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1. ABSTRACT

This report describes work performed on the “Absolute Flow Control” study by Linköping University (LIU) and AVTECH Sweden AB (AVTECH) during the period July to December 2001.

The purpose of the study was to investigate methods to understand, stabilize and maximize the flow of air traffic with particular emphasis on the approach and landing phases. There is a substantial amount of literature covering studies of road traffic, but few in-depth studies have been done for air traffic. Due to the inherent differences between road and air traffic, the road traffic work has had limited applications for air traffic; there are however, certain similarities that provide valuable information.

The interim results of this study indicate that control methods may be applied that would allow stable air traffic flow rate to be increased to closely approach the limits set by physical factors such as runway occupancy time and wing vortex avoidance. The accuracy provided by the methods is in the order of meters and fractions of a second. The airborne equipment needed is available or will soon become available. The required modification to ground-based equipment is simple in technical terms, however, the ground – air (operator – ATM) procedures and responsibility allocation may take significant time to develop and negotiate.

2. OBJECTIVE

The objective of the “Absolute Flow Control” study is to investigate methods that could be used to significantly increase the flow of air traffic by proper use of the improved navigation and information transfer equipment, FMS with GNSS update and Automatic Dependent Surveillance – Broadcast (ADS-B), becoming available to the industry. The necessary understanding of traffic flow was obtained through literature studies and simulations. The simulations also provided necessary information about flow qualities and requirements.

3. PROJECT TEAM

AVTECH Sweden AB, founded in 1988 and located just north of Stockholm, Sweden, is a consulting company with expertise in aviation technology. AVTECH provides a wide range of services in particular within the areas of airborne operations and future ATM issues. Airborne issues relating to the development of operational concepts for future ATM systems, certification and validation requirements for new technologies and implementation of ADS-B technology are some of the key areas in which AVTECH provides expertise. AVTECH staff is comprised of active and retired technical and test pilots as well as aviation engineers, who collectively have over 150 years of experience in the airline industry since the 1960s.

For the “Absolute Flow Control” study, AVTECH provided project leadership and technical guidance relating to aviation issues under the advisement of Captain Jon Ertzgaard.

Linköping University was founded in the 1960’s, and has established itself as an innovative and modern institution in both education and research. The university was first founded as an independent college and in 1975 LIU established three faculties: the Institute of Technology, the Faculty of Arts and Sciences and the Faculty of Health Sciences. Research and education are performed within the Department of Science and Technology (ITN) in four broad cross-disciplinary scientific fields: Computer Science and Electrical Engineering, Communication and Transport Systems, Mathematics and Physical Sciences and Media Technology. The ITN department is experiencing a rather rapid rate of expansion. The current staff of approximately 120 persons, is projected to increase yearly by 20-30 persons over the next few years in order to meet the forecasted expansion in undergraduate and graduate students.

LIU Graduate student Håkan Andersson represents LIU in the Absolute Flow Control study, under the guidance of Professor Peter Värbrand.
4. INTRODUCTION

4.1 AIR TRAFFIC CONTROL (ATC)

Presently, the major task and effort for ATC is problem solving of a continuously self-generating chaotic situation caused by unacceptable density variations in non-metered merging or crossing flows, i.e. the number of aircraft allowed into the flow by the Central Flow Management Unit (CFMU) is not limited to what the system can handle without the need to correct local density peaks. Even when traffic is far below the theoretical maximum there can be periods when density peaks exceed the maximum acceptable level. These periods increase rapidly when the flow increases. Lack of accurate strategic planning makes tactical flow intervention necessary.

The intention when slot times were introduced was to keep the magnitude of flow density peaks manageable, not to create a sufficiently accurate metered flow to avoid flow control intervention. There are several reasons for this, among them that the 4-D navigation accuracy of past airborne equipment has not been adequate. Generally, this is no longer the case, however the necessary major change in ATS – Operator (ground – air) interactive procedures has not yet been realized; in fact, not yet been attempted.

4.2 SEPARATION STANDARDS

The approach for landing phase of flight is where the minimum separation (highest density) is required and allowed. At present, IFR separation is based on radar information. Lower separation is allowed under Visual Meteorological Conditions (VMC) when the responsibility for the execution of the separation assurance is delegated to the Flight Deck based on visual contact to preceding aircraft, even though visual estimation of distance is far inferior to the use of radar.

The uncertainties in radar and visual separation estimation and the difficulties in predicting aircraft response to control instructions causes ATC to add an extra margin to ensure that the minimum separation standard is not violated. This extra margin, necessary for safety reasons, may be seen as airspace waste in a future system where, with the introduction of GNSS-based position and time, navigational inaccuracy will be negligible.

In addition, the FMS-based flight profile is available as intent information substituting a highly accurate prediction in place of the currently very low accuracy based on real-time visual information and the somewhat more accurate, but historical radar information.

4.3 MAXIMUM AIR TRAFFIC FLOW

The only viable method available to achieve maximum stable flow is to meter the flow (plan and execute to plan). In a metered flow no more flow is allowed into any part of the system than the maximum that can be processed through the most severe constraints. Maximum flow is achieved when the flow is stable. When the density exceeds that of maximum flow or when a disturbance initiates a pulsating flow at lower density, the obtainable flow rate will decrease, often significantly below that for a stable flow.

4.3.1 METERED FLOW

Planning the flow using accurate slot times for take-off and landing, and controlling the flow to meet these constraints can only achieve metered air traffic flow. This requires proper traffic analysis and planning functions on the ground (Air Traffic Services) and accurate 4-D (Time) navigation on-board the aircraft.

Interactive ATS - Operator procedures for this process need to be developed. The following broad outline describes the required functions:

- The operator (airline) must negotiate a landing slot time that corresponds to the expected pushback time plus the taxi-out and flight time.

- The operator (airline) must negotiate a take-off slot time that corresponds to the landing slot time minus the optimum flight time. If this is not available, a new pair of landing and take-off slot times must be renegotiated and the desired adjustment to the pushback slot time made.

The planning phase of a metered flow requires issuing slot times to individual units in a 4-D flow.
Following the issued slot times a flight can proceed on an optimum flight profile as planned. This has, quite misleadingly been called a “Free Flight Profile”. While the operator may freely select the flight profile itself, the execution of the flight profile is very constrained in order to meet the required slot times. Small aberrations may be absorbed by speed control, however larger aberrations require renegotiation of landing slot time, alternatively reversion to relative positioning of a string of aircraft when the density of the flow is controlled directly by the separation between the individual aircraft in the flow. This method may be desirable for flows approaching an end point (landing), especially if there has been a disturbance that invalidates the slot times, and/or the aircraft in the flow have mixed equipage.

Relative positioning of aircraft in a string is the traditional, and rather outdated, method used for separation control of aircraft during the approach and landing phase. The new concept is the transition to time in lieu of distance for separation control. This study shows that a significant increase in the landing flow rate may be achieved even using existing separation criteria when improved navigation and information transfer systems are used in combination with the concept of time separation.

**4.3.2 FLOW STABILITY**

The stability of a flow is a function of several parameters such as density, speed, information transfer lag and flow compressibility characteristics, as well as type and magnitude of disturbances that may incite flow fluctuations.

**4.3.2.1 Density**

The density of an air traffic flow must be related to the required minimum separation standard used. Maximum density is reached when the separation between units (aircraft) is equal to the minimum legal separation plus any extra margin(s) added by the controller.

**4.3.2.2 Information Transfer**

In order to establish a stable air traffic flow, it is important that the lag time for information transfer is kept to a minimum. Inaccuracies and uncertainties in position determination can be treated as transfer lag. Predictive information provided by a system or by estimation of an experienced controller, tends to stabilize the flow.

A compressible flow will be more prone to disturbances and less stable than a non-compressible flow. Compressibility introduces an information transfer lag time between the units in the flow. This can be exemplified by comparing the flow of a long train and the flow of highway traffic. In poor visibility there is a considerable lag in the information a driver extracts from the taillights of the preceding car and speed must be reduced to avoid accident-causing fluctuations in the flow density. With a train on the other hand, even though the density is much higher, instantaneous and accurate information is provided from one car to the next, ensuring that any fluctuations will be minimal and of high frequency, and almost entirely independent of the length and the speed of the flow.

**4.3.2.3 Speed**

When the speed of a compressible flow is reduced, the density increases and major disturbances that incite flow oscillations tend to be introduced. An air traffic flow will decelerate during descent as the Ground Speed for a constant Indicated Airspeed is reduced. This will cause the density of the flow to increase and the flow to be more prone to oscillation. (See more under section 3.5 Time Separation).

**4.4 FLOW CONTROL PRINCIPLE**

The density of a flow of air traffic is a direct function of the physical distance between the respective aircraft in the flow. Maximum density is obtained when there is no wasted space between the zones of air defined by the minimum separation for each aircraft. The flow rate is a function of the density and the speed of the flow. The method used to control separation for both merging and crossing flows has traditionally been to adjust the physical distance between the respective aircraft, i.e. in nautical miles horizontally and feet vertically. Physical distance has been the only parameter available for display on radar-type 2-D displays. It is easy to interpret and understand as a measure of the separation between individual aircraft. Consequently, physical distance has been used to define the minimum separation standards.

Air traffic flow is characterized by certain specific constraints, the most typical being the high minimum flow speed limited by the minimum acceptable flying speed and the highly variable, unpredictable and limited acceleration and
deceleration available for density control. This makes it desirable to use track adjustment for gross control of density and speed control only for fine adjustment and to keep an established flow stable. Speed control alone provides the advantage of stringing a flow along the same track for minimum lateral dispersion.

4.5 TIME SEPARATION

The highest and most critical density of air traffic flow is reached during the approach and landing phases of flight. Many physical limitations that determine the minimum safe separation are time-related, for instance, the runway occupancy time (ROT) and the decay time for wing vortices. Time separation has not been a practical or possible parameter to compute and display using radar. For display reasons, time has been translated into physical distance. However, using physical distance for separation requires continuous adjustments to obtain and maintain a minimum separation for approach due to the density being increased when the speed is reduced. For example, a 1 minute separation during cruise translates into about 8 NM, while during final approach it is only about 2.5 NM. This requires a continuous adjustment that is difficult and requires extensive controller training and experience if it is to be anywhere near accurate.

This situation changes dramatically with the introduction of accurate GNSS position and time information and the use of data link (ADS-B) for information transfer, and allows for two different methods to display and use time as a separation parameter. One is based on the use of accurate 4-D navigation when an aircraft is controlled to be at a specific geographic position at a specified time. The other is the TRAIL method described in this paper in chapter 10, when an aircraft is controlled to a specified time separation relative to another aircraft. 4-D navigation requires accurate time information. This is not the case for TRAIL, which allows time separation to be based entirely upon relative position and speed.

5. WORK PLAN

The work was organized and divided into three phases.

Phase 1: Study:
A background study was done to find information related to the project. To be innovative, we searched for information in several different fields, such as road traffic and fluid flow. The search was performed primarily in related organizations’ and companies’ Internet databases.

In this phase we also tried to find the most suitable simulation tool/language for Phase 2.

Phase 2: Development of Models.
The purpose of this phase was to develop a simulation environment to be used for testing and analysing the two proposed methods: string control (SC) and absolute reference control (ARC). Analyses of present ATM flow behaviour were also performed during this phase.

Phase 3: Analysis and conclusions
The purpose of Phase 3 was to analyse the results and draw conclusions from the simulations in Phase two. This phase is part of a roadmap for continued studies.

