315</td>
<td>210</td>
<td>2.37</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>B-747-400</td>
<td>CF6-80C2B1</td>
<td>4</td>
<td>57900</td>
<td>5</td>
<td>181529</td>
<td>285765</td>
<td>385555</td>
<td>8</td>
<td>511</td>
<td>2134</td>
<td>3337</td>
<td>206</td>
<td>2.33</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>B-757-200</td>
<td>RR211-535E4</td>
<td>2</td>
<td>43100</td>
<td>4</td>
<td>57039</td>
<td>89810</td>
<td>104325</td>
<td>8</td>
<td>185</td>
<td>1460</td>
<td>1714</td>
<td>171</td>
<td>1.93</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>B-767-200</td>
<td>CF6-80A2</td>
<td>2</td>
<td>50000</td>
<td>5</td>
<td>83733</td>
<td>129273</td>
<td>175540</td>
<td>8</td>
<td>283</td>
<td>1650</td>
<td>2774</td>
<td>191</td>
<td>2.08</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>MD-83</td>
<td>JT8D-219</td>
<td>2</td>
<td>17100</td>
<td>2</td>
<td>36145</td>
<td>63276</td>
<td>72575</td>
<td>9</td>
<td>118</td>
<td>1585</td>
<td>2552</td>
<td>170</td>
<td>2.33</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>MD-87</td>
<td>JT8D-217C</td>
<td>2</td>
<td>20000</td>
<td>2</td>
<td>33237</td>
<td>58060</td>
<td>63503</td>
<td>9</td>
<td>118</td>
<td>1429</td>
<td>1859</td>
<td>175</td>
<td>2.3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>DC-10-30</td>
<td>CF6-50C2</td>
<td>2</td>
<td>52500</td>
<td>6</td>
<td>121198</td>
<td>182798</td>
<td>261268</td>
<td>7</td>
<td>368</td>
<td>1630</td>
<td>3170</td>
<td>180</td>
<td>2.02</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>MD-11</td>
<td>CF6-80C2D1</td>
<td>3</td>
<td>61500</td>
<td>5</td>
<td>131035</td>
<td>195040</td>
<td>273289</td>
<td>8</td>
<td>339</td>
<td>2130</td>
<td>3200</td>
<td>200</td>
<td>2.16</td>
<td>3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

### 10.2 The Kinematic Module

The kinematic model originally developed for SIMAST (version 1.0) [13, 14] considers different movement phases of the aircraft. The possible movement phases considered are:

- For departing aircraft:
  - taxiing to the departure runway and takeoff;
- For arriving aircraft:
  - landing and taxiing to the apron or gate area.

The taxiing movements on the airport themselves are subdivided in accelerating, decelerating, turning, holding and taxiing at a constant speed. The taxi phase is now defined as the movement along a straight taxiway, with a constant speed. Due to lack of information about aircraft movements on the apron area, the start-up and push-back phases have not been implemented in the simulation. The movement phases implemented in the kinematic model (SIMAST 2.0) for aircraft movements and their relationship are given in figure 10.2. Ground based vehicles, such as follow-me cars, fuel trucks and baggage carts, go through the same movement phases (accept for the takeoff and landing phases) as aircraft would while moving over the airport surface.
The position of the vehicles on the airport surface is determined by use of the following equations of motion:

\[
x(t + \Delta t) = x(t) + V(t) \sin(\chi) \Delta t + \frac{1}{2} \alpha(t) \sin(\chi) \Delta t^2
\]

\[
y(t + \Delta t) = y(t) + V(t) \cos(\chi) \Delta t + \frac{1}{2} \alpha(t) \cos(\chi) \Delta t^2
\]

\[
V(t + \Delta t) = V(t) + \alpha(t) \Delta t
\]

(10.1)

The heading of the vehicle is dictated by the link it is currently travelling on. The speed follows from the old state of the vehicle. The acceleration of the vehicle, which is the control variable, is dependent upon the vehicle model and the current movement phase.
Most of the movement phases described in figure 10.2 were already present in the original version of SIMAST (1.0). However, the acceleration and deceleration during taxiing on the taxiway were not accurately modelled and the turn movement wasn't present at all.

10.2.1 The Deceleration Phase
During ground movements, the equation of motion of an aircraft reads:

$$\frac{W}{g} \frac{dV}{dt} = T - D - D_g$$

(10.2)

where

- $D$: aerodynamic drag (N)
- $D_g$: drag due to friction between the tires and the aircraft (N)
- $g$: acceleration of gravity (m/s²)
- $dV/dt$: acceleration of the aircraft (m/s²)
- $T$: aircraft thrust (N)
- $W$: aircraft weight (N)

The aerodynamic forces acting on the aircraft may be neglected at the relatively low taxi speeds. The rate of deceleration then becomes:

$$a = g \left( \frac{T}{W} - \mu \right)$$

(10.3)

where

- $\mu$: the sum of rolling and braking coefficients of friction.

However, the applied thrust setting is not known. In SIMAST 1.0 the thrust was set to exactly match the rolling friction of the aircraft. Another approach would be to set the thrust to idle, which is usually done by pilots:

$$\frac{T_{idle}}{W} = \mu_{roll}$$

(10.4)

Combination of (9.3) and (9.4) yields the rate of deceleration of an aircraft on the taxiway system during braking, assuming the rolling friction coefficient $\mu$, to be a constant:

$$a = g \left( \frac{T_{idle}}{W} - \mu \right)$$

(10.5)

Inspection of the rate of deceleration following from (9.5), showed that the assumption of $\mu$ being a constant is rather inaccurate. Rates of deceleration of up to 7 m/s² are no exception. Better results might be achieved by use of a more sophisticated aircraft model, where $\mu$ is no longer constant, but a function of the aircraft's speed, tire pressure and surface conditions and material. This would impose a more extensive and complex set of input data. It has therefore been chosen not to calculate the rate of deceleration, but rather to include these in the set of input data for each type of aircraft. The rates of deceleration which are used in the simulation
are listed in table 10.1 for the different aircraft types. The values can easily be changed in the input data file.

10.2.2 The Acceleration Phase
Equation (7.3) is also valid for an accelerating aircraft on the taxiway system. However, $\mu$ is now equal to the rolling friction coefficient. Again, the thrust setting is not known. This problem is solved in the same way as for the deceleration phase. The rates of acceleration which are used in the simulation are listed in table 10.1 for the different aircraft types. The values can easily be changed in the input data file.

10.2.3 The Turn Phase
In the previous version of SIMAST (1.0), the turn phase was not modelled. Taxiway turns have an important impact on the speed of the aircraft on the taxiway system. They have a negative effect on the throughput of the taxiway system, since aircraft will have to traverse these at a lower speed than straight taxiways. Because of the impact on the taxiway system throughput and to simulate the movement of aircraft on the airport surface more realistically, the turn phase has been implemented. A constant speed will be assigned to the aircraft during the turning phase. This may not be completely in accordance with reality, but since no information is available about the behavior of aircraft in taxiway turns, the turning speed of aircraft is constant for the time being. This speed depends upon the radius of the turn (table 9.1). The aircraft will have to decelerate before entering the turn (if necessary) and will accelerate after coming out of the turn.

10.2.4 Runway Turnoffs
The turn phase can also be used for runway turnoffs, using table 9.1. Runway turnoffs were not modelled in the previous version of SIMAST (1.0). Aircraft would decelerate up to their taxiing speed on the runway before vacating the runway and entering one of the runway exits. This approach totally neglects the high speeds at which aircraft may vacate the runway by using a high-speed exit.

The function of runway turnoffs is to enable aircraft to vacate the runway. When the turnoff or exit taxiway is at an angle of about 30° with the runway, the term high-speed exit is often used. Transport and military aircraft can safely and comfortably turn off runways via a high-speed exit at speeds up to 60 Miles per hour (52 knots).

The actual turnoff curve ($R_2$, fig. 10.4) needs to be preceded by a larger radius curve ($R_1$) to provide a gradual transition from a straight tangent section to a curved path section. The length of the transition curve is denoted by $L_1$. The relation ship between $R_1$, $R_2$, $L_1$ and the exit-speed of the aircraft is displayed in figure 10.5. This is of course an approximation of what happens in reality. Since no data was available about the geometric of an actual high-speed exit, the design proposed by Horonjeff has been used [19].

It was felt that the forces acting on the aircraft, caused by the change in exit radius, might produce a significant deceleration of the aircraft. To see whether this is true, the aircraft is modelled as a mass point. The exit taxiway configuration is taken from figure 10.5 for an exit speed of 60 Miles per hour:
- $V = 60 \text{ mph} \approx 26.8 \text{ m/s}$;
- $R_1 = 960 \text{ m}$;
- $R_2 = 563 \text{ m}$;
- $L_1 = 87 \text{ m}$.

![Diagram](image_url)

**Figure 10.4 Exit configuration**

The path the aircraft follows during the turnoff can be approximated by a spiral [19]. This seems logical, since the aircraft can turn sharper as it decelerates due to friction with the runway surface. The origin of rotation is $M_2$. To provide a smooth transition from the start point of the spiral up to the endpoint, it is assumed that the radius is dependent upon the distance traveled along the transition curve, $s$:

$$R(t) = R_2 - \frac{R_0 - R_2}{L_1} s(t) \quad (10.6)$$

The value for $R_0$ can be obtained from the geometry in figure 9.4:

$$R_0 = \sqrt{\left(\frac{L_1}{R_1}\right)^2 + \left(\frac{R_1}{R_1} + \frac{R_2 - R_1}{R_1}\cos\left(\frac{L_1}{R_1}\right)\right)^2} = 565 \text{ m} \quad (10.7)$$

Apparently, the change in turning radius is very small (two meters). Therefore, the forces acting on the aircraft due to the change in radius will also be very small, and may be neglected safely, since it is already assumed that the aircraft speed will be constant in a taxiway turn.
figure 10.5 Radii of curvature and entrance curves for taxiways.

Source: Horonjeff and McKelvey [19].
11 The Control Model

The control model controls the behaviour of the aircraft on the airport surface and on final approach for runways belonging to the simulated airport. This is done by dictating the aircraft state or movement phase. The possible movement phases of the aircraft during simulation are shown in figure 10.2. The various control functions incorporated in the control model originally developed for SIMAST [14] are shown in figure 3.5. The control functions for traffic generation, exit assignment and route generation have not actually been built yet. For SIMAST to function as a testbed for the taxi-planning function, they won't be needed (chapter 4). In order for the control functions sequencing/scheduling and conflict prediction to deal with the increased complexity of the airport (multiple runways and taxiways), they will have to be improved.

11.1 The Conflict Prediction and Resolution Function

During taxi operations at an airport, conflicts may arise. The conflict prediction and resolution function detects possible conflicts. When a possible conflict is detected, the function will resolve the conflict by changing the movement phase of (one of) the aircraft involved. The different conflict situations which can arise on the taxiway system and the way they are resolved are the subject of the following paragraphs.

11.1.1 Longitudinal Separation Conflict

The longitudinal separation is defined in figure 11.1. The required longitudinal separation minima are dependent upon aircraft speeds, braking performance, size of the aircraft involved and human and system response times:

\[ S_t = S_{\text{brake}} + S_{\text{reaction}} + S_{\text{min}} + S_{\text{jet}} + S_{\text{ac}} \]  

(11.1)

with:

- \( S_{\text{brake}} \) = distance needed to decelerate the aircraft to an appropriate speed
- \( S_{\text{reaction}} \) = distance traveled during the total system reaction time of pilot, air traffic controller and radar system in use
- \( S_{\text{min}} \) = minimum distance to be maintained between two aircraft or an aircraft and another object at all times, excluding jet blast effects. A typical value is 15 m [2]
- \( S_{\text{jet}} \) = distance behind an aircraft which is to be kept clear to avoid jet blasts.
- \( S_{\text{ac}} \) = length of the aircraft. The sum of \( S_{\text{ac}} \) is typically 75 m [2]

![Longitudinal separation diagram](image)

Figure 11.1 Longitudinal separation
The longitudinal separation has to be considered in four different ways:

1. an aircraft moving towards a stationary object or a stop bar. The required separation then equals:

\[ S_t = \frac{V_b^2}{2a_b} + V_b T_s + S_{\text{min}} \]  \hspace{1cm} (11.2)

2. an aircraft moving towards a stationary aircraft. The required separation then equals:

\[ S_t = \frac{V_b^2}{2a_b} + V_b T_s + S_{\text{min}} + S_{\text{jet}} + S_{\text{ac}} \]  \hspace{1cm} (11.3)

3. two aircraft moving in the same direction, while the trailing aircraft A is overtaking the leading aircraft B \((V_a > V_b)\). The required separation then equals:

\[ S_t = \frac{V_b^2}{2a_b} - \frac{V_a}{a_b} + \frac{V_a^2}{2a_a} + V_b T_s + S_{\text{min}} + S_{\text{jet}} + S_{\text{ac}} \]  \hspace{1cm} (11.4)

4. two aircraft moving in an opposite direction. The required separation then equals:

\[ S_t = \frac{V_b^2}{2a_b} + \frac{V_a^2}{2a_a} + (V_a + V_b) T_s + S_{\text{min}} \]  \hspace{1cm} (11.5)

with:

\(a_a\) = deceleration rate of aircraft A \((\text{m/s}^2)\);

\(a_b\) = deceleration rate of aircraft B \((\text{m/s}^2)\);

\(V_a\) = initial velocity of aircraft A \((\text{m/s})\);

\(V_b\) = initial velocity of aircraft B \((\text{m/s})\);

\(\text{cor}\) = air traffic controller reaction time, set equal to 1 second [2];

\(\text{pir}\) = pilot reaction time, set equal to 1 second [2];

\(\text{sar}\) = safety reaction time, set equal to 1 second [2];

\(\text{syr}\) = radar system reaction time, set equal to 2 seconds [2];

\(T_e = \text{cor} + \text{pir} + \text{sar} + \text{syr}\) (ATC responsible for avoiding conflicts) or

\(\text{pir} + \text{sar}\) (pilot responsible for avoiding conflicts).

In the cases 1 through 3, a possible conflict can be resolved by decelerating or stopping the trailing aircraft B, until the separation criterion is satisfied. Another way to resolve the arisen conflict is to re-route (one of) the aircraft involved. An on-line taxi-planning support tool is in development, which could be used to generate alternate taxi routes in the case of possible conflicts [20]. For the time being, only stopping or decelerating the trailing aircraft will be taken into consideration.

In case 4 (aircraft moving in opposite directions), a separation conflict is resolved by stopping both aircraft simultaneously. This kind of conflict is highly undesirable, since both aircraft will be positioned head-on, with no alternate taxi path (figure 11.2). The taxiway will now be
blocked for all traffic.

**figure 11.2**

11.1.2 Lateral Separation Conflict
Lateral separation conflicts may arise when two aircraft approach a taxiway crossing at the same time (figure 11.3)

**figure 11.3 Lateral separation**

The minimum lateral separation to be maintained in the situation of figure 11.3 can be expressed by equation 11.3. This equation also accounts for the effects of the jetblast of aircraft A, in case this aircraft will follow path 2 (figure 11.3). Equation 8.2 could be used in the case that aircraft A will follow path 1. However, it is safer to use equation 8.3 and take the jet blast into consideration. This way lateral separation will be maintained without the pilot of aircraft B knowing, which path aircraft A will follow (1 or 2).

If the separation criterium (8.3) is violated, the aircraft farthest from the taxiway crossing (aircraft B in figure 11.3) is stopped. The other aircraft (A) is given permission to cross the taxiway crossing first. If aircraft A has passed the taxiway crossing, aircraft B is given permission to resume taxiing if no other separation criteria are violated.

Another approach to resolving a lateral separation conflict is to re-route (one of) the aircraft involved. An on-line taxi-planning support tool is in development, which could be used to
generate alternate taxi routes in the case of possible conflicts [20]. For the time being, the aircraft farthest away from the crossing will be held, until the other aircraft has passed the crossing.

11.1.3 Runway Incursion
Aircraft cannot be allowed to cross active runways while an aircraft is about to land on or takeoff from that runway (figure 11.4).

![Figure 11.4 Runway incursion](image)

To prevent this from happening, the aircraft will stop at the stop bar, at a safe distance from the runway centerline (with a default value of 90 m [19]). If no aircraft are about to land on the runway, or if they are more than 2 nautical Miles out and no other aircraft is about to takeoff from the same runway, the aircraft can safely cross the runway. Otherwise it will have to wait for the departing or landing aircraft to pass its position before crossing the runway.

11.2 The Sequencing and Scheduling Function
The sequencing and scheduling functions are there to ensure that the minimum separation between aircraft on final approach and between departing flights is maintained at all times. Dependent upon the runway configuration, the traffic on a runway may be dependent upon the traffic on some other runway.

11.2.1 Parallel Runways
The spacing between parallel runways varies widely. Depending on the separation between the centrelines of two parallel runways the runway spacing can be classified as close, intermediate and far (fig 11.5, table 11.1). The interdependency of the runways also depends on the sort of flight operations (VFR or IFR). The FAA-rules which must be taken into consideration are stated in tables 11.2 for VFR operations and table 11.3 for IFR operations.

