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Data system in flight and emission modelling

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ABSTRACT

Flight and emission modelling is applied in operational applications and in engineering to quantify aircraft emissions by aviation activities. A data system, called the flight and emission model, is designed to comply with both types of usage. Main features of this data system are described. Traffic processing as special feature is highlighted, especially related to large volume data processing on multiple platforms. Methods have been applied to improve the computational performance by creating a flight sequence that minimises the number of calculation steps. Results show that model performance can be increased by such methods, in addition to the definite gain from the increasing power of computer platforms. The data system provides the framework for integrating flight and emission model components. The resulting flight and emission model has proven to be successful in studies performed at NLR and has been embedded in a policy analysis instrument for the national government.

1. INTRODUCTION

The need for flight and emission modelling arises from the growing interest in the effects of aviation emissions and in ways to reduce fuel use and emissions through technological improvements, new flight procedures or other measures. This interest is twofold. Global aviation emissions are quantified to study large-scale atmospheric impacts and effective reduction options [Ref. 3]. Local aviation emissions are quantified for monitoring and evaluating the effects in air traffic regions or the direct environment of airports.

Experts on flight and aircraft technology contribute to research studies by making flight and emission models representing the situation during the flight. They collect data and create algorithms; assisted by software engineers, they carry out calculations providing the model results that support the analysis and the study objectives. Until recently, results were generally presented in documents. As aircraft emissions and noise abatement are becoming key issues for governments, public organisations, airports and airlines, there is a shift towards end-user applications in the transport sector. Planning of air traffic and monitoring the environment is not longer restricted to the laboratory but is becoming an operational task.

As a national aerospace laboratory, NLR is involved in this field for several years. Flight and emission algorithms as well as software programs have been developed to support analysis tasks such as:

- Generation of aircraft emission inventories
- Classification of aircraft and engine types
- Sensitivity analysis
- Policy analysis on emission reduction options
- Processing large air traffic registers

The strong interrelation between these tasks made clear that an integrated approach is necessary.

2. DEVELOPMENT APPROACH

A driving force to structure data and computational methods was the participation by NLR in the Aviation emissions and Evaluation of Reduction Options (AERO) project in which models are developed and integrated aiming at a full-blown aviation policy analysis instrument for the Dutch civil aviation organisation [Ref. 6]. One of the basic models in the system is the Flight and Emission model (FLEM) developed by NLR. A typical output of the model is aviation emission on the world grid (Fig. 1).

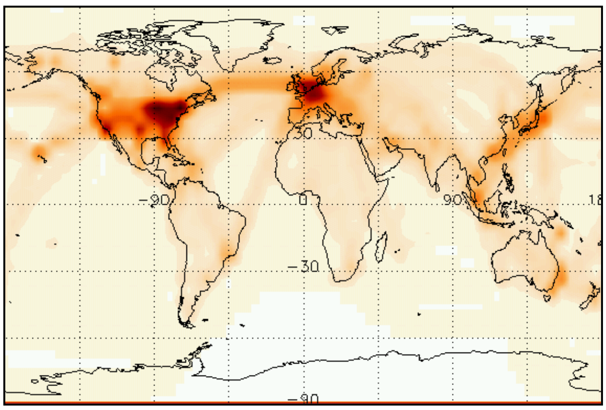


Figure 1: Global aviation emissions (AERO project)

Standard software engineering principles were applied to the development of FLEM: requirement analysis, specification of modelling, software design, testing, verification and validation. The result was the FLEM data system – a framework containing the model components and its database. New phases in the AERO project [Ref. 1] and other studies [Ref. 4, 8, 9] led to new versions of FLEM. Each time the engineering steps were taken to keep track of the system development. Tests were enhanced or added to verify new requirements. Regression tests were regularly performed to see if existing requirements were still met.