6. FLOW FUNDAMENTALS

Flow is a term that can be used for several different subjects or identities, for example how much water flows through a pipe per hour, or how many cars pass a point on the road per hour. Flow is the rate of a quantity during time. A mass that flows can be either compressible or incompressible [7]. In a compressible flow, the density (distance between the units) may vary, but in the incompressible flow the density is constant. The analogies and theories are quite different for the two types of flow, making it important to define which type of flow is being studied.

A flow can be 1-2- or 3-dimensional, depending on how the components will affect the calculations. For the velocity field (u, v and w for example), there could be situations where one component may be small relative to the other components, in which case it may be advantageous to neglect the smaller component and assume that the flow is two-dimensional. For example, simplify to give \( V = u_i + v_j \), where \( u \) and \( v \) are function of \( x \) and \( y \). It is sometimes possible to simplify a flow analysis by assuming that two of the velocity components are negligible, leaving the velocity field to be approximated as a one-dimensional flow field, \( V = u_i \). There are many flow fields for which the one-dimensional flow assumption provides a reasonable approximation. A flow is mainly defined by two
parameters: speed and density. If the flow is incompressible, then it is a linear function of speed. In a compressible flow, the function between speed and flow is more complicated. The stability of a compressible flow is usually harder to control. To maintain the stability of a compressible flow it is important to have an understanding of the behaviour of the particles or units in the flow, for example molecules, cars or airplanes. If the units are controllable it may be possible to increase the stability using a control algorithm, thereby increasing the flow. A traffic flow is compressible when each individual unit has a unique behaviour determined by the characteristics of the vehicle and the driver/pilot.

7. FLUID FLOW

In a flow study it is natural to search for analogies and theories in the field of fluid flow. Almost all flows have a relationship to fluid flow theories and analogies. Concepts from fluid flow regarding flow and density are used for several other scientific fields. The infinitesimal particles of a fluid are tightly packed together.

There is a great difference in density between traffic flow and fluid flow. Usually it is assumed that the density will vary continuously throughout the fluid, i.e. the fluid is treated as a continuum. A study of road traffic (see section 4.2 Road Traffic) concluded that road traffic has too low a density to be treated as fluid flow. It is therefore reasonable to conclude that this is true for air traffic as well, as air traffic has an even lower density. The analogy of fluid flow may still however, prove interesting for parts of the air traffic study.

8. ROAD TRAFFIC

The flow of road traffic became a problem in the 1950s due to traffic jams in urban areas, causing a need for better understanding of flow behaviour of road traffic. Better understanding would make it possible to build roads that could more effectively meet traffic demands as well as localize and remove bottlenecks.

A “bird’s eye” view of a freeway allows one to visualize the vehicle traffic as a stream or a continuum fluid flow. It seems therefore quite natural to associate road traffic with fluid flow [14]. Because of this analogy, traffic is often described in terms of flow, concentration, and speed. Road traffic is treated as a one-dimensional compressible fluid flow. The main problem in road traffic is the variety of characteristics of the drivers and vehicles affecting the stability of the flow. In order to address this, a number of control systems have been evaluated to decrease the effect of the problem. In a recent project called Intelligent Transport System (ITS), applications like Intelligent Cruise Control (ICC) have been developed and tested to improve the stability of the flow.

8.1 MICRO, MACRO AND HUMAN APPROACH

There are three main approaches to understanding and quantifying traffic flow: the macroscopic, the microscopic and the human-factors approach.

The macroscopic approach looks at the flow in an aggregate sense. Based on such physical analogies as heat flow and fluid flow, the macroscopic approach is most appropriate for studying steady-state phenomena of flow and hence best describes the overall operational efficiency of the system.

The microscopic approach considers the response of each individual vehicle in a disaggregate manner. Here, the individual driver-vehicle combination is examined, such as car maneuvering. This approach is used extensively in highway safety work.

The human-factors approach seeks basically to define the mechanism by which an individual driver (and his or her vehicle) locates himself /herself with reference to other vehicles and to highway/guidance systems.

Related to air traffic, the macroscopic approach has been used to assess overall traffic flow behaviour.

8.2 PARAMETERS IN ROAD TRAFFIC FLOW STUDIES

At least eight variables and several other stream characteristics derived from these are used when describing road traffic flow. The three primary variables are volume ($q$), speed ($v$), and density ($k$). Three other variables used in traffic flow analysis are headway ($h$), spacing ($s$) and occupancy ($\rho$). In addition, two more parameters corresponding to spacing and headway called clearance ($c$) and gap ($g$) are used.
8.2.1 VOLUME (Flow)

Traffic volume is the number of vehicles actually observed passing or predicted to be passing a point during a given time interval. From this volume it is possible to calculate the rate of flow \( q \). If the number of vehicles is \( n \) and the time interval is \( \Delta t \), the rate of flow is calculated as follows:

\[
q = \frac{n * 60}{\Delta t} \quad \text{(Equation: 1)}
\]

8.2.2 SPEED

Speed is the rate of motion or distance per unit of time, such as km/h or m/s. There is often a large variation in the speed of individual vehicles in a stream of road traffic, therefore an average (or mean) speed is computed. One way to define the mean speed is to measure the travel time, \( t_i \), for the number of vehicles, \( n \), over a length of the road, \( L \).

\[
V_s = \frac{nL}{\sum_{i=1}^{n} t_i} \quad \text{(Equation: 2)}
\]

\( V_s \) is called the space mean speed and is the harmonic mean speed. Another way to calculate the mean speed is to calculate the time mean speed \( (V_t) \) by measuring the speed of each vehicle and computing the average of the collected speeds. These two speed definitions are used in the macroscopic approach. In the microscopic approach the individual speeds are used. Variations in the speed of individual vehicles cause local density fluctuations.

\[
V_t = \frac{\sum_{i=1}^{n} V_i}{n} \quad \text{(Equation: 3)}
\]

8.2.3 DENSITY

Density is defined as the number of vehicles occupying a given length of lane or roadway, usually expressed as vehicles per km or mile. The density is calculated as in Equation 4.

\[
\text{Density} = \frac{\text{number of vehicles}}{\text{length of lane or roadway}}
\]

As shown in lane 2 of figure 1, the density can vary within the section where the measurement is made. In lane 1 and 2 the density is equal if measured over the length \( L_1 \). The individual density is normalised in lane 1, but not in lane 2. It is important to measure density in road traffic over a length, \( L \) that is tailored to the situation. If \( L \) is too small, it will not be possible to analyse the proper density. Fluctuations and other characteristics will be more apparent when the density is measured over a smaller \( L \).
8.2.4 SPACING AND HEADWAY

Headway is the microscopic description of flow and spacing of density. Spacing is defined as the distance in meters between successive vehicles in a traffic stream measured from front bumper to front bumper. Headway is the corresponding time between successive vehicles as they pass a point on a roadway. Headway is an important flow characteristic that affects the safety, level of service, driver behaviour, and capacity of the system. Consequently, there is a great advantage having a method to stabilise headway.

8.2.5 OCCUPANCY

Occupancy is a measure used in freeway surveillance calculated by dividing the sum of the vehicle lengths on a road section with the road section’s length.

8.3 PARAMETER RELATIONSHIP (macro)

A fundamental relationship between the three main parameters of flow, speed and density has been defined for road traffic. Speed and density are assumed to have a linear relationship, see figure 2 [8], meaning that the driver is adjusting the speed according to the density. This is intuitively correct, but can theoretically lead to negative speeds or densities. The figures in figure 2 describe the relationship for uninterrupted flow such as highway traffic flow.

Both speed – flow (figure 2; b) and density – flow (figure 2; c) curves are dependent on the jam density \(k_j\) and the free speed \(u_f\) as can been seen in equations 5 and 6.

\[
u = u_f - \frac{u_f}{k_j} \quad \text{(Equation: 5)}
\]

\[
q = u_f k - \frac{u_f}{k_j} k^2 \quad \text{(Equation: 6)}
\]

The most interesting figure to study is figure 2 c. From this curve it easy to understand the relationship between all three parameters. The parabolic curve in figure 2 c describes what the flow is at a unique density. The speed can also be measured in this figure by drawing a vector from point of origin through the point on the flow-density curve for where you want to know the speed. The speed equals the slope of the drawn vector.
Figure 3: Flow-density diagram

At point A in figure 3 there are few vehicles on the road. These few vehicles can, to a large extent determine their own individual speed. At point B, the number of vehicles has increased but conditions are still “free flow” with hardly any restrictions, although such restrictions keep increasing steadily until point C is reached. Between point B and C, the flow condition may be called “normal”, but when the density increases, the freedom to choose speed and lane is reduced. Around point C traffic tends to be unstable; the speeds and densities fluctuate with small changes in volume. At point C, maximum flow is reached. If the density is further increased the flow will decrease, as speed reduction will overcompensate for the increase in density. Such a flow is called forced flow and prevails the entire way from point C to point D. Flow at point D is almost at zero, with cars stacking up bumper to bumper at near zero speed. The density at point D is called jam density ($k_j$).

In the present section, the discussion is valid when the flow is the same everywhere, meaning that the road is homogenous and there is no bottleneck or any flow reduction. The concept can be extended to a heterogeneous highway. A heterogeneous highway has different widths, for example one that changes from two lanes to one lane. If we suppose that there are two lanes upstream and one lane downstream, we could under no circumstances get a higher flow than the one lane section allows. The flow upstream will never be over saturated but the downstream can easily be over saturated. The flow density curves can be illustrated as in figure 4. The dashed curve is the two lane flow curve, $q_2(k)$, and the continuous curve is the one lane, $q_1(k)$. $q_{max}$ denotes the capacity of the bottleneck; this value is the maximum possible flow for the system. A bottleneck of this kind will work at capacity because the two-lane section will under very low flow conditions exceed $q_{max}$.

Figure 4: Relationship between flow and density on a non-homogenous road section
8.4 STABILITY AND SHOCK WAVES

The flow-density curve (figure 2 c) is of use when analysing the stability of road traffic. Instability may create shockwaves in the flow. It is important to understand shock wave behaviour, as it will affect the flow. When studying shock waves it is important to define the observation point. To a static observer on the bank of a stream, the waves in the stream will move and the density fluctuate, while to an observer moving at the crest of a wave, the density will be constant and no observable waveform will be evident.

The flow density diagram in figure 5 shows how a shock wave propagates through the system with changing density. From points A to B, a forward moving shockwave is formed. A forward moving shockwave will not penalize the stability of the flow, but groups of cars tend to be formed. This phenomena can easily be seen when observing a road from the roadside; first a few cars pass, then suddenly a group of cars passes. The speed of the shock wave ($\gamma_{AB}$) is dependent on the slope of the line that joins the points of different states. This is mathematically described by equations 7 and 8, with the assumption that there is no reduction in number of vehicles ($N$) between the two states. The speeds at the different states A and B are $u_A$ and $u_B$ respectively.

$$N_A = q_A * t = (u_A - \omega_{AB})k_A * t \quad \text{(Equation: 7)}$$

$$N_B = q_B * t = (u_B - \omega_{AB})k_B * t$$

if

$$N_A = N_B$$

$$\omega_{AB} = \frac{q_A - q_B}{k_A - k_B} \frac{\Delta q}{\Delta k} \quad \text{(Equation: 8)}$$

Traffic flow is not sensitive to disturbances if the density is below $k_{opt}$. When changing state from A to C the slope of the line joining the points will be negative. This will result in a backward moving shock wave that travels opposite to the traffic direction and reduces the traffic flow. This shock wave will travel through the traffic and stop only if the density becomes lower than $k_{opt}$, when the shockwave can be absorbed. Backward moving shock waves usually grow larger while moving.

