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EXECUTIVE SUMMARY

Work package 2.4.4 of Episode 3 assesses the environmental impact of operational improvements of the air traffic management system from SESAR. The goal of this report is to describe the study on the effects of operational improvements on the local air quality carried out by the Dutch National Aerospace Laboratory NLR. The report gives insight in both the study results and the used assessment method. A methodology to assess the impact of operational improvements on the local air quality is important to assure that new concepts do not result in an increase in local emissions at and near airports. This report describes the used methodology and summarizes the obtained results. The study gives the average emissions per flight on the 20 busiest European airports for a baseline scenario and for several scenarios with the effects of one or more improvements incorporated. The results show improvements that lead to a decrease in queuing time and taxiing with a reduced number of operating engines reduce local emissions. According to the calculations reduced engine taxiing and towing are the most effective measures to reduce the local emissions of CO and HC. Also for SO_x emissions these measures show the best results, however, no auxiliary power unit and aircraft tractor SO_x emissions are calculated due to a lack of data. Towing of aircraft leads to a decrease in NO_x, CO and HC emissions but at the expense of an increase in PM10 emissions. However, both towing and taxiing with a reduced number of operating engines can lead to operational problems. The use of electrical ground power and Pre-Conditioned Air Units instead of auxiliary power units results in the largest reduction of NO_x and PM10 emissions. The optimization of surface movements leads to a reduction of the emissions of all considered pollutants.

1 INTRODUCTION

This report describes a study on the effects of several operational improvement (OI) steps from the SESAR Operational Concept on local air quality (LAQ). The National Aerospace Laboratory of the Netherlands (NLR) carried out this study in the context of the Episode 3 project (EP3). This report is deliverable D2.4.4-04 of work package 2.4.4 Environmental assessment.

The effects of the OI steps on the LAQ as mentioned in this document are on a per flight basis, so effects of traffic growth are excluded. Since EP3 concerns air traffic management (ATM) related measures, background concentrations and emissions of buildings and vehicles at or near the airport are neglected in this text, which means that only aircraft emissions are considered unless other emissions, i.e. aircraft tractor emissions, are a direct effect of investigated measures. However, instead of local aircraft emissions, the term local air quality is used.

1.1 PURPOSE OF THE DOCUMENT

The goal of this report is to provide insight into the study on measures to reduce local aircraft emissions carried out by the NLR. This report describes both the approach of the study and the obtained results. The results of Episode 3 D2.4.4-02, Environmental and meteorological screening and scoping of the SESAR Concept [16], are the basis for this study. This report provides a list of OI steps with the largest expected beneficial effect on the reduction of local aircraft emissions.

This study assesses the effect of the most promising OI steps as defined in Episode 3 D2.4.4-02 [16] on the local aircraft emissions in more detail. Not all of these OI steps are analysed as explained later in this report. The selection of the OI steps is based on available input data, the feasibility of investigating the OI steps and on the expected effect of the OI steps.

The following study goals are defined to give insight into the effect of the investigated OI steps on the local aircraft emissions:

- Calculate the key performance indicators (KPIs) defined for LAQ in Episode 3 D2.4.4-01, Environmental assessment validation framework [17] for the investigated OI steps. The KPIs are calculated on a per flight basis;
- Give an indication of the effect of the OI steps on an ECAC-wide scale.

The first goal of this study is to calculate the KPIs defined in Episode 3 D2.4.4-01 [17]. This document specifies the following KPIs for the LAQ:

- Fuel burn below an altitude of 3000 ft;
- CO_2 emissions below 3000 ft;
- NO_x emissions below 3000 ft;
- SO_x emissions below 3000 ft;
- CO emissions below 3000 ft;
- HC emissions below 3000 ft;
- VOC emissions below 300ft;
- TOG emissions below 3000ft;
- PM10 emissions below 3000 ft;

- PM2.5 emissions below 3000 ft[1].

The goal of this study is to assess the effect of several OI steps. This is achieved by comparing the differences between a baseline scenario and a scenario with one or more applied OI steps. It is not necessary to calculate all emissions below 3000 ft because this study investigates the difference between two situations. Since all of the selected OI steps only affect the emissions on the airport surface, the emissions during the take-off phase and final landing phase will not change due to the considered OI steps. To reduce the number of calculations the airborne part of the flights is disregarded. This means that the KPIs are changed from emission below an altitude of 3000ft to airport surface emissions. In order to provide insight in the amount of emissions at the airport surface relative to the emissions of the final landing and take-off phase, one calculation is done to determine the amount of emissions during these phases.

For this research several analysis methods are used. Results are obtained by making use of the tools ALAQS and LEAS-iT; furthermore some other analysis methods are used to determine the effect of OI steps on the KPIs. Chapter 5 describes the methods in more detail.

The calculated KPIs give an indication of the ECAC-wide effects of the different OI steps. This translation from KPI to ECAC-wide effect is not a simple extrapolation of the calculated local values of a KPI. This is caused by the fact that the emissions on the airport surface are influenced by the local situation, i.e. runway configuration, traffic composition and taxi-route lay-out. This means that if an OI step leads to a certain result at one airport this does not automatically imply that this OI step causes a similar effect on another airport. The approach followed in this research aims to give an indication of ECAC-wide effects on the LAQ by providing generic results for a range of airports but the reader should keep in mind that each airport is unique so that the effects of an OI step on the LAQ may differ from airport to airport.

Summarizing the above, the goal of this report is to inform the reader about a study on the effects that improvements of the ATM systems have on the LAQ. The report describes the used approach, the results and the final conclusions in such a way that it presents a complete overview of the study. This way the report presents a methodology for the assessment of LAQ mitigation measures at airports next to describing the estimated effects of a number of OI steps.

1.2 INTENDED AUDIENCE

This report is deliverable D2.4.4-04 of the 6th framework project Episode 3. For this reason the primary audience is the European Commission (EC). Furthermore it is intended for readers interested in the environmental effects of new ATM concepts, in particular the effects on local aircraft emissions. It is further hoped that the present report is a valuable input to the future work on SES JU WP16.3.

For the last category of readers two aspects of the report are of interest. First of all the report describes a methodology that is suitable for the assessment of new ATM concepts. The used approach is described step by step; this offers the possibility to use this approach for future environmental assessments. Depending on the level of detail of the input data the suggested method is suitable for more detailed local environmental assessments on airport level, but it can also be used to determine the effects of new ATM concepts on a larger scale as is the case in this study.

This chapter and the next chapter are suited for readers without specialized knowledge on LAQ; these chapters give an introduction and a brief description of the used approach. Chapters 3 to 5 require more specialised knowledge of LAQ and ATM. However, less experienced readers can also read section 5.2. This section describes the investigated

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[1] The assessment tools and methods applied for this study are not capable of calculating PM2.5 emissions. For that reason this study does not take these emissions into account.

improvements. Most of the information in chapters 6 and 7 does not require detailed knowledge about LAQ and ATM so that all readers can at least understand the greater part of the text.

1.3 DOCUMENT STRUCTURE

The structure of this report is based on the EUROCONTROL best practise approach. Figure 1-1 gives a schematic overview of this method. This approach is not followed exactly, but it is used as a guideline.