Design criteria were established during the development of the system. New needs were analysed to ensure that the data system became a multipurpose framework in flight and emission related work. These criteria address basic qualifications of the data system:

- Hosting various computational methods
- Monitoring all model variables
- Configuration by enabling methods and data
- Policy and sensitivity analysis capability
- Integration into end-user applications
- Stand-alone operation
- Support on various platforms
- Large volume data processing
- Aircraft/flight detailed processing

These qualifications are in headlines addressed in the next section.

3. DATA SYSTEM

The primary task of the model is to calculate the spatial distribution of aircraft emissions and flight related values such as fuel use. The first step is to translate the flight information from the aviation activity data into flight properties along the flight path using aircraft technology data. The flight profile sets the distance, altitude, speed, thrust and fuel flow at intermediate flight points. The next step is to extend the profile with emission index values, the amount of emitted substance per unit of fuel, at flight points applying engine technology data. The third step is to map the flight profile and ground track onto a three-dimensional air space grid, calculating total values on flight segments that contribute to grid cells. For commercial aviation, these steps can be taken because flights are registered with known departure and arrival. For military aviation, less detailed records are available requiring another way of modelling. Military traffic processing is not further considered in the remainder of this paper [Ref. 11].

The data system now contains four calculation components as shown in Figure 2. This figure also shows the sequencing of the components and the external model data. Monitoring all model data is necessary to keep track of calculation cases and related data. Model data are defined as array-based variables and stored in the model database, controlled by a dedicated data manager [Ref. 2]. It supports data management on the UNIX and Windows environment.

Methods of calculation can be put into place at the parent component by conforming to its defined interfaces. Model controls are introduced to activate the methods in the calculation steps.

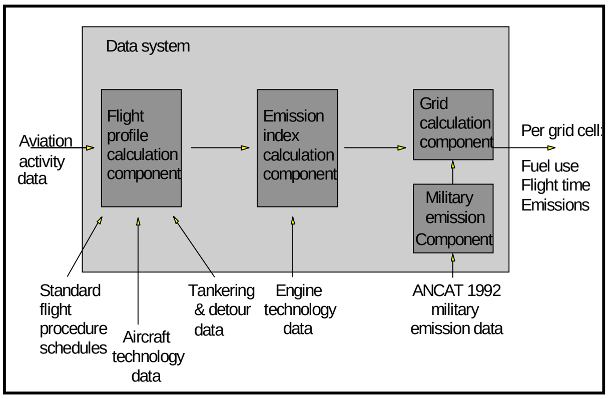


Figure 2: Data system overview

The analysis capability requires an approach for handling scenarios and measures. This is achieved by model parameters that affect the model calculations. Each type of data has a set of change factors related to the base values of the data set. For example aircraft and engine technology data have technology change factors on fuel use and engine emission index. Examples of change factors on flights in air traffic are detour factor, load factor and flight-level limit.

In stand-alone operation mode, the model has to be provided with model data files for aviation activity, aircraft data and engine data. Composition of these data sets is an extensive task and requires expert knowledge. Base data sets are gathered from flight manuals, aircraft/engine databanks and traffic registers [Ref. 7]. Model controls and parameters can be provided by a user interface program, which sets values for controls, scenarios and measures.
In integrated operation mode, other data systems can supply the air traffic data, aircraft technology [Ref. 1, 5], or at least model parameters related to the base input data. The model output can be used as input for visualisation or other models on environmental or atmospheric impact.

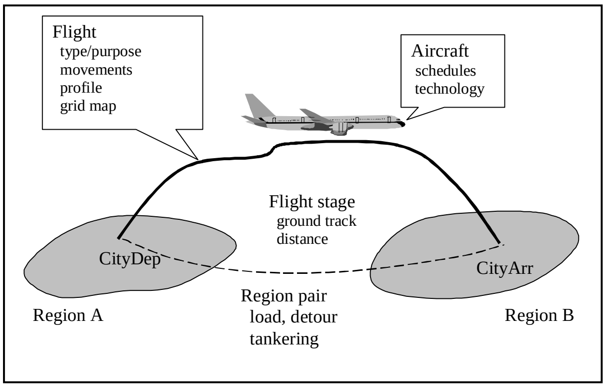
Large volume data processing versus specific detailed processing demands the most of fast traffic processing. Methods for efficient processing without blocking detailed calculations require knowledge of data modelling and its dependencies.