![Figure 5: Flow-density diagram for shock wave analysis](image)

Fluctuation in density (instability) can have a very large effect on the flow throughout the system. If control of the distance between each individual vehicle could be improved however, the onset of shock waves would be delayed and the effect of the shock waves would be greatly reduced.

8.5 APPLICATIONS TO INCREASE FLOW (ICC, ITS)

To increase safety and stabilize flow in road-traffic, great effort has been expended to develop an intelligent cruise control (ICC). The ICC is a further development of conventional cruise control (CCC). ICC uses the distance to the
car ahead when computing the speed setting. An ICC equipped car can maintain a constant speed as with CCC, but if the distance to the car ahead becomes too small, the speed is reduced to maintain a safe distance. Both computer simulations and field studies on the ICC have been made. Studies show that with a large number of ICC equipped cars in a traffic-system the flow could be increased. The results also show that the control algorithms used in the tested system are not stable enough to handle more than maximum three cars in trail [15].

9. ATM FLOW

It has not been possible to find a description of the relationship between speed, flow and density for air traffic. In this study, the relationship between the above mentioned parameters for air traffic have been studied using the analogy from road traffic described in the road traffic section. Road traffic is a one-dimensional compressible flow, while air traffic is a 3-dimensional and less compressible flow where a legal separation is assumed to be observed. In the first approach we decided to simplify air traffic to a 1-dimensional compressible flow, valid for situations like final approach.

Some characteristics of air traffic are significantly different from road-traffic:

- Air-traffic is often operating in 4 dimensions
- Air traffic has flight plans and restrictions exist that dictate how the individual aircraft should be operated
- Aircraft are limited by a maximum speed that varies dependent on configuration, altitude etc.
- Aircraft are limited by a minimum flying speed that is significantly above zero and varies dependent on configuration etc.
- The separation between aircraft is large in an air traffic flow, however, the separation between the units, defined as the space required to meet the legal separation may be small
- When air traffic is over-saturated, leakage of flow (removing units) must be used in lieu of speed reduction below minimum acceptable speed. Parking when airborne is not an option.

These inherent differences make application of theories from road-traffic on air traffic difficult, however the analogy is useful. There are also several similarities between the two types of traffic, among them that both need to be controlled with a precision of one second or better. In both air traffic and road traffic there are large variations between vehicles and driver/pilot/controller performance. There are many approaches to solving the flow problem such as sequencing algorithms that may increase flow, however the tendency for instability in the flow at maximum density still exists and consumes expensive time at peak hours.

9.1 PHYSICAL FLOW LIMITATIONS

The physical limitations in air-traffic flow are most restrictive at or near airports. This study focused on the landing sequence because that is where flow density approaches critical levels due to the speed reduction before landing. The two major physical limitations, wake-vortex decay time and runway occupancy time, limit the traffic flow. Maximum flow for one runway is reached when takeoff and landings are mixed, as this reduces the separation restrictions from wing vortices. The maximum approach flow is reached if the flow is completely stable with minimum separation. The flow can never be greater than allowed by the minimum separation (max density). Presently it is not possible to establish a completely stable minimum separation. A wide distribution of separation accuracy is found, primarily caused by lack of accuracy in the methods and equipment used for aircraft spacing.

9.2 SIMULATIONS AND DATA ANALYSIS

To be able to define parameters like flow and density, there is a need to understand how a choked flow behaves. Definition of the precision of current methods and how the density may fluctuate was necessary.

With help from the Swedish ATC Academy (SATSA) a simulation was performed to investigate air traffic during a peak hour flow. SATSA has two simulation tools, the Re-organized ATC Mathematical Simulator (RAMS) and the Simulator Multi-role ATM Research & Training (SMART); SATSA used their fast time simulator RAMS for the purpose of this study. When performing the simulation it was found that RAMS optimised the flow so that no
disturbance ever occurred. It was not possible to turn off the optimisation algorithm, making it necessary to switch to SMART instead.

For this study, SATSA decided to use a simulation model that was recently used in their SMART simulator. SMART simulation involves both controller and pilots, thus variations in the flow from human factors was present. The purpose of the simulation was to investigate how the Gothenburg/Landvetter airport would be able to handle 44 movements per hour [13]. This simulation was of particular interest as choked flow is a current problem and necessitated review of the precision and capacity of the current method. Arrival flow was analysed by recording the distribution of touch down separation. The mix of aircraft in the simulation was as follows:

- 3 aircraft of weight category Heavy (H)
- 50 aircraft of weight category Medium (M)
- 6 aircraft of weight category Light (L)

To analyse flow stability, aircraft of only one weight category, category M, were selected for the study. The separation criteria followed the Swedish Rules for Air Traffic Services (ICAO Doc 4444), (BFT) section 2 chapter 6 paragraph 3.6.4.

To be able to visualize touch down separation, it was necessary for at least two aircraft to touch down on the runway after each other. The selection criteria used were:

- Both aircraft had the same weight category, medium (M)
- The touchdowns were done sequentially with no departure in between.

16 aircraft pairs fulfilled the criteria; the longest uninterrupted sequence of landing aircraft was eight, generating seven pairs.

**9.3 STATISTICS FROM SELECTED DATA SET**

The touchdown time spacing distribution for the 16 pairs was interesting, in particular the speed profile used during the approach for the 7 pairs that did touch down in one sequence without any departures in-between.

![Separation distribution](image)

**Figure 6: Separation time distribution at touchdown.**

The mean value of the touch-down spacing is 105 seconds and the standard deviation is 30 seconds. The lower boundary was at 71 seconds and the upper at 189 seconds of separation time.
In-depth study of the speed variation during the final approach for the selected data set is of particular interest. By transferring the lateral/longitudinal data to one dimension, it is possible to see what speed the aircraft used at different distances from the airport, zero distance representing the touchdown point.

Figure 7 shows the variations in speed with 4 aircraft in trail. For the flow to be stable the speed should be almost the same for each aircraft at the same position on final approach, i.e. the aircraft should follow the same speed schedule.

![Graph showing speed vs. distance from touchdown](image)

**Figure 7: Speed vs. distance from touchdown**

### 9.4 SEPARATION DISTRIBUTION

As seen in the above analysis, the touchdown separation is widely distributed with a mean value that is much larger than the legal separation. This analysis contained a very small number of aircraft; in the study “Final approach throughput analysis for conventional and enhanced air traffic management”, performed by the Boeing Company [10], a Monte Carlo simulation method was used and all 1000 aircraft involved in the simulation were of category heavy with a desired separation of 3NM. When our results are compared with those of this much larger simulation, showing a mean value of 100 seconds, the results seem to be realistic. Figure 8 shows the touchdown distribution of the simulation. The mean value is directly related to the airport acceptance rate; an arrival rate of 36 aircraft per hour is equivalent to a mean arrival time of 100 seconds. The standard deviation parameter is directly related to the precision with which the controller can sequentially space aircraft onto final approach. The standard deviation in the SMART simulation was about 30 seconds.

It is important not to confuse accuracy with precision. While precision describes the (lack of) scatter or spread from the mean value, accuracy is how close the mean value is to the desired value. We constructed a 99% confidence interval of the data set. The resulting confidence interval was 86 seconds – 124 seconds. Clearly, the mean value of the touchdowns for a greater number of touchdowns will be within the 99% confidence interval.
Figure 8: Arrival time distribution

Figure 9 shows the results from the Boeing simulation [10]. At the maximum arrival rate there are 2 aborted landings per hour, i.e. an initial approach flow rate of 38 gives an arrival rate of 36. As the flow rate is increased above 38 the number of aborted landings increases more rapidly than the increase in flow rate giving a negative effect on the arrival rate.

Figure 9: Baseline Capacity study, missed approaches per 1000MC trials

Over-saturation of controller workload leads to aborted landings that cause the arrival rate to decrease. Increased control precision decreases the standard deviation and allows the arrival rate to be increased for a certain initial approach flow rate. The flow and arrival rates are dependent upon how large a margin the individual controller adds to the legal separation in order to ensure that the minimum legal separation is not violated. The size of the margin depends on a large number of factors such as runway quality, type of preceding aircraft, wind shear, weather, radar resolution, airliner routines, the individual controller’s experience and mental state and, not the least, the controller’s environment regarding punitive action following a violation.

The added margin is waste of airspace leading to a direct loss of arrival rate, however current controller equipment and methods/procedures do not allow for significant reduction of the margin.

9.5 SUMMARY OF DATA ANALYSIS

Both the SMART data and the simulation performed by The Boeing Company [10] show that great density fluctuations occur during final approach. It is obvious that the current method used for spacing aircraft has low accuracy and needs to be improved to increase arrival flow. With increased precision it should be possible to increase the average (mean) flow rate and significantly increase the arrival rate.

The results from this analysis are useful when defining the parameters for flow and density for air-traffic in section 7.5.
9.6 DEFINITION OF DENSITY, FLOW, SPEED ETC in ATM

9.6.1 DENSITY

In air traffic, the airspace an aircraft is allocated ensures separation according to existing regulations, forming a volume in the shape of an oval cylinder (protected zone) \[11\]. Maximum density is reached when there is no space between the individual separation volumes.

One method used to analyse density is to take screen shots from the radar map at specific time ticks. The airspace is divided into unit volume blocks in order to make a density map. This method shows the overall density for the specified airspace.

Another method is to look at a stream of traffic moving to the same point in space. This allows the traffic stream to be simplified into a one-dimensional flow. This method can be described using the example of a traffic stream on final approach. All aircraft heading to the same runway can be transferred to a one-dimensional description. Each aircraft in the stream is dependent on how the aircraft in front is acting. The analogy from road traffic will then be true except for a few qualities. This method is suitable for the study of the stability in a stream of aircraft.

9.6.2 FLOW/DENSITY/SPEED RELATIONSHIP

An initial description of the relationship between flow and density using the analogy from road traffic is shown in figure 10. The unique minimum speed for the air traffic flow determined by the minimum flying speed (\(V_{\text{min}}\)) must be defined. This limits the flow-density curve on the right hand side. The line for the maximum speed (\(V_{\text{max}}\)) known as free speed in the road traffic section defines the left side of the area permitted to operate in, figure 10 a. The boundary of this permitted area consists of the maximum density (minimum separation \(k_{\text{max}}\)), \(V_{\text{max}}\) and \(V_{\text{min}}\).

![Diagram of flow/density/speed relationship](image)

\[a) \text{first approach} \quad b) \text{second approach}\]

**Figure 10 a and b: Flow/ Density relationship, white section free flow, light grey section forced flow, dark grey section over saturated flow.**

The maximum flow rate is reached at the coffin corner. At the coffin corner, speed cannot be used to control density, it cannot be increased and any decrease will increase the density and result in a violation of the minimum separation. The only method available for control is to remove a unit (or units) from the flow by trajectory change(s).