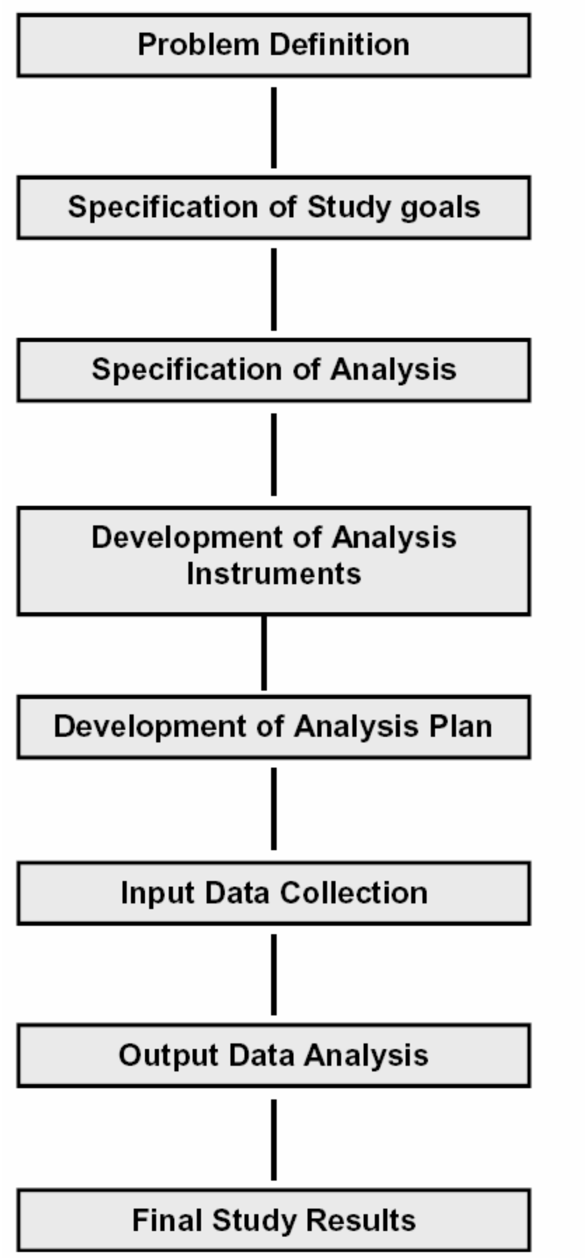

Figure 1-1: EUROCONTROL best practise approach

The introduction defines the problem definition and specification of the study goals. Chapter 2 discusses the specification of analysis design. Thereafter chapter 3 describes the different analysis instruments that are used for this study. Chapter 4, input data collection, summarizes the different inputs that are used to carry out the study and chapter 5 describes the analysis plan. Chapter 6 gives the results are given and finally chapter 7 presents the conclusions and recommendations.

1.4 BACKGROUND

The goal of the Episode 3 project is to start the validation of the operational concept expressed by SESAR Task 2.2 [1] and consolidated in SESAR D3 [2]. The primary goal of Episode 3 is to obtain a system level assessment of the concept's ability to deliver the defined performance benefits in the 2020 time horizon corresponding to ATM Capability Level 2/3 and the Operational Improvement Step IP 2.

The project activities were divided into 7 work packages (WPs), of which WP2 was dedicated to system consistency. Amongst others, the global assessments of the SESAR operational concept were included in this WP. One of the global assessments was the environmental assessment. This activity was covered in WP2.4.5 and its goal was to investigate the effect of the SESAR operational concept on noise, global emissions and LAQ. Several fast time simulations (FTS) that had to be carried out in other WPs would provide most of the required input data.

The project initiation of Episode 3 took place at the end of Q1 of 2007 and the activities in WP2.4.5 started in the beginning of 2008. However at the beginning of Q2 of 2008 the project was suspended and during the suspension the WPs were redefined. In Q3 the project was restarted with the revised description of work (DOW) [18].

The revision of the DOW resulted in a reduction of the number of WPs and a reduction of the required effort in a number of WPs. For WP2.4.5 the revision had the following three main consequences:

- The name of the WP changed into WP2.4.4;
- Other deliverables were defined for WP2.4.4. Instead of the detailed environmental assessments the following two deliverables were defined:
    - D2.4.4-03: Requirement enhancements of noise assessment models;
    - D2.4.4-04: Measures to reduce local aircraft emissions.
- The number of fast time simulations was reduced, so that less input data was available for assessing the environmental effects of the SESAR operational concept.

This report is D2.4.4-04 from the revised DOW. Due to the reduction of the number of fast time simulations, the available input data for this study was reduced. For this reason this study also comprises a literature study in order to obtain sufficient input data. With the effort available for this study it was not possible to produce primary analysis data to replace the FTS exercise data and therefore it is not possible to generate input data with the same level of detail as would have been the case with the planned FTS exercises.

However, this study still gives an indication of the effects on the LAQ of a number of OI steps from the SESAR operational concept. Furthermore the method described by this report can be used to investigate the effect of new ATM concepts on the LAQ.

When a new ATM concept is designed, it is important to assess its effect on the LAQ. Since the usage of air transport has grown over the past decennia and since the impact of the air transport system on the environment became more and more important. For these reasons it is important to consider the effects of new ATM concepts on the environment.

Besides the effect on global emissions, air traffic has three effects on the local environment near an airport. First of all it has an effect on third party risk around an airport. Since aircraft fly over houses and other buildings there is a risk that an aircraft crashes into one of these buildings. Secondly air traffic leads to noise production in areas in the vicinity of airports and may lead to nuisance; especially in urban areas. Finally the pollution caused by aircraft and other vehicles on and near the airport surface have an effect on the LAQ. The effect of air transport on the LAQ is important since it directly affects the health of people working at or living near an airport.

During the design of new ATM concepts these effects on the local environment should be taken into account in order to create acceptance for these new concepts. Designing concepts that lead to a reduction in local emissions is also desirable since it will usually also decrease the fuel consumption, which is not only beneficial from an environmental but also from an economical point of view.

This study focuses on the effects of air transport on the LAQ, more particular, it gives insight in the effect of improvements of the ATM system on the emissions of aircraft on the airport surface. This means that the effect of other sources of pollution on the airport surface such as ground handling equipment will not be taken into account.

As mentioned, this study provides an indication of the effects on the LAQ of a number of OI steps from the SESAR operational concept. As opposed to many other LAQ studies that are aimed at particular airports, the results of this study provide not only information on single airport level, but also on an ECAC wide level. This is achieved by investigating the effects of OI steps for the 20 largest airports in terms of aircraft movements. When an improvement is implemented on an ECAC wide scale, it is important to have an indication of the overall effects of the improvement instead of the effects at only one or a few airports. Since it is important to estimate the overall effects a new ATM concept, the methodology and results of this study are useful when new ATM concepts are designed and implemented.

1.5 ABBREVIATIONS AND GLOSSARY OF TERMS

1.5.1 Abbreviations

Abbreviation	Definition
ALAQS	Airport Local Air Quality Studies
AMAN	Arrival Management
AO	Airline Operator
APU	Auxiliary Power Unit
ATM	Air Traffic Management
AUO	Airspace User Operations
BTV	Brake To Vacate
CAEP	Committee on Aviation Environmental Protection
CDA	Continuous Descent Approach
CODA	Central Office for Delay Analysis
CTA	Controlled Time of Arrival
CTO	Controlled Times of Over-fly
DCB	Demand and Capacity Balancing
DMAN	Departure Management
DMEAN	Dynamic Management of the European Airspace Network
DOW	Description Of Work
EC	European Commission
ECAC	European Civil Aviation Conference
EOT	Engine Out Taxiing
EP3	Episode 3
ft	Feet
FOA3	First Order Approximation 3
FTS	Fast Time Simulation
GIS	Geographical Information System
GPU	Ground Power Unit
GSE	Ground Support Equipment
ICAO	International Civil Aviation Organization
FR	Instrument Flight Rules
KPI	Key Performance Indicator
LAE	Local Aircraft Emissions
LAQ	Local Air Quality
LEAS-iT	Aviation Emissions Inventory Tool for Airports
LTO	Landing and Take-off cycle

Abbreviation	Definition
maxECS	Maximum Environmental Control System
MS	Microsoft
MTOW	Maximum Take-Off Weight
NM	Nautical Mile
OI	Operational Improvement
PAC	Polycyclic Aromatic hydroCarbon
PCAU	Pre-Conditioned Air Unit
PM	Particulate Matter
P-RNAV	Precision Area Navigation
RET	Rapid Exit Taxiways
RMI	Regeling Milieu Informatie (Dutch)
ROT	Runway Occupancy Time
RTS	Real Time Simulation
SES	Single European Sky
SESAR	Single European Sky ATM Research
SMAN	Surface Management
T/D	Touchdown
TIM	Time In Mode
TMA	Terminal Control Area
TOG	Total Organic Gasses
TS	Traffic Synchronisation
UAC	Upper Area Control
VOC	Volatile Organic Compounds
WP	Work Package

1.5.2 Glossary of Terms

Term	Definition
Actual take-off time	The time at which the aircraft departs from the runway.
Excess time during taxi-out phase	Time difference between the time of the taxi-out phase and the unimpeded time.
Local Air Quality (LAQ)	In this report 'local air quality' refers to aircraft emissions on the airport surface only. This means that LAQ does not refer to the effects of emissions produced by other sources than aircraft and that no calculations on concentrations of pollutants are performed.
Off-block time	The time at which the aircraft departs from the gate.
Taxi-in phase	The time from touch-down to arrival block time.
Taxi-out phase	The time from off-block time to the actual take-off time.