![Figure 11.5 Parallel runway separation](image)
**table 11.1** Parallel runway spacing  
*source: [19]*

<table>
<thead>
<tr>
<th>runway spacing</th>
<th>runway centerline separation (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>close</td>
<td>700 - 2500</td>
</tr>
<tr>
<td>intermediate</td>
<td>2500 - 4300</td>
</tr>
<tr>
<td>far</td>
<td>≥ 4300</td>
</tr>
</tbody>
</table>

**table 11.2** Parallel runway interdependency during VFR operations  
*source: [19]*

<table>
<thead>
<tr>
<th>runway spacing</th>
<th>runway interdependency during VFR operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>close</td>
<td>Simultaneous departure and arrival allowed if wingspan less than 171 ft. Otherwise the centerline spacing must be at least 1200 ft. Wake avoidance procedures must be used.</td>
</tr>
</tbody>
</table>
| intermediate   | 1) Simultaneous departure and arrival allowed.  
                2) Simultaneous arrivals on both runways allowed. |
| far            | 1) Simultaneous departure and arrival allowed.  
                2) Simultaneous arrivals on both runways allowed.  
                3) Simultaneous departures on both runways allowed. |

**table 11.3** Parallel runway interdependency during IFR operations  
*source: [19]*

<table>
<thead>
<tr>
<th>runway spacing</th>
<th>runway interdependency during IFR operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>close</td>
<td>Runways cannot be used simultaneously.</td>
</tr>
</tbody>
</table>
| intermediate   | 1) Simultaneous departure and arrival allowed if centerlines of the runway thresholds are not staggered.  
                2) Simultaneous departure and arrival allowed if centerline spacing ≥3500 ft in non-radar environment. |
| far            | 1) Simultaneous departure and arrival allowed.  
                2) Simultaneous arrivals on both runways allowed.  
                3) Simultaneous departures on both runways allowed. |

69
11.2.2 Intersecting Runways

A lot of airports have a pair of runways in different directions, which intersect. When winds are strong from one direction, only one of a pair of intersecting runways can be used. If winds are relatively light, both runways may be used simultaneously. The interdependency of the traffic on the different runways depends on the location of the intersection and the aircraft-mix. The closer the intersection is to the takeoff and landing threshold, the more traffic the runway pair can handle [19].

If both runways are used for arrivals, the Dependent Converging Instrument Approach (DCIA), developed in the USA may be used. The principle of this method is shown in figure 11.7. The aircraft are mirrored with respect to the intersection of the runways. These mirror images are known as ghosts. The air traffic controller now has to maintain the appropriate separation between the real aircraft and the ghost images. The separation should be set to a value that ensures safe operations in the case of an eventual overshoot of one of the aircraft or breakdown of the radar or communication equipment.

Clear rules as how to operate a pair of intersecting runways have not been found. The existing rules are usually airport dependent and are thus hard to implement in a general model. For the time being, intersecting runways will not be incorporated in the sequencing and scheduling function.

[Image: Intersecting runways]

figure 11.6 Intersecting runways

[Image: DCIA technique]

figure 11.7 The DCIA technique.

11.2.3 Open-V Runways

Open-V runways are runways in different directions, which do not intersect (fig 11.8). When winds are strong, only one runway of a pair of open-V runways can be used. If winds are relatively light, both runways may be operated at the same time. The runway pair can accommodate more traffic if the flight operations are away from the V (fig 11.8). The capacity under these circumstances may range from 60 to 180 operations per hour for VFR flights and from 50 to 80 operations per hour for IFR flights.

When operations are towards the open-V, the capacity of the runway pair is reduced to 50-100 operations per hour for VFR flights and 50-60 operations per hour for IFR flights [19]. Clear rules as how to operate a pair of open-V runways have not been found. As is the case with intersecting runways, these rules are usually airport dependent and thus difficult to implement in general model. For the time being, open-V runways will not be incorporated in the sequencing and scheduling function.

70
11.2.4 Arriving Flights
Consecutive arrivals on the same runway need to maintain a minimum separation for safety reasons. These separations depend on the weight classes of the aircraft involved and are maintained by the air traffic control in the case of IFR flights. The separations prescribed by the FAA are listed in table 118.4.

VFR pilots have to maintain a safe separation themselves. These separations are not prescribed by the FAA or any airworthiness regulations. The values listed in table 8.4 are the average separations which have been observed to be maintained by pilots of VFR flights.

Separation over the Final Approach Fix (FAF) is not important for the simulation. As long as the scheduling function ensures that two consecutive aircraft satisfy the separations in table 11.4, when the leading aircraft is over the runway threshold, the separation over the FAF will also be satisfied.

Landing aircraft are given full preference when runways are operated in mixed mode. The scheduling function will therefore hold any departures if a flight is coming in for landing. The incoming aircraft is given permission to land if the runway is clear of any other traffic.

table 11.4 Horizontal separation for arriving aircraft in Nautical Miles (NM)
source: [19]

<table>
<thead>
<tr>
<th>leading aircraft</th>
<th>VFR</th>
<th>trailing aircraft</th>
<th>IFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>heavy</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>heavy</td>
<td>2.7</td>
<td>3.6</td>
<td>4.5</td>
</tr>
<tr>
<td>large</td>
<td>1.9</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>small</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>
11.2.5 Departing Flights
The VFR and IFR separation rules for consecutive departures from the same runway are expressed in time according to table 11.5. For the time being, arrivals are given full preference to departing flights. Departures will have to try and fit in the slots between arrivals if the runway is operated in mixed mode. Before a flight is allowed to enter the runway and subsequently takeoff, the following checks have to be performed:

- Is there an arrival on final approach for this runway? If so, is there enough separation to allow takeoff?
- Has the previous arrival vacated the runway to be used?
- Is the separation with the previous departure from the runway to be used sufficient to allow takeoff?
- Is there no other traffic on the runway preventing a safe takeoff?

If all of this checks out, the aircraft is given permission to enter the runway and takeoff. If one of the criteria is violated, the aircraft will be held short of the runway and will have to wait until the traffic situation allows for a takeoff.

| leading aircraft | VFR  |  | trailing aircraft |  |  |
|------------------|--|--|--|--|--|--|
|                  | heavy | large | small | heavy | large | small |
| heavy            | 90    | 120   | 120   | 120   | 120   | 120   |
| large            | 60    | 60    | 50    | 60    | 60    | 60    |
| small            | 50    | 45    | 35    | 60    | 60    | 60    |

| source: [19] |
12 Interface with The Taxi-Planning Support Tool

One of the goals of this thesis assignment was to enable the use of SIMAST as a testbed for taxi-planning support tools. Two other thesis assignments are aimed at the development of a on-line and an off-line taxi-planning support tool. The development of the on-line taxi-planning support tool has started too late to be included in this thesis assignment. Therefore, the new version of SIMAST (version 2.0) can only serve as a testbed for the off-line taxi-planning support tool. In the envisioned concept of the off-line planner, the movement of ground traffic should be planned in a conflict-free fashion, some 20 minutes before the involved vehicles or aircraft actually enter the system. The taxi-planning support tool is still under development and not operational yet. This chapter deals with the interface between SIMAST and the off-line taxi-planning support tool.

12.1 The Taxi Plan

The off-line taxi-planning support tool produces a taxi-route for every aircraft in the simulation. For the time being, vehicles other than aircraft are not planned. This taxi plan describes the path the aircraft has to follow on the airport surface as a series of nodes. The first node being the apron exit point and the last node being the runway entry point for departing flights. For arriving flights, the first node is the runway exit point and the last node is the apron entry point. For each node, an arrival time (in seconds from simulation start) is specified. A taxi plan for one aircraft produced by the taxi-planning support tool, should be similar to the following:

<table>
<thead>
<tr>
<th>nodes</th>
<th>1</th>
<th>12</th>
<th>25</th>
<th>19</th>
<th>36</th>
<th>44</th>
<th>102</th>
<th>96</th>
<th>87</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>100</td>
<td>121</td>
<td>156</td>
<td>207</td>
<td>356</td>
<td>405</td>
<td>428</td>
<td>492</td>
<td>516</td>
<td>617</td>
</tr>
<tr>
<td>at node</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

12.2 Taxi Display

If a conflict free taxi-plan exists for a certain flight, with a minimum of stops and delay(s), the pilot will have to be informed about his progress along the assigned taxi-route. If this is not done, the pilot will not be able to adhere to the optimal taxiplan, with the consequence that his and perhaps other flights might incur delays which would not have been necessary. To enable the pilot to follow the assigned taxi-plan in space and time, the pilot has to receive feedback with respect to any deviations from the optimal taxi-plan. This could be done in the form of a taxi display, showing a virtual map of the airport with the assigned taxiroute and the relative position of the aircraft as well as that of other traffic. If deviations from the taxiplan are detected by an external system, advisories may be sent to the pilot to speed up, slow down, halt, take a left or right turn. These advisories serve the purpose of trying to keep the flight on track and time according to the optimal taxi-plan. An example of a possible display with advisories can be seen in figure 2.6.
12.3 Aircraft Speed Adjustments
Based on the taxiplan introduced above, it is possible to determine the taxi speed with which the aircraft should be travelling over the airport surface. This $V_{\text{wish}}$ can be calculated as follows:

$$V_{\text{wish}} = \frac{\text{distance to next node}}{\text{arrival time at next node} - \text{current time}} \quad (12.1)$$

It is assumed that the fictional pilots of the simulated aircraft are given information about the deviation from their taxi plan and will try to correct these as much as possible. The aircraft's taxi speed is continuously adjusted if the projected arrival time at the next node is $\Delta t_{\text{allowed}}$ earlier or later than the planned arrival time. The value of $\Delta t_{\text{allowed}}$ can be specified before simulation start, in the simast.ini file, to simulate system precision, and it's impact on the traffic flow.

The aircraft's actual taxi speed is allowed to differ slightly from the taxi speed $V_{\text{wish}}$ derived from the taxiplan. The maximum allowed difference between the aircraft's actual taxi speed and $V_{\text{wish}}$, $\Delta V_{\text{allowed}}$ can be specified in the simast.ini file, to simulate system precision, and it's impact on the traffic flow.

Whether the aircraft will really taxi with $V_{\text{wish}}$ is dependent upon the traffic situation. The separation between aircraft has to be maintained at all times and the aircraft are not allowed to travel at speeds above the maximum taxi speeds specified for the path segments they are travelling on. Tests showed, that if the separation criteria and the maximum speed limits are not violated, the aircraft will indeed stick to their assigned taxiplans.

12.4 Taxi Plan Evaluation
To be able to evaluate the taxiplan generated by the off-line taxi-planning support tool, one needs to know which aircraft were delayed and what the amount of delay was. If aircraft are delayed (arrive at a node later than planned), the delay is noted. The delay is specified for each aircraft as well as the cumulative delay of all aircraft for each link. This way it can be seen which aircraft were delayed and where on the airport surface most of the delays occurred. This information is saved in an outputfile for evaluation purposes. This output file is the covered in chapter 14.
13 Modeling the Stochastic Behaviour of Aircraft

The movement of aircraft on the airport surface are modelled by a set of mathematical equations. These mathematical equations describe the relationship between the output (variables of interest) and the input (system description). Obtaining values for the input variables is not always easy. Many variables, such as the wing area of an aircraft, can be accurately determined. However, vehicle movements on and around an airport's surface are inherently stochastic in nature. This implies that some of the input variables, such as the approach speed or aircraft weight, will have to reflect this stochastic nature, in order to realistically simulate the movement of the vehicles. One of the methods which can be used to obtain these stochastic variations, is Monte Carlo sampling. The stochastic behaviour of aircraft can be modelled with the use of Monte Carlo sampling [8].

13.1 Monte Carlo Sampling

Often, when the value of a variable is uncertain, a number of values which the variable may take on is known. This set of values is called the domain of the variable. If information about the number of times values in the domain occur is available, it is possible to define a probability density function (pdf). The value of the pdf in a certain point \( z \) reflects the chance that the variable will take on the value \( z \). The higher the value of the pdf in point \( z \), the more likely it is the variable will take on the value \( z \). The problem of generating stochastic varying variables can now be transformed in the problem of generating values from the domain of the pdf, such that points with a high pdf value will occur more often than points with a low pdf value. The process of generating these points is called sampling. The points themselves are called samples. By transforming a number of independent uniform deviates, each drawn from the uniform distribution on the interval \([0,1]\), a number of samples from the desired pdf can be generated.

13.1.1 Generating Uniform Independent Deviates

In practice, the independent uniform deviates are substituted by a number of normalised pseudo-random numbers on the interval \([0,1]\) [10]. The pre-fix pseudo conveys their less than perfect random character.

Let \( Z_i \) \((i \geq 0)\) denote a sequence of nonnegative numbers with maximum value \( Q - 1 \). These numbers will be used to generate a sequence of uniform independent derivatives \( U_i : \)

\[
U_i = \frac{Z_i}{Q} \quad (i \geq 0)
\]  

(13.1)

The \( Z_i \) are pseudo-random numbers. One of the most frequently implemented types of generator is the multiplicative congruential generator:

\[
Z_i = A Z_{i-1} \pmod{M} \quad \text{or} \quad Z_i = A^t Z_0 \pmod{M}
\]  

(13.2)
A is called the multiplier. To generate numbers from this expression, the generator has to be primed with a number or seed \( Z_0 \). Expression 2 provides reproducibility of the sampled values, because \( Z_0 \) completely determines the \( Z_i \) once \( A \) and \( M \) are fixed. This property may be used to ones advantage during the development of a Monte-Carlo experiment. The number of distinct values that \( Z_i \) assumes cannot exceed \( M-1 \). The maximum number of samples or period that can be drawn before the seed \( Z_0 \) recurs is thus:

\[
P_f(A, Z_0) = \min\{n \geq 1 : A^nZ_0 \pmod{M} = Z_0\} \tag{13.3}
\]

Let \( \mathcal{M} = \{1, 2, \ldots, M-1\} \). One would want \( P \) to be as large as possible so that \( Z_i \) attains as much of the integer values in \( \mathcal{M} \). As \( P \) increases, the discrete valued sequence \( \{U_i = Z_i/M, 1 \leq i \leq P\} \) becomes more dense in \((0,1)\). Therefore, the error for regarding \( U_i \) as continuous on \((0,1)\) becomes less important. If \( P = M-1 \), then the generator offers the additional benefit of generating as many distinct values for \( Z_i \) as possible in \( M \).

To achieve a maximum period, one would want to make \( M \) as large as possible. However, the word size of the computer limits the maximum value of \( M \). For 32-bit word size PCs, this results in \( M = 2^{31}-1 \) as the largest possible prime number (sign bit neglected). The choice of \( A \) also has an important impact on the attainable period \( P \). If \( M \) is a prime number, then the generator (13.2) has maximum period \( P = M-1 \) if and only if \( A \) is a primitive root of \( M \). Not every primitive root of \( M \) achieves the same degree of randomness. A value of \( A = 950706376 \) produces a good apparent randomness [9].

Due to the large numbers involved, directly performing integer arithmetic to calculate \( AZ_{i-1} \) will inevitably result in an overflow for some \( i \) on 32-bit computers. This problem may be solved by splitting the arithmetic operations in a way that eliminates the overflow problem and ensures portability. An alternative expression for the generator (13.2) is:

\[
Z_i = [X_i + Y_i + \frac{A_1Z_{i-1}}{2^{31}} + \frac{A_2Z_{i-1}}{2^{31}}] \pmod{2^{31} - 1} \tag{13.4}
\]

with:

- \( A_i = A \pmod{2^{31}} \);
- \( A_i = A - A_i \);
- \( X_i = A_1Z_{i-1} \pmod{2^{31}} \);
- \( Y_i = A_2Z_{i-1} \pmod{2^{31}} \);

The pseudo random numbers generated by expression (13.4) can be used to obtain the normalized pseudo-random numbers \( U_i \) on \([0,1)\):

\[
U_i = \frac{Z_i}{M} \tag{13.5}
\]

13.1.2 Sampling From the Normal Distribution pdf

All generating methods produce samples from a specified pdf by transforming a sequence of normalized pseudo-random numbers [10]. Several algorithms are available to perform these
transformations for various pdf's [10]. Some aircraft parameters can be approximated by the normal distribution, denoted by $\mathcal{N}(\mu, \sigma^2)$ [24,25]. This distribution is characterized by the following pdf, with mean $\mu$ and standard deviation $\sigma$, where $z$ is a random variable:

$$f(z) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(z-\mu)^2}{2\sigma^2}} \quad \sigma^2 > 0, \quad -\infty < z < \infty$$  \hspace{1cm} (13.6)$$

One of the properties of this distribution is that if $Y$ is from $\mathcal{N}(0,1)$, then $Z$ is from $\mathcal{N}(\mu, \sigma^2)$:

$$Z = \mu + \sigma Y$$  \hspace{1cm} (13.7)$$

This makes it clear that one will only need to obtain a sample from $\mathcal{N}(0,1)$. Expression (13.7) generalizes the application of the normal distribution. The algorithm [10] proposed to generate samples from $\mathcal{N}(0,1)$ is described in Appendix B. This algorithm can be used to generate samples for any variable which can be approximated as a normal distributed parameter, with mean value $\mu$ and standard deviation $\sigma$.

Suppose the speed of some vehicle can be approximated by a normal distribution with mean 22.5 knots and standard deviation of 6.5 knots. The resulting pdf (13.6) is displayed in figure 13:1; together with the pdf resulting from sampling this speed using the described algorithms. As can be seen from the figure, the sample algorithm reproduces the normal distribution rather nicely, prohibited that a great number of samples is generated (50,000 in the case below).
13.2 Stochastic Modeling of Aircraft Movements

It is very difficult to accurately model the stochastic behaviour of aircraft on the airport surface, since there is practically no input data available. For instance there is very little data available about taxi and turning speeds. Each of the various movement phases will be treated separately.

13.2.1 The Landing Phase

The amount of runway needed for an aircraft during the landing phase is stochastic in nature. It is amongst others dependent upon the approach speed, touchdown location, aircraft weight and the rate of deceleration during the landing roll. Four random variables have been selected to reflect the stochastic nature of the landing phase in the model [13]. The chosen random variables are:

> aircraft landing weight;
> threshold crossing altitude;
> flight path angle on final approach;
> the rate of deceleration during the landing roll.

The aircraft's weight itself will not be used as a random variable, but rather a dimensionless weight factor [25]:

\[ w_{\text{land}} = \frac{W_{\text{land}} - OEW}{MLW - OEW} \quad (13.8) \]
\[ W_{\text{land}} = OEW + w_{\text{land}} (MLW - OEW) \]  

(13.9)

with:

*MLW* = Maximum Landing Weight;  
*OEW* = Operational Empty Weight;  
*w_{\text{land}}* = landing weight factor;  
*W_{\text{land}}* = actual landing weight.