The gap between \(V_{\text{max}}\) and \(V_{\text{min}}\) will depend on the situation and the sequence of aircraft, for example on final approach there will only be a small gap in speed to operate in.
This simple solution in figure 10a will be true only if the flow is completely stable with no transfer lags, like the train model. To estimate a curve for air traffic, the analogy from road-traffic was used, however because the road traffic curve is based on the assumption that the density may reach jam density at zero speed, a formula (Equation 9) will not define the correct shape of the curve for air traffic. Jam density in air traffic occurs when the controller has to remove unit(s) from the flow by trajectory change (or holding) in order to handle the incoming flow. In air traffic a number of components affect the shape of the curve. In real life maximum flow at maximum density is not reached, because the controllers are adding margins in order to handle disturbances in the system.

In the Boeing study [10], the effect of flow rate on the number of aborted landings was investigated. The results show that when the arrival rate increases over a certain limit aborted landings increase dramatically. Density is optimum at the maximum flow point on the curve. If density is allowed to increase above the optimum density, aborted landings increase rapidly causing the arrival rate to decrease. The optimum density for the current ATM system is the separation minima plus the margin the controllers add to avoid aborted landings due to inaccuracies and disturbances in the system. The necessary margin is highly dependent on the update frequency of information. The update rate is a highly important tool in any control loop system. When increasing the update frequency the accuracy of the control loop improves.

Figure 10 b is divided into three sections: white, light grey and dark grey. In the white section, aircraft may be moving independently of each other. The workload on the controller is low and the rate of aborted landings is negligible. In the light grey section, the aircraft are highly dependent on each other. The workload on the controller may be high and the number of aborted landings begins to increase. In the dark grey section, the flow is over-saturated with a rapidly increasing number of aborted landings and a reduced arrival rate.

When a landing is aborted the arrival flow rate is reduced because of the empty space created by the aborted landing. The controllers’ workload will be increased by the need to handle the aborted aircraft around and back into the approach flow. Finally, the aborted aircraft will occupy and block a new time space in the traffic flow.

Compared to road traffic, shock waves in air traffic will be of a different nature because of the possibility to remove units from the traffic stream. The theories in road traffic assume that there is no reduction of units in the traffic stream. Removing an aircraft from the traffic stream will absorb a backward moving shock wave in air traffic. However, if the controllers use speed as an instrument to handle the situation, then there will be a backward moving shock wave. Forward moving shock waves will occur as in road traffic by creating platoons of aircraft.

The curve in figure 10 b is an approximation of how the relationship could look. The real curve may have a different shape, but it is obvious that up to a certain approach flow rate the arrival rate will increase as the density increases. Thereafter the arrival rate decreases as the density increases due to the number of aborted landings or the removal of units from the landing stream. The difference between the optimum density and the maximum allowable density (minimum separation) is a measure of airspace waste and the inefficiency of the system.
Increased precision is needed to minimize the separation distribution. The dashed curve in figure 11 symbolizes the present distribution curve for the touch down sequence showing a large spread in distribution. The solid curve shows how it would look for a system with improved precision. Improved precision will allow increased flow, reduced waste of airspace and a reduced number of aborted landings. It should also, in time, allow for the option of reduced separation minima.

As navigation and surveillance systems gain improved accuracy and information transfer lag time is reduced, a significant reduction in the difference between the optimum and allowable densities can be expected. Initially this should decrease airspace waste and increase the arrival rate to a point that approaches the theoretical maximum as determined by the present separation criteria. Later, it could lead to separation criteria close to the physical limits set by factors such as wake vortex decay time and runway occupancy time.

Air-traffic flow is a heterogeneous flow, assuming there are \( N \) airways leading toward one runway \( X \). The sum of the \( N \) flows should never be greater than the maximum landing flow at \( X \) or the flow will be oversaturated causing further reduction in the arrival flow. For this study the incoming flows were restricted by the runway capacity.

### 9.7 CONTROL BASICS

A control system consists basically of the components shown in the block diagram, figure 12. For an aircraft, the control system consists of the elements, or blocks in figure 12, necessary to ensure the desired organized behavior. Given that the objective is to keep the aircraft at constant speed, the first block for consideration is the detection, or measurement element, measuring the actual speed of the aircraft. If the aircraft is manually controlled, the speed is displayed on the speed indicator for the pilot to record and process. The pilot compares the actual speed with the reference value and calculates the appropriate action to be taken. In control language, the pilot performs the functions of a comparator and a compensator. The compensator and comparator blocks are called the controller. The signals emanating from the compensator portion of the pilot’s brain activate the muscles to move the throttles. The arm is the actuator, providing both power amplification and motion. Using auto-throttle, a computer performs the comparator and compensator processes, and the actuator function would be performed by a servo.
The path from measurement to comparator is usually called the feedback loop. Such a system is defined as a closed loop system. Feedback is a very important part of the control process as it is essential for maintaining stability and for fine-tuning.

When the reference value is fixed, the control problem is called regulation, and the control system a regulator. When the reference value varies, the control problem is called tracking, and the system may be called a tracker.

9.8 SEPARATION DEFINITION

There are advantages to using time in lieu of distance as the separation control parameter. This may be exemplified by an analogy from road traffic. When driving a car at distance $S_1$ behind another car running at the same speed, $V_1$, the headway time $T_1$ is equal to $S_1$ divided by $V_1$. Increasing the speed to $V_2$ on both cars while keeping the distance at $S_1$ gives a new headway time of $T_2$ that is less than $T_1$. $S_1$ is the minimum safe distance at speed $V_1$ that makes it possible to avoid a tail-strike accident if the car in front suddenly uses maximum deceleration rate down to a complete stop. $S_1$ will therefore not provide a safe distance if the speed is increased to $V_2$. However, if $T_1$ is held constant by allowing the distance to vary, it would be possible to avoid a tail-strike accident at any speed. Time is therefore a better control parameter to use to acquire and maintain a safe distance than distance itself. This would also be the case for air traffic.

Many physical limitations determining the minimum safe separation are time-related, for instance the Runway Occupancy Time (ROT) and the decay time of wing vortices. Time separation has not been a practical or possible parameter for computation and display of position information using Radar. However, using physical distance for separation requires continuous adjustments to obtain and maintain a minimum separation for approach, for example one aircraft following 1 minute behind another will be about 8 NM behind during cruise, but only about 2.5 NM behind during final approach. This adjustment is difficult and requires extensive controller training to become anywhere near accurate.

For display reasons, time has been translated to physical distance. Introduction of accurate GNSS position and time information and the use of data link (ADS-B) for information transfer will change this to allow time separation to be used. This provides for two different methods to display and control time separation. One is based on the use of accurate 4-D navigation when an aircraft is controlled to be at a specified geographic position at a certain time. The other is the TRAIL method described in chapter 10, when an aircraft is controlled to a specified time separation relative to another aircraft.

4-D navigation requires accurate time information. This is not the case for TRAIL, described in chapter 10, which allows time separation to be based entirely on relative position and speed.
9.9 AIR TRAFFIC CONTROL METHODS

Presently, the major task and effort for ATC is problem solving of a continuously self-generating chaotic situation caused by unacceptable density variations in non-metered merging or crossing flows, i.e. the number of aircraft allowed into the flow is not limited to what the system can handle without the need to correct local density peaks. Even when traffic is far below the theoretical maximum there can be periods when density peaks exceed the maximum acceptable level. These periods increase rapidly when the flow increases, hence the lack of accurate strategic planning makes tactical flow intervention necessary.

The intention when slot times were introduced was to keep the magnitude of flow density peaks manageable, not to create a sufficiently accurate metered flow to avoid flow control intervention. There are several reasons for this, among them that the 4-D navigation accuracy of past airborne equipment has not been adequate. Generally, this is no longer the case, however the necessary major change in ATS – Operator (ground – air) interactive procedures has not yet been realized; in fact, not yet been attempted. Based on available surveillance information, ATC attempts to even out the density to allow as high flow as possible without violating the separation rules. For approach this is normally done by stringing aircraft based on relative position to each other, more rarely based on geographic position.

Presently three methods are used for surveillance: visual observation, radar observation and procedures.

The visual observation method, even though far less accurate than radar, allows less (2,5NM) separation as the responsibility for separation is delegated to the pilot under the assumption that he has correctly identified and can accurately determine the distance to the preceding aircraft. This assumption is not always valid. The transfer of responsibility for separation as well as allocation of punitive action for separation violation from the controller to the pilot has played a part in allowing separation to be reduced.

Note: Pilots, through their unions, have recently shown great reluctance to accept responsibility for separation using 4-D navigation ACM equipment. Logically, that should be a far safer method, both regarding the risk for airborne conflict and the risk for consequential punitive action, than the willingly accepted visual approach.

The radar observation method provides only historic, but reasonably accurate position information for slow moving targets. The low display update frequency and the information transfer lag, ambiguities and uncertainties of using aural radio communication require the use of conservative separation criteria, normally 3 NM during approach for landing.

The procedural method requires by far the largest separation. For separation during approach it requires that aircraft separation be confirmed by passage of waypoints.

Most of present FMS navigation equipment uses DME-DME updates to achieve very accurate 2-D position determination when within DME range. The 3-D information is less accurate due to poor synchronization of time. The equipment provides intent information. This highly accurate information will be significantly improved and extended to provide extremely accurate and global 4-D information when updated by GNSS. The position and intent information provided by the present FMS equipment is far superior to the historic information displayed on radar screens, but is as yet unavailable to ATS. Radio link systems are available, but only in the early stages of implementation. These will become available with the transition to FMS/GNSS update and will also allow ACM functions to be implemented.

For aircraft to be able to navigate to the precision provided by the new navigation equipment, Auto-throttle will most likely need to be used for speed and separation control. To achieve navigation accuracy better than ±1 second, a new control law has been proposed, see section 8.3.

10. PROPOSED TRAIL METHODS

10.1 STRING CONTROL

With the string control (SC) method the second aircraft is controlled relative to the first, the third to the second and so on. String control is the normal method presently used by ATC for approach. The analogy from road traffic is driving a car in foggy conditions where the driver uses speed to control the distance based solely on the information from the taillights of the preceding car, see figure 13. The arrows symbolize the data transfer between the units.
Figure 13: String control

With perfect information transfer between the units, String control provides complete stability. In reality a string of aircraft is not perfect and a control law is required to achieve stable flow in the string. Two algorithms that are useful for String control have been found: stimuli response and our own TRAIL1.

One problem with string control is the risk of disturbance transfer. If an aircraft upstream in the string causes a disturbance, the disturbance may escalate along the way downstream. It is necessary to use an extremely accurate control algorithm to avoid disturbances transfer.

10.2 ABSOLUTE REFERENCE CONTROL

The other proposed method for string control is Absolute Reference Control (ARC), whereby all units in the string control to the same reference, which could either be an aircraft in the string, a “ghost” aircraft not yet on the string track or a synthetic aircraft. The information transfer is visualized in figure 14 where all aircraft are controlled relative to the master aircraft. It is possible to use the same control algorithm for ARC as for string control. ARC with only two units is actually String control.

String control will ensure separation or detect separation violation between each aircraft pair. This is not ensured with ARC where lack of position holding (station keeping) of one aircraft in the string will not directly be detected by and affect the control of the next aircraft in the string. Compared to String control, ARC has the potential to enhance the stability of the flow. One could imagine when using ARC to achieve flow stability that String control be used in parallel to supervise separation between pairs of aircraft. This could also be applicable to ensure minimum separation when basing control on 4-D navigation.

Figure 14: AbsoluteReference Control using the lead aircraft as the absolute reference.