Data modelling and dependencies
Aircraft are modelled by a number of aircraft categories. Individual aircraft are assigned to a category e.g. by seat band and distance haul. A

category has a representative aircraft type that is used for calculating the flight and emission characteristics. Matching factors are supplied with its aircraft and engine data to give a close representation of the individual aircraft it represents. Technology is modelled by a technology level, referring to average characteristics of e.g. old and current part of the fleet.

Aviation activity is represented by an air traffic distribution containing a list of traffic lines. A traffic line contains the number of movements by aircraft of particular usage on one flight stage. The usage is expressed in terms of aircraft purpose (freighter or passenger) and flight type (scheduled or charter). The aircraft is set by aircraft type and technology level. An example of a flight on a traffic line is a scheduled passenger flight with current aircraft type on the flight stage between region A and region B (Fig. 3).

Figure 3: Flight representation



A flight stage is modelled as departure and arrival on city level. Each flight stage identifies a city pair and flights between both cities are represented in traffic by the same flight stage identifier. Track modelling sets the ground track and the distance to be covered, e.g. as great circle distance. A detour on distance depends only on region pair and aircraft type. Another region pair dependent property of a flight is the load factor that models the average payload weight.

Thus a flight is defined by its flight stage (fs), aircraft purpose (ap), aircraft type (at) and technology level (tl). The flight stage sets the region pair (rp). As result of data analysis, four main types of dependencies can be distinguished in the data system:

1. Flight dependency – fs, ap, at, tl
2. Aircraft category dependency – at, tl
3. Flight stage dependency – fs
4. Region pair dependency – rp, at, ap

Model variables can be arranged to groups of variables in which each variable is a function of the indicated dependent variables or a subset thereof. Calculations depend on one or more dependency types, e.g. ground track calculation depends on flight stage only, and

access of flight schedules and emission index tables depending on aircraft category only.

4. TRAFFIC PROCESSING

In traffic processing the data system traverses the air traffic data, picks up the flight information and starts the calculation steps that lead to a flight grid map. Then these grid cells with flight contributions are multiplied by the number of movements and added to the totals in the result grid. Computational performance of traffic processing can be critical when the data system is integrated in an interactive application or when a large number of calculation results have to be generated for analysis purposes. The data system must provide solutions for three main factors:

- Level of detail
- Data system efficiency
- Hardware platform

Data dimensions and calculation methods determine the level of detail. Hardware choice determines the absolute run time. Independent of this, data efficiency can be influenced by design methods and measures to get the most out of the system.

Time consuming steps

Traffic processing is a repetitive sequence of the same kind of data manipulations and computations per flight. The number of flights scales the model run time. From performance investigations it appears that data manipulations play even a more important role than computations [Ref. 10]. Processor speed of hardware is not the only determining factor. Another result was that flight profiling and grid mapping were about equally time consuming steps. Program code was reviewed and improved on frequent data access and control loops.

Another perspective is to look at the complete flight sequence. A convenient processing sequence can establish a reduction of processing time by sharing calculated results between flights whenever possible. Equal profile parts or flight grid maps can be shared and need not be recalculated for the next flight. A condition is that the design incorporates stores to save intermediate results of one flight for sharing those results between subsequent flights. The traversal of traffic can be crucial to the effectiveness of such approach. At this point the preceding dependency analysis can help to find methods for improvement.

Methods

1. The *threshold* method puts a limit on the minimum number of annual movements to be processed. The

data system is instructed to skip traffic activity not exceeding this threshold. This reduces the number of flights, but is less accurate by leaving out traffic. This method can be useful as first impression of results.