Term	Definition
Unimpeded time	The unimpeded time is an estimate of a theoretical optimum for each airport. It is derived by analyzing per stand-runway combination the reported taxi-out times for situations with no influence of congestion.

2 SPECIFICATION OF THE ANALYSIS DESIGN

The goal of this report is to describe both the methodology and the results of the study on measures to reduce local aircraft emissions. This chapter gives a general description of the approach that was used to investigate a number of OI steps.

Out of the complete set of OI steps from the SESAR concept of operations [1], a screening and scoping activity preceding this study selected the ten most promising improvements. The main selection criterion for the list was the potential for reducing emissions that have an effect on the LAQ at and near airports. For Episode 3 D2.4.4-02 [16] a qualitative analysis of all OI steps provided by the SESAR Concept of operations [1] was carried out. Annex 1 provides the list with improvements. This list is used as basis for this study. The analysis of the OI steps involved the following activities:

- Performing a literature study based on the list of selected OI steps. The literature study provides insight in previous studies, the availability of input data and reference data (see section 4.1) ;
- Development of a plan of approach and analysis methods to assess the impact of the OI steps on the LAQ;
- Performing an assessment to obtain results for the different KPIs per OI step for a range of airports within the ECAC region;
- Drawing overall conclusions and providing recommendations.

For the analysis a generic approach was chosen that is applicable to a wide range of airports in the ECAC area. Basis for the study is the EP3 traffic (three days in July 2006) from Episode 3 D2.4.1-01, 2006-2020-X3 Reference Traffic [19], data from the Performance Review Report 2008 and data for 2007 provided by the central office for delay analysis (CODA), all three covering a range of airports.

The list with possible improvements contains OI steps that have potential to decrease local emissions by several means. Some of the effects of OI steps on the LAQ are strongly influenced by local circumstances such as:

- Runway configuration;
- Taxiway configuration;
- Traffic composition, nature of the traffic;
- Diurnal, weekly or yearly variations in the traffic;
- Local weather conditions and the variation in weather over the year;
- The initial situation at an airport before OI steps are implemented.

These effects and the limited availability of data make it difficult to give accurate indications of the effects for each separate airport, and especially to do so for the ECAC wide situation. For that reason an analysis methodology was chosen that provides an upper limit of the emission reductions. The OI steps are assessed using several tools and methods. Chapter 5 gives a more detailed description of the analysis methods.

This study investigates the effects of OI steps on the 20 busiest European airports. The focus is on large airports because the local aircraft emissions increase with the traffic volume. Another reason to use the 20 busiest airports is that a part of the study focuses on measures that mitigate line-up delay; in general line-up delay problems are largest on the biggest airports.

The fact that the considered airports experience more delay than the smaller airports means that the ECAC wide effects of improvements that decrease queuing delays are overestimated when the results of the 20 busiest airports are considered to be representative for all other

European airports. It is likely that the implementation of queuing reduction measures do not prove useful at small airports due to the lack of queuing delays.

3 ANALYSIS INSTRUMENTS

This chapter describes the different software tools used for this study. It gives an overview of the used Microsoft (MS) tools, of the Airport Local Air Quality Studies tool (ALAQS) and of the Aviation Emissions Inventory Tool for Airports (LEAS-iT).

3.1 MICROSOFT ACCESS AND EXCEL

For this research MS Access and Excel are used for emission calculations. It is assumed that these programs do not require any further introduction. Calculations of fuel burn and emissions of taxiing aircraft, APUs and aircraft tractors are performed according to the methodologies described in the ICAO Airport Air Quality Guidance Manual [3]. An extensive description of the calculation methodology is presented in chapter 5.

3.2 ALAQS

Episode 3 D2.4.4-01 [17] gives the following description of ALAQS:

“The ALAQS-AV toolset is a GIS (Geographical Information System)-based research tool. It is a testbed that can be used to investigate the sensitivity of different inventory and dispersion methodologies. The choice of a GIS as a test bench simplifies the process of defining the various airport elements (runways, taxiways, buildings, etc.) and allows the spatial distribution of emissions to be visualized.

The ALAQS-AV tool set provides the classical LAQ analysis features enhanced with capabilities to allow comparison of different inventory and dispersion methods.

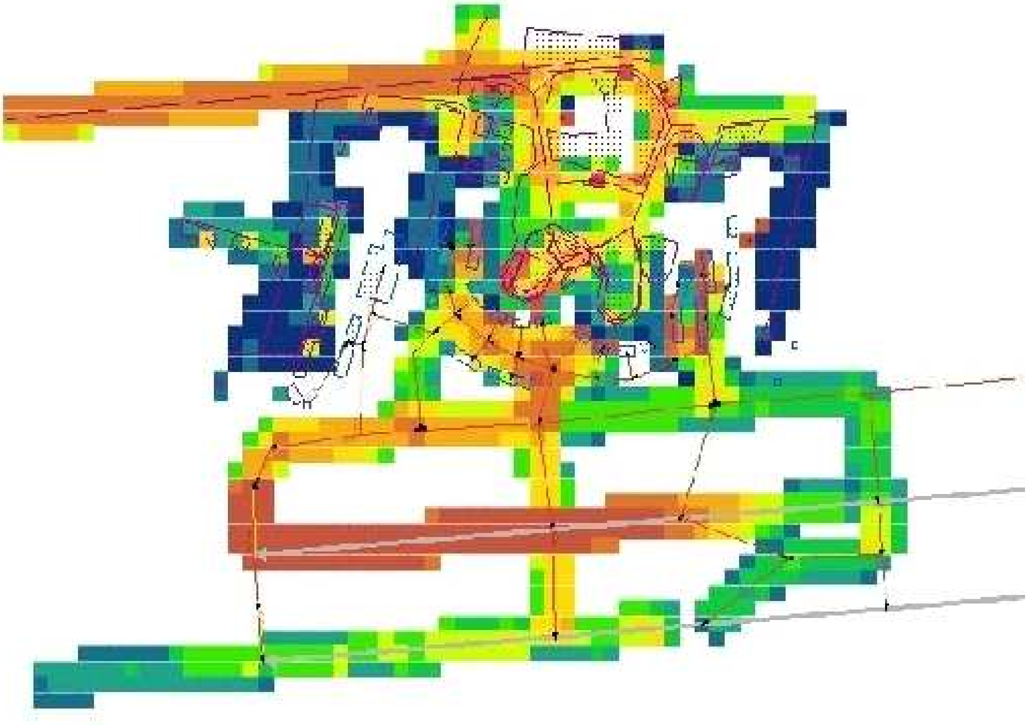

Figure 3-1: Example of the result of an ALAQS study.

The toolset provides:

- 4D emission inventory. The inventory uses the ARCVIEW tool to provide a geospatial and hourly inventory of airport emissions sources. Different inventory methodologies can be compared for all sources related to airport activities – including aircraft (main engines, auxiliary power unit (APU) and brake/tyre wear), road vehicles (landside and airside), ground handling (GSE and GPU), infrastructure, and stationary sources (fuel storage, construction, maintenance, power plants, etc.);
- Air Quality Dispersion Assessment. It allows to compare different dispersion methods (Gaussian, Lagrangian and Eulerian), using the results of the 4D inventory. The toolset can also be used to model local air pollution concentrations for actual, generic and future situations;
- Mitigation Planning: forecast the efficiency of proposed air pollution abatement measures in the context of reducing emissions from airport related sources."

Within this study, ALAQS-AV is not used to perform the calculations. Instead of ALAQS, MS Access and Excel are used for the emission calculations. The fact that these tools are used is caused by the limited required level of detail. For instance, within this study the location of emissions at the airport is not considered, no detailed GSE calculations are done and the airport lay-out is not used in the calculations. When this level of detail should have been required, the use of ALAQS is preferred instead of the use of the MS tools. However, several databases from the tool are used as input for the emission calculations with MS Access and Excel. The used databases contain information about i.e. aircraft data, engine data and generic APU data such as emission indices and time in modes (TIMs). The methods to calculate the emissions are described in sections 5.3 and 5.4.