10.3 CONTROL ALGORITHMS

As mentioned previously, it is important to create an accurate control algorithm to control separation. During the study we have found two algorithms developed to control separation between moving aircraft: TRAIL 1, and the stimuli response algorithms. TRAIL 1 was initially developed in the Traffic In Line (TRAIL) project [9]. For the Absolute Flow Control study we made some adjustments to improve the algorithm. The stimuli response algorithm is well known in the field of road traffic control.

10.3.1 TRAIL 1

The concept of TRAIL is to control the time separation between two aircraft by using a control law. The TRAIL Project [9] evaluated a control law for string control. The control law is based on a PDI-controller. This control method is commonly used to control industry processes like robot arms or transport belts. A PDI-controller contains a proportional (P), a derivative (D) and an integral (I) part.
The PDI-controller’s input will be the **time error**. Time error is the desired separation time minus the actual separation time, see section 10.5 TIME ERROR. The control law is shown in equation 9 below:

\[
Force(t) = K_p \text{timeError}(t) + K_p \frac{d}{dt} \text{timeError}(t) + K_I \int_{t-r}^{t} \text{timeError}(t) dt \quad \text{(Equation: 9)}
\]

By adjusting \(K_p\), \(K_D\), and \(K_I\) it is possible to change the system’s output. By increasing \(K_p\) and \(K_I\) the system will respond more quickly at the cost of reduced stability. Increasing \(K_D\), which works as a damper in the system, will enhance the stability. The output from the controller is the ideal accelerator to eliminate the time error. If the time error is large the output will be large, sometimes exceeding aircraft performance. In that case the output must be limited to the maximum acceleration/deceleration performance for the actual aircraft by truncating the signal.

The value of the constants was derived empirically, initially based on studies and assumptions. This is the normal way to set the constants when there is a manipulation of the output. A range of different values will make the system stable, but give different responses.

**10.3.2 STIMULI RESPONSE METHOD**

The stimuli response control method is based on the sensory stimuli to and the response actions of a driver. Control inputs are made by mental calculation of what the driver sees. Mental calculation of distance has low accuracy, especially for moving objects and shows large variations between individual drivers.

Another important human factor component is reaction time, which also shows large variations between individual drivers and, over time, is largely dependent on the physical and mental states of the respective persons. Equation 10 shows the stimuli response algorithm, known as the car following model. One assumption is that a driver adjusts his speed according to the preceding car; in other words, the speed is adjusted as a function of the density.

\[
d^2x_n(t+T)\over dt^2 = c \left( \frac{dx_n(t)}{dt} - \frac{dx_{n-1}(t)}{dt} \right) \quad \text{(Equation: 10)}
\]

The position at time \(t\) for the \(n\)th car is represented by the \(x_n(t)\), where \(T\) is the reaction time. The constant \(c\) is chosen so the formula agrees well with observed data on a given highway. In Intelligent Cruise Control (ICC) this algorithm is the basis for controlling separation between the cars. Interesting for us in this algorithm is that spacing distance is used; we prefer to use headway instead.

**10.4 TRANSFER LAG**

Transfer lag and update frequency are very critical components in a control process. The update frequency describes how often the information is sampled. To be able to track a signal properly, the sampling rate has to be modulated correctly to avoid loss of important information. The sampling rate in the present ATM system may be acceptable for the purpose, but a severe information transfer lag may exist. By increasing the sampling rate and decreasing the information transfer lag, the system will be easier to control. A predictive signal may help to control the system in between the information samples.

There are numerous sources in the present ATC system that cause transfer lag. A simplified control loop can be described as:

- The radar illuminates a target based on \(t_R\) seconds old data.
- The controller makes a mental calculation on the information from the radar, which takes \(t_C\) seconds to perform.
- The controller uses voice communication to transmit the calculated speed/path to the pilot. This takes \(t_T\) seconds.
- The pilot performs the command from the controller in \( t_p \) seconds.
- The aircraft responds and after \( t_f \) seconds the reaction is observed by the controller on the radar screen.

In this way the loop is completed with a total transfer lag of, 
\[
T = t_R + t_C + t_f + t_P + t_r
\]
each time. The size of \( T \) has not been investigated, but it is obviously large as \( t_R \) could only be about 7 seconds. The size of \( T \) will highly affect the accuracy in the control loop. In future ATM systems, equipment like ADS-B will reduce the transfer lag and will be supported by accurate GNSS data.

10.5 TIME ERROR

When trying to control an aircraft using time separation it is important to define how to calculate the time error. We have found different methods for the calculation. The equation we find to be most correct, is equation 11, where \( t_{ordered} \) is the ordered time between the aircraft, \( x_{n-1}(t) \) is the position for the leader and \( x_n(t) \) for the follower.

\[
t_{error} = t_{ordered} - \frac{\left(x_{n-1}(t) - x_n(t)\right)}{\Delta X \left(V_n(t-1)\right)} = t_{ordered} - \frac{\Delta X}{\gamma_n(t-1)}
\]

(Equation: 11)

This equation gives a negative value when the separation is too large and vice versa. The speed used in this calculation is for the follower. It is also possible to use the lead aircraft’s speed, but the answer will be different when the leader changes speed causing the follower to overreact; when the leader decreases speed the desired distance in meters between the aircraft decreases. The follower compensates this by increasing speed. It would have been desirable to reduce speed but at lower rate than the leader to compensate for the distance reduction. For this reason the follower’s speed was used to calculate the time error.

11. SIMULATION

11.1 SIMULATION OF SC AND ARC

The simulation tool allows for testing and analyzing five aircraft in trail using either the string control or the absolute reference control method. Further information is found in appendix 1, TRAIL simulator. The TRAIL 1 control algorithm was used for all simulations because it was the most proven at the time.

3 scenarios were used:

- Scenario 1: Reference at constant speed
- Scenario 2: Reference increasing speed
- Scenario 3: Reference using final approach speed profile

In scenario 1, the first (reference) aircraft in the string is traveling at a constant speed during the whole simulation. In scenario 2 the first aircraft in the string at point 1000 starts to increase speed from 200 m/s to 250 m/s. The speed profile in scenario 3 is as would be for a final approach. The initial speed is 113 m/s for all aircraft. When the lead (reference) aircraft passes point 1000 (“Final ATM Advisor”) it starts a speed reduction to 85 m/s. When then passing point 28000 (FAF/OM), a further speed reduction to 67 m/s, touch down speed, is made.

Case 1 uses scenarios 1 and 2 and involves two aircraft in the simulation. It shows the importance of the damper in the control system.

A more complex simulation with five aircraft involved is performed in cases 2 and 3. Case 2 is run with two different scenarios, scenarios 1 and 3.

Finally, case 3 shows how a change of relative position in the string can be executed. This case is described as rescheduling the order of the traffic stream before final approach.
11.2 Case 1
This case is an introduction of string control to illustrate the performance characteristics. Using only two aircraft in the simulation model makes it easier to understand the controllers’ performance and criticality.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Max GS</th>
<th>Min GS</th>
<th>Max deceleration</th>
<th>Max acceleration</th>
<th>Max shock</th>
<th>Initial speed</th>
<th>Ordered time sep.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC1</td>
<td>280 m/s</td>
<td>180 m/s</td>
<td>-0.7 m/s²</td>
<td>1.0 m/s²</td>
<td>0.2</td>
<td>200 m/s</td>
<td>None</td>
</tr>
<tr>
<td>AC2</td>
<td>280 m/s</td>
<td>180 m/s</td>
<td>-0.7 m/s²</td>
<td>1.0 m/s²</td>
<td>0.2</td>
<td>200 m/s</td>
<td>60</td>
</tr>
</tbody>
</table>

Table1: Aircraft data

11.2.1 SCENARIO 1
The performance of both aircraft is according to table 6:1. The initial condition for this run has both aircraft flying at a constant speed of 200 m/s with a separation of 67 seconds. The ordered separation between the aircraft is 60 seconds. The task for the follower is to eliminate the -7 seconds time error (equivalent to about 1400 m distance error). The damper gain of the controller is varied to visualize the importance of the damper. Figure 15 a, shows the time error chart for a low damped controller, figure 15 b, shows the time error with higher damper gain.

![Figure 15 a) Time error for a low damped system, b) time error for a damped system.](image)

The low damped system is quicker than the damped system, but gives a greater over-shot, about 1.20 seconds compared to 0.7 seconds (equivalent to 240 m and 150 m respectively). Oscillation occurs with low damping. The low damped system needs more time to become dynamically stable, so the damped system will be stable earlier. It is possible to increase the damper to prevent overshooting, but at the cost of some time.

When an oscillation occurs in time error there tends to be a great instability of the acceleration, as shown in figure 16 a. When there is more than one aircraft in trail, any oscillations tend to increase downstream. The need for effective damping in the system is obvious.
After about 50 seconds the follower aircraft (AC2) is at a stable separation of 60 seconds to the lead aircraft (AC1), however already after about 20 seconds the time error is within a second.

In the speed – time chart, figure 17, the speed profile during the run is shown. The maximum speed reached is 221 m/s at about 27 seconds. Afterward, the speed is decreased continuously down to the leader’s speed of 200 m/s.

A damper will increase the stability in the process. Oscillations in acceleration will not be acceptable because they may have negative effects on the engines.

### 11.2.2 SCENARIO 2

In this simulation, the follower initially maintains a stable separation of 60 seconds behind the lead (reference) aircraft. The lead aircraft then changes speed from the initial speed of 200 m/s to 250 m/s. The task for the follower is to keep the separation constant during the speed change. The aircraft performances are according to table 1 and the controller is fully tuned with all components added.

Of interest in this run is the time error vs. time and speed vs. time (figure 18 a and b). In the time error diagram it can be seen that the disturbances are negligible, the time error is never greater than 80 milliseconds (equivalent to about 20 m).
The speed profile is interesting to study. AC2 uses a lower rate than AC1 because the distance between the aircraft pair will increase as the speed is increased. AC2 compensates for this by using a lower acceleration profile.

The distance separation between aircraft is visualized in figure 19. As can be seen in the figure 19, with fixed time separation the distance between aircraft is a proportional function of the speed. In this case the initial distance separation is 12000 meters at the speed of 200 m/s. When the speed increases to 250 m/s, the distance between aircraft increases to 15000 meters.

As mentioned before, the ARC is a string control with two aircraft. If the number of aircraft that use AC1 as an absolute reference is increased, the time error, acceleration and speed profiles will be equal for all aircraft in an absolute reference control, given that all aircraft are equal. If AC1 changes speed, all aircraft will get an equal impulse to their controller and will perform an equal output. The only difference will be that the performed action will be made at different geographical positions.

11.3 Case 2

11.3.1 SCENARIO 1

In this case the behaviour of a string of five aircraft in String Control is investigated. Scenario 1 is used for the first run. A time error of -7 seconds is added to all aircraft so that all aircraft are 7 seconds behind
their respective target position as shown in figure 20. The task for the trailing aircraft is to eliminate the time error down to the ordered separation of 60 seconds between each aircraft pair. The simulation is similar to the one that was performed in case 1, but with five aircraft in the string. The aircraft performance is according to table 2.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Max GS</th>
<th>Min GS</th>
<th>Max deceleration</th>
<th>Max acceleration</th>
<th>Max shock</th>
<th>Initial speed</th>
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<td>AC1</td>
<td>280 m/s</td>
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<td>200 m/s</td>
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<td>200 m/s</td>
<td>60 s</td>
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<td>1.0 m/s²</td>
<td>0.2</td>
<td>200 m/s</td>
<td>60 s</td>
</tr>
<tr>
<td>AC5</td>
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<td>-0.7 m/s²</td>
<td>1.0 m/s²</td>
<td>0.2</td>
<td>200 m/s</td>
<td>60 s</td>
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</table>

Table 2: Aircraft set-up for the time elimination.