2. The *shared-result* method reuses calculated results between subsequent flights whenever possible. Candidate results for sharing are:

- Flight dependent results - flight profile, emission index profile and flight grid map.
- Aircraft category dependent results - flight schedules and engine emission table
- Flight stage dependent results – ground track

A mechanism is provided to keep track of the flight processing state: properties of previous and actual flight are saved. The data system performs checks on these properties in order to decide if previous stores can be used for the current flight.

3. The *flight-sequence* method optimises the usage of shared results. Three main sequences are obtained by:

a) Sort key (fs-ap-at-tl)
By default traffic is sorted primary on flight stage. This method benefits most of sharing the same ground track, the same region pair dependent data and in second place the same aircraft categories.

b) Sort key (fs-at-tl-ap)
Flights are still sorted on flight stage, but now having the same aircraft categories in sequence. Flight profile and flight grid map can be shared if sequential flights have the same purpose.

c) Sort key (at-tl-fs-ap)
Flights are sorted on aircraft category as primary key. Flight stages are sorted on region pair and increasing distance. On equal aircraft category and region pair, same schedules and tables are shared, but flight profiles are different because these depend on payload and distance.

A flight sequencer is added to the data system. It analyses traffic on shared flight properties. Based on this analysis a most convenient flight sequence can be found by the best average number of shared results, or equivalent, effective reduction in number of flights. A flight list is composed, in which each entry specifies the traffic line (tr) and aircraft category (at, tl). Now this flight list is sequentially traversed.

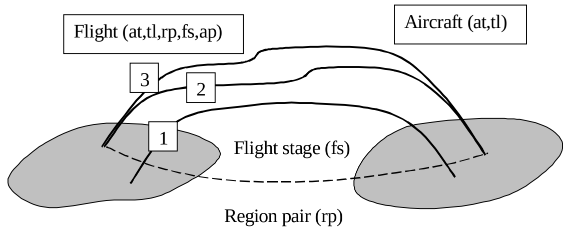
4. The *flight-category* method allocates flights to flight categories. Flights are sorted on sort key (c). The next step is to make a list different flight profiles, defined by weight band and distance band. A flight is allocated to a flight category by take-off weight, landing weight and flight distance. This method reduces the effective number of calculations through fewer calculations of flight profiles, but with some loss in accuracy depending on the bandwidth of the categories.

To accommodate this method, the flight sequencer introduced by the third method is extended. Now it analyses traffic also on flight categories. Furthermore additional features are needed in the flight profile calculation component.

Flight categories

Some background on flight profile composition is provided to make clear the underlying principles of the flight-category method. Consider flights on one region pair (Fig. 4). Within one aircraft category all region pair dependent model parameters have the same impact. As for flight 2 and 3, only different payload factors can lead to different weights and therefore different flight profiles, even on the same flight stage. They could fall into the same flight category, but in this case they got different weight bands (500 kg).

Take-off and climb are calculated from take-off weight. Landing and descent are calculated backwards from landing weight. For each climb, one (stepped) cruise phase is calculated, starting from the end of climb distance up to the maximum distance required within the region pair. Finally, depending on flight distance and the distance band, end of cruise is connected to the descent part. The number of profile calculations per combination of aircraft category and region pair is the sum of climbs, cruises and descents; i.e. twice the number of take-off weight bands plus the number of landing weight bands.



at, tl, rp	Take-off (kg)	Landing (kg)	Distance (km)
4, 0, 3	136000	96000	7100
6, 0, 3	335500	225000	8500
6, 0, 3	320000	225000	8500

Figure 4: Flight categories

5. CASE RESULTS

Results on model performance are presented as a case from the AERO project. The performance goal of the model has been stated in the early beginning of the data system development:

“Calculate flight and emission data for global annual air traffic on a world grid within 10 minutes on an average commercial personal computer”

To create a reference for this statement, the model data and model configuration defaults for FLEM are according to the latest version applied in the AERO project (1998). Primary data dimensions are shown in Table 1. Now the performance goal can be reformulated into a processing speed of 55 flights per second. Results are supplied addressing the three identified aspects of computational performance: level of detail, data system efficiency and hardware platform