3.3 LEAS-IT

The LEAS-iT tool is developed for the calculation of an emission inventory around airports. It makes use of routes, procedures, traffic descriptions and engine emission coefficients in order to produce a 4D (space plus time) presentation of the emissions in the vicinity of an airport. The tool is developed as a general tool and is therefore applicable to any airport and any number of runways. LEAS-iT output can provide input data for an air quality calculation model, e.g. the STACKS model of KEMA (NL). Figure 3-2 gives an overview of a LEAS-iT emission calculation.

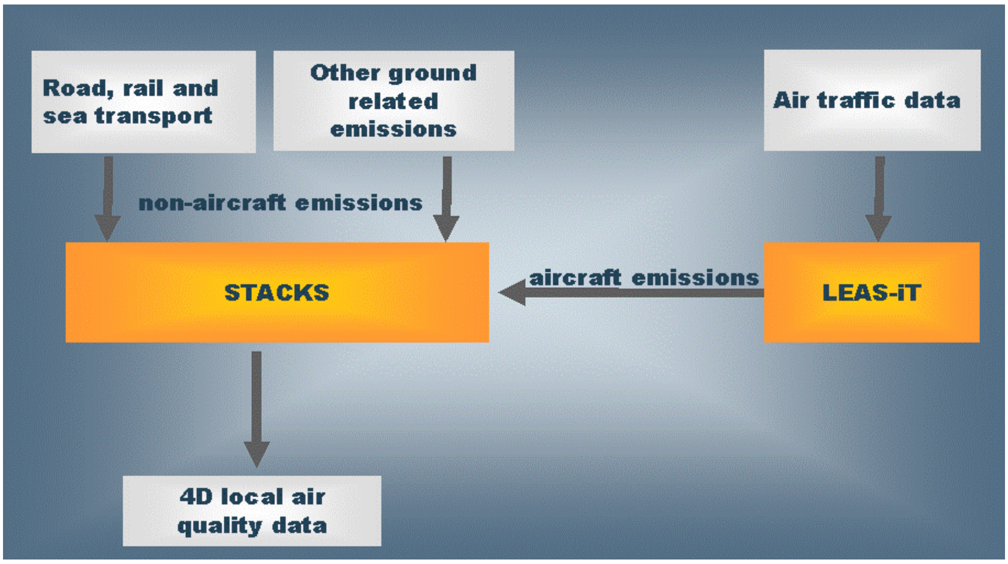

Figure 3-2: Overview of emissions calculation using LEAS-iT.

The outputs include fuel burn and the following emissions: H_2O, CO_2, NO_x, unburned hydrocarbons, VOC and lead (Pb). Further estimates are being made of the amount of benzene, polycyclic aromatic hydrocarbons (PACs) and non-volatile PM10 emissions from aircraft engines. Figure 3-3 shows the result of an example LEAS-iT calculation.

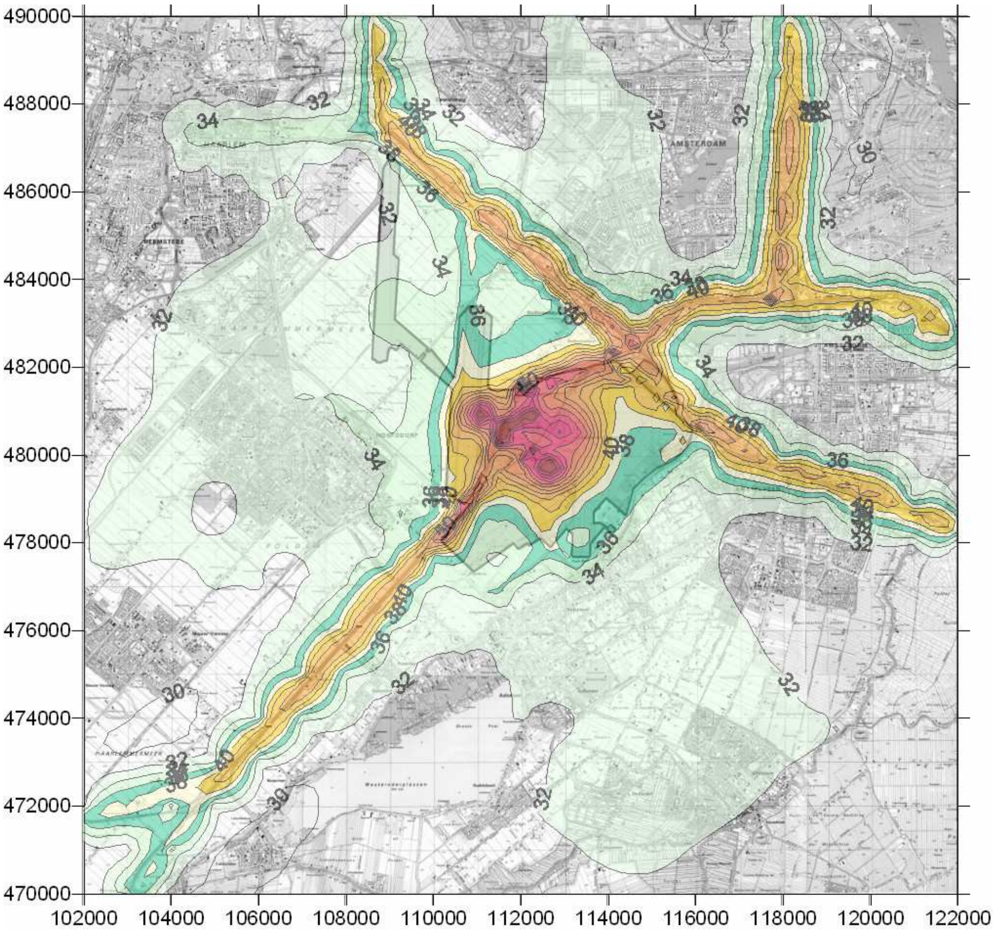

Figure 3-3: Example of a LEAS-iT result.

For the calculation of aircraft engine emissions during the flight, LEAS-iT determines the fuel flow along the flight trajectory from the thrust setting, altitude and speed. It then calculates the emissions using emission indices. Data on emissions indices for a wide range of engines and flight phase specific fuel flows are available from the ICAO Aircraft Engine Emissions Database. Finally, corrections are made for atmospheric conditions with the Boeing (-2) method and the emissions are integrated over the modelled flight path and distributed over time and space (three dimensional grid).

In the current study on the effects of the OI steps, LEAS-iT is used to quantify aircraft emissions of the take-off and landing segments below 3000 ft. These figures are interesting with respect to the observation of the severity of emissions on the airport surface relative to the emissions of flight phases below 3000 ft.

4 INPUT DATA COLLECTION

In order to perform this study input data is required. This chapter describes the different input data collection methods that are used. First of all, a short explanation is given about the literature study that was carried out. Secondly, information about the used taxi and delay times is provided. The final paragraph gives information on the data that is used to give an indication of the ECAC-wide effect of the different OI steps.

4.1 LITERATURE STUDY

Before calculating the effects of the OI steps on the LAQ, a literature study was carried out to:

- Give insight in what research has already been done on the effects of ATM-related improvements on the LAQ;
- Provide input data for the analysis concerning the selection of the OI steps. The literature study gave insight in the availability of data related to the different OI steps, which is an important consideration in the development of the analysis plan;
- Provide input values for the calculations, for instance the warm-up time of aircraft engines;
- Provide reference values of the effect of OI steps, like that a certain OI step generally reduces the NO_x emissions by 10%.

The outcomes of the literature study are not presented separately in this section, but its results are used throughout the remainder of this report.

4.2 TAXI AND DELAY TIMES

The taxi times during the taxi-out phase (taxi-out times) and excess times during the taxi-out phase are provided by the EUROCONTROL Performance Review Commission for the year 2008. The dataset is based on data that is reported on a voluntary basis by aircraft operators to the CODA [4]. The CODA database covers approximately 62% of traffic under instrument flight rules (IFR) in the ECAC region for the years 2007 and 2008. For taxi-out 2007 data per aircraft category is used and for taxi-in times a dataset for 2008 aggregated to wake turbulence classes is provided by CODA.