Figure 20: Initial separation for the time elimination simulation.

The first aircraft keeps the initial speed of 200 m/s in constant for all aircraft during the simulation. All aircraft have the same performance because in this run only the methods and the precision of the algorithms are being investigated. The lead aircraft starts at position 0. The following aircraft are spaced to the left (negative) in the coordinate system.

It is important to note that the second aircraft in the stream is chasing a target that maintains constant speed. AC 2 is actually the same as in the first run in case 1. The aircraft downstream from the second are chasing targets that change speed. The speed profile and time error curves for the last three aircraft are very similar.

Figure 21: Time error vs. time during whole simulation and zoomed around zero.

By looking at the time error chart we find that all aircraft are stable with 60 seconds spacing after 90 seconds. There is an overshoot in time error of about 0.4 seconds for the last three aircraft. The second aircraft in the stream has a greater overshoot, 0.8, because it is trailing an aircraft that maintains constant speed. The other aircraft in the stream have equal behaviours during the time error elimination. There are practically no oscillations or travelling disturbances. The signal is well damped even as the number of aircraft in the string increases. The speed profile is almost identical for the last three aircraft during the
acceleration phase, but differs during the deceleration phase. This is easily explained by the fact that all aircraft use the same maximum acceleration while the approach to time error zero occurs differently for the aircraft because of very different total corrections (7 seconds for AC2, 14 seconds for AC 3, 21 seconds for AC 4 and 28 seconds for AC 5).

Figure 22: Speed vs. time (speed profiles)

11.3.2 SCENARIO 2

The purpose of this scenario was to investigate if it would be possible to maintain a stable landing sequence by using the string control method. Initially all aircraft had the same speed, 113 m/s and were stable at a time spacing of 60 seconds to the aircraft in front. When aircraft 1 reaches point 1500, it starts to reduce speed to 85 m/s.

As can be seen in figure 23a there are only small disturbances in time error for this run. An important comment is that the damper is not of great use for small changes such as in this simulation because the damper value is almost negligible in the processes. The speed profile for the first aircraft has a greater rate than for the second aircraft. The reason being that the second aircraft compensates for the decrease in distance separation due to decreasing speed. This is the same for all following aircraft as can be seen in figures 23b and 24.

Figure 23: a) time error vs. time, b) speed vs. time.

In this scenario it also interesting to investigate speed vs. geographical distance to see if the aircraft will be able to reach the landing speed before touch down. The speed seems to be phased such that the first aircraft reaches the required speed at 25 NM and the last aircraft in the string at 35 nm from the start of the run.
A follow-up study should investigate how to shape the control law to improve synchronization of speed vs. distance (to runway). The accuracy and stability of the control law is such that some degradation may be sacrificed in order to improve characteristics like geographical synchronization, see section 14 ROAD MAP. One method to synchronize speed vs. distance is to activate the string control at a geographical point, for instance at distance 1500 for all aircraft. The simulation shows that all aircraft start to decelerate at the same point where the first aircraft started. This will cause the time error to increase temporarily after the lead aircraft starts decelerating, but will result in the same speed profile for the last four aircraft.

If we had used ARC instead of SC, the speed profile would have looked different. In figure 25 the speed profile using ARC is visualized. All speed curves and time errors for the last four aircraft are the same because they work with the same parameters. The speed will be more out phased compared to SC. For this purpose ARC may not be a desirable method for final approach and landing.

11.4 Case 3

This simulation investigated how string control could be used in ATM to establish a desired sequence of landing aircraft as shown in figure 26. The sequence at the beginning is \{1, 2, 3, 5, 4\} and the task in this simulation is to organize the aircraft in the order \{1, 2, 3, 4, 5\}. All aircraft are initially established with stable separation of 60 seconds. Because of the undesired initial sequence, AC 4 has a +120 second (too close) time error and AC 5 has a – 60 second (too far) time error. Aircraft performance in this run is according to table 2.

This can be the situation if there is a need to reorganize the sequence approaching an airport. Each aircraft has its own ghost aircraft to follow, for example the second aircraft trailing the ghost of the first.
Figure 26: Overview of the scenario set up.

In figure 27 a, the time history of the switch that occurs between aircraft 4 and 5 is shown. In figure 27 b the time error is shown. AC 5 is limited by the minimum flying speed of 180 m/s (figure 27 c) causing a longer time to get into position. AC 4 never reaches the maximum speed of 280 m/s before it starts to decelerate. AC 4 makes a large time error overshoot because of the high speed, but when starting to decelerate, the overshoot gradually decreases. The reason for the time error overshoot is that it is based on ordered time minus time spacing (t) where time spacing is the actual distance between the aircraft divided by the current speed. The temporary time error is, in this case, desirable to complete the maneuver as rapidly as possible.
Figure 27 a, b and c:  a) position – time (left), b) time error – time (right), c) speed – time (left below)

A string control correction can handle a situation of this type, however, it takes in the order of 10 minutes to complete. It would be desirable to expand the control law to include the use of trajectory changes in order to expedite gross corrections, see section 14 ROAD MAP.

12. SUMMARY OF SIMULATIONS

Study of the available literature and analysis of simulation data have shown that there are some common relationships between road-traffic flow and air-traffic flow. The shapes of the flow density curves are similar, however the curve for air traffic flow is affected by the relatively small spread of maximum and minimum speeds for aircraft. The flow will increase as the density increases up to a certain density (optimum). Beyond optimum density the flow decreases for air traffic because of rapid rise in aborted landings and over-saturated controllers. Present optimum density is much lower than the theoretical maximum due to the low accuracy of spacing aircraft. If the precision of spacing aircraft on final approach is increased, there is a potential to increase the mean arrival rate. Increased precision will provide better use of airspace and airport capacity. To meet future demands of air traffic there is a great need to implement the improvement in navigation and surveillance accuracy that will be provided by GNSS FMS update and to implement ADS-B information transfer. There is an equal need to develop a control method with a control law that facilitates full use of the above improvements and to develop an infrastructure that supports this.

Of the proposed control methods Absolute Reference Control (ARC) and String Control (SC), SC uses the presently established principle of relative spacing and has been looked at more closely. When SC uses the TRAIL 1 control law it has shown in our simulations to provide a very stable and accurate flow. The ARC method may be feasible if used in combination with SC. Relative spacing must always be controlled to the nearest aircraft for safety reasons. For the controller the use of SC will be familiar as he controls spacing as presently to the nearest preceding aircraft.

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In simulations SC using the TRAIL control law showed an accuracy of 100 milliseconds or better allowing a near linear relation between density and flow up to the maximum speed of the flow.

13. CONCLUSIONS
This study has investigated factors that affect air traffic arrival flow rate and flow stability.

The results of the study indicate that control methods may be applied that will allow stable air traffic flow rate to be increased to closely approach the limits set by physical factors such as runway occupancy time and wing vortex avoidance. The accuracy provided by the methods is in the order of meters and fractions of a second. The airborne equipment needed, ADS-B and capable Flight Management Systems, is or will be available in the near future. The required modification to ground-based equipment would in many cases be simple in technical terms, however, the ground – air (operator – ATM) procedures and responsibility allocation may take significant time to develop and negotiate.

Simulations using the TRAIL control law for string control indicate that this provides a stable flow with at least the accuracy and flow rate of 4-D navigation with GNSS update.

Several factors, like the effect of low information update frequency on flow stability, the use of TRAIL for gross corrections and the optimum use of combined 4-D navigation and TRAIL need further investigation and optimisation. The methodology for planning and executing an undisturbed metered flow needs, however, to be investigated further. There is also a need to define the infrastructure and the procedural and regulatory requirements set by the new systems and the proposed methods.

14. ROAD MAP

14.1 ORIENTATION
4-D high accuracy flight planning and navigation may provide the Air Traffic Service (ATS) with the proper data for planning a metered flow that will significantly reduce the need for downstream controller intervention.

Maximum flow of air traffic is obtained when aircraft are spaced with minimum separation and the flow is stable without disturbances that cause oscillatory behaviour. Flow density exceeding the optimum level will cause disturbances that may reduce the flow rate far below that of a stable flow. To ensure maximum flow rate it is essential that a deeper understanding be gained of the stability of air traffic flow, as well as knowledge of how to develop the proper systems and procedures that will create a metered flow with minimum density fluctuations and other disturbances. 4-D high accuracy flight planning and navigation data can provide ATS with the necessary strategic data for planning an optimum metered flow that may reduce the need for downstream controller tactical intervention. However, it may not be expected that the need for controller intervention can be completely eliminated. During the initial phase of Air Traffic Management (ATM) 4-D flow planning, when there will be extensive mixed equipage and before the full use of high accuracy 4-D navigation has been fully explored, it must be expected that the approach and landing sequences are controlled using the present principle of stringing aircraft using relative spacing between aircraft pairs. It is, however, required that the accuracy of relative spacing be improved to match that of 4-D navigation in order to maximize the flow. It is our position that to achieve this a transition to time separation in lieu of distance separation is required. A string of different aircraft using 4-D navigation can probably not achieve maximum density (minimum separation) as they use individual speeds that require additional spacing to absorb the drift in separation. Therefore, to achieve maximum final approach density and maximum arrival flow rate a string control method using relative time spacing could be used. This inherently requires aircraft to use the same speed profile except for the very last part of the approach when individual stabilisation at threshold speed is necessary.

When intervention is necessary or desirable, time reference traffic in line (TRAIL) provides the controller with an accurate and low workload method to string aircraft with minimum separation. The proposed TRAIL method aircraft uses only speed control to acquire a required time separation. Speed is, however, a low authority control method that is too time consuming for gross control. Methods for gross control based on trajectory adjustments have been identified; they need to be developed and integrated with the speed control method.

The TRAIL control law has not yet been optimised for the decelerating approach when it tends to give a “rubber band” effect that desynchronises speed vs. distance for the trailing aircraft. Methods to reduce this have been
studied, but further work is required. The interactive processes and responsibilities needed to implement new systems and methods have not yet been developed. This work should start as soon as possible, in order to avoid delaying the implementation or preventing the optimum use of a mature and developed technology due to procedural deficiencies.

14.2 STUDY ITEMS, DISCUSSION

METERED FLOW
The purpose of metered flow is to eliminate or reduce downstream disturbances that are caused when flows are merging or crossing. The procedures and methodology for planning and executing metered flow should be further investigated. The methods for reducing environmental disturbances from, for example unpredictable winds and the methods to correct, like renegotiation of slot time, should be studied.

FLOW STABILISATION AND CONTROL
High precision should make it possible to operate closer to the minimum separation limit ($k_{max}$). This will increase the flow rate. The description in figure 28 is an idealized view of how it would look, however the flow will still be influenced by operational factors such as weather changes that are not included in figure 28.

![Figure 28: Flow and density diagram for high precision controlled density.](image)

Fig 28 shows a one-dimensional model that includes time. A three-dimensional model would probably increase the possibility to improve control loop accuracy.

String control (SC) needs further development to study flow stability, the effect of low information update frequencies, disturbance tolerance etc. When used for final approach, it may be necessary to include a geographical relation in the formulation to prevent out-phasing of speed vs. distance when a string of aircraft follows a decelerating approach profile. There are several possible solutions to this problem, but more studies are needed before a conclusion of which solution would be the most beneficial is reached.