Table 1: Dimensions for 1992 traffic (AERO project)

Dimension	Value	Description
Aircraft Type	9	Seat band/haul
Technology level	2	Old/current technology
Aircraft Purpose	2	Passenger/freighter
Flight type	2	Scheduled/charter
Flight stages	16700	City pairs
Region pair	196	IATA region pairs
Traffic lines	23288	1992 unified traffic
Flights	37237	Flights movements>12
Flight profile	60	Maximum profile points
Grid	36,72	5 degree grid cells
	15	1000 m altitude spacing

Incremental development
The first version of the model in 1994 contained the basic modelling and traffic created from the ANCAT source [Ref. 7]. When the first calculation results became available, it was clear that the target performance was hard to achieve on the state-of-the-art PC platforms. The strategy was to carefully inspect the data system where possibly gain could be achieved, and meanwhile take advantage of the rapidly increasing computing power on personal computers. An investigation on model performance resulted into a number of improvements [Ref. 10]. A gain of more than 50 percent was found on sample calculations.

Table 2: Development and performance

Year	Model	Time	Fl/s
1994	1	2h15m	4
1995	2	1h50m	5,5
1997	3	1h45m	6
1998	4	30m	20

Approximate figures on Windows PC - 90MHz, 32 Mb

The second version incorporated the suggested improvements. The data system was improved by economising calculations and optimising frequent data access. But also a more detailed flight profiling method was included, based on stationary symmetrical movement equations using lift/drag curves.

The third version was extended with new features such as military traffic, a stepped climb method and a new emission index calculation method [Ref. 11]. Model controls were added e.g. to select methods, parts of traffic or result grid area.

The fourth version was hosted to the Windows95 operating system. The change to a 32-bit program gave a major step forward. Other activities included extensive testing and calibration of model data.

The results of the incremental development process in Table 2 show that:
1. The increase of detailed modelling practically balances the gain achieved from data system efficiency improvements
2. Early PC configurations are not sufficient to satisfy the performance goal.

Comparison of traffic processing methods
The methods of threshold, shared results, flight sequence and flight category have been evaluated on a UNIX workstation for five cases (Table 3). This table shows the processing time, the flight rate and the gain in flight rate. The gain expresses also the effective number of flights as if fewer flights were processed. The results on timing and flight rate are obtained from model runs, except for the flight-category method. Results for this case refer to accurate estimates on the number of calculations to be performed. Other methods were also verified this way. This verification method calculates the effective number of flights based on a distribution of processing over calculation steps and actual counts of calculation steps.

Table 3: Traffic processing and performance

Method	Time	Fl/s	Gain (%)
Default sequence(N>0)	16m30	52,5	0
Threshold (N>12)	12m	52,5	0
Shared results	10m	60	17
Flight sequence	9m	67	28
Flight category	3m	187	255

Approximate figures on UNIX workstation – 180 MHz, 64 Mb

First, the reference is created - processing of all traffic in default sequence, with sort key (a), without sharing results between subsequent flights. Second, a threshold (N) is applied by skipping on average monthly flights. As expected, this improves only the processing time but not the flight rate. Next cases all apply this threshold. Third, the mechanism of shared results is activated on default traffic sequence. This reduces the effective number of flights to be processed in a modest way. The fourth case optimises ‘sharing’ by sorting the flights, with sort key (b), in a way that equal flights are sequentially processed. This extra gain comes easy. The fifth case does alternative sorting on traffic, with sort key (c), and also applies the flight category method. This method is gives the model performance the big push forward.

The results of the traffic processing methods show that:

1. Flight sorting and sharing results provides a simple mechanism to optimise the traffic processing.
2. Sorting on flight categories generates model speed.

Comparison on platforms

The portability of the data system enables the transition to various platforms. Supported platforms include Windows PC and UNIX workstations. In addition, the models are also supported on the central computer facilities of NLR, including UNIX main frame, the super computer and network with workstations. This general service provides accessibility of the data system at the engineer's working place.

Table 4: Performance on platforms

Platform	Description	Time	Fl/s
DEC Pentium Personal	90MHz, 64Mb Win95	30m	20
COMPAQ PII Personal	233MHz, 32Mb WinNT	6m	100
HP9000 Workstation	100 MHz, 32Mb UNIX	30m	20
SGI O2 Workstation	180 MHz, 64 Mb UNIX	10m	60

Method: default sequence, shared results, N> 0

Performance results are gathered for both UNIX workstations and Windows PC, comparing a dated configuration from the initial start (1994) to a modern configuration (1998). The numbers in Table 4 are based on model runs with default traffic sequence including threshold and shared results. An average PC platform of today scores 100 flights per second, approximately twice the performance goal initially stated. Combined with the method of flight category this would translate into a 2 minutes model run and a corresponding flight rate of 300 flights per second.

The results on platforms show that:

1. Computing power of desktop platforms brings interactive analysis closer.
2. NLR central computing facility assists model runs for extensive analysis tasks.

6. CONCLUSIONS AND FUTURE PLANS

Growing demands in application areas require flight and emission modelling with high standards. Flexibility is required to host various calculation methods, to handle air traffic definitions, aircraft technology, global (or local) data referencing. The developed data system provides the framework for model components and traffic processing. At technical level, the traffic processing methods and hardware technology have improved the system performance considerably and, as result, make analysis available at the desktop. The combination of both reduced the global aviation processing from more than two hours to less than ten minutes on a personal computer.

The current data system reached the level to provide quality emission data. It has been applied in NLR research studies, but also successfully embedded in a policy analysis instrument. Decision-makers and analysts have obtained an instrument to see the effects of technological scenarios and policy measures. Another field of interest is the introduction of emission monitoring and planning systems, in which air traffic has to meet emission limits at airports. Local traffic management is not longer limited to control traffic flows under strict safety constraint, but environmental restrictions on noise and emissions become more and more important.

A grasp of current activities and future plans for the data system include:

- Continuation of model support in policy analysis
- Steps to support both emission and noise
- Extended effort in model composition capabilities
- Airport model enhancements
- Promotion of operations on multiple platforms.

The fundamental data and modelling concepts are a solid basis for enhancements and make the data system prepared to challenge the future.

REFERENCES

1. AERO 1997, AIMS general report and user manual, Resource Analysis, Delft, the Netherlands.
2. AERO 1997, AIMS data manager reference guide, Resource Analysis, Delft, the Netherlands.
3. AERONOX 1995, The impact for NOx emissions from Aircraft upon the Atmosphere at Flight Altitudes 8-15 km, Final report, February 1995.
4. Brok, P.H.H. 1998, IATA study on operational measures, preliminary report, NLR, Amsterdam, the Netherlands.
5. Have, H.B.G. ten, T.D. de Witte 1997, Aircraft Technology model - general report, NLR-CR 97326-L, Amsterdam, the Netherlands.
6. Have H.B.G. ten 1996, NLR participates in national project on reduction of aviation emissions, NLR news, 23, July 1996.
7. Gardner, R.M. (Ed.) 1998, ANCAT/EC2 aircraft emissions inventories for 1991/1992 and 2015: Final Report, produced by the ECAC/ANCAT and

EC Working Group.
8. Olivier, J.G.J. et al. 1996, Description of EDGAR version 2.0, a set of global emission inventories, RIVM Report 771060002, the Netherlands.
9. Roos, J.H.J et al. 1997, Energy usage and aviation emissions and other ways of passenger traffic (Dutch), CE, Delft, the Netherlands.
10. Witte T.D. de 1995, Performance analysis of the Flight and Emission Model version 1 (AERO memo MN-78), NLR Amsterdam, the Netherlands.
11. Witte T.D. de, H.B.G. the Have 1997, Flight and Emission model - general report, NLR-CR97327-L, Amsterdam, the Netherlands.