The following data from the CODA database is used for the assessment:

- The duration of the taxi-out phase. The taxi-out time is the time between the off-block time and the take-off time as reported by the airports to CODA;
- The take-off time as reported by the airports to CODA;
- The duration of the taxi-in phase;
- The unimpeded time; this is an estimate of an empirical optimum for each airport.

The primary interest of the analysis in this report is on the excess time in the taxi-out phase. The excess time during the taxi-out phase is the difference between the actual duration of the taxi-out phase and the unimpeded time. It is derived by analyzing the reported taxi-out times for each stand-runway combination for situations with no influence of congestion.

The taxi-out time includes the push-back time and delays due to, amongst others, congestion, de-icing and line-up for take-off. The analysis of the unimpeded time is based on observational data and there are no exact criteria neither to determine which of these factors are included in the unimpeded taxi-out time nor to what extent. However the following assumptions are made:

- The push-back time is likely to be included equally in both the actual observed taxi-out time and the unimpeded taxi-out time. Delay during pushback is expected to occur independent of the amount of congestion. In other words, excess time during the taxi-out phase is expected not to include a significant share of delay during push-back;
- Despite the fact that de-icing is not caused by congestion, it is a cause of congestion. Since the analysis of the unimpeded taxi times is based on disregarding flights that take place during congestion it is reasonable to assume that delay caused by de-icing has partially but not completely been filtered out in the analysis. It is assumed that the excess time in the taxi-out phase represents an unknown amount of delay caused by congestion due to de-icing. Delays due to de-icing will only occur for a small percentage of the total amount of traffic, due to the fact that the temperatures at a large number of airports do not fall below zero frequently;
- It is unknown what portion of the excess time is line-up delay and what portion is of another type of congestion related delay. The focus of the analysis however is on the effects of measures that reduce either taxi-times or line-up delay times. Since aircraft emissions during line-up delay and taxiing are modelled in the same manner using the same values for thrust settings (see also paragraphs 5.3 and 5.4) the apportionment is not of influence on the results.

In this study the excess times are assessed per airport and aircraft category.

4.3 ECAC-WIDE RESULTS

One of the goals of this study is to generate quantitative results of the effects of an ECAC-wide application of operational improvements. The study has been conducted on a range of European airports that cover approximately 34% of all intra European and intercontinental IFR traffic to and from Europe. The assessment of the OI steps will provide results that quantify the effect of the investigated OI step on the LAQ at the considered airports.

The result is an average effect of an OI step on the LAQ. Since the effect of an OI step on the LAQ depends on several local airport parameters, such as taxi and runway configuration, the effects of an OI step may differ from airport to airport.

5 ANALYSIS PLAN

As discussed in chapter 1, the goal of this report is to provide insight into the study on measures to reduce local aircraft emissions. This study assesses the effect of a number of OI steps on the local aircraft emissions. For the LAQ assessment the following KPIs are defined:

- Fuel burn below an altitude of 3000 ft;
- CO_2 emissions below 3000 ft;
- NO_x emissions below 3000 ft;
- SO_x emissions below 3000 ft;
- CO emissions below 3000 ft;
- HC emissions below 3000 ft;
- VOC emissions below 3000 ft;
- TOG emissions below 3000 ft;
- PM10 emissions below 3000 ft;
- PM2.5 emissions below 3000 ft.

The assessment tools and methods applied for this study are not capable of calculating (reliable) PM2.5 emissions. For that reason this study does not take these emissions into account.

Since all investigated OI steps have an effect on emissions at the airport surface only, the values of the KPIs during the flight phase are not calculated separately for each OI step so that only the effect on emissions on the airport surface is considered. Although the in-flight emissions are not incorporated in the calculations, they must be considered when an OI step is implemented. For example, it is not desirable if an OI step leads to a reduction of the taxi emissions at the cost of a larger increase in in-flight emissions. In order to compare the calculated emissions on the airport surface to the emissions of the flight phase a LEAS-iT calculation is performed to estimate the emissions during the flight phase.

In the analysis, a baseline scenario with no measures in place is compared with scenarios representing situations with the implementation of one or more operational improvements. The results give an indication of the potential for emission reductions in relation to the emissions of a baseline situation.

The effects of operational improvements and the degree to which they can be implemented are dependent on local factors at the airports of interest (as described in chapter 2). Potential airport specific constraints related to the implementation of the improvements are not taken into consideration. This approach will yield results that indicate the maximum reduction of emissions that should be possible to achieve. In other words, this study provides an upper limit for the potential emissions reduction that can be realized by the implementation of the improvements.

This chapter gives a general description of the analysis plan and briefly explain the steps of the analysis. Paragraphs 5.1 and 5.2 describe respectively the scenarios that are used for the calculations and the different (groups of) OI step(s) that are analysed in this study. After that, the remainder of this chapter discusses the analysis methods for both the baseline scenario and the different (groups of) OI step(s).

5.1 SCENARIOS

The baseline scenario is a scenario that represents the reference situation in which the proposed OI steps are not in place at all or to a limited extent only. The available data for the baseline scenario are actual traffic data from the year 2006. Ideally, corrections for OI steps that were already implemented should have been made in order to remove the effects of the improvements. Since it is unknown to what extent the proposed operational improvements are already in place and how they affect the traffic, the data is not corrected for the effects of implemented OI steps. However, since all proposed OI steps have the goal to improve the existing situation at airports the assumption that the suggested improvements are not extensively used currently is valid.

For several OI steps and some groups of OI steps separate scenarios are developed so that both the accumulated effect of (groups of) individual measures can be presented. The accumulated effect is not necessarily equal to the sum of the individual effects. For instance, if certain measures result in a shorter taxi time, this will influence the potential effect of measures such as towing or taxiing with a reduced number of engines (also called engine out taxiing; EOT). This issue is addressed in chapter 6.

The reference scenario and OI step scenarios are studied using two sets of traffic data. The first dataset includes intra-European flights and intercontinental flights to and from Europe departing and arriving during three days in July 2006 (Tuesday the 18th, Friday 21st and Sunday the 23rd). The dataset includes the following information on IFR traffic:

- The origin/destination airport of arrivals/departures;
- The aircraft type;
- Actual take-off time;
- Duration of the flight;
- Estimated arrival time (derived from the actual take-off time and the duration of the flight).

The dataset contains more fields, but those are not used for the present study. The dataset has also been used in other EP3 work packages; this has the advantages of consistency with other EP3 work. A disadvantage however is the fact that the traffic composition may vary during the year. This dataset will only provide results that are applicable to a mid summer situation. In general the amount of traffic in this period is higher when compared to other times of the year.

The second data set concerns taxi-in and taxi-out times as well as delay from the Central Office for Delay Analysis, as provided by the Performance Review Commission. This dataset covers IFR traffic for the years 2007 and 2008 for a range of European airports and is specified by aircraft category.

This study investigates the effects of OI steps on the 20 busiest airports. The focus is on busy airports because the local aircraft emissions increase with the traffic volume. The fact that Episode 3 focuses on a reduction of the emissions on a per flight basis is also a reason to choose the largest European airports since these airports accommodate the largest number of flights. Another reason to use the 20 busiest airports is that a part of the study focuses on measures that mitigate line-up delay; in general line-up delay problems are largest on the biggest airports.

5.2 OVERVIEW OF OPERATIONAL IMPROVEMENTS

The screening and scoping process [16] resulted in a list of most promising OI steps. Annex 1 provides this list. This paragraph discusses the list of operational improvements, as selected during the screening and scoping. The improvements from the list in Annex 1 tend to reduce local emissions through the following means:

- Reduction of ground queuing. This is done by OI steps that aim at improving the traffic at the airport surface, but also by improvements that lead to an increase in runway capacity;

- Reduction of taxi times;
- Application of alternative energy sources to reduce APU usage;
- The use of procedures for airport manoeuvring areas that reduce gaseous emissions such as towing.

For the analysis of the effects of the different OI steps on the LAQ, the OI steps are subdivided into three groups. The OI steps are grouped based on their operational impact and they are defined as follows:

- Ground movement techniques to reduce gaseous emissions; this comprises the following three operational improvements:
    - Engine out taxiing (EOT), this is taxiing with not all engines operating;
    - Towing the aircraft to/from the runway with all engines off;
    - The use of electric ground power and a pre-conditioned air unit (PCAU) instead of the APU.
- Optimization of surface movements; i.e. optimized design of the airports taxiways and procedures;
- Optimization of airport/airspace operations; i.e. managing interactions between departure and arrival traffic.