A simulation in a SMART (Simulator multi-role ATM research & Training) where string control is fully implemented for the final approach phase would also be needed to get an understanding of how the flow will behave and how the controller workload will be affected when using string control. A feasibility study of the possibility to carry out a simulation in this kind of simulator environment, SMART, has been conducted. The following step should be to evaluate how the control law works with real aircraft dynamics in A/C simulators.

EXPANDED TRAIL CONTROL LAW
The TRAIL method is intended to provide the controller with an accurate and low workload method to string aircraft when tactical intervention is necessary or desirable. The proposed Time Referenced trAffic In Line (TRAIL) method uses only speed to acquire and keep a required separation. Speed is a low authority method that is not adequate for gross control. The optimum combination of trajectory adjustments to enhance gross control, and
speed control-based methods should be part of an expanded study. This will increase the complexity of the control law, but may be necessary to enable full use of such a model.

ATM USE OF TRAIL
Of the highest priority should be another, separate study to define the interactive processes when using the proposed systems and methods. This should be started as soon as possible in order to avoid that procedural deficiencies prevent optimum use of a mature technology. This study should include the use of high-accuracy 4-D information for flow planning and the optimum use of 4-D and string control for gate-to-gate flow execution.

ECONOMICAL ASPECTS
By using TRAIL it should be possible to reduce the number of aborted landings that have a negative effect on arrival flow rate as well as the environment. An increased accuracy in the flow will enable better punctuality. This will increase the quality of travelling by air and should reduce secondary costs and inconveniences for passengers.

The economical benefits from the system need to be studied, however, any accurate estimate of this can be reached only after simulations of the total system in realistic scenarios have confirmed the increase in arrival flow rate.

14.3 PROPOSALS FOR WORK PACKAGES

14.3.1 ATM FOR METERED FLOW
Listed below are the proposed components for further study in this area:

- The flow study initiated in this preliminary study should be expanded to gain a deeper understanding of flow qualities including flow stability and flow control.
- The optimum use of 4-D and TRAIL should be investigated considering maximum flow, workload and system robustness for handling aberrations and failures.
- An investigation is needed to define ATM Procedures and Processes (ATMP&P) necessary to establish a metered flow. These must include all Central Flow Management Unit (CFMU) and collaborative ATM airline procedures and processes.
- The scenarios for simulating the ATMP&P must be defined. Eventually all normal, abnormal and emergency conditions must be included. To a large extent the same requirements must be set for the ground segment as are set for the air segment.
- The ATMP&P must be verified in simulations, flight tests and operations. The type of simulations and flight tests needed must be defined.

14.3.2 TRAIL
Listed below are the proposed components for further study in this area:

- The TRAIL control method should be investigated in an aircraft simulator environment to verify its performance using real aircraft performance and dynamics.
  Of particular interest is the potential to increase arrival flow rate.
- A Simulator Multi-role ATM Research & Training (SMART) real time simulation with partial and full string control implementation is needed to investigate flow behaviour and the effect on controller workload. An initial assessment has already been made regarding how this type of SMART simulation could be performed.
- An expanded study of system tolerances to disturbances and low update frequencies should be made.
- An inventory study of possible gross control methods using trajectory adjustment suitable for integration with the TRAIL method is needed.
- The gross (trajectory) and fine (time) control methods need to be integrated and run through a SMART type simulation to develop and verify the total control law.

- A study should be made of how to use the string control law to ensure that minimum separation is not violated when aircraft are using individual speed profiles during 4-D navigation.

The results from these studies would lead to: better utilization of the 4-D ATM concept, reduced traffic delays, reduction of the gate-to-gate flight time and reduction of the environmental load. The goal must therefore be to meet future demands in traffic, taking into consideration environmental aspects with the smallest possible changes to the infrastructure.
15. REFERENCES

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## Glossary

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>4-D</td>
<td>Four dimension</td>
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<tr>
<td>AC</td>
<td>Aircraft</td>
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<td>ACM</td>
<td>ATC Communications Management</td>
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<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance – Broadcast</td>
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<td>ARC</td>
<td>Absolute Reference Control</td>
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<td>ATC</td>
<td>Air Traffic Control</td>
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<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>ATMP&amp;P</td>
<td>ATM Procedures and Processes</td>
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<td>ATS</td>
<td>Air Traffic Service</td>
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<td>Avtech</td>
<td>Aviation Technology Consultants</td>
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<td>BFT</td>
<td>Swedish Rules for Air Traffic Services</td>
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<td>CCC</td>
<td>Conventional Cruise Control</td>
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<tr>
<td>CFMU</td>
<td>Central Flow Management Unit</td>
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<td>DMD</td>
<td>Digital Massage Device</td>
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<td>DME</td>
<td>Distance Measuring Equipment</td>
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<tr>
<td>FAF</td>
<td>Final Approach Fix</td>
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<tr>
<td>FMS</td>
<td>Flight Management System</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>ICC</td>
<td>Intelligent Cruise Control</td>
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<td>IFR</td>
<td>Instrument Flight Rules</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transport system</td>
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<td>LIU</td>
<td>University of Linköping</td>
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<td>OM</td>
<td>Outer Marker</td>
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<tr>
<td>RAMS</td>
<td>Re-organized ATC Mathematical Simulator</td>
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<td>ROT</td>
<td>Runway Occupancy Time</td>
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<td>SATSA</td>
<td>Swedish ATC Academy</td>
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<td>SC</td>
<td>String Control</td>
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<td>Simulator Multi-role ATM Research &amp; Training</td>
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<td>TRAIL</td>
<td>Time Referenced Traffic In Line</td>
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<td>VMC</td>
<td>Visual Meteorological Conditions</td>
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APPENDIX A

A1: TRAIL SIMULATOR 2

A2: DATA ANALYSIS 6
A1. TRAIL SIMULATOR

A1.1 Introduction
To test and analyse string control (SC) and absolute reference control (ARC) we created a simulation tool in the programming language JAVA. JAVA enables expansion of the simulation tool. There are also a great number of useful add-on packages, such as chart printers. JAVA is object oriented, which is advantageous in this kind of simulation, i.e. each aircraft type could be represented as an object. The simulation model is built as a dynamic time discrete model.

The simulation tool handles a large number of aircraft. We chose to involve five aircraft during simulation. Five aircraft will give enough information about disturbances such as the rubber band effect or any other disturbance that will influence stability.

To set up a simulation, different parameters were defined, for example aircraft type and initial separation between aircraft. Before the simulation is run, a method (SC or ARC) was selected.

During simulation, calculations of new acceleration, speed and position were made according to the method selected. New calculations are made each second. The result of the simulation is presented in text-files and in five charts:

- Speed – time
- Time error – time
- Acceleration – time
- Speed – geographical distance
- Geographical position – time

A1.2 Structure
An overall structure of the process is described in figure A1. The simulation begins with ten iterations without the control algorithm connected (see below). The reason for this is the need for history data in the control process. After ten iterations the controlled process is started and runs through the pre-set iteration length.

When the iterations are finished, a text-file for each aircraft is created with data about the current run. Text-file information includes:

- Acceleration (m/s²)
- Ground speed (m/s)
- Time Error (s)
- Position (m)

The text-file is created if there is a need to analyse the data in software such as Matlab or Excel. The last action in the run is to print the five charts.
Figure A1: System structure

The calculation loop for a follower is as described in figure A2. There is an input of positions from leader and followers. A delta separation is calculated from these input values. By dividing the delta distance with the follower speed the time spacing is calculated. Time error is the ordered time spacing minus the current. A too great separation produces negative values and vice versa.

Figure A2: Block diagram over the computations.

The controller (Equation A3) uses the current time error and old time errors to make it possible to perform operations such as derivate and integration. The estimated acceleration is checked to see if it would be feasible according to the aircraft performance (see a/c performance). From the resulting acceleration new speed is calculated using Equation A2. Current speed multiplied by the time step (\( t_s \)) will give how long the follower has travelled. The new position is computed using Equation A2. During the first 10 iterations the controller block is inactivated, as mentioned previously.

\[
V_n = V_{n-1} + t_s * a_n \quad \text{(Equation A1)}
\]

\[
X_n = X_{n-1} + V_n * t_s \quad \text{(Equation A2)}
\]

\[
Force(t) = K_p * timeError(t) + K_d \frac{d}{dt} timeError(t) + K_i \int_{t-\delta}^{t} timeError(t)dt \quad \text{(Equation A3)}
\]
A1.3 Aircraft performance

In the simulator there are aircraft with different performance capabilities. All aircraft types in our model have the aircraft dependent constants:

- max speed
- min speed
- max acceleration
- max deceleration
- max shock

The model includes 3 aircraft that are different in performance, B737, B747 and MD-80. Only recently we have modulated the performance for the MD-80 by using data from The Base of Aircraft Data (BADA).

To get a dynamic of the acceleration we used an acceleration factor. Acceleration could never be greater than the acceleration factor. With increased speed the acceleration factor will linearly decrease. This is a simplification of the real dynamic the acceleration factor would decrease with the square.

The shock constant is the comfort factor that limits acceleration change; as well when the controller estimates a higher acceleration change, the shock factor will truncate the value to the max shock value.

Speed below minimum or above minimum is never possible because there occurs a control if the speed is a feasible or not. So when the minimum speed is reached, the min speed will be held constant until there is an impulse from the controller to increase speed.

A1.4 Time step

In this model we have assumed that information transfers (i.e. the aircraft communicate with each other exchanging position data) occur once during each simulation iteration. This simplifies the model but would not be valid if such information transfer occurred less frequently than each second. If the position information is updated (i.e. the aircraft communicate with each other) less frequently than that, we will need to calculate speed and position of the leading aircraft during the time gap between information transfers. However with an information transfer frequency of 5 seconds, the model is still close to reality / the error in the model is still limited / acceptable.

A1.5 Scenarios

In the model we have created three scenarios that are possible to run. These are based on how the first aircraft (master aircraft) behaves. These are called:

- Scenario 1: Reference at constant speed.
- Scenario 2: Reference increasing speed.
- Scenario 3: Reference using final approach speed profile.

In scenario 1, the master uses constant speed of 200 m/s during the simulation. This scenario is of use when wanting to simulate the behaviour of time error elimination, i.e. then aircraft in the stream are not at a correct time separation when simulations start.

Scenario 2 is created to show how the string of aircraft behaves when the master aircraft increases speed from 200 m/s to 250-- m/s.

For scenario 3 we have created a final approach speed profile for the master aircraft. The speed schedule is as in figure A3.
Figure A3: speed schedule for the master aircraft in scenario 3.

All aircraft have an initial speed of 113 m/s and at point 1000 the master aircraft gets an order to reduce speed down to 85 m/s. Next speed order occurs at point 35000 where the master has to reduce the speed down to a speed of 67 m/s (landing speed).

A1.6 Coordinate system

TRAIL v1.0 is a one-dimensional model where all aircraft are distributed on a line. The first aircraft in the model starts at point zero and the following aircraft are spaced out to the left (negative) segment. The unit of the system is in meters (m), each step equals one meter.

Figure A4, Coordinate system for the TRAIL v1.0 simulator.