The landing weight factor may be approximated by a normal distribution [25], with a mean value and a standard deviation which depend upon the class of aircraft:

<table>
<thead>
<tr>
<th>table 13.1 Landing weight factors, source [25]</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter</td>
</tr>
<tr>
<td>( \mu w_{\text{land}} )</td>
</tr>
<tr>
<td>( \sigma w_{\text{land}} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>table 13.2 Aircraft weight classes, source [19]</th>
</tr>
</thead>
<tbody>
<tr>
<td>aircraft class</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
</tbody>
</table>

Airworthiness regulations (FAR 25) require the aircraft to cross the runway threshold at an altitude of 50 ft (15.3 m). To reflect the stochastic variations in this parameter, the mean value \((\mu)\) of the runway threshold altitude is set to 15.3 meters (50 ft) and the standard deviation \((\sigma)\) may be set equal to 1.5 meters [25].

The same airworthiness regulations dictate a flight path angle of 3 degrees on final approach. The stochastic variations in this parameter can be obtained by setting the mean value of the flight path angle equal to 3 degrees and the standard deviation equal to 0.15 degrees [25].

The aircraft's mean rate of deceleration is estimated by using the landing distance requirement provided by the manufacturer [13, 25]. The standard deviation is set to 7% of the mean value.

If the delay of arriving aircraft can be approximated by a normal distribution for a certain airport, than with a known mean delay value and a standard deviation, it is possible to generate delays for arriving flights. The problem is to find the mean value and the standard deviation. The flight information distributed over the Dutch cable network, could be used to obtain these
parameters for Amsterdam Airport.

13.2.2 The Takeoff Phase
The amount of runway needed for an aircraft during the takeoff phase is stochastic in nature. It is amongst others dependent upon the rate of acceleration and takeoff weight. Four random variables have been selected to reflect the stochastic nature of the takeoff phase in the model. The chosen random variables are:
- aircraft takeoff weight;
- the altitude at which the takeoff run is considered completed;
- flight path angle at lift-off;
- the rate of acceleration during the takeoff run.

The aircraft weight again is not varied itself, but a dimensionless weight factor is chosen as the random variable, analogous to the landing phase [13,25]:

\[ w_{to} = \frac{W_{to} - OEW}{MTOW - OEW} \] (13.10)

\[ W_{to} = OEW + w_{to} (MTOW - OEW) \] (13.11)

\[ \text{MTOW = Maximum Takeoff Weight.} \]

The mean value and the standard deviation used for the weight factor \( w_{to} \) will be taken equal to the values in table 13.1.

According to airworthiness regulations (FAR 25), the end of the takeoff run is reached when the aircraft climbs to an altitude of 35 ft (10.7 m), commonly known as the screenheight. To reflect variations in the takeoff run, the mean value of the screenheight is set to 10.7 meters and the standard deviation to 1 meter or 10% of the mean value [13].

The mean flight path angle at lift-off can be approximated by [13, 26]:

\[ \gamma_{lof} = 0.9 \frac{T}{W_{to}} - 0.3 \frac{\sqrt{A}}{W_{to}} \]

\[ T = 0.75 \frac{5 + B}{4 + B} T_{to} \] (jet aircraft) (13.12)

\[ T = 0.321 P_{to} \left( \frac{\sigma N D^2}{P_{to}} \right)^{1/3} \] (turboprop aircraft)
with:
\[ A = \text{aspect ratio}; \]
\[ D_p = \text{propeller diameter (m)}; \]
\[ P_t = \text{takeoff power (kgm/s)}; \]
\[ W_{\text{m}} = \text{maximum takeoff weight (kg)}; \]
\[ B = \text{engine bypass ratio}; \]
\[ N_e = \text{number of engines}; \]
\[ T_{\text{e}} = \text{takeoff thrust (kg)}; \]
\[ \sigma = \text{ratio of air density at 0 meters ISA}. \]

The standard deviation of the flight path angle at lift-off is set to 5% of the mean value [13].

13.2.3 The Taxi Phase

The random variable selected to reflect the stochastic behaviour of aircraft during the taxi phase, is the aircraft taxi speed. Very little data is available with respect to this variable. Useful values of taxi speeds were collected by Swedish [24], but these measurements are old and only available for a couple of aircraft types. Recently new measurement were performed on Amsterdam Airport to obtain more information about aircraft taxi speeds (chapter 14). These measurements could provide more accurate input data, if they become available. For the time being, the aircraft taxi speed is assumed independent of the aircraft type, with a mean value of 22.5 knots and a standard deviation of 6.5 knots [13]. In SIMAST's present form (version 2.0), the taxi speeds produced through variation, are overridden by the taxi plan (chapter 11). This taxiplan dictates where the aircraft should be at a certain point in time. The taxi speed of the aircraft, thus follows from the taxi plan, and the stochastic variation of the taxi speed is not needed.

13.2.4 The Accelerating Phase

The rate of acceleration of the aircraft may be varied to reflect the stochastic behaviour of aircraft on the taxiway system. However, there is no data available with respect to this parameter. For the mean rate of acceleration, the values from table 10.1 can be used. However, the standard deviation of the rate of acceleration remains unknown for the time being. Until more information about the behaviour of aircraft during the acceleration phase becomes available, one will have to guess about the value for the standard deviation of the rate of acceleration.

13.2.5 The Decelerating Phase

As is the case for the accelerating phase, no data is available about the behaviour of aircraft during deceleration on the taxiway system. Table 10.1 supplies some information about the mean rate of deceleration of an aircraft on the taxiway system, but little is known about an appropriate standard deviation.

13.2.6 The Turning Phase

Table 9.1 provides information about the relationship between an aircraft's speed during the turning phase and the radius of the turn. These can be used as the mean values for the corresponding turn radius. However, one will have to guess about the standard deviation, since no data is available.

13.3 Conclusion

The algorithm described in Appendix B can be used to generate stochastic variations in variables, which may be approximated by a normal distribution. Algorithms for other distributions are also available [10]. The problem with stochastically varying of parameters, with respect to airport surface traffic, is that there is very little information available, allowing
one to use the described, or other algorithms. Because of this, stochastic variations will be limited to the following parameters:

- aircraft weight;
- rate of acceleration/deceleration on the runway;
- flight path angle during landing/takeoff;
- altitude at which the takeoff run is considered completed for outbound flights;
- altitude at which the runway threshold is crossed for inbound flights.
14 Data Output For Simulation Analysis

At the end of program execution or after a user break, a data file called output.dat is generated. This output file contains the parameters with respect to the aircraft and information about the cumulative delays incurred specified per link. The parameters contained in the output file have been formatted such that it is extremely easy to visualise the data by the use of graphics with a spreadsheet program for example.

14.1 Aircraft Specific Output Parameters
For evaluation of the simulation run, a number of parameters with respect to the aircraft are dumped in the output file. these parameters are specified for each aircraft. Departures and arrivals are grouped together. The parameters written to the output file are the following:

- **Arriving aircraft:**
  - callsign;
  - Actual Time of Arrival (ATA);
  - Estimated Time of Arrival (ETA);
  - time at which the aircraft enter the apron and enter the simulation;
  - total delay incurred by the aircraft;
  - Runway Occupancy Time (ROT);
  - total time spent taxiing (decelerating, turning and accelerating included);
  - total time spent holding (zero taxi speed);
  - aircraft type;
  - taxiroute number;
  - aircraft weight;
  - landing distance.

- **Departing aircraft:**
  - callsign;
  - time at which the aircraft leave the apron and enter the simulation;
  - Estimated Time of Departure (ETD);
  - Actual Time of Departure (ATD);
  - total delay incurred by the aircraft;
  - Runway Occupancy Time (ROT);
  - total time spent taxiing (decelerating, turning and accelerating included);
  - total time spent holding (zero taxi speed);
  - time spent in lineup;
  - aircraft type;
  - taxiroute number;
  - aircraft weight;
  - takeoff distance.

The format of the outputfile is such that it can easily be accessed by a spreadsheet program to create diagrams. With the help of these diagrams it is easier to evaluate the simulation run. An example of such diagrams is seen in figure 14.1 and 14.2.
figure 14.1 Output parameters for departing aircraft

figure 14.2 Output parameters for arriving aircraft
14.2 Link Specific Output Parameters
The delays of all the aircraft incurred on a link are noted. This way it is possible to check where possible bottlenecks are on the airport surface. The links where delays occurred are specified in the output file with their accumulated delays. For easy identification of bottlenecks on the airport surface, bar graphs can be created (figure 14.3).

![cumulative delay incurred on links](image)

figure 14.3
15 Identification of Aircraft Taxiing Behaviour

In view of the ongoing research into A-SMGCS, various movement models for taxiing aircraft are under development. To ensure that the developed movement models realistically reflect actual taxi movements, calibration of the models is of paramount importance. Therefore, operational data with respect to the behavior of aircraft during taxiing is needed. Unfortunately, this kind of data is not available. This is a complication for the development of various simulators and research projects, which use these kind of movement models. Examples of these research projects are:

- **AIRPORT-G**, development and evaluation of an A-SMGCS guidance function [4];
- **MANTEA⁴**, development of decision support tools for improving surface traffic management at airports [4];
- **ATHOS**, seeks to design and test a new tower controller’s working position [4];
- **NLR Tower Research Simulator (TRS)**, a 360° degree tower simulator, with synthetically generated aircraft [16].
- **SIMAST**, fast time SIMulation of Airport Surface Traffic.

The Holland Institute of Traffic Technology B.V. (HITT) has developed an operational A-SMGCS surveillance function, which has been installed for a couple of weeks at Amsterdam Airport for demonstration purposes. The NLR was given permission by HITT and the LVB to extract data with respect to aircraft behaviour on the taxiway system from this A-SMGCS surveillance demonstrator. For the time being, the data obtained via the HITT system may only be used by the NLR.

15.1 Aircraft Movement Data

For the evaluation and calibration of movement models for taxiing aircraft, one would like to have an extensive database with respect to the behaviour of aircraft on an airport’s surface. To create such a database, a wide variety of parameters needs to be obtained. The intention is to identify the following parameters for every aircraft on the taxiway system, complete with the standard deviation, minimum, maximum and mean value:

- The average speed, acceleration and deceleration during taxiing dependent on:
  - aircraft type, the taxiway or part of the taxiway, inbound or outbound flight, airline.
- For inbound flights, as a function of the type of aircraft:
  - approach speed, touchdown point, average deceleration during landing, landing distance, Runway Occupancy Time (ROT).
- For outbound flights, as a function of the aircraft type:
  - average acceleration during takeoff, lift-off point, takeoff distance, ROT.
- Use of runway exits depending on:
  - the airline and the aircraft type.
- Various delays:
  - gate delays, takeoff delays, arrival delays, delays at taxiway/taxiway intersections and at taxiway/runway intersections.

⁴Management of Surface Traffic on European Airports
The following two paragraphs describe the data that has actually been registered and with which the parameters described above will have to be obtained if possible.

15.2 Data Extracted From the HITT System
The vehicles on the airport surface are detected by the Surface Movement Radar (SMR) or Airport Surface Detection Equipment (ASDE). The HITT A-SMGCS surveillance function provides detection, identification and tracking of the traffic present on the airport surface, based on the information supplied by the ASDE. During the process, the analog radar data is digitized, enabling easy registration and processing of the radar data. For every rotation of the radar dish (typically, 1 per second), the following parameters are logged for every vehicle:
- aircraft position;
- aircraft track;
- time/date.
This data was intermittently collected, with a total of a little over 7 days (24 hours a day).

15.3 Data Supplied by the LVB
The information with respect to the position, speed and possibly the acceleration/deceleration of aircraft extracted from the HITT system, is not enough to identify all of the parameters described in paragraph 15.1. A lot of relevant information with respect to the taxiing movements of aircraft is still missing. To reconstruct the meteorological conditions (visibility especially) at the time of data extraction information about the meteorological conditions is needed. Furthermore, the information contained in the flight plans available to the SARP system (Signaal Automatic Radar data Processing) would be extremely useful. These flight plans contain valuable information about the airline, aircraft type, ETA/ETD, destination and more. With this data it is possible to reconstruct delays of flights and aircraft behavior dependencies upon aircraft type and/or airline (if they exist). This information has been provided by the LVB. The LVB data concerns the following parameters:
- meteo: visibility conditions, temperature, air pressure, wind speed and direction;
- surface condition of the taxiway system and the runways;
- runway configuration;
- flightstrip info: airline, callsign, aircraft type, ETD/ETA, ATD/ATA, assigned runway, gate, taxiroute, aircraft ID (transponder).

15.4 Taxi Movement Database
The lay-out of the airport and the known coordinates of characteristic points (e.g. centerline intersections) provide a basis for the processing of the data extracted from the HITT system. The time it takes a specific aircraft to travel the distance between two of these characteristic points on the airport surface, needs to be calculated. With the available data, this is possible. Once this has been done, a database can be constructed (fig. 15.1). This database contains the distance traveled by every aircraft, along its assigned taxi route, as a function of time. With this information it is possible to calculate the average speed of an aircraft while travelling over (a part of) a taxiway between two points:

$$ v = \frac{S(t + \Delta t) - S(t)}{\Delta t} $$

(3.1)
With:
\( V = \) aircraft speed;
\( S = \) distance traveled along the taxi route;
\( \Delta t = \) revolution speed of the radar dish (typically 360\(^\circ\)/s).

Once the data extracted from the HITT system is correlated with the data supplied by the LVB, additional information can be added to the database (fig. 15.1). Data obtained from these measurements have already been used by the NLR to validate the push-back times incorporated in TAAM.

![Diagram of cumulative distance travelled along taxi route](image)

**Figure 15.1** A database example

Analysis of the database will have to provide the parameters mentioned in paragraph 15.1. Whether every parameter can be obtained depends on the accuracy of the surveillance/radar system. There is also an unknown influence of the pilot and the controllers present. The pilot will apply brakes and throttle during taxiing, but these actions have an unknown influence on the behavior of the aircraft during taxiing. Pilots may also be instructed to halt at an intersection by the air traffic controller. How instructions such as these and others influence the taxiing traffic remains unknown. Interviewing pilots and controllers might shed some light on this subject.
16 A Sample Simulation Run and SIMAST’s Limitations

This chapter describes a sample simulation run, illustrated with screen dumps made during the simulation run. This is done to demonstrate the possible scenarios which can be simulated using SIMAST. Furthermore, it will also show the limitations of the simulation program. Because of the number of figures, these have been placed at the end of this chapter.

16.1 Sample Simulation run

The airport at Amsterdam, The Netherlands, has been selected as the airport to be used for validation of the simulation concept. The layout of the airport is shown in figure 16.1. The numbers indicate the node identification, used to define the taxi-paths of the aircraft. The corresponding files, describing the layout of the airport are given in appendix D. For this simulation run, taxiroutes have been defined for the various aircraft. These taxiroutes do not only specify the path to be followed, but also the time at which an aircraft should arrive at the nodes, defining the taxi-path. The taxiroutes have been constructed manually, since the off-line taxi-planning support tool has not been developed so far that it can generate optimal taxiroutes for a complex airport such as the one at Amsterdam. The traffic sample simulated by SIMAST is defined in the FLTPLANS.DAT file, described in appendix D. In the following text, the flights present in the simulation will be addressed by their callsign, defined in the datafile containing the flightplans of the aircraft.

The first picture (figure 16.2) shows the simulation graphics almost 4 minutes after simulation start. Various aircraft are taxiing over the taxiway system and flight UK263 is just taking off from runway 19L. On runway 19R flight MA729 is just landing. The state of the aircraft is shown in the bottom part of the screen, together with the ETA/ETD, callsign and type of aircraft. Aircraft for which no state is specified are still dormant and will become active later in the simulation run. During simulation, this is also indicated with colors, but this is not visible in the black and white screen dumps shown here.

The next picture (figure 16.3) shows that flight MA729 has reached its assigned exit. This is a highspeed exit and flight MA729 will thus vacate the runway with a speed of approximately 60 knots. While zooming in on flight MA729, we see that once flight MA729 has vacated the runway and entered the high-speed exit, it starts to decelerate (state is decel) up to a comfortable taxi speed (figure 16.4). This taxi speed is derived from the taxi-plan as explained in chapter 12.

Zooming in on another part of the airport, it seems that a conflict is about to occur (figure 16.5). Flights AR279 and SA354 are approaching a mutual taxiway crossing and action will have to be undertaken to satisfy the separation criteria and prevent a possible collision. Since flight SA254 is closer to the taxiway intersection than flight AR279, flight SA354 is given permission to proceed. Flight AR279 is instructed to decelerate and hold short of the intersection (figure 16.6 check the state in the lower part of the screen). Once the separation criteria are no longer violated, flight AR279 receives permission to resume taxiing and continues to travel to its destination (figure 16.7).
More than seven minutes into the simulation, flight JA946 is about to cross runway 09/27. However, flight AR266 is just coming in for landing on this runway, forcing flight JA946 to hold short of the runway and delay crossing (figure 16.8). Once flight AR266 has passed the position of Flight JA946, this flight is cleared to cross runway 09/27 and continues to taxi along its assigned route (figure 16.9).

Figure 16.10 shows flight KL321, which has just landed and vacated the runway, nearing a turn on the taxiway system. The state of the aircraft is changed to turn and the aircraft decelerates up to an appropriate speed with which the turn can be negated safely and comfortably (figure 16.11). The speed of the aircraft remains constant during the turn (figure 16.12). Exiting the turn, flight KL321 accelerates up to its taxiing speed, resuming its route with a constant speed (figure 16.13).

After almost nine minutes of simulation time, flights JA 946 is decelerating to hold short of runway 19L, until it receives takeoff clearance (figure 16.14). Flight NW789 is also in lineup for the same runway, but uses another runway entry. Due to its size (B737) it does not need the entire length of the runway. Both flights will have to wait until flight ML935, which is on final approach for runway 19L, has vacated the runway. After ten minutes of simulation, flight ML935 has vacated the runway and flight NW789 is just taking off (figure 16.15). Flight JA946 is held, because flight NW789 was scheduled to depart earlier. When sufficient separation with flight NW789 is achieved and no other aircraft are about to land on runway 19L, flight JA946 will be allowed to takeoff and fly to its destination (figure 16.16). This figure also shows flight BA753 in the lineup for runway 19L. This flight was scheduled to depart at eleven minutes and 40 seconds into the simulation. The simulation time, however, is 00:11:53.0. Flight BA753 has thus incurred a delay, caused by bad runway planning. This flight will have to wait a little longer before it can takeoff, until flight JA946 has established sufficient separation.

A couple of minutes later (figure 16.17), flight BA753 takes off from runway 19L. At the same time flight SA354 cannot takeoff from 19R, because flight IB373 is scheduled to land on this runway. Flight SA354 is denied takeoff clearance until flight IB373 vacates the runway. This causes a delay for flight SA354.

The final figure (figure 16.18) shows flight IB373 taxiing to its destination and flight SA354 taking off. When flight IB373 reaches its destination, the simulation run is completed and the output report is generated. This report can be used to produce figures 16.19, 16.20 and 16.21.

Figure 16.19 Shows that all of the arriving flights arrived at the planned time, except for flight IB123. This flight has been delayed due to the fact that the flightplan did not satisfy the separation criteria on final approach for flights IB123 and flight KL321. Since flight IB123 is the trailing aircraft, this was delayed, causing a difference between the ETA and the ATA. For the other aircraft there were no separation violations on final approach. Most of the arrivals seem to have incurred a slight delay on the taxiway system. This is not caused by separation conflicts, but a bad taxi-plan. Apparently the aircraft should taxi at speeds faster than the maximum allowed speed on the taxiway system. Since this is prohibited, they incur a slight delay.
A sample of the data available with respect to the departures is shown in figure 16.20. Due to the bad runway planning, most flights have a delay at the time of takeoff. This can be concluded from the difference between the ATD and the ETD. The amount of time spent in the lineup for the takeoff runway is a measure for bad runway planning. Part of this delay may also be caused by conflicts on the taxiway system. A measure for the amount of time lost due to conflicts is the time spent in hold. However, if the aircraft is holding behind another flight in lineup, there is off course a conflict, but actually the aircraft itself is also in lineup. This is one of the shortcomings of the current SIMAST version (2.0). If multiple aircraft are in a runway lineup, only the first aircraft is granted the state lineup, while the others receive the status hold. The amount of delay the aircraft incur is a measure for the taxi-plan. Apparently, the taxi-plan used is not very good, because most aircraft have a delay before they can takeoff.

To see where most of the problems occur, we can take a look at figure 16.21, which has been constructed from the data in table D11 in appendix D. This figure shows the cumulative delay aircraft incur on specific links. Apparently, most of the delays are caused by the aircraft having to wait for takeoff clearance. As was already said before, some delay is also caused due to the fact that aircraft may not exceed the maximum speed defined in the LINKS.DAT file. Despite the simplicity of the report, it is possible to identify bottlenecks on the taxiway system and problems in the taxi-plan.

16.2 Simulation Limitations
The current SIMAST version (2.0) is a useful tool for the evaluation of existing taxiplans, which may be generated manually or by taxi-planning support tools [20, 27]. Furthermore, SIMAST can be used to track down bottlenecks on an airports taxiway system by simulating an ordinary day on an airport. Despite the increased functionality of the program, it should be pointed out, that not all of the functions described in the top-level design of the simulator (chapter 7) have been implemented. The software has its limitations, which will be discussed here.

16.2.1 Limitations of The Geographic Airport Model
The geographic airport model has been improved and is now able to model just about any airport. However, taxiway turns are not actually modelled, but emulated during simulation, and SIDs and STandard Arrival Routes STARS have not been implemented yet. For the simulation of takeoff-after procedures the SID’s will have to be incorporated in the geographic airport model. More ingenious scheduling and sequencing functions would also require the incorporation of STARS in the airport model.

16.2.2 Limitations of The Kinematic Model
Only movement models for the various movement phases of aircraft on the airport surface have been implemented in the kinematic model. Movements of aircraft around the airport (missed approach, fly-by) and the movements of helicopters have not been modelled nor implemented. Movement models for ground-based vehicles have been developed, but are not implemented in SIMAST.
The simulation of aircraft movement is restricted to the taxiway system and the runways. Movements on the aprons are not simulated, nor have they been modelled. Doing so would be an elaborate and complicated task. Furthermore, the lack of information of aircraft movements on the apron area prevents a realistic simulation of these movements.

Due to lack of information about the actual layout of taxiway turns, taxiway turns are emulated. The aircraft will travel along the straight links. Arriving at a node, the heading of the aircraft changes instantaneously when moving from one link to another. The only concession made to taxiway turns is the adjustment of the taxiing speed of the aircraft.

The same is true for the turnoff manoeuvre of an aircraft vacating the runway. The aircraft will vacate the runway at a speed of about 60 knots (high-speed exit). Moving from the runway onto the exit, the heading of the aircraft changes instantaneously and the aircraft starts to decelerate. The turnoff manoeuvre as modelled in [13] is not used in the current version of SIMAST.

Average taxiing speeds for aircraft still need to be obtained as well as the corresponding standard deviation. For the time being, the average taxi speed and the standard deviation are independent of aircraft type and location on the airport surface. The maximum speed allowed on a taxiway can however be specified, but the values used are more or less arbitrary due to the lack of input information.

The influence of the weather conditions is totally neglected in SIMAST’s movement models. Only the length of the landing run is affected by the condition of the runway surface (wet or dry). The movement models developed [13] take wind into consideration, but the effects of wind are not considered in SIMAST. Wind would only substantially influence the takeoff and landing performance of aircraft. For the validation of the simulation concept, these effect are not deemed relevant.

Again due to the lack of information, the input parameters which model the behaviour of the pilot, are independent of aircraft type and/or carrier.

To reflect a realistic spread in aircraft performance, the movement models need to be modified by stochastic variations. The technique proposed in chapter 13 to generate these variations has not been implemented. The variations are generated by other means, but these do not provide the same apparent randomness as the monte carlo sampler described in appendix B.

16.2.3 The Limitations of The Control Model
The control model has been improved to allow it to control the traffic on complex airports with more than one runway. It automatically handles all the traffic on the airport. The user is not able to influence the simulation while it is running. The traffic is processed according to the defined flightplans and conflicts are detected and resolved automatically by decelerating and holding (one of) the aircraft involved. Re-routing flights is not considered, but this can be done by the on-line taxi-planning tool under development [20].
For the purpose of SIMAST to be used as a testbed for the off-line taxi-planning support tool [27], the automatic generation of traffic and corresponding taxiroutes is not necessary. The planning tool will supply SIMAST with a traffic sample and corresponding taxiroutes. Since the taxiroutes are defined before simulation start, also the need for the exit assignment function is cancelled. However, for use with an on-line taxi-planning support tool [20], the automatic generation of airport traffic would be useful.

The sequencing of arrivals and departures has been implemented in the control model. For parallel independent runway configurations, the corresponding functions in the control model will see to it that the minimum separation between subsequent arrivals and departures is maintained. The control model is not equipped to maintain adequate separation for traffic when configurations, with intersecting runways, open-V runways and parallel runways which cannot be operated independently are used.

16.2.4 Simulation Output Parameters
The output generated by SIMAST can easily be used to produce graphics such as figures 16.20 and 16.21. The time spent in hold is an indication of delays caused by conflicts. Remind that (one of) the aircraft involved in a conflict is instructed to hold. Thus the time spent in hold can be used as a measure for the supplied taxi-plan. The problem however is that if more than one aircraft is in the same departure queue for a runway, only the first aircraft is granted the state lineup, whilst the other aircraft receive the state hold. It would be better if all these aircraft would have the state lineup, since their all waiting to takeoff. The delay is caused by bad runway planning and does not necessarily have anything to do with the taxi-plan being optimal or not.

16.2.5 Software Limitations
Thanks to the improvements made to SIMAST’s software, the simulator is more flexible than before. However, all data with respect to a simulation run is stored in memory before simulation start. Due to the fact that the memory available to SIMAST is limited to the first MB of RAM (base memory), the simulation speed drops drastically if many aircraft are present in the simulation. The available memory also limits the number of aircraft which can be simulated and thus also the length of the simulation run. A better approach would be to reserve memory for active aircraft only. Once an aircraft becomes active, it should be loaded in memory. After completion of its flightplan, an aircraft can be removed from memory. The use of available extended or expanded memory will speed up the simulation and enable the simulation of more aircraft and longer simulation runs.

16.3 Future Simulator development
SIMAST is primarily intended as a tool for the generation of airport surface traffic, which may be used for the testing and evaluation for future A-SMGCS tools. The simulation of aircraft movements on the airport surface can be performed by the current version of SIMAST. However, testing and evaluation of several A-SMGCS tools will require real-time simulation, with air traffic controllers and (pseudo) pilots included in the simulation. This calls for several changes to SIMAST's control model. A possible design, with a (pseudo) pilot included in the simulation has been introduced in chapter 2. The application of SIMAST as a synthetic traffic generator for tower simulators also requires the simulation to be real-time. Furthermore, such an application demands graphics capabilities out of reach for SIMAST. A possible approach
would be to integrate SIMAST within FLIGHT, being a flight simulator with an animated view from the cockpit or control tower.

Of the four basic functions within an A-SMGCS (surveillance, guidance, control and routing) only the control and guidance function have been implemented in the current version of SIMAST. The surveillance function is not implemented. The state of the aircraft is directly supplied by the kinematic model. The routing function within an A-SMGCS can be simulated with the taxi-planning support tools [20, 27].

The scheduling and sequencing functions in the control model should be changed to enable the use of runway configurations other than fully independent runways. It is also be possible to create a separate runway planning function. This function would produce time targets for aircraft to arrive at the runway, so that they may takeoff or land without any delays caused due to separation conflicts. These time targets could be used as an input for the taxi-planning tools, which subsequently generates taxi-plans for the aircraft in the simulation. SIMAST may then be used to evaluate the resulting runway planning and taxi-plans.

The evaluation and testing of the taxi-planning support tools under research at the DUT/FAE [20, 27] do not require real-time simulation. The present version of SIMAST can be used for the validation of existing taxi-plans supplied by the off-line taxi-planning tool [27]. Desired time targets are used as input. The actual traffic situation is constantly monitored and compared to the target traffic situation. If the actual traffic situation deviates from the target situation, directives are sent to the autonomous aircraft, with the intent to restore the actual traffic situation to the target situation. If it is no longer possible to restore the actual traffic situation to the target situation, a new target situation will have to be defined. This is the purpose of the on-line taxi-planning support tool [20]. In the future, this tool will become an integral part of SIMAST, allowing SIMAST to generate new taxi-plans when the current taxi-plans can no longer be maintained. The present version of SIMAST cannot do so, but will try to restore the target situation, even if the situation is hopeless.

In the current version of SIMAST, action is taken if a conflict is detected. Another approach would be to separate the conflict prediction from the conflict resolution. This would allow one to investigate how serious occurring conflicts are, by monitoring the conflict situation, but not undertaking any actions to prevent a possible collision.

The developed and implemented movement models [13, 14] (control, kinematic and geographic airport model) have not been validated. In order to do so, a substantial amount of data with respect to airport surface traffic movements would be needed. Unfortunately, this kind of data is not available at the moment. The NLR has recently acquired an amount of airport surface traffic data, but for the time being, this data is for NLR use only.
Figure 16.1 Model of Amsterdam Airport
Arrival: Callsign Type ETA State Departure: Callsign Type ETO State

IB123 A-320-600 00:06:56.5 AR279 MD-87 00:06:40.0 TAXI
KL321 A-320-200 00:06:46.5 NA789 B-737-400 00:07:35.0 TAXI
MV229 MD-83 00:06:30.5 LANDING NA789 B-737-400 00:11:40.0 TAXI
AR266 B-727-300 00:02:21.5 U8268 Fokker100 00:03:20.0 TAKEOFF
IB273 B-747-400 00:14:27.5 N8844 B-737-400 00:04:35.0 TAXI
NL335 Fokker100 00:09:09.5 JA8944 MD-11 00:08:20.0 DECEL

figure 16.2

Arrival: Callsign Type ETA State Departure: Callsign Type ETO State

IB123 A-320-600 00:06:56.5 AR279 MD-87 00:06:40.0 ACCEL
KL321 A-320-200 00:06:46.5 NA789 B-737-400 00:07:35.0 DECEL
MV229 MD-83 00:06:30.5 LANDING NA789 B-737-400 00:11:40.0 TAXI
AR266 B-727-300 00:02:21.5 U8268 Fokker100 00:03:20.0 TAKEOFF
IB273 B-747-400 00:14:27.5 N8844 B-737-400 00:04:35.0 TAKEOFF
NL335 Fokker100 00:09:09.5 JA8944 MD-11 00:08:20.0 DECEL

figure 16.3

98
figure 16.4

figure 16.5
### figure 16.6

<table>
<thead>
<tr>
<th>Arrivals Callsign</th>
<th>ETA</th>
<th>State</th>
<th>Departures Callsign</th>
<th>ETO</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB123 A-300-600</td>
<td>00:06:56.5</td>
<td></td>
<td>MB278 MD-37</td>
<td>00:06:40.0</td>
<td>DECEL</td>
</tr>
<tr>
<td>KL321 A-320-200</td>
<td>00:06:46.5</td>
<td>TAXI</td>
<td>BA769 B-747-400</td>
<td>00:07:15.0</td>
<td>TAXI</td>
</tr>
<tr>
<td>MV285 MD-45</td>
<td>00:06:30.5</td>
<td></td>
<td>BA763 B-747-400</td>
<td>00:11:40.0</td>
<td>ACCEL</td>
</tr>
<tr>
<td>NL256 B-737-300</td>
<td>00:06:21.5</td>
<td></td>
<td>BA764 B-737-400</td>
<td>00:04:30.0</td>
<td>TAKOFF</td>
</tr>
<tr>
<td>IB127 B-747-400</td>
<td>00:14:47.5</td>
<td></td>
<td>BA764 MD-11</td>
<td>00:08:15.0</td>
<td>TAXI</td>
</tr>
<tr>
<td>NL835 Fokker100</td>
<td>00:08:03.5</td>
<td></td>
<td>SK854 B-747-400</td>
<td>00:12:30.0</td>
<td>TAXI</td>
</tr>
</tbody>
</table>

### figure 16.7

<table>
<thead>
<tr>
<th>Arrivals Callsign</th>
<th>ETA</th>
<th>State</th>
<th>Departures Callsign</th>
<th>ETO</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB123 A-300-600</td>
<td>00:06:56.5</td>
<td></td>
<td>MB278 MD-37</td>
<td>00:06:40.0</td>
<td>DECEL</td>
</tr>
<tr>
<td>KL321 A-320-200</td>
<td>00:06:46.5</td>
<td>LANDING</td>
<td>BA769 B-747-400</td>
<td>00:07:15.0</td>
<td>TAXI</td>
</tr>
<tr>
<td>MV285 MD-45</td>
<td>00:06:30.5</td>
<td>TAXI</td>
<td>BA763 B-747-400</td>
<td>00:11:40.0</td>
<td>ACCEL</td>
</tr>
<tr>
<td>NL256 B-737-300</td>
<td>00:06:21.5</td>
<td></td>
<td>BA764 B-737-400</td>
<td>00:04:30.0</td>
<td>TAKOFF</td>
</tr>
<tr>
<td>IB127 B-747-400</td>
<td>00:14:47.5</td>
<td></td>
<td>BA764 MD-11</td>
<td>00:08:15.0</td>
<td>TAXI</td>
</tr>
<tr>
<td>NL835 Fokker100</td>
<td>00:08:03.5</td>
<td></td>
<td>SK854 B-747-400</td>
<td>00:12:30.0</td>
<td>TAXI</td>
</tr>
</tbody>
</table>

100
figure 16.8

figure 16.9
figure 16.12

figure 16.13
Arrivals: Callsign  Type  ETA  State  Departures: Callsign  Type  ETD  State
IB123  A-300-600  00:08:11.0  DECEL  AR229  H-67  00:06:46.0  TAKEOFF
KL321  A-320-200  00:08:46.5  TAXI  N4789  B-737-400  00:07:35.0  LINEUP
PV729  MD-83  00:08:52.5  TURN  BV863  B-747-400  00:11:40.0  TAXI
AR226  B-737-300  00:07:21.5  TAXI  JA946  MD-11  00:05:20.0  DECEL
IB393  B-747-400  00:14:47.5  TAXI  SK254  B-747-400  00:14:35.0  TAXI
ML359  Fokker100  00:09:05.5  TURN  YK697  DC-10-30  00:07:30.0  TURN

figure 16.14
figure 16.16

figure 16.17
Arrivals Callsign Type ETA State Departures Callsign Type ETD State
IB373 B-747-400 00:14:47.8 TAXI 85264 B-747-400 00:12:48.0 TAKEOFF

figure 16.18
delay incurred on specific links

figure 16.21
17 Conclusions

The further development of the SIMAST airport surface traffic simulation tool has been aimed at the application of SIMAST as a tool for the evaluation of taxi-planning support tools [20, 27]. Existing movement models for airport surface traffic, developed during a previous thesis assignment [13, 14], have been improved to enable the simulation of all aircraft movements on an airport surface.

The previous version of SIMAST (1.0) used a model of a rather simple single runway airport at Rotterdam, The Netherlands. For validation of the taxi-planning concept and the simulation concept, a more complex airport with multiple runways has been selected. The selected airport is located near Amsterdam, The Netherlands. This airport has been modelled using the geographic airport model [13]. To allow for the increased complexity of the airport, several enhancements have been made to the geographic airport model. Due to its generic design, the resulting model can be used for the simulation of any airport.

The old airport model used by SIMAST, had only one runway, with the taxiway situated between the apron area and the runway. This implicates that runway crossings do not occur on this airport. Furthermore, the traffic flows of arriving and departing flights are practically automatically separated. The complexity of the new airport model, with multiple runways, called for the logic to control traffic flow intersections and runway crossings. This logic had to be introduced in the control model. The implemented control model enables a satisfactory control of airport surface traffic. The traffic is handled automatically on the basis of the "see and avoid" principle. If a conflict is detected on the taxiway system, the control model takes action to resolve the conflict. The model also allows for the separation of aircraft landing and/or taking off from parallel independent runways.

A basic guidance function has been incorporated in the control model. This guidance function tries to minimize the delay of aircraft with respect to their assigned taxi-plans. These taxi-plans specify the route of the aircraft as well as a target time at which the aircraft should arrive at discrete points on the taxiway system. The taxi-plans may be generated manually or with the help of an off-line taxi-planning support tool [27].

The kinematic model incorporated in SIMAST has been enhanced and expanded with new movement phases for runway turnoffs and taxiway turns. The improved kinematic model allows for the simulation of all possible aircraft movements on an airports' surface, except for movements on the apron area.

The animation produced by SIMAST during simulations, has been enhanced to provide the user with a good overview of the simulation run in progress. After completion of a simulation run, a report is generated. This report can be used for the analysis of the simulation run and the supplied taxi-plan as well as for tracking down bottlenecks on the taxiway systems of airports.

The modular design of SIMAST and the flexibility of the software allows for enhancement of the simulator by the addition of new modules, adding new capabilities and improving performance.

109
The developed movement models for airport surface traffic, can be modified stochastically using a monte carlo sampling technique. This provides for a realistic spread in aircraft performance. However, the movement models (the kinematic model, control model and geographic airport model) need to be validated. Until this has been done, the accuracy of the models and the simulation using these models, cannot be estimated.

It is suggested to continue work on the following topics. First of all, the developed movement models need to be validated. This calls for the need of a survey to collect data input parameters with respect to the behaviour of aircraft behaviour on airports. The NLR has recently obtained a collection of such data, with which the movement models could be validated accurately. Unfortunately, the use of this data has been restricted to the NLR for the time being. Secondly, the missing modules in SIMAST can be implemented during further development, taking the limitations of the program, described in the previous chapter, into account. Thirdly, the on-line taxi-planning support tool, which is being developed as part of the joint NLR-DUT/FAE research activities, should be integrated within SIMAST.

Attention could also be directed to the development of a runway-planning function. This function may provide the taxi-planning tools with time targets, serving as objectives, at which aircraft should arrive at the runway. Investigating the possibility of including an air traffic controller and a (pseudo) pilot in the simulation is another option. This real-time simulation would enable the controller and the (pseudo) pilot to respectively control the traffic on the airport surface and an aircraft. Such a simulation could be used to study the interaction of pilot and controller with the taxi-planning support tools.

Finally, models of helicopter movements and aircraft movements around the airport (missed approach, fly-by) need to be developed. The movements of surface vehicles have been modelled [13], but these are not implemented in SIMAST.
18 Literature


24. Swedish, J.W., Some measures of aircraft performance on the airport surface, MIT FTL report R-72-4, Massachusetts Institute of Technology, flight transportation laboratory, May 1972


Appendix A Thesis Assignment

Improvements to Simast

Professor: Prof. Dr. ir. Th. Van Holten
Mentoren TU Delft: Ir. R.M. van der Haagen
Dr. ir. H. G. Visser
Student: Dhr. A. Rodenburg

1 BACKGROUND

Since the beginning of this year (1996) the NLR has been involved in a number of ECARDA projects. Several of these projects are concerned with the development and improvement of a so-called Advanced Surface Movement and Guidance/Control System (A-SMGCS). The purpose of A-SMGCS is to enhance airport ground movement efficiency while at least maintaining current levels of safety, in all weather conditions. Recently also the Faculty of Aerospace Engineering of the TU Delft (TUD/FAE) has joined the A-SMGCS project. As a matter of fact, a prototype fast-time simulator for airport surface traffic, christened SIMAST, has already been developed on behalf of this project in the framework of a thesis assignment. The continued participation of students within the project is encouraged by both the NLR and the TUD. To support the cooperation a project coordinator from the TUD (i.e., ir. Roderick van der Haagen) has been stationed at the NLR. One of the tasks of the project coordinator involves liaison, so that students can remain completely informed on the status of the project and receive appropriate feedback and directions for research. In view of the broad scale of the project, the TUD/FAE activities will not concern every aspect of the project, but will be focussed on two topics:

- The development of simulation tools for surface traffic movement.
- The development of taxi-planning support tools.

The latter topic is within the realm of operations research. Indeed, the purpose of the taxi-planning support tool is to optimize the sequencing and scheduling of traffic, such as to minimize delays and to reduce the number of stops during taxying. In the envisioned concept, the movement of ground traffic should be planned in a conflict-free fashion, some 20 minutes before the involved vehicles/aircraft actually enter the system. We will refer to this as the off-line planning. In contrast, the on-line control concerns an activity primarily based on observations of the current state of the system and performed in a relatively short period of time to allow subsequent interventions on the controlled traffic. In the proposed concept, such an on-line (real-time) re-planning function is also envisaged. At present two thesis assignments are aimed at the development of both an on-line tool (S.G. Knijnenburg) and an off-line tool (M.A.R. van Velthuizen). The taxiplans produced by these planning tools may subsequently serve as inputfiles for the ground movement simulator to be developed within the framework of the present thesis assignment. Needless to say, that a concurrent development of the various tools is highly desirable.
2 THESIS ASSIGNMENT

From the introduction it can be concluded that a simulation program to evaluate the various tools developed in the framework of the A-SMGCS project is of paramount importance. For this reason the present thesis assignment is directed towards the continued development of the SIMAST ground movement simulation tool.

SIMAST was originally conceived as a basic tool only for the evaluation and testing of new features of the A-SMGCS (notably the taxi planning function) but also as a basis for synthetic aircraft generation within tower visual simulators. It is important to realize that both applications bring about different requirements for ground movement simulator capabilities. In its present state of development, SIMAST is perhaps better equipped to facilitate the testing of taxi planning functions rather than to serve as a synthetic traffic generator for the tower visual simulator. One of the main reasons for this is that at present SIMAST is configured as a fast-time batch simulator. All aircraft are processed according to their pre-defined flight (taxi) plans, and when separation conflicts arise, these are automatically detected and resolved. In other words, SIMAST operates autonomously, essentially responding on the basis of the "see-and-avoid principle". For the tower visual simulation function it is required that SIMAST can be operated in a real-time mode, with the human-in-the-loop (i.e., controllers and pilots) providing and/or executing taxiing directives.

A second shortcoming of SIMAST for tower visual simulation relates to the limited graphical (animation) capabilities. Although a very useful prototype traffic display has been developed for SIMAST, which can potentially serve as a basis for future (moving) map display in the tower and/or cockpit, the overall required graphical capabilities go well beyond this particular device. Indeed, the overall animated view from the tower and cockpit needs to be generated, including possible A-SMGCS features (e.g., airfield lighting and other visual aids for guidance along the route).

The shortcomings of SIMAST, along with suggestions for improvements and extensions to overcome these shortcomings are described in great detail in Refs. 2 and 3. These suggestions can be exploited in the present assignment as guidelines for continued development of the ground movement simulation program SIMAST, especially with respect to enhancing the capabilities for assessing A-SMGCS taxi planning functions. To support this development, a similar package, named SIMMOD (developed by the FAA), has also been recently acquired. It is suggested that SIMAST should be equipped with at least the same capabilities as SIMMOD. Note that unlike SIMAST, SIMMOD is available as an executable only, and therefore cannot be modified or expanded.

The improvements and extensions suggested in REF. 3 can probably not all be realized within the framework of a single thesis assignment. Depending on the outcome of the results, the speed of progress and personal preference, a suitable selection of topics can be made. If so desired, attention can be directed to the tower visual simulator application. In this respect the objective is to integrate SIMAST within FLIGHT, which is a flight simulator with an animated view from either the cockpit or the control tower, and available in C code on a silicon graphics workstation. Of course the graphics of FLIGHT also need to be customized to facilitate the envisioned application. the results reported in REF. 5 indicate that such an adaption of the
graphics is certainly feasible. In order to properly model pilot/controller behaviour, also the dynamics implemented in FLIGHT need to be refined. It is proposed to utilize the technique described in REF. 6 for this purpose. The primary benefit of this technique is that it allows to simulate traffic movements with the fidelity of a higher order-model (e.g., 6-DOF model), yet with the computational burden of a low-order model (e.g., a point-mass model).

Since the SIMAST code is written in C language, it is recommended to use this particular language also for the present assignment. The thesis assignment is to be concluded with a comprehensive report written in English. In view of the fact that the assignment is carried out in the framework of a joint project, intermediate reports and/or presentations may be requested by the project coordinator.

3 REFERENCES

Appendix B The Monte Carlo Sampling Algorithm

The following algorithm [Fishman] may be used to generate samples for a parameter which can be approximated by a normal distribution.

Algorithm 1:

At compilation time set a flag \( F \) to 1.
Execution:
\( F = -F \)
if (\( F > 0 \))
\[ \text{return } Z = X \]
Randomly generate \( U \) from the uniform distribution \( U(0,1) \) using expression (13.4)
if (\( U < 0.5 \))
\[ B=0 \]
else
\[ B=1 \]
Randomly generate \( V \) from the exponential distribution \( \mathcal{E}(1) \), using algorithm 2
\[ S = V + V \]
Randomly generate \( W \) from the non-central Cauchy distribution \( \mathcal{C}(0,1) \), using algorithm 3
\[ Z = \sqrt{S(1 + W^2)} \]
\[ X = WZ \]
if (\( B = 0 \))
\[ \text{return } Z \]
else
\[ \text{return } -Z \]

Algorithm 2:
Generate \( W \) randomly from the exponential distribution \( \mathcal{E}(1) \)

\[ q = 0.6931471805599453; \]
\[ b = 1.4142135623730950; \]
\[ p = 0.9802581434685472; \]
\[ B = 3.3468106480569850; \]
\[ D = 0.0587864376269050; \]
\[ a = 5.7133631526454228; \]
\[ c = -5.6005707569738080; \]
\[ A = 5.6005707569738080; \]
\[ H = 0.0026106723602095; \]

Randomly generate \( U \) from the uniform distribution \( U(0,1) \) using expression (13.4)
\[ K = c \]
\[ U = U + U \]
while (\( U < 1 \))
\[
\begin{cases} 
  U = U + U 
\end{cases}
\]

117
K = K + q

U = U - 1
if (U ≤ p)
    return V = K + A/(B - U)
while ( [UH + D] [b-U]² > e^{(Y + φ)})
{
    Randomly generate U and U' from Ξ(0,1)
    Y = a/(b - U)
}
return V = K + Y

**Algorithm 3:**
Generate W randomly from the non-central Cauchy distribution Θ(0,1)

\[ a = 0.6380631366077803; \]
\[ q = 0.9339962957603656; \]
\[ A = 0.6366197723675813; \]
\[ H = 0.0214949004570452; \]
\[ b = 0.5959486060529070; \]
\[ W = 0.2488702280083481; \]
\[ B = 0.5972997593539963; \]
\[ P = 4.9125013953033204; \]

Randomly generate U from the uniform distribution Ξ(0,1) using expression (13.4)
T = U - 0.5
S = w - T²
if (S > 0)
    return W = T(A/S + B)
while ( S²[(1 + W²)(HU' + P) - q] + S > 0.5 )
{
    T = U - 0.5
    S = 0.25 - T²
    W = T(a/S + b)
}
return W
Appendix C The SIMAST (2.0) Software Design

This appendix describes the software design of SIMAST (2.0). The design is explained by the use of flowcharts, which graphically show how the program works. The flowcharts in this chapter have been used for the actual software implementation of SIMAST (2.0). The software itself has been written in ANSI-C where possible to provide portability. The routines which have to do with graphics or mouse control are not portable due to the machine dependency of graphics operations and mouse communication.

During the simulation the aircraft move over the airport surface according to kinematic models developed during a previous thesis assignment [13, 14]. The aircraft kinematic models are under the direct control of the control model, which emulates ATC control and pilot control. The ATC control comprises conflict handling on the taxiway system and sequencing and scheduling of departures and arrivals. The pilot control comprises movement during takeoff, landing and taxiing at a constant speed over the airport surface, modelled by the geographic airport model, along an assigned taxiroute. The pilot control and ATC control are established on the basis of input parameters, such as minimum separation requirements and reaction speeds.

The execution of the program starts with the module main, described in figure C1. This module makes consecutive calls to other modules, which after being executed return control of the program back to the main module.

The first call made by main is to the module init, which is shown in figure C2. This module defines and initialises the constants and global variables and assigns memory to store the variables in. Thereafter, the input data files are opened and read, storing the input data into the appropriate variables. If the module is finished, control is returned to the main module, which makes the next call to the convert_plan module (figure C3).

The taxi plans for the various aircraft in the simulation are defined in one of the input files as a series of nodes, describing the taxi path from the apron exit up to the runway entry or vice versa. This is a convenient way for the human operator and the taxi-planning support tool to define a taxi path, but during program execution it has its advantages to define the taxi path as a series of links, each with its own specific characteristics. The convert_plan module translates the taxiplan from a series of nodes into a series of links and also adds the runway links to the taxiplan. If this module has performed its duties, the control is once more returned to the main module. The main module now frees any memory which was reserved for data, which is no longer needed such as the taxiplan in the form of a series of nodes.

The next step is to determine whether or not the graphics screen should be initialised. In the initialization file simast.ini, one may ask for the graphics screen to be turned on or off. A simulation run can be executed much faster with the graphics turned off. If the graphics have been turned on, the airport is plotted as a background for the aircraft movements, the simulation clock is initiated and shown on the screen and it is checked, if a mouse driver is present. If so, the mouse is activated. If the mouse driver is not present, the main module calls for the cleanup module (figure C4), which displays an error message and exits the program, aborting the simulation.
Now that the simulation has been initiated, the actual control loop of the program is called upon. This is the timer module (figures C5 a,b,c). The inner loop of this module processes all the aircraft in the system. At the start of the simulation (time = 0), all aircraft are assigned their specific parameters (position, taxi speed, braking performance,...) via a call to the module newpln (figure C6). Various of these parameters may be passed as mean values to the module normal (figure C7) together with a standard deviation. The normal module generates variates based on the normal distribution to create a realistic spread in aircraft performance. These variates are generated for the aircraft taxiing speed, threshold crossing altitude for arrivals, the flight path angle during the approach, the rate of deceleration during the landing ground roll, the flight path angle at lift-off, the rate of acceleration during the takeoff ground run and the aircraft weight. Consecutively the module getturn is called if the aircraft is a departure. The getturn module (figure C8) is called to calculate the position of the first turn.

Aircraft are dormant until they enter the airport system and are activated. For arrivals this is when the simulation time is equal to or exceeds the aircraft's ETA. If the aircraft is to be activated, arrivals are handed over to the landsq module by changing their state to landseq. Departures are activated, when they enter the taxiway system. This time is dictated in the taxi plan. Upon entering the taxiway system, the state of departures is changed from newpln into accel, to allow for acceleration up to the taxi speed.

If the aircraft is an arrival and according to its ETA is about to land, the module landseq (figure C9) is called. The landseq module checks whether the assigned runway is clear for landing and ensures that appropriate minimum separation between consecutive aircraft is maintained. If possible, the arriving aircraft is given landing clearance. Otherwise, the flight will be delayed until it is safe to land the aircraft. If the aircraft has received landing clearance, its state is changed from landseq to landing.

When an aircraft receives landing clearance, the land module is called upon by the timer module. The land module (figure C10) moves the aircraft along the runway according to the movement models developed earlier [13, 14]. The module convert_plan has already determined whether the aircraft will be using a high-speed exit or a normal one. If the aircraft vacates the runway via a normal exit, the aircraft’s state is changed to taxi. If the aircraft uses a high-speed exit to vacate the runway, then the state of the aircraft will be changed to decel to decelerate the aircraft until it reaches its taxiing speed. After reaching the taxiing speed, the state of the aircraft will be changed to taxi.

Departing aircraft will start to accelerate up to their taxiing speed upon entering the taxiway system. If this speed has been reached, the state of the aircraft will be changed to taxi. For aircraft with state taxi, timer will call upon the module taxi (figure C11 a,b). This module moves the aircraft along its assigned taxiroute according to the previously developed movement models [13, 14]. If a departing aircraft is close to its assigned departure runway and it has not received a takeoff clearance yet, the state of the aircraft will be changed to decel, to come to a full stop near the stopbar at the runway entry point. If the aircraft has received takeoff clearance, it will continue to taxi until it has reached the runway surface. Upon reaching the runway surface, the aircraft state is changed to decel to come to a full stop. The taxi module also moves arriving aircraft along their assigned taxiroute over the taxiway system. When the aircraft reaches the apron entry point, its state is changed to outsim and the aircraft leaves the
During the simulation, the timer module calls the module `get_speed` (figure C12) for every aircraft at every time step. This module checks if the aircraft’s taxing speed is in compliance with the taxi plan assigned to the aircraft. If not, the state of the aircraft is changed (accel or decel) to adjust the taxing speed.

While the aircraft are taxing over the taxiway system, they may have to cross runways. The module `crossing_near` (figure C13) detects such crossings and changes the state of the aircraft to decel, so that it will come to a full stop before crossing the runway, preventing any runway incursions.

The module decel decelerates the aircraft and moves it to the next position according to movement models developed earlier [13, 14]. If the aircraft has come to a full stop, dependent upon the situation, the state of the aircraft may be changed to hold, rwy-crossing, lineup or takeoff. Aircraft that are at a runway crossing will be given the state `rwy-cross`. If a departure comes to a full stop at the assigned runway, it will be given the state `lineup`. The state of aircraft on the runway will be changed to `takeoff`, once their taxispeed has been reduced to zero. In any other case that an aircraft comes to a full stop, the state of the aircraft will be set to `hold`. The module is depicted in figure C14.

The module `turn_near` (figure C15) detects if an aircraft is close to a taxiway turn. If so, the state of the aircraft is changed to `turn`, to allow the aircraft to slow down and negate the taxiway turn at a safe speed. The module `turn` is shown in figure C16.

The module which controls whether or not an aircraft can cross a runway is called `rwy-cross` and is shown in figure 17. The `rwy-cross` module checks if any departures are about to takeoff from the runway to be crossed and if so, if they’re held long enough to allow crossing. If this is not the case, the aircraft will have to wait before it can cross the runway. Another check is made to ensure that there are no arrivals about to land on the runway to be crossed, and if there are, if there is enough time to safely cross th runway. If it is not safe to cross the runway, the aircraft will have to delay crossing. Otherwise, the aircraft’s state will be changed to `accel` and the aircraft will cross the runway.

If the state of the aircraft is equal to `accel`, the timer module calls for the `accel` module. This module moves and accelerates the aircraft along its assigned taxiroute according to the movement models previously described. The module is depicted in figure C18. If the taxispeed of the aircraft is reached, the state of the aircraft is changed to `taxi`.

If the timer module encounters a departure with state `lineup`, it calls for the `toseq` module (figure C19). The state `lineup` means that the aircraft has reached the entry point to the departure runway. This module checks whether the runway is clear for takeoff and if the separation to the previous departure is satisfactory according to the rules described in section 11.2. It is also checked to see if any arrivals are on final approach for the departure runway. If this is the case, the departure is held, since arrivals are given full preference. Otherwise, the aircraft is granted takeoff clearance and the state of the aircraft is set to `accel`, allowing the aircraft to taxi onto the runway.
Once on the runway, the departing aircraft will come to a full stop before starting its takeoff run by a change of aircraft state to takeoff. For aircraft with state takeoff, the timer module calls the takeoff module (figure C20). This module will move the aircraft along the takeoff path, according to the movement models [13, 14]. If two minutes have passed since takeoff, the state of the aircraft is set to outsim and the aircraft is removed from the simulation.

If the minimum separation between two aircraft on the taxiway system (section 11.1) is not maintained, a conflict occurs. The conpred module checks for these conflicts and resolves them by changing the state of (one of) the aircraft involved. The module is shown in figure C21.

When all the aircraft in the simulation have been processed, control is returned to the outer loop of the timer module. Consecutive calls are made to the modules mouse, plot and print. The mouse module (figure C22) checks for mouse action, which is used to zoom in and out on the graphics screen. The module plot (figure C23) displays all the aircraft, present in the simulation, on the screen. The module print (figure C24) displays the flight information on the screen.

If there are no more aircraft left in the simulation, control of the program is returned to the main module. Otherwise the timer module continues to execute until all the aircraft have left the simulation. At the end of every timestep, the timer module checks for any keyboard hits. The keyboard may be used to influence the speed of the simulation or the flight information displayed.

After the timer module has returned control of the program to the main module, a call is made to the module cleanup, which displays a message on the screen and closes the graphics screen after which control is returned to the main module. The next call to the output module (figure 25) takes care of the creation of an output file, with information about the simulation run for analysis purposes.
main

- call init
- call convert_plan

free memory no longer needed

- graphics on?
  - yes: plot airport
  - no: call cleanup (no_mouse)

- show simulation clock

- mouse driver present?
  - no: call cleanup (no_mouse)
  - yes: activate mouse and set limits for mouse movement

- call timer
- call cleanup (execution successful)
- call output

stop

Figure C1: The main module
figure C2 The module init

Define function prototypes
Define constants and global variables
Initialise global variables
Read input data files

return

figure C3 The module convert_plan

convert taxiplan from a series of nodes to a series of links

return

figure C4 The module cleanup

cleanup

close graphics screen and display error messages if an error has occurred

return
Figure C5a: The module timer
figure C5b The module timer (continued)
figure C5c The module timer (continued)
figure C6 The module newpln
**Figure C7** The module `normal`

**Figure C8** The module `getturn`
figure C9 The module landseq
**figure C10** The module land

**figure C11a** The module taxi
figure C11b The module taxi (continued)
figure C12 The module get_speed
figure C13 The module crossing_near

crossing near

does the end of the current link intersect with a runway?

no

yes

calculate aircraft's distance to runway intersection

calculate distance needed to come to a full stop

dist to intersection <= dist needed to stop

no

yes

aircraft state = decel

return
figure C14 The module decel

figure C15 The module turn_near
figure C16 The turn module

figure C18 The module accel
figure C17 The module rwycross
Figure C19: The module toseq
**figure C20** The takeoff module

**figure C21** The conpred module
figure C22 The module mouse

left mouse key down?

yes

get coordinates of zoom window and calculate new zoom factor

return

no

right mouse key down?

yes

reduce zoom factor to the previous lower zoom factor

no

figure C23 The module plot

plot

plot the airport and each aircraft in the simulation

return

figure C24 The module print

print

print relevant information for each aircraft in the simulation

return

figure C25 The module output

output

create data output file and write the output parameters to this file

return
Appendix D Data Input Parameters

The program uses various sets of data input parameters, amongst others with respect to the airport model, kinematic aircraft model, ATC procedures, flights schedules and taxi routes. In total, 9 data input files have been defined, which will be introduced in the following paragraphs. These data files may be created with any editor, keeping the following considerations in mind:

- the files should be in ASCII format;
- comment lines should start with /* and end with */ and are only allowed at the start of the file and not in between the data;
- void lines are not allowed in the input files. If there is a void line in an input file, this may cause errors during program execution;
- consecutive parameters on one line may be separated with an arbitrary number of spaces. The examples of input files in this section may contain multiple comment lines at the top of the pages, in between data. However, this is not allowed in the actual input files.

D.1 Geographic Airport Model Input Data Parameters

The parameters with respect to the geographic airport model are located in three different files. These files contain the node coordinates, link and runway specific information. The coordinates of all the nodes, defining the airport layout and the radius of curvature at each node are given in the NODES.DAT file (table D1). The links connecting the nodes on the airport surface are defined in the LINKS.DAT file (table D2). This file describes the type of link (RWY, TXI, HSX), end and start node of all the links on the airport surface and the maximum speed allowed on the links in consecutive columns. Finally, the runways are defined in the RUNWAY.DAT file (table D3). This file describes the runways with their designation (e.g. 19L) and the nodes which define the runway.

D.2 Airport Meteo Input Parameters

Parameters with respect to the environmental conditions on the airport are placed in the METEO.DAT file (table D4). Information about the windspeed, air density, the runway surface condition (wet or dry) and the coefficient of rolling friction is given in this file.

D.3 Aircraft Type Specific Parameters

The file AICRTYPE.DAT (table D5) contains information with respect to various type of aircraft. The parameters in this file have already been defined in table 10.1. This table defines the following parameters in consecutive columns for the various aircraft types: aircraft type, wake turbulence category, engine type, number of engines, takeoff thrust per engine, bypass ratio of the engines, Operational Empty Weight (OEW), Maximum Landing Weight (MLW), Maximum TakeOff Weight (MTOW), aspect ratio of the wing, the area of the wing, the landing run distance as specified by the manufacturer, the takeoff distance, the average tire pressure, the maximum lift coefficient during takeoff, the maximum coefficient of lift during the landing, the average rate of acceleration on the taxiway system and the average deceleration rate on the taxiway system.
D.3 Piloting Technique Parameters
Due to lack of information, the parameters with respect to the piloting technique are independent of the type of aircraft or carrier. These parameters are defined in the PILOT.DAT file (table D6), detailing information about: duration of the first and second free roll segment, aircraft turning speed (currently not actually used during simulation), takeoff height at which the takeoff run is considered complete, the standard deviation of this height, the threshold crossing altitude during the landing, the standard deviation of the threshold crossing altitude, flight-path angle during final approach, standard deviation of the flight-path angle during final approach, the load factor during the takeoff flare, the load factor during the landing flare, the landing weight factor, the standard deviation of the landing weight factor, the takeoff weight factor and its standard deviation.

D.4 Flight Plan Parameters
The flightplan details information about the flights in the simulation run. This information is placed in the FLTPLANS.DAT file (table D7). It describes the callsign, type of aircraft, bound (arrival or departure), the assigned runway and the assigned taxiroute (defined in the ROUTES.DAT file) for each flight in the simulation run.

D.5 Taxiplan Parameters
The file ROUTES.DAT describes a taxiroute for all the aircraft in the simulation run. This means that at least as many taxiroutes need to be defined as there are aircraft present in the simulation. The ROUTES.DAT file (table D8) describes the path to be followed by the aircraft as a series of nodes (defined in the NODES.DAT file). The second line of a taxiroute dictates the time at which an aircraft should reach the node described one row up in the same column.

D.6 Parameters Concerning Air Traffic Control
The parameters with respect to the ATC can be found in the ATC.DAT file (table D9). This file defines minimum separation criteria for VFR and IFR flights for both arrivals and departures. These minimum separation criteria have been defined in tables 11.4 and 11.5. The minimum longitudinal ($S_{L} + S_{E} + S_{MIN}$) and lateral separations as described in section 11.1.1 and 11.1.2 are also defined in this file.

D.7 Simulation initialization Parameters
The SIMAST.INI file (table D10) contains information which influences the simulation. This file allows the user to switch the simulation graphics on or off. Without graphics output, the simulation will run much faster. This file also defines the amount of time aircraft are allowed to deviate from their taxiplan as defined in the ROUTES.DAT file. The speed of the aircraft depends on the taxiplan (section 12.3). The deviation of the taxispeed of the aircraft from the "ideal speed" of the aircraft with respect to the taxiplan is defined in the SIMAST.INI file. Finally, the total system response in the case of possible conflicts on the taxiway system time is defined here.
<table>
<thead>
<tr>
<th>/*node /*number</th>
<th>x-position (m)</th>
<th>y-position (m)</th>
<th>radius of curvature (m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>2852</td>
<td>1735</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>2755</td>
<td>203</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>2971</td>
<td>3601</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>1408</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>187</td>
<td>4711</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>569</td>
<td>3090</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>579</td>
<td>2971</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>3979</td>
<td>3303</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>3213</td>
<td>1327</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>4529</td>
<td>2870</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>2949</td>
<td>3231</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>94</td>
<td>1422</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>2726</td>
<td>1710</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>2901</td>
<td>3596</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>76</td>
<td>2071</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>2380</td>
<td>1755</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>99</td>
<td>2610</td>
<td>30</td>
</tr>
<tr>
<td>18</td>
<td>123</td>
<td>3179</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>2881</td>
<td>2221</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>2908</td>
<td>2615</td>
<td>30</td>
</tr>
<tr>
<td>21</td>
<td>2919</td>
<td>2769</td>
<td>30</td>
</tr>
<tr>
<td>22</td>
<td>2798</td>
<td>888</td>
<td>30</td>
</tr>
<tr>
<td>23</td>
<td>1438</td>
<td>865</td>
<td>30</td>
</tr>
<tr>
<td>24</td>
<td>1980</td>
<td>1191</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>2456</td>
<td>1495</td>
<td>30</td>
</tr>
<tr>
<td>26</td>
<td>2740</td>
<td>1661</td>
<td>30</td>
</tr>
<tr>
<td>27</td>
<td>1741</td>
<td>3165</td>
<td>30</td>
</tr>
<tr>
<td>28</td>
<td>2080</td>
<td>3184</td>
<td>30</td>
</tr>
<tr>
<td>29</td>
<td>2258</td>
<td>3195</td>
<td>30</td>
</tr>
<tr>
<td>Node</td>
<td>x-position (m)</td>
<td>y-position (m)</td>
<td>Radius of curvature (m)</td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
<td>---------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>30</td>
<td>582</td>
<td>2886</td>
<td>30</td>
</tr>
<tr>
<td>31</td>
<td>1132</td>
<td>2922</td>
<td>30</td>
</tr>
<tr>
<td>32</td>
<td>2792</td>
<td>3440</td>
<td>30</td>
</tr>
<tr>
<td>33</td>
<td>2780</td>
<td>3221</td>
<td>30</td>
</tr>
<tr>
<td>34</td>
<td>2299</td>
<td>1703</td>
<td>30</td>
</tr>
<tr>
<td>35</td>
<td>293</td>
<td>2875</td>
<td>30</td>
</tr>
<tr>
<td>36</td>
<td>193</td>
<td>2445</td>
<td>30</td>
</tr>
<tr>
<td>37</td>
<td>274</td>
<td>2466</td>
<td>30</td>
</tr>
<tr>
<td>38</td>
<td>292</td>
<td>2783</td>
<td>30</td>
</tr>
<tr>
<td>39</td>
<td>266</td>
<td>2307</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>163</td>
<td>1881</td>
<td>30</td>
</tr>
<tr>
<td>41</td>
<td>258</td>
<td>1918</td>
<td>30</td>
</tr>
<tr>
<td>42</td>
<td>242</td>
<td>1728</td>
<td>30</td>
</tr>
<tr>
<td>43</td>
<td>229</td>
<td>1592</td>
<td>30</td>
</tr>
<tr>
<td>44</td>
<td>371</td>
<td>1629</td>
<td>30</td>
</tr>
<tr>
<td>45</td>
<td>214</td>
<td>1466</td>
<td>30</td>
</tr>
<tr>
<td>46</td>
<td>1175</td>
<td>984</td>
<td>30</td>
</tr>
<tr>
<td>47</td>
<td>1099</td>
<td>1025</td>
<td>30</td>
</tr>
<tr>
<td>48</td>
<td>1399</td>
<td>1210</td>
<td>30</td>
</tr>
<tr>
<td>49</td>
<td>1075</td>
<td>931</td>
<td>30</td>
</tr>
<tr>
<td>50</td>
<td>1540</td>
<td>1296</td>
<td>30</td>
</tr>
<tr>
<td>51</td>
<td>1727</td>
<td>1424</td>
<td>30</td>
</tr>
<tr>
<td>52</td>
<td>1975</td>
<td>1579</td>
<td>30</td>
</tr>
<tr>
<td>53</td>
<td>1562</td>
<td>1213</td>
<td>30</td>
</tr>
<tr>
<td>54</td>
<td>2099</td>
<td>1552</td>
<td>30</td>
</tr>
<tr>
<td>55</td>
<td>2081</td>
<td>1651</td>
<td>30</td>
</tr>
<tr>
<td>56</td>
<td>2257</td>
<td>1774</td>
<td>30</td>
</tr>
<tr>
<td>57</td>
<td>1523</td>
<td>2863</td>
<td>30</td>
</tr>
<tr>
<td>58</td>
<td>1415</td>
<td>2856</td>
<td>30</td>
</tr>
<tr>
<td>59</td>
<td>1145</td>
<td>2838</td>
<td>30</td>
</tr>
<tr>
<td>/*node */number</td>
<td>x-position (m)</td>
<td>y-position (m)</td>
<td>radius of */ curvature (m) */</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>60</td>
<td>597</td>
<td>2803</td>
<td>30</td>
</tr>
<tr>
<td>61</td>
<td>1405</td>
<td>2944</td>
<td>30</td>
</tr>
<tr>
<td>62</td>
<td>1594</td>
<td>2957</td>
<td>30</td>
</tr>
<tr>
<td>63</td>
<td>1790</td>
<td>2969</td>
<td>30</td>
</tr>
<tr>
<td>64</td>
<td>2565</td>
<td>1736</td>
<td>30</td>
</tr>
<tr>
<td>65</td>
<td>2516</td>
<td>1838</td>
<td>30</td>
</tr>
<tr>
<td>66</td>
<td>1567</td>
<td>3054</td>
<td>30</td>
</tr>
<tr>
<td>67</td>
<td>2169</td>
<td>3128</td>
<td>30</td>
</tr>
<tr>
<td>68</td>
<td>1977</td>
<td>2992</td>
<td>30</td>
</tr>
<tr>
<td>69</td>
<td>2417</td>
<td>2991</td>
<td>30</td>
</tr>
<tr>
<td>70</td>
<td>1523</td>
<td>2952</td>
<td>30</td>
</tr>
<tr>
<td>71</td>
<td>2633</td>
<td>1908</td>
<td>30</td>
</tr>
<tr>
<td>72</td>
<td>2688</td>
<td>1968</td>
<td>30</td>
</tr>
<tr>
<td>73</td>
<td>2339</td>
<td>1835</td>
<td>30</td>
</tr>
<tr>
<td>74</td>
<td>2460</td>
<td>1913</td>
<td>30</td>
</tr>
<tr>
<td>75</td>
<td>2582</td>
<td>1978</td>
<td>30</td>
</tr>
<tr>
<td>76</td>
<td>2583</td>
<td>2194</td>
<td>30</td>
</tr>
<tr>
<td>77</td>
<td>2584</td>
<td>2392</td>
<td>30</td>
</tr>
<tr>
<td>78</td>
<td>2588</td>
<td>2534</td>
<td>30</td>
</tr>
<tr>
<td>79</td>
<td>2392</td>
<td>2536</td>
<td>30</td>
</tr>
<tr>
<td>80</td>
<td>2696</td>
<td>2630</td>
<td>30</td>
</tr>
<tr>
<td>81</td>
<td>2694</td>
<td>2394</td>
<td>30</td>
</tr>
<tr>
<td>82</td>
<td>2694</td>
<td>2526</td>
<td>30</td>
</tr>
<tr>
<td>83</td>
<td>2684</td>
<td>2179</td>
<td>30</td>
</tr>
<tr>
<td>84</td>
<td>2485</td>
<td>2631</td>
<td>30</td>
</tr>
<tr>
<td>85</td>
<td>2400</td>
<td>2721</td>
<td>30</td>
</tr>
<tr>
<td>86</td>
<td>2406</td>
<td>2816</td>
<td>30</td>
</tr>
<tr>
<td>87</td>
<td>2339</td>
<td>2780</td>
<td>30</td>
</tr>
<tr>
<td>88</td>
<td>1889</td>
<td>2872</td>
<td>30</td>
</tr>
<tr>
<td>89</td>
<td>3050</td>
<td>2775</td>
<td>30</td>
</tr>
<tr>
<td>node number</td>
<td>x-position (m)</td>
<td>y-position (m)</td>
<td>radius of curvature (m)</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>90</td>
<td>3084</td>
<td>2651</td>
<td>30</td>
</tr>
<tr>
<td>91</td>
<td>3417</td>
<td>2801</td>
<td>30</td>
</tr>
<tr>
<td>92</td>
<td>3987</td>
<td>2837</td>
<td>30</td>
</tr>
<tr>
<td>93</td>
<td>4003</td>
<td>2986</td>
<td>30</td>
</tr>
<tr>
<td>94</td>
<td>3992</td>
<td>3145</td>
<td>30</td>
</tr>
<tr>
<td>95</td>
<td>2174</td>
<td>2672</td>
<td>30</td>
</tr>
<tr>
<td>96</td>
<td>1639</td>
<td>2866</td>
<td>30</td>
</tr>
<tr>
<td>97</td>
<td>1728</td>
<td>2870</td>
<td>30</td>
</tr>
<tr>
<td>98</td>
<td>2136</td>
<td>1690</td>
<td>30</td>
</tr>
<tr>
<td>99</td>
<td>793</td>
<td>871</td>
<td>30</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>525</td>
<td>30</td>
</tr>
<tr>
<td>101</td>
<td>2705</td>
<td>1788</td>
<td>30</td>
</tr>
<tr>
<td>102</td>
<td>165</td>
<td>1453</td>
<td>30</td>
</tr>
<tr>
<td>103</td>
<td>881</td>
<td>826</td>
<td>30</td>
</tr>
<tr>
<td>104</td>
<td>1355</td>
<td>1302</td>
<td>30</td>
</tr>
<tr>
<td>105</td>
<td>1503</td>
<td>1380</td>
<td>30</td>
</tr>
<tr>
<td>106</td>
<td>1674</td>
<td>1490</td>
<td>30</td>
</tr>
<tr>
<td>107</td>
<td>1913</td>
<td>1698</td>
<td>30</td>
</tr>
<tr>
<td>108</td>
<td>2026</td>
<td>1757</td>
<td>30</td>
</tr>
<tr>
<td>109</td>
<td>2203</td>
<td>1882</td>
<td>30</td>
</tr>
<tr>
<td>110</td>
<td>2270</td>
<td>1974</td>
<td>30</td>
</tr>
<tr>
<td>111</td>
<td>2429</td>
<td>1962</td>
<td>30</td>
</tr>
<tr>
<td>112</td>
<td>2496</td>
<td>2209</td>
<td>30</td>
</tr>
<tr>
<td>113</td>
<td>2457</td>
<td>2404</td>
<td>30</td>
</tr>
<tr>
<td>114</td>
<td>2124</td>
<td>2608</td>
<td>30</td>
</tr>
<tr>
<td>115</td>
<td>1152</td>
<td>2731</td>
<td>30</td>
</tr>
<tr>
<td>116</td>
<td>1527</td>
<td>2770</td>
<td>30</td>
</tr>
<tr>
<td>117</td>
<td>1851</td>
<td>2811</td>
<td>30</td>
</tr>
<tr>
<td>118</td>
<td>320</td>
<td>3588</td>
<td>30</td>
</tr>
<tr>
<td>119</td>
<td>340</td>
<td>4234</td>
<td>30</td>
</tr>
<tr>
<td>node number</td>
<td>x-position (m)</td>
<td>y-position (m)</td>
<td>radius of curvature (m)</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>----------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>120</td>
<td>357</td>
<td>4700</td>
<td>30</td>
</tr>
<tr>
<td>121</td>
<td>272</td>
<td>4284</td>
<td>30</td>
</tr>
<tr>
<td>122</td>
<td>170</td>
<td>4149</td>
<td>30</td>
</tr>
<tr>
<td>123</td>
<td>150</td>
<td>3599</td>
<td>30</td>
</tr>
<tr>
<td>124</td>
<td>539</td>
<td>323</td>
<td>30</td>
</tr>
<tr>
<td>link/*number</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>0</td>
<td>RWY</td>
<td>0</td>
<td>124</td>
</tr>
<tr>
<td>1</td>
<td>RWY</td>
<td>124</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>RWY</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>RWY</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>RWY</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>RWY</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>RWY</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>RWY</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>RWY</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>RWY</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>10</td>
<td>RWY</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>RWY</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>RWY</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>RWY</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>14</td>
<td>RWY</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>15</td>
<td>RWY</td>
<td>18</td>
<td>123</td>
</tr>
<tr>
<td>16</td>
<td>RWY</td>
<td>123</td>
<td>122</td>
</tr>
<tr>
<td>17</td>
<td>RWY</td>
<td>122</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>RWY</td>
<td>6</td>
<td>27</td>
</tr>
<tr>
<td>19</td>
<td>RWY</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>20</td>
<td>RWY</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>21</td>
<td>RWY</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>22</td>
<td>RWY</td>
<td>33</td>
<td>11</td>
</tr>
<tr>
<td>23</td>
<td>RWY</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>24</td>
<td>RWY</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>TXI</td>
<td>100</td>
<td>103</td>
</tr>
<tr>
<td>26</td>
<td>TXI</td>
<td>103</td>
<td>49</td>
</tr>
<tr>
<td>27</td>
<td>TXI</td>
<td>49</td>
<td>46</td>
</tr>
<tr>
<td>28</td>
<td>TXI</td>
<td>46</td>
<td>53</td>
</tr>
<tr>
<td>29</td>
<td>TXI</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>/<em>link</em>/</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>30</td>
<td>TXI</td>
<td>54</td>
<td>34</td>
</tr>
<tr>
<td>31</td>
<td>TXI</td>
<td>34</td>
<td>16</td>
</tr>
<tr>
<td>32</td>
<td>TXI</td>
<td>16</td>
<td>65</td>
</tr>
<tr>
<td>33</td>
<td>TXI</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td>34</td>
<td>TXI</td>
<td>71</td>
<td>72</td>
</tr>
<tr>
<td>35</td>
<td>TXI</td>
<td>72</td>
<td>83</td>
</tr>
<tr>
<td>36</td>
<td>TXI</td>
<td>83</td>
<td>81</td>
</tr>
<tr>
<td>37</td>
<td>TXI</td>
<td>81</td>
<td>82</td>
</tr>
<tr>
<td>38</td>
<td>TXI</td>
<td>82</td>
<td>80</td>
</tr>
<tr>
<td>39</td>
<td>TXI</td>
<td>80</td>
<td>21</td>
</tr>
<tr>
<td>40</td>
<td>TXI</td>
<td>21</td>
<td>89</td>
</tr>
<tr>
<td>41</td>
<td>TXI</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>42</td>
<td>TXI</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>43</td>
<td>TXI</td>
<td>92</td>
<td>93</td>
</tr>
<tr>
<td>44</td>
<td>TXI</td>
<td>93</td>
<td>94</td>
</tr>
<tr>
<td>45</td>
<td>TXI</td>
<td>94</td>
<td>8</td>
</tr>
<tr>
<td>46</td>
<td>TXI</td>
<td>89</td>
<td>90</td>
</tr>
<tr>
<td>47</td>
<td>TXI</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>48</td>
<td>TXI</td>
<td>49</td>
<td>47</td>
</tr>
<tr>
<td>49</td>
<td>TXI</td>
<td>46</td>
<td>47</td>
</tr>
<tr>
<td>50</td>
<td>TXI</td>
<td>53</td>
<td>50</td>
</tr>
<tr>
<td>51</td>
<td>TXI</td>
<td>55</td>
<td>54</td>
</tr>
<tr>
<td>52</td>
<td>TXI</td>
<td>34</td>
<td>56</td>
</tr>
<tr>
<td>53</td>
<td>TXI</td>
<td>16</td>
<td>73</td>
</tr>
<tr>
<td>54</td>
<td>TXI</td>
<td>65</td>
<td>74</td>
</tr>
<tr>
<td>55</td>
<td>TXI</td>
<td>71</td>
<td>75</td>
</tr>
<tr>
<td>56</td>
<td>TXI</td>
<td>76</td>
<td>83</td>
</tr>
<tr>
<td>57</td>
<td>TXI</td>
<td>77</td>
<td>81</td>
</tr>
<tr>
<td>58</td>
<td>TXI</td>
<td>78</td>
<td>82</td>
</tr>
<tr>
<td>59</td>
<td>TXI</td>
<td>78</td>
<td>84</td>
</tr>
<tr>
<td>link number</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>60</td>
<td>TXI</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>61</td>
<td>TXI</td>
<td>79</td>
<td>95</td>
</tr>
<tr>
<td>62</td>
<td>TXI</td>
<td>95</td>
<td>88</td>
</tr>
<tr>
<td>63</td>
<td>TXI</td>
<td>88</td>
<td>97</td>
</tr>
<tr>
<td>64</td>
<td>TXI</td>
<td>97</td>
<td>96</td>
</tr>
<tr>
<td>65</td>
<td>TXI</td>
<td>96</td>
<td>57</td>
</tr>
<tr>
<td>66</td>
<td>TXI</td>
<td>57</td>
<td>58</td>
</tr>
<tr>
<td>67</td>
<td>TXI</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>68</td>
<td>TXI</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>69</td>
<td>TXI</td>
<td>60</td>
<td>38</td>
</tr>
<tr>
<td>70</td>
<td>TXI</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>71</td>
<td>TXI</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>72</td>
<td>HSX</td>
<td>35</td>
<td>18</td>
</tr>
<tr>
<td>73</td>
<td>TXI</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>74</td>
<td>TXI</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>75</td>
<td>TXI</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>76</td>
<td>TXI</td>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td>77</td>
<td>TXI</td>
<td>42</td>
<td>44</td>
</tr>
<tr>
<td>78</td>
<td>TXI</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>79</td>
<td>TXI</td>
<td>43</td>
<td>45</td>
</tr>
<tr>
<td>80</td>
<td>TXI</td>
<td>45</td>
<td>102</td>
</tr>
<tr>
<td>81</td>
<td>TXI</td>
<td>102</td>
<td>12</td>
</tr>
<tr>
<td>82</td>
<td>TXI</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>83</td>
<td>TXI</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>84</td>
<td>TXI</td>
<td>40</td>
<td>41</td>
</tr>
<tr>
<td>85</td>
<td>HSX</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>86</td>
<td>TXI</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>87</td>
<td>TXI</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>88</td>
<td>HSX</td>
<td>36</td>
<td>17</td>
</tr>
<tr>
<td>89</td>
<td>TXI</td>
<td>44</td>
<td>47</td>
</tr>
<tr>
<td>Link/Number</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>90</td>
<td>TXI</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>91</td>
<td>TXI</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>92</td>
<td>TXI</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>93</td>
<td>TXI</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>94</td>
<td>TXI</td>
<td>52</td>
<td>55</td>
</tr>
<tr>
<td>95</td>
<td>TXI</td>
<td>55</td>
<td>98</td>
</tr>
<tr>
<td>96</td>
<td>TXI</td>
<td>98</td>
<td>56</td>
</tr>
<tr>
<td>97</td>
<td>TXI</td>
<td>56</td>
<td>73</td>
</tr>
<tr>
<td>98</td>
<td>TXI</td>
<td>73</td>
<td>74</td>
</tr>
<tr>
<td>99</td>
<td>TXI</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>TXI</td>
<td>75</td>
<td>76</td>
</tr>
<tr>
<td>101</td>
<td>TXI</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>102</td>
<td>TXI</td>
<td>77</td>
<td>78</td>
</tr>
<tr>
<td>103</td>
<td>TXI</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>104</td>
<td>TXI</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td>105</td>
<td>TXI</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>106</td>
<td>HSX</td>
<td>33</td>
<td>69</td>
</tr>
<tr>
<td>107</td>
<td>TXI</td>
<td>69</td>
<td>86</td>
</tr>
<tr>
<td>108</td>
<td>TXI</td>
<td>69</td>
<td>67</td>
</tr>
<tr>
<td>109</td>
<td>TXI</td>
<td>69</td>
<td>68</td>
</tr>
<tr>
<td>110</td>
<td>TXI</td>
<td>86</td>
<td>87</td>
</tr>
<tr>
<td>111</td>
<td>TXI</td>
<td>86</td>
<td>85</td>
</tr>
<tr>
<td>112</td>
<td>TXI</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>113</td>
<td>TXI</td>
<td>85</td>
<td>87</td>
</tr>
<tr>
<td>114</td>
<td>TXI</td>
<td>87</td>
<td>68</td>
</tr>
<tr>
<td>115</td>
<td>TXI</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>116</td>
<td>TXI</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>117</td>
<td>TXI</td>
<td>63</td>
<td>88</td>
</tr>
<tr>
<td>118</td>
<td>TXI</td>
<td>62</td>
<td>66</td>
</tr>
<tr>
<td>119</td>
<td>TXI</td>
<td>62</td>
<td>70</td>
</tr>
<tr>
<td>Link</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>120</td>
<td>TXI</td>
<td>70</td>
<td>61</td>
</tr>
<tr>
<td>121</td>
<td>TXI</td>
<td>70</td>
<td>57</td>
</tr>
<tr>
<td>122</td>
<td>TXI</td>
<td>61</td>
<td>58</td>
</tr>
<tr>
<td>123</td>
<td>TXI</td>
<td>61</td>
<td>66</td>
</tr>
<tr>
<td>124</td>
<td>TXI</td>
<td>61</td>
<td>31</td>
</tr>
<tr>
<td>125</td>
<td>HSX</td>
<td>66</td>
<td>27</td>
</tr>
<tr>
<td>126</td>
<td>TXI</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>127</td>
<td>TXI</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>128</td>
<td>TXI</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>129</td>
<td>TXI</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>130</td>
<td>TXI</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>131</td>
<td>TXI</td>
<td>43</td>
<td>45</td>
</tr>
<tr>
<td>132</td>
<td>HSX</td>
<td>53</td>
<td>23</td>
</tr>
<tr>
<td>133</td>
<td>HSX</td>
<td>54</td>
<td>24</td>
</tr>
<tr>
<td>134</td>
<td>TXI</td>
<td>65</td>
<td>64</td>
</tr>
<tr>
<td>135</td>
<td>HSX</td>
<td>64</td>
<td>25</td>
</tr>
<tr>
<td>136</td>
<td>TXI</td>
<td>71</td>
<td>101</td>
</tr>
<tr>
<td>137</td>
<td>TXI</td>
<td>101</td>
<td>13</td>
</tr>
<tr>
<td>138</td>
<td>TXI</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>139</td>
<td>TXI</td>
<td>72</td>
<td>1</td>
</tr>
<tr>
<td>140</td>
<td>HSX</td>
<td>82</td>
<td>19</td>
</tr>
<tr>
<td>141</td>
<td>TXI</td>
<td>59</td>
<td>31</td>
</tr>
<tr>
<td>142</td>
<td>RWY</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>143</td>
<td>TXI</td>
<td>68</td>
<td>67</td>
</tr>
<tr>
<td>144</td>
<td>HSX</td>
<td>67</td>
<td>29</td>
</tr>
<tr>
<td>145</td>
<td>TXI</td>
<td>80</td>
<td>84</td>
</tr>
<tr>
<td>146</td>
<td>TXI</td>
<td>85</td>
<td>79</td>
</tr>
<tr>
<td>147</td>
<td>TXI</td>
<td>88</td>
<td>68</td>
</tr>
<tr>
<td>148</td>
<td>TXI</td>
<td>20</td>
<td>82</td>
</tr>
<tr>
<td>149</td>
<td>HSX</td>
<td>67</td>
<td>28</td>
</tr>
<tr>
<td>Link Number</td>
<td>Type</td>
<td>Endnode</td>
<td>Startnode</td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>150</td>
<td>TXI</td>
<td>75</td>
<td>72</td>
</tr>
<tr>
<td>151</td>
<td>TXI</td>
<td>99</td>
<td>103</td>
</tr>
<tr>
<td>152</td>
<td>TXI</td>
<td>48</td>
<td>104</td>
</tr>
<tr>
<td>153</td>
<td>TXI</td>
<td>50</td>
<td>105</td>
</tr>
<tr>
<td>154</td>
<td>TXI</td>
<td>51</td>
<td>106</td>
</tr>
<tr>
<td>155</td>
<td>TXI</td>
<td>52</td>
<td>107</td>
</tr>
<tr>
<td>156</td>
<td>TXI</td>
<td>55</td>
<td>108</td>
</tr>
<tr>
<td>157</td>
<td>TXI</td>
<td>56</td>
<td>109</td>
</tr>
<tr>
<td>158</td>
<td>TXI</td>
<td>73</td>
<td>110</td>
</tr>
<tr>
<td>159</td>
<td>TXI</td>
<td>74</td>
<td>111</td>
</tr>
<tr>
<td>160</td>
<td>TXI</td>
<td>75</td>
<td>111</td>
</tr>
<tr>
<td>161</td>
<td>TXI</td>
<td>76</td>
<td>112</td>
</tr>
<tr>
<td>162</td>
<td>TXI</td>
<td>77</td>
<td>113</td>
</tr>
<tr>
<td>163</td>
<td>TXI</td>
<td>95</td>
<td>114</td>
</tr>
<tr>
<td>164</td>
<td>TXI</td>
<td>59</td>
<td>115</td>
</tr>
<tr>
<td>165</td>
<td>TXI</td>
<td>57</td>
<td>116</td>
</tr>
<tr>
<td>166</td>
<td>TXI</td>
<td>88</td>
<td>117</td>
</tr>
<tr>
<td>167</td>
<td>TXI</td>
<td>35</td>
<td>118</td>
</tr>
<tr>
<td>168</td>
<td>TXI</td>
<td>118</td>
<td>119</td>
</tr>
<tr>
<td>169</td>
<td>TXI</td>
<td>119</td>
<td>120</td>
</tr>
<tr>
<td>170</td>
<td>TXI</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>171</td>
<td>TXI</td>
<td>119</td>
<td>121</td>
</tr>
<tr>
<td>172</td>
<td>TXI</td>
<td>121</td>
<td>122</td>
</tr>
<tr>
<td>173</td>
<td>TXI</td>
<td>118</td>
<td>123</td>
</tr>
<tr>
<td>174</td>
<td>TXI</td>
<td>100</td>
<td>124</td>
</tr>
</tbody>
</table>
### Table D3: Example of RUNWAY.DAT for Amsterdam Airport

<table>
<thead>
<tr>
<th>Name</th>
<th>Node 0</th>
<th>Node 1</th>
<th>Node 2</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS06</td>
<td>0</td>
<td>124</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AMS24</td>
<td>1</td>
<td>26</td>
<td>25</td>
<td>24</td>
<td>23</td>
<td>124</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AMS19R</td>
<td>5</td>
<td>122</td>
<td>123</td>
<td>18</td>
<td>17</td>
<td>15</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>AMS01L</td>
<td>4</td>
<td>15</td>
<td>17</td>
<td>18</td>
<td>123</td>
<td>122</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>AMS09</td>
<td>6</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>33</td>
<td>11</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>AMS27</td>
<td>8</td>
<td>11</td>
<td>29</td>
<td>28</td>
<td>27</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMS19L</td>
<td>3</td>
<td>11</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>1</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>AMS01R</td>
<td>2</td>
<td>22</td>
<td>1</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

### Table D4: Example of METEO.DAT

<table>
<thead>
<tr>
<th>Air density (kg/m³)</th>
<th>Winds Speed (m/s)</th>
<th>c_wet</th>
<th>mu_roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225</td>
<td>0</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table D5: Example of AIRCTYPE.DAT

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>WTCD</th>
<th>Engine Type</th>
<th>Ne</th>
<th>To (lb)</th>
<th>B (kg)</th>
<th>OEW (kg)</th>
<th>MLW (kg)</th>
<th>MTOW (kg)</th>
<th>A (m/s²)</th>
<th>ir (m)</th>
<th>Sto (psi)</th>
<th>pire</th>
<th>CL</th>
<th>accel (m/s²)</th>
<th>decel (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-300-600</td>
<td></td>
<td>CF6-80C2A3</td>
<td>2</td>
<td>60200</td>
<td>5</td>
<td>90339</td>
<td>140000</td>
<td>170500</td>
<td>8</td>
<td>260</td>
<td>1555</td>
<td>2290</td>
<td>180</td>
<td>2.58</td>
<td>3.2</td>
</tr>
<tr>
<td>A-310-300</td>
<td></td>
<td>CF6-80C2A2</td>
<td>2</td>
<td>53500</td>
<td>5</td>
<td>80344</td>
<td>123000</td>
<td>150000</td>
<td>9</td>
<td>219</td>
<td>1479</td>
<td>2408</td>
<td>217</td>
<td>2.81</td>
<td>3.2</td>
</tr>
<tr>
<td>A-320-200</td>
<td></td>
<td>V2527-A5</td>
<td>2</td>
<td>26500</td>
<td>5</td>
<td>41782</td>
<td>64500</td>
<td>73500</td>
<td>9</td>
<td>122</td>
<td>1540</td>
<td>2336</td>
<td>163</td>
<td>2.29</td>
<td>2.3</td>
</tr>
<tr>
<td>Fokker100</td>
<td></td>
<td>Tay250-15</td>
<td>2</td>
<td>15100</td>
<td>3</td>
<td>24375</td>
<td>39915</td>
<td>43090</td>
<td>8</td>
<td>93.5</td>
<td>1360</td>
<td>1840</td>
<td>136</td>
<td>2.01</td>
<td>3</td>
</tr>
<tr>
<td>B-737-300</td>
<td></td>
<td>CFM56-3C1</td>
<td>2</td>
<td>23500</td>
<td>5</td>
<td>31895</td>
<td>51719</td>
<td>56472</td>
<td>8</td>
<td>105</td>
<td>1393</td>
<td>2027</td>
<td>200</td>
<td>2.38</td>
<td>2.6</td>
</tr>
<tr>
<td>B-737-400</td>
<td></td>
<td>CFM56-3C1</td>
<td>2</td>
<td>23500</td>
<td>5</td>
<td>33434</td>
<td>54885</td>
<td>62822</td>
<td>8</td>
<td>105</td>
<td>1497</td>
<td>2315</td>
<td>210</td>
<td>2.37</td>
<td>3</td>
</tr>
<tr>
<td>B-747-400</td>
<td></td>
<td>CF6-80C2B1</td>
<td>4</td>
<td>57900</td>
<td>5</td>
<td>181529</td>
<td>285765</td>
<td>385555</td>
<td>8</td>
<td>511</td>
<td>2134</td>
<td>3337</td>
<td>206</td>
<td>2.33</td>
<td>1.8</td>
</tr>
<tr>
<td>B-757-200</td>
<td></td>
<td>RB211-535E4</td>
<td>2</td>
<td>43100</td>
<td>4</td>
<td>57039</td>
<td>89810</td>
<td>104325</td>
<td>8</td>
<td>185</td>
<td>1460</td>
<td>1714</td>
<td>1.93</td>
<td>3</td>
<td>2.7</td>
</tr>
<tr>
<td>B-767-200</td>
<td></td>
<td>CF6-80A2</td>
<td>2</td>
<td>50000</td>
<td>5</td>
<td>83733</td>
<td>129273</td>
<td>175540</td>
<td>8</td>
<td>283</td>
<td>1650</td>
<td>2774</td>
<td>191</td>
<td>2.08</td>
<td>1.7</td>
</tr>
<tr>
<td>MD-83</td>
<td></td>
<td>JT8D-219</td>
<td>2</td>
<td>21700</td>
<td>2</td>
<td>36145</td>
<td>63276</td>
<td>72575</td>
<td>9</td>
<td>118</td>
<td>1585</td>
<td>2552</td>
<td>170</td>
<td>2.33</td>
<td>1.9</td>
</tr>
<tr>
<td>MD-87</td>
<td></td>
<td>JT8D-217C</td>
<td>2</td>
<td>20000</td>
<td>2</td>
<td>33237</td>
<td>58060</td>
<td>63503</td>
<td>9</td>
<td>118</td>
<td>1429</td>
<td>1859</td>
<td>175</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>DC-10-30</td>
<td></td>
<td>CF6-50C2</td>
<td>3</td>
<td>52500</td>
<td>6</td>
<td>121198</td>
<td>182798</td>
<td>261268</td>
<td>7</td>
<td>368</td>
<td>1630</td>
<td>3170</td>
<td>180</td>
<td>2.02</td>
<td>1.8</td>
</tr>
<tr>
<td>MD-11</td>
<td></td>
<td>CF6-80C2D1</td>
<td>3</td>
<td>61500</td>
<td>5</td>
<td>131035</td>
<td>195040</td>
<td>273289</td>
<td>8</td>
<td>339</td>
<td>2130</td>
<td>3200</td>
<td>200</td>
<td>2.16</td>
<td>2.1</td>
</tr>
</tbody>
</table>
### table D6 Example of PILOT.DAT

```plaintext
/* t_fr1 (s)  V_turn (kts) sigma_hth sigm_hth sigma_gammap n_fli sigma_wfland sigma_wfto */
/* t_fr2 (s)  h_to (ft)  h_th (ft)  gamma_ap (deg)  n_lof  w_fland  w_flo */

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>10</td>
<td>35</td>
<td>3.5</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>10</td>
<td>35</td>
<td>3.5</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>10</td>
<td>35</td>
<td>3.5</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>10</td>
<td>35</td>
<td>3.5</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>0.15</td>
</tr>
</tbody>
</table>
```

### table D7 Example of FLTPLANS.DAT

```plaintext
/* aircraft callsign  type  A/D  runway  taxiroute */

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IB123</td>
<td>0</td>
<td>A</td>
<td>AMS19R</td>
</tr>
<tr>
<td>2</td>
<td>AR279</td>
<td>10</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>3</td>
<td>KL321</td>
<td>2</td>
<td>A</td>
<td>AMS19R</td>
</tr>
<tr>
<td>4</td>
<td>MA729</td>
<td>9</td>
<td>A</td>
<td>AMS19R</td>
</tr>
<tr>
<td>5</td>
<td>AR266</td>
<td>4</td>
<td>A</td>
<td>AMS27</td>
</tr>
<tr>
<td>6</td>
<td>NW789</td>
<td>5</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>7</td>
<td>BA753</td>
<td>6</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>8</td>
<td>UK268</td>
<td>3</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>9</td>
<td>NW454</td>
<td>5</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>10</td>
<td>JA946</td>
<td>12</td>
<td>D</td>
<td>AMS19L</td>
</tr>
<tr>
<td>11</td>
<td>SA354</td>
<td>6</td>
<td>D</td>
<td>AMS19R</td>
</tr>
<tr>
<td>12</td>
<td>TU697</td>
<td>11</td>
<td>D</td>
<td>AMS19R</td>
</tr>
<tr>
<td>13</td>
<td>IB373</td>
<td>6</td>
<td>A</td>
<td>AMS19R</td>
</tr>
<tr>
<td>14</td>
<td>ML935</td>
<td>3</td>
<td>A</td>
<td>AMS19L</td>
</tr>
</tbody>
</table>
```
| 105 | 50 | 53 | 54 | 34 | 16 | 65 | 71 | 72 | 83 | 81 | 82 | 20 |
| 100 | 125 | 150 | 175 | 200 | 225 | 250 | 275 | 300 | 325 | 350 | 375 | 400 |
| 105 | 50 | 53 | 54 | 34 | 16 | 65 | 71 | 72 | 83 | 81 | 82 | 20 |
| 150 | 175 | 200 | 225 | 250 | 275 | 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 |
| 105 | 50 | 53 | 54 | 34 | 16 | 65 | 71 | 72 | 83 | 81 | 82 | 20 |
| 200 | 225 | 250 | 275 | 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 | 500 |
| 113 | 77 | 81 | 82 | 80 | 33 | 32 | 14 | 3 |
| 113 | 77 | 81 | 82 | 80 | 33 | 32 | 14 | 3 |
| 150 | 175 | 200 | 225 | 250 | 275 |
| 113 | 77 | 81 | 82 | 80 | 33 | 32 | 14 | 3 |
| 200 | 225 | 250 | 275 | 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 | 500 |
| 113 | 77 | 81 | 82 | 80 | 33 | 32 | 14 | 3 |
| 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 625 | 650 | 675 | 700 |
| 116 | 57 | 70 | 61 | 31 | 30 | 120 | 5 |
| 200 | 225 | 250 | 275 | 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 | 500 |
| 15 | 40 | 42 | 44 | 47 | 46 | 53 | 50 | 48 | 104 |
| 300 | 325 | 350 | 375 | 400 | 425 | 450 | 475 | 500 | 525 |
| 17 | 36 | 39 | 41 | 42 | 44 | 47 | 46 | 53 | 54 | 55 | 108 |
| 400 | 425 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 625 | 650 | 675 |
| 18 | 35 | 38 | 60 | 59 | 115 |
| 450 | 475 | 500 | 525 | 550 | 575 |
| 27 | 66 | 61 | 58 | 57 | 96 | 97 | 88 | 117 |
| 500 | 525 | 550 | 575 | 600 | 625 | 650 | 675 | 700 |
| 15 | 40 | 41 | 39 | 37 | 38 | 60 | 59 | 115 |
| 950 | 975 | 1000 | 1025 | 1050 | 1075 | 1100 | 1125 | 1150 |
| 1 | 72 | 83 | 76 | 75 | 74 | 73 | 110 |
| 600 | 625 | 650 | 675 | 700 | 725 | 750 | 800 |
### Table D9 Example of ATC.DAT

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td>27</td>
<td>36</td>
<td>45</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4</td>
<td>19</td>
<td>19</td>
<td>27</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>90</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table D10 Example of SIMAST.INI

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>10</td>
<td>2</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table D11 Link specific output parameters

<table>
<thead>
<tr>
<th>link</th>
<th>delay</th>
<th>stnode</th>
<th>endnode</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>00:00:20.5</td>
<td>46</td>
<td>53</td>
</tr>
<tr>
<td>29</td>
<td>00:01:19.5</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>33</td>
<td>00:00:02.0</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td>35</td>
<td>00:00:02.5</td>
<td>72</td>
<td>83</td>
</tr>
<tr>
<td>36</td>
<td>00:00:19.5</td>
<td>83</td>
<td>81</td>
</tr>
<tr>
<td>38</td>
<td>00:00:04.0</td>
<td>82</td>
<td>80</td>
</tr>
<tr>
<td>39</td>
<td>00:00:07.5</td>
<td>80</td>
<td>21</td>
</tr>
<tr>
<td>50</td>
<td>00:00:13.0</td>
<td>53</td>
<td>50</td>
</tr>
<tr>
<td>57</td>
<td>00:00:01.5</td>
<td>77</td>
<td>81</td>
</tr>
<tr>
<td>74</td>
<td>00:00:07.5</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>75</td>
<td>00:00:00.5</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>83</td>
<td>00:00:16.0</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>86</td>
<td>00:00:16.5</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>89</td>
<td>00:00:50.5</td>
<td>44</td>
<td>47</td>
</tr>
<tr>
<td>106</td>
<td>00:00:51.5</td>
<td>33</td>
<td>69</td>
</tr>
<tr>
<td>107</td>
<td>00:00:01.0</td>
<td>69</td>
<td>86</td>
</tr>
<tr>
<td>113</td>
<td>00:00:01.0</td>
<td>85</td>
<td>87</td>
</tr>
<tr>
<td>114</td>
<td>00:00:12.5</td>
<td>87</td>
<td>68</td>
</tr>
<tr>
<td>121</td>
<td>00:00:13.5</td>
<td>70</td>
<td>57</td>
</tr>
<tr>
<td>126</td>
<td>00:00:19.5</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>130</td>
<td>00:00:03.5</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>145</td>
<td>00:00:02.5</td>
<td>80</td>
<td>84</td>
</tr>
<tr>
<td>148</td>
<td>00:00:11.0</td>
<td>20</td>
<td>82</td>
</tr>
<tr>
<td>162</td>
<td>00:00:00.5</td>
<td>77</td>
<td>113</td>
</tr>
<tr>
<td>167</td>
<td>00:00:38.0</td>
<td>35</td>
<td>118</td>
</tr>
<tr>
<td>168</td>
<td>00:00:25.5</td>
<td>118</td>
<td>119</td>
</tr>
</tbody>
</table>
Appendix E SIMAST User Manual

The SIMAST 2.0 software should run smoothly on any PC with a 486DX processor (or better) and a EGA or VGA monitor and graphics card. It can be run on slower machines, but it is recommended to turn the graphics off in such a case.

Program execution starts by typing SIMAST at the DOS prompt in the directory where the SIMAST executable is located. The program will search for a graphics driver, which should be located in the directory ..../SIMAST/BGI. The data input files have to be located in a directory ..../SIMAST/DATA. The output file, which is generated at the end of program execution will also be placed here. The simast.ini file, located in the ..../SIMAST/DATA directory, may be used to turn the graphics on or off and supply some additional parameters to the simulation run [Appendix D].

With the graphics turned on, the screen is divided in two parts. The top part of the screen is dedicated to displaying the airport and the aircraft on the airport surface. The bottom part of the screen supplies the user with the flight information of the aircraft present in the simulation.

The airport with its runway(s) and taxiway system is visible on the screen as well as the current simulation time. The runways are indicated with a thick line, while the taxiways are indicated with a thin line. The apron area is not visible and is not simulated. The active aircraft are represented by an aircraft symbol with a label. This label describes the callsign of the aircraft, the type of aircraft and the speed of the aircraft in knots. Arriving aircraft appear when they cross the runway threshold. Departing flights remain visible until they fly off the screen. Their label disappears when they reach screenheight.

If a conflict is detected on the taxiway system and (one of) the involved aircraft has to be halted, the aircraft symbol corresponding with that aircraft is turned red. In any other case, the aircraft symbol is green, indicating no problems.

It is possible to zoom in on parts of the airport by using the mouse. Clicking the left mouse button once activates the mouse pointer and halts the simulation. Move the mouse pointer to the upper left corner of the area to be zoomed in on. Press and hold the left mouse button and drag the rectangular box over the zoom-area. When the desired area is indicated by the zoom box, release the mouse button. The screen will zoom in on the desired area and the simulation will be resumed. It is possible to zoom in a couple of times. By clicking the right mouse button, it is possible to zoom out to the previous zoom area. Repeated clicking of the right mouse button will retract the zooming step by step, until the original situation has been restored.

The bottom part of the screen displays the flight information of the aircraft in the simulation. The flight information is divided into departures (right) and arrivals (left). If not all the information can be displayed on one screen, it is possible to flip through the flight information pages by using the Page Up and Page Down keys on the keyboard. While aircraft are not active, the flight information will be dark red, indicating dormant aircraft. Active aircraft are indicated by green flight information, unless there is a conflict and the aircraft is halted. In that case, the flight information will be colored bright red to clearly indicate problems on the taxiway system.
The flight information displayed comprises the following parameters:
- callsign;
- type of aircraft;
- ETA or ETD;
- current state of the aircraft.

The ETA of an arriving flight changes to the ATA as soon as the flight has landed. The current state of the aircraft can be one of the following:
- ACCEL, accelerating aircraft on the airport surface (takeoff run excluded);
- DECEL, decelerating aircraft on the airport surface (landing run excluded);
- HOLD, aircraft that are waiting behind an aircraft in the departure queue or anywhere else on the airport surface.
- LANDING, arrivals above or on the runway surface);
- LINEUP, aircraft waiting for takeoff clearance at the departure runway threshold;
- RWYCROSS, aircraft that are waiting for clearance to cross a runway;
- TAKEOFF, departures on the runway or already airborne);
- TAXI, aircraft travelling over a straight part of the taxiway system at a constant speed;
- TURN, aircraft that are travelling over a taxiway turn.

As a flight leaves the simulation (2 minutes after takeoff or when reaching the apron entry point), the flight information of that flight is removed.

The simulation speed can be set by pressing the keys ‘1’ through ‘5’ on the keyboard. Pressing the ‘1’ key results in the lowest simulation speed, whilst pressing the ‘5’ key resets the simulation speed to the default maximum value.

The simulation may be paused by hitting the ‘p’ key or broken off by pressing the ‘q’ key. This exits the program, returns the user to the operating system and saves the output file for the flights which have completed their flight plans. The information contained in the output file, can be used to generate graphics for analysis of the simulation run. A spreadsheet program should not have any problem doing so.

**User Controls:**
- exiting the program: press ‘q’;
- simulation speed: keys 1 (low speed) through 5 (maximum speed);
- pause the simulation: press ‘p’. Hit any other key to continue;
- flip through he flight information pages: Page Up and Page Down;
- zoom control:
  - zoom in with the left mouse button;
  - zoom out with the right mouse button.