Table 5-1 summarizes the different groups of OI steps and the approach for the analysis of these measures.

Table 5-1: Overview of operational improvement and analysis approach

Group of measures	OI step code(s)	Approach
1. Ground movement techniques	AUO 0802	Upper boundary emission calculations for 20 ECAC airports.
2. Optimization of surface movements	AO-0207, TS-0201, TS-0202, TS-0203, TS-0306, AO0704, AO-0602	Emission calculations according to LTO cycle methodology, presumption that the group of measures will reduce delay time to zero.
3. Optimization of airport and airspace operations	AO-0701, AO-0402, AO-0403, AUO-0701, AUO-0702, AUO-0703, TS-0301, TS-0304, DCB-0201, TS-0102, TS-0103, TS-0104, TS-0106, TS-0303 and TS-030	Assessment of potential effects based on literature study.

These groups of OI steps are assessed in order to determine their effect on the LAQ. Not all of the OI steps from Table 5-1 are analysed in this study. The selection is performed on the basis of available input data (for instance for TS-0301), the suitability for research of the OI steps (for instance for AO-0701), scope of the project and closer consideration of the expected effect of the OI steps. The approach for the first two groups is described in more detail in sections 5.4 and 5.5.For the third group of OI steps no analyses are carried out since it is not possible to quantify their effects on the LAQ within the scope of this study. Paragraphs 5.2.1 to 5.2.3 discuss the groups of OI steps in more detail.

5.2.1 Ground movement techniques

This category consists of only one OI step: AUO-0802 *Ground movement techniques to reduce gaseous emissions and noise disturbance*. This OI step leads to a reduction in local emissions by the following means:

- EOT;
- Towing the aircraft to/from the runway with all engines off;
- The use of electrical ground power instead of the auxiliary power unit.

The first possible improvement is to reduce the number of operating engines during taxiing. According to R. Yamartino et al. [5] EOT leads to a 35% reduction of HC of aircraft LTO's emissions and a 4.7% reduction of NO_x emissions. However, several operational aspects must be kept in mind when EOT is implemented:

- Problems can occur with pre-departure taxiing due to the risk of a failed engine start. This will result in additional queuing and in delays;
- The applicability of EOT is constrained by the occurrence of steep turns and uneven terrain and also by severe weather conditions such as strong wind (see V. Kumar et al. [6]).

An alternative for EOT is to tow aircraft to and from the runway. The aircraft engine emission reduction programme Zurich airport [7] reports that towing has a potential of 1 to 2% reduction in NO_x LTO emissions if all departing aircraft are towed. For the implementation of this improvement, it is recommended to use environmentally friendly tow techniques. For example, according to J. Oganda [8] a future option to reduce aircraft fuel consumption and emissions is the use of a so-called wheeltug. This device makes it possible to taxi using an electric engine. The use of wheeltugs should lead to a reduction in emissions since no aircraft tractors are needed when wheeltugs are used. However, the additional weight of the wheeltugs will probably lead to an increase in emissions during the flight.

For the implementation of towing, there are several technical and operational aspects to be considered:

- The landing gear of current generation aircraft is not designed for extensive towing and this can result in damage to the landing gear especially if departing aircraft with full tanks are towed to the runway. This implies that if this measure is implemented, modifications to next generations of aircraft are required. The effect of additional weight of new designed landing gears on emissions should be considered in order to determine the feasibility of towing;
- A complication with towing for departing aircraft is that once an aircraft is towed to the runway and one of the engines fails to start, the aircraft must return to the gate. This leads to additional emissions and queuing;
- Minimizing the distance travelled by aircraft trucks without towing an aircraft leads to a reduction of emissions. To make an accurate assessment of these movements one has to look at cases based on actual airports since they are dependent on airport layout as well as the design of the measure;
- The use of additional aircraft tractors might require an extension of the airport infrastructure. For instance areas to disconnect aircraft from the aircraft tractors and additional roads for aircraft tractors that are not towing an aircraft are required;
- Operational consequences of lower speeds of towed aircraft compared to taxiing aircraft have not been taken into account;
- The effects of lower speeds and thus longer taxi times on APU emissions;

- This measure also has an impact on the safety at the airport. Starting the main engines away from the apron reduces the exposure to ground staff. However, the fire service availability at the engine start point may need reviewing to maintain safety requirements. For that reason fire equipment may need re-locating to be positioned nearer the engine start points.

The third operational measure within this group is the use of fixed ground power. According to E. Fleuti et al. [9], using a fixed energy system instead of the APU can result in a 60% reduction of APU NO_x emissions, which was equal to 4.3% of all NO_x emissions at the investigated airport (Zurich). A. Hoolhorst et al. [10] even reports a maximum obtainable reduction in NO_x emissions of 75%. The analysis methods for the ground movement techniques are discussed in paragraph 5.4.

5.2.2 Optimization of surface movements

This category covers measures that are aimed at preventing delay and reducing taxi times during the taxi-in and taxi-out phase. This will lead to a reduction in local aircraft emissions. The literature study showed that some data on the effects of the individual operational improvements is available. However the effects on one airport do not guarantee the same effects on other airports, since the effects differ from airport to airport due to local circumstances such as the runway and taxiway configuration.

5.2.2.1 Surface management integrated with DMAN and AMAN (OI step AO-0207).

Surface management (SMAN) integrated with DMAN and AMAN increases the efficiency of traffic on the airport surface. Integration of AMAN and SMAN can reduce holding times and flight times within the TMA. Integration of DMAN and surface management may result in a more efficient trajectory from gate to runway before take-off, reducing the time that aircraft have engines running unnecessarily.

5.2.2.2 Departure traffic synchronisation and optimization (OI steps TS-0201, TS-0202, TS-0203, TS-0306).

Several problems exist with regard to optimising departure sequences. Uncertainties with respect to pushback, start-up and taxi times limit the capability of aerodrome control to achieve their preferred sequence. A number of actors influence the sequence of the departures, with each actor seeking to apply local and individual optimization resulting in a potential for underutilisation of the runway. The goal of these improvements is to develop a system that determines the optimum runway for departure (if appropriate) and the optimum order for the departure sequence while taking into account departure times, slot constraints, runway constraints such as departure rate, wake vortex separation, distance in trail, etc. In order to achieve these goals the following improvements are suggested:

- Basic departure management (DMAN);
- Departure management synchronised with pre-departure sequencing;
- Integration of surface management constraint into departure management;
- Optimized departure management in the queue management process.

The aircraft engine emission reduction programme [6] reports that at Zurich, the DMAN system has saved a total of 1150 tons of fuel in one year, 4.2 tons of NO_x, 4.0 tons of HC and 33.7 tons of CO on emissions. These results were achieved by increasing the time that aircraft were waiting with their engines turned off instead of queuing with their engines running. In total the time that aircraft queued with running engines was reduced with 1740 hours. The report does not state how large these reductions are relative to the total emissions caused by taxiing aircraft.

5.2.2.3 *Optimized design and procedures for airport manoeuvring areas to reduce gaseous emissions and noise disturbance (OI step AO-0704).*

This OI step improves the environment by designing taxiways in such a way that the queuing and taxi times are reduced. During the design of new taxi routes the following improvements are suggested:

- Minimize the distance between apron and runway;
- Design conflict free taxi routes preventing aircraft with running engines to hold;
- Design rapid exit taxiways (RET) so that all aircraft can leave the runway after landing as quickly as possible in order to reduce the runway occupancy time (ROT).

The associated procedures for this infrastructure are developed considering reductions to air pollution and noise disturbance levels. At Zurich airport new aircraft stands were built closer to the runway than previously used stands. The use of these new stands lead to a reduction of taxi-time and resulted in an emission reduction of approximately 1.5% in the ICAO LTO cycle emissions according to the aircraft engine emission reduction programme Zurich airport [6]. The effect of these improvements will differ from airport to airport, since it strongly depends on the existing taxiway layout. Therefore the effects of these improvements are not incorporated in the calculations.

5.2.2.4 *Collaborative pre-departure sequencing (OI step AO-0602).*

The objective of this OI step is to enable flights to leave their stands in the optimum order based on the operational situation. The resulting pre-departure list is used by ATC while sequencing departing aircraft, as and when feasible. This OI step leads to a reduction in queuing times which is favourable for the LAQ.

5.2.3 Optimization of airport and airspace operations

The third group of OI steps contains measures that lead to an improvement of the LAQ by improving airport and airspace operations. The largest beneficial effect of these OI steps on the LAQ is obtained by increasing the airport capacity. An increased capacity of an airport means that queuing will decrease, which is beneficial for the emissions per flight. If the runway capacity increases, more aircraft can take-off and land at the optimal runway with respect to emissions. Since the main effect of these measures is an increased capacity, these measures are most effective at high density airports where capacity is a limiting factor for the airport operations.

Besides the positive effect of an increased capacity on the queuing times, it may also lead to an increase of the traffic volume and consequentially an increase in the total amount of emissions. Still, due the reduced congestion, the emissions per flight will decrease due to these measures and since this study focuses on the emission reductions per flight, the effect of traffic volume increase is not considered.

The effect of an OI step on the LAQ is difficult to quantify if the main effect of the OI step is an increase in capacity due to the fact that the increased capacity has an indirect effect on the LAQ. Since the effect on the LAQ is an indirect effect, this report will not quantify the potential reduction in local aircraft emissions due to these measures. The remainder of this paragraph will discuss the effects of the OI steps from this group based on the screening and scoping deliverable and on the literature study. For some OI steps an estimate of the effect on capacity is given and if literature was found on the effects on local emissions, the possible effects on these emissions are provided.

5.2.3.1 *Effective collaboration between ATM stakeholders supported by environmental management systems (OI step AO-0701).*

The goal of this OI step is to manage the operation and onward development of an airport in such a way as to effectively curb the facility's impact on the environment. The airport operators therefore have to introduce a modern, long-term environmental management system. Finally this will result in a reduction of local aircraft emissions, but since this OI step does not specify to what concrete improvements it leads, its effects on the LAQ cannot be quantified.

5.2.3.2 *Using runways configurations to full potential (OI steps AO-0402, AO-0403, AUO-0701, AUO-0702 and AUO-0703).*

The use of runways configurations to full potential contains the following improvements:

- Interlaced take-off and landing;
- Optimized dependent parallel operations;
- Use of ROT reduction techniques;
- Brake to vacate (BTV) procedure;
- Automated BTV using datalink.

These improvements increase the runway capacity, which in turn leads to lower queuing times and therefore this OI step is beneficial for the LAQ. BTV especially leads to less queuing if the concept of interlaced take-offs and landings is introduced since the capacity for departing aircraft increases when arriving aircraft occupy the runway during a shorter period. Also the increased capacity per runway makes it easier to use runways that give the shortest taxi times as much as possible.

Interlaced take-off and landing and *optimized dependent parallel operations*. To accommodate these measures in an efficient way, also other improvements such as departure traffic synchronization and integrated SMAN, AMAN and DMAN are desirable.

The *use of runway occupancy time (ROT) reduction techniques* can consist of several measures. The main flight operations elements that affect the ROT include not only braking distance or runway/taxiway design but also pilot's awareness of ROT requirements, pilot's reaction times to line-up/departure clearances, pre-departure actions, etc. This improvement addresses enhancements to operating practices of airlines and pilots in that respect. Since this OI step contains a collection of different improvements, the result of all these improvements together cannot easily be determined. For that reason its effect on capacity is not quantified.

One of the methods to reduce ROTs is BTV. The goal of (automated) BTV is that arriving aircraft can make optimal use of existing exits (runway exit taxiways or other) by adapting their braking techniques. Assisting the pilot in optimal braking techniques will result in lower ROTs and will thus increase capacity. Automated BTV consists of leaving the runway at a pre-selected runway exit as coordinated with ground ATC through a datalink. This improvement is based on BTV avionics that controls the deceleration of the aircraft to a fixed speed at the selected exit.

A FTS carried out in WP5.3.3 of Episode 3 investigates the effect of BTV. In this experiment, the results for BTV are expressed as runway occupancy time. The gains were in the order of 2-3 minutes less runway occupancy time in a one hour period. The study hypothesis specifically did not mention increases in throughput or capacity. One of the constraining factors for increasing the runway capacity is the minimum radar separation required on final approach. Further research is required to assess whether reduced runway occupancy times can lead to reduced separation times. Summarizing the above, this means that the figure of 2-3 minutes less runway occupancy time per hour gives the upper limit of the effect of BTV on runway capacity. This effect implies that it is possible to increase the capacity with at most 3 to 5 %. Another advantage of BTV is the fact that the higher certainty that an aircraft leaves the runway at a predetermined exit; leads to a smaller risk of missing the intended runway exit with consequent increased time on the runway and possibly a longer taxi time.

Applying BTV has several implications for the LAQ. The goal of BTV is to reduce ROTs and thereby increasing the runway capacity. However, BTV also affects emissions from the engines (reduced use of thrust or use of thrust reversers) and emissions of particulates from breaking. A more detailed investigation of these aspects is needed in order to develop BTV procedures optimized for local emissions.

Aircraft can decelerate after landing by using reverse thrust in addition to the aircraft brakes. Using more than idle reverse thrust instead of the brakes results in additional fuel consumption. Engine Thrust Reverser Emissions at Zurich Airport [11] estimates the NO_x emissions to increase with about 1 to 2 % of the operational LTO cycle emissions for the case studied at Zurich airport. However, additional usage of the brakes leads to additional PM10 emissions. So, both methods of reducing speed produce different emission spectra. The use of more than idle reverse thrust also affects noise levels and using the brakes will result in wear which increases operational costs.

5.2.3.3 Managing interactions between departure and arrival traffic (OI steps TS-0301 and TS-0304).

These OI steps contain the following improvements:

- Integrated arrival/departure management for full traffic optimizations, including within the TMA airspace;
- Integrated arrival/departure management in the context of airports with interferences (other local/regional operations).

One of the effects of these improvements is an increase in the runway capacity. However, the main effect of these improvements takes place in the air, thus not on the airport surface. For this reason it is difficult to estimate the exact effect of these measures on the runway capacity, queuing times or local emissions.

5.2.3.4 Interactive network capacity planning (OI step DCB-0201).

This OI step increases the capacity of an airport, which indirectly is beneficial for the queuing times and thus for the LAQ. According to the screening and scoping study [16], the analysis of the DMEAN case study at Maastricht UAC in 2005 indicates that average delivered capacity increased by 26%. This provides a useful indicator of the latent capacity that can be released by wide-ranging and co-ordination actions and its benefits. The increase in capacity is possibly beneficial for the LAQ; however the mentioned capacity increase does not solely refer to runway capacity. Still this figure shows options exist to make air traffic more efficient, which in turn leads to decreased taxi times.

5.2.3.5 Arrival traffic synchronisation (OI steps TS-0102, TS-0103, TS-0104, TS-0106, TS-0303 and TS-0305).

These OI steps contain the following improvements:

- Arrival management supporting TMA improvements (incl. CDA, P-RNAV);
- Controlled time of arrival (CTA) through use of datalink;
- Integration of SMAN constraint into AMAN;
- Multiple controlled times of over-fly (CTOs) through use of datalink;
- Arrival management into multiple airports;
- Arrival management extended to the en route airspace.

These improvements lead to a more predictable arrival sequence and an increased runway capacity. This will have a positive effect on the LAQ. However, no data on the quantity of the effect on runway capacity or on local emissions were found.

5.3 EMISSIONS IN THE BASE CASE SCENARIO

This section describes the method for calculating the emissions for the baseline scenario. This assessment includes the calculation of aircraft emissions during taxiing and the emissions of APUs at the aircraft stands. Also the in-flight emissions up to 3000 ft are calculated so that it is possible to compare the amount of emissions produced on the airport surface to the in-flight emissions.

5.3.1 Emissions during taxiing

The calculation of fuel burn and emissions of NO_x, CO, HC, SO_x and PM10 during taxiing has been based on the LTO cycle methodology. For each aircraft and corresponding engine type the emissions are calculated as follows:

$$E_{ijk} = T_{jk} * FF_j * EI_{ij} * NE_j \qquad \textbf{Equation 1}$$

Where:

E_{ijk} = Emissions for pollutant *i* (for instance NO_x emissions) by aircraft type *j* with a specified type of engine at airport *k*;

T_{jk} = Time of taxi-out phase. The engine is presumed operate in taxi idle mode (7% thrust). The taxi-out phase includes push-back, line-up delay and other types of delay occur during the taxi-out;

FF_j = Fuel flow of one engine on aircraft type *j* in Taxi idle mode;

EI_{ij} = Emission rate for pollutant *i* of engine on aircraft type *j* in Taxi idle mode;

NE_j = Number of engines on aircraft type *j*.

Emission indices are from the aircraft engine emissions databank issue 15 [13]. The emission indices for PM10 are derived using first order approximation 3 (FOA3) described in the IATA fuel book [14]. The used approach gives an estimate of taxiing emissions, however the emissions caused by engine start-up, braking, tyre wear and tyre tear are neglected in the calculations.

5.3.2 APU Emissions

The calculations for APU emissions are based on the three days of arrival and departure traffic. For each flight in the traffic the aircraft type is known. However, the specific APU type used in each aircraft (if used at all), is not given in the traffic files. A few methods are available for calculating APU emissions. CAEP/7-WP28 [12] describes three methods for calculating APU emissions:

- A Simple Approach;
- An Advanced Approach;
- A Sophisticated Approach.

The next section describes these methods. The Simple Approach uses two generic APU types, one for a short haul aircraft group, and the other for a long haul aircraft group with no distinction between APU settings. The Advanced Approach describes three APU operating load conditions:

- Start-up / no load;
- Maximum Environmental Control System (maxECS) / normal running;
- Main engine start / high load.

Furthermore, different generic APU types are defined for eight aircraft groups (business, regional, turboprop, small jet older, small jet newer, medium jet, large jet older, large jet newer). The third approach described is the Sophisticated Approach. Here, each aircraft is coupled with a specific APU. This approach requires detailed knowledge of APU type per aircraft type, operating modes and time in modes (TIMs), fuel burn, aircraft operators, procedures and emission factors.

According to CAEP/7-WP28 [12], the Simple Approach has a large order of uncertainty. The Simple Approach is most useful when little information about aircraft types is available. In this study, the aircraft type for each flight is known, so the Simple Approach is appropriate due to the limited level of detail of the results. For the Sophisticated Approach more information is required. First of all, the specific APU has to be linked with an aircraft type. This information is not readily available combined with specific information on for example TIMs. Besides, the results of this method are too detailed for this high level-study. Therefore, the Sophisticated Approach is too detailed for this study. The Advanced Approach where eight different generic APUs with three operating modes are used is the most suitable. There is enough information to link the generic APUs with the aircraft types in the traffic and information on the TIM is available in ALAQS databases. However, these TIMs are estimates for the different generic APU types. CAEP/7-WP28 [12] describes eight types of APU:

- APU Jet Business (<100 Seats);
- APU Jet Regional (<100 Seats);
- APU Jet Small Newer Types (100-200 Seats);
- APU Jet Small Older Types (100-200 Seats);
- APU Jet Mid-Range (200-300 Seats);
- APU Jet Large Older Types (>300 Seats);
- APU Jet Large Newer Types (>300 Seats);
- APU Turboprop.

All aircraft in the traffic must be put into one of these generic APU categories. However, a full list of aircraft or representative aircraft for each APU category is not given in CAEP/7-WP28 [12].

Besides jet and turboprop aircraft the traffic also contains propeller (piston) aircraft and helicopters together with a few aircraft in the category ‘Various’. The propeller (piston) aircraft, helicopters and some ‘Various’ aircraft are not classified within an APU group since they do not have an APU. Therefore they do not contribute to APU emissions.

The jet and turboprop aircraft are classified based on their maximum take-off weight (MTOW), maximum passenger capacity and year of first flight. This information is not available in CAEP/7-WP28 [12] and is collected using amongst others Jane’s databases and the ALAQS databases.

Aircraft that are defined Turboprop in the traffic are put in the ‘APU Turboprop’ category. Aircraft that are defined Jet Business in the traffic are classified ‘APU Jet Business’ category. The same procedure holds for Regional Jets in the traffic. They are put in the category ‘APU Jet Regional’ except for some aircraft that seem to be Business Jets based on their Range and seat capacity. Regional Jet aircraft with a max range over 2500 nautical mile (NM) and with a small passenger capacity are classified ‘APU Business Jet’ category.

Small, medium and large jets are divided into categories based on their MTOW, maximum passenger capacity and year of first flight. For MTOW the following rule of thumb is used (based on expert judgement given the number of seats):

- Small jet: <125000kg MTOW;
- Mid-Range jet: 125000-250000kg MTOW;
- Large jet: >250000kg MTOW.

For the APU classes a second distinction is made as well; namely between ‘older’ and ‘newer’ types. However, CAEP/7-WP28 [12] does not suggest which aircraft types fall in the ‘older’ and ‘newer’ category. To assign aircraft to ‘older’ or ‘newer’, the year 1995 (for first flight of the aircraft type) is chosen. This choice is based on expert judgement. Aircraft with a first flight before 1995 are defined ‘older’. Aircraft with a first flight after 1995 (1^{st} of January 1995) are defined ‘newer’.

Primarily the aircraft are assigned to the small, mid-range and large jet APU category based on their MTOW and their year of first flight. However, the APU categorization also defines a range for passenger capacity. Therefore, when for example an aircraft is assigned to the APU category for Mid-Range range jets based on MTOW, but the number of seats exceeds 300, the aircraft is put into the Large Jet APU category. The same procedure is followed for aircraft that are first put in the Small Jet APU category, but belong in the Mid-Range Jet APU category based on their number of seats. The complete list of aircraft types that are represented in the traffic and their appropriate APU class is presented in Annex 3.

The APUs have three different operating modes together with different TIMs and averaged emission rates for CO, HC, NO_x and PM10 (kg/h). These emission rates are described in CAEP/7-WP28 [12]. The ALAQS database provides standard values for the TIMs. These TIMs are the defaults for APU calculations in ALAQS and are based on the type of aircraft within each generic APU class. Since this method does not provide the fuel flow due to the APU usage, it is not possible to calculate the SO_x emissions.

The APU emission calculation are performed for each aircraft movement on each airport in the traffic database. The TIMs and emission rates for each mode are used to calculate the APU emission for each aircraft type. Next, the traffic specifies which aircraft type visited an airport. With a simple addition the APU emissions are calculated for each airport.

5.3.3 In-flight emissions below 3000 ft

The aircraft engine emissions below 3000 ft produced during take-off and landing are calculated using LEAS-it (see paragraph 3.3). For arrival and departure routes standard straight-in and straight-out routes are used. For arrivals a procedure with a horizontal segment at 3000 ft and for departures an appropriate climb out profile is chosen. The choice of the profile depends on the distance to the destination airport; it is assumed that the aircraft takes more fuel onboard as the flight distance increases so that the weight increases as the distance to the destination increases. The additional weight influences the flight profile. The departure profiles are mainly ICAO-A starts. As necessary for the calculation of the KPIs in this study, the emissions are only calculated up to a height of 3000 ft. The output of the emission calculations is the number of kg's of CO, NO_x, PM10, SO_x and HC. In chapter 6 the average emissions per flight are determined and presented.

5.4 EFFECTS OF GROUND MOVEMENT TECHNIQUES ON EMISSIONS

This paragraph discusses the first group of OI steps. These improvements aim to reduce aircraft emissions at the airport surface.

5.4.1 Engine out taxiing

For engine out taxiing (EOT) the upper boundary for the potential emissions reduction is calculated. The potential for emissions reduction is equal to the difference between the emissions that occur in the base case situation and the situation where aircraft taxi with not all engines operating. The effect of this OI step is calculated for both taxi-in and taxi-out. The effect of the lower weight of arriving aircraft is not taken into account.

The emissions of EOT are calculated according to Equation 1, but using a different input set for the number of engines for the time span that the measure is in effect. For every occurring engine configuration the number of engines that remain on when operating with a reduced number of engines is given in Table 5-2.

Table 5-2: Number of operating engines during EOT

Total number of engines	Operating engines during EOT
1