A1.7 Expandability

Recent models can be expanded to three-dimensional (exclusive time component) models, which add the feature of using horizontal track adjustment (gross control) to the control algorithm. When increasing the model to three-dimensions, the computation time will be increased because there will be several other aircraft dynamic aspects to take into account (like descent and climbing performance) and the distance between aircraft will be calculated on four components instead of two. In further study the expansion from one- to three-dimension is necessary, and more aircraft with variation in performances need to be included.
A2. DATA ANALYSIS

A2.1 Introduction

To get an understanding of the air-traffic flow during final approach we needed a set of data to analyze and contacted the Swedish ATS academy (SATSA). We found that it would be useful to use one of SATSA’s simulators to get a data set for an analysis. SATSA has two simulators for analysing air-traffic, SMART and RAMS. These are mainly built for tests and analysis of the controller workload. SMART is a real-time simulator that needs human actors within the simulation and RAMS is a fast-time simulator. At the first stage we intended to use RAMS and prepared two scenarios to be executed. But personnel at SATSA soon realized that RAMS optimised the results and always gave best-case results, thus we could not visualize a true air-traffic flow with disturbances. SATSA offered a data set from a recently performed simulation in SMART instead. This simulation was suitable for us as there was a choked flow and the simulation was very near to reality, as human factors were in the loop.

A2.2 The selected simulation

This section will give a brief background of and accomplishments from the simulation used, written by the staff at SATSA.

A2.2.1 Purpose

Air traffic is continuously growing and Airline Companies have increasingly higher expectations on effectiveness on the airports. With this in mind the Managing Director of Landvetter Airport initiated a study to state the prerequisites to increase the capacity at Landvetter up to 44 movements per hour. As a consequence of this ATS Landvetter decided to simulate and evaluate the airspace and organisation with increasing air traffic.

The purpose of the real-time Simulation for ATS Landvetter was to study and verify whether the current organization with three (3) working positions and current airspace complemented by two new two holding points, BEBSI and KOLLE, and new procedures as stated in simulation condition 3, could manage an increase of traffic to forty-four (44) movements to and from Landvetter Airport and additional air traffic in Göteborg terminal control area and traffic to and from Säve.

A2.2.2 Background

During last year the Managing Director of Division Landvetter initiated a preliminary study with the purpose of stating the prerequisites to increase the capacity to 44 movements (arrivals and departures) per hour at Landvetter Airport. ATS was promptly involved in this task and the result of the preliminary study showed that the construction of a number of new taxiway exits would increase the capacity so that the aim of 44 movements was reached. A report was presented to the Director General of the Swedish Civil Aviation Administration who acknowledges the continuation of the work. As a consequence of the continued work and to verify ATS possibilities to guarantee not to be a limitation for the progress of the airport, ATS Landvetter needed to carry through two simulations at SATSA. A ground simulation based on the conclusions from the preliminary study initiated by the Airport Director and an airspace simulation which would show whether the current airspace design and ATS organisation will manage the increasing traffic at Landvetter. Because of among others requirements from LFV Safety Department, which led to conceivable changes to the design of the apron, the sequence of the simulations was changed at a late state. The planned ground simulation was postponed to a later date and the first simulation at SATSA was an airspace simulation, which was of our interest.

A2.2.3 Accomplishment

The simulation was conducted in the SMART Simulator between 11 - 13 May 2001 at SATSA (Swedish ATS Academy).

The simulation included 3 Radar Control Positions: TE – Terminal Control, Sector East; TW – Terminal Control, Sector West and ARR E/W – Director to TE/TW. 4 Dummy positions: Landvetter Tower; Adjacent Towers; Malmö sector 5 and Malmö sector 1 including Copenhagen ATC.
A total of 6 simulator sessions were carried through. Each session lasted 60 minutes and the simulated runways were alternatively 03 and 21. The organisation in the Approach Unit was the same as today and in the Tower the organisation was reduced to one position, which controlled the runway.

One scenario with totally 62 aircraft, 21 departures, 34 arrivals to and from Landvetter or Säve and 7 over flights, was made and used as a basis for the whole simulation. The simulated traffic is based on the LFV (Swedish CAA) prognosticated traffic for Landvetter Airport of the year 2005.

A total of 12 Approach Controllers from ATS Landvetter and one from Malmö ATCC took part together with personnel from SATSA.

Leif Wennström, Manager for the Approach Control Unit in Stockholm ATCC took part as a very active observer during all 3 days. Representatives from Malmö ATCC also visited the simulation.

A simulation information folder was produced at SATSA and distributed to the participants as training guidance material. Using this, the Controllers could, in advance before arriving at SATSA, prepare and familiarise themselves with the operational procedures to be used during the simulation.

The Analysis and Evaluation study of the simulation is based on views and comments from the participating ATC personnel. The participants had to answer questionnaires after each session. Likewise, hour-long discussions took place during the debriefings held after each session. Notes were taken. Additionally, statistical data was provided by the SMART Evaluation and Recording system (RUT) as basis for the analysis.

The successful results of the simulation weren’t only the good technical results but also the overall benefit for an ATC unit to come together and improve the team spirit.

Thanks to the very good pseudo pilots’ work the result of this simulation was very good and without pilots working very realistically the outcome wouldn’t be trustworthy.

A2.3 Purpose

The purpose of this data analysis was primarily to examine how the separation distribution will look for a choked flow. The separation distribution will give us information with what precision that controller are able to space aircraft on final approach. If the distribution is great the precision will be low and vice versa.

We were also interested how the speed profiles look during final approach. In a stable flow the speed profiles will be equal. The number of ordered speed changes during the simulation will also be of interest then analyzing the stability.

A2.4 Separation criteria

The separation criteria followed the Swedish Rules for Air Traffic Services (ICAO Doc 4444), (BFT) section 2 chapter 6 paragraph 3.6.4. Which is as follows

- Behind Heavy (H) should at least:
  - H be 4Nm behind
  - M be 5Nm behind
  - L be 6Nm behind

- Behind Medium (M) should at least
  - H and M be 3Nm behind
  - L be 5Nm behind

- Behind Light (L) should at least
  - H, M, and L be 3Nm behind

A2.5 Data selection

The smart simulator generates a great value of data, which is stored in an Oracle database. When simulation is finished it is possible to ask questions to the database. The data collection from this simulation was large and includes unnecessary information for our study. The SATSA staff made a selection of a suitable set of data for our purpose. We import the data to an Exel sheet, which give us the opportunity to make selections in the data.
The data set we made our selection from includes aircraft information about:
- Time (clock time)
- Speed (m/s)
- Event type
- Vehicle
- Weight category
- Latitude
- Longitude
- Flight level

In this simulation there was 17 different event types:
- COMPLETED_LANDING
- CREATE_VEHICLE
- ENTER_HOLD
- LEAVE_GROUND
- PASS_NRP
- PASS_UP THROUGH_LEVEL
- START_APPROACH
- START_CHANGE_BEARING
- START_CHANGE_SPEED
- START_CLIMBING
- START_DESCENDING
- START_TAKEOFF
- STOP_CHANGE_SPEED
- STOP_CLIMBING
- STOP_DESCENDING
- TERMINATE_AIR_VEHICLE
- TOUCH_DOWN

We had the intention to analyze the touchdown frequency so we created a table that only included the events TOUCH_DOWN and START_TAKEOFF. The selection is viewed in table A1. From table A1 we selected the touchdowns that occurred in pairs, e.g. with no START_TAKEOFF in between. By these criteria we got 16 touchdown separation times to analyze. The separation time was calculated by subtracting the leader’s touchdown time with that of the follower’s.

<table>
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<th>Time</th>
<th>Leader</th>
<th>Follower</th>
<th>Leader Speed (m/s)</th>
<th>Follower Speed (m/s)</th>
<th>Leader Latitude</th>
<th>Follower Latitude</th>
<th>Leader Longitude</th>
<th>Follower Longitude</th>
<th>Leader Flight Level</th>
<th>Follower Flight Level</th>
<th>Separation Time (s)</th>
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</tbody>
</table>

Table A1: The selected data set includes both touchdowns and arrivals.
In column 12 the separation time between the aircraft is presented. To avoid confusion we selected aircraft with the separation criteria of 3Nm, e.g. M behind M and H behind M.

**A2.6 Analysis**

The mean value \( (t_{sep}) \) of the touchdown times \( (t_{sep}) \) was interesting to determine the accuracy of the touchdowns. When calculating the mean value we use equation A4 where \( N \) equals the number of observations. The mean value is of use when calculating the airport capacity, e.g. dividing 3600 with the mean value will give the rate over one hour.

\[
 t_{sep} = \frac{\sum t_{sep}}{N} \quad \text{(Equation A4)}
\]

By calculating the standard distribution \( (S) \) there was an opportunity to determine the precision which the controller has for spacing aircraft on to final approach.

\[
 S = \sqrt{\frac{N\sum t_{sep}^2 - (\sum t_{sep})^2}{N(N - 1)}} \quad \text{(Equation A5)}
\]

A confidence interval was also calculated to see within what interval the mean would be for an increased number of touchdowns.

To visualize the speed distribution during the simulation we selected four aircraft touching down with no departures in-between. Distance to touchdown was calculated from the latitude and longitude values that were saved in the data set.

**A2.7 Result**

The analysis resulted in the separation mean value of 105 seconds and the median of 97 seconds. The flow based on a mean value as a base is 34 arr/h and with median 37 arr/h. The mean value may be a too pessimistic value but the median would cut off the extreme values and give optimistic values.

To get a view of the distribution of the touchdown time we made a chart where we collected the numbers of touchdowns that occurred in 5 second intervals, on the time line of 60 to 200 seconds. The result is viewed in table A2 and figure A5.
The standard distribution for the selected 17 touchdowns was 30 seconds, which we think is a quite high value. This means that the precision with which the controller can space aircraft on to final approach is 30 seconds. In the simulation there was a comment that a sequencing system and increased experience for spacing aircraft would slightly reduce the fluctuations in the traffic flow. So the distribution could be reduced by a few seconds when the controllers become used to working with a traffic flow of this kind.

If the flow would be stable, the speed profiles should be the same for an aircraft pair. We selected four aircraft, which touched down after each other with no arrivals in between to visualize the speed profiles. In figure A6 the speed profiles are viewed and the order of the aircraft is {SAS1448, BCS085, BRA464, SAS169}.
The speed profiles are obviously not equal and therefore we will have a fluctuation in the density (separation) in the flow. It is important to note that a lot of speed changes occur during the last 60NM (figure A6) before touchdown. For example the SAS169 gets 20 speed commands during the simulation.

![Speed - distance](image)

**Figure A6:** Speed profiles for four aircraft during whole simulation (Figure 7 in main report).

In figure A7 the speed profiles for the last 40 NM are presented. In this figure the difference in speed is more obvious, i.e. BRA464P has a more aggressive deceleration rate than BCS085 that is the BRA464P leader. There is also a difference in number of speed settings, which is visualized by the break point in the diagrams.

![SPEED - DISTANCE](image)

**Figure A7:** Speed profiles for four aircraft, during the last 40 NM.
A2.8 Conclusions

The data set could seem small, only 16 aircraft pairs were included. It is obvious that a larger set of data would increase the reliability of the analysis results. By comparing the results of a study recently performed by The Boeing Company [10], the results are almost equal. We assume that the results have a high reliability because controllers were forced to pack the aircraft during approach to fulfil the demanded capacity.

The results indicate a great distribution of the touchdown separation times. The speed profiles are also widely distributed. We made the conclusion that the precision of spacing aircraft during approach is low. Improving the separation precision will dramatically increase the arrival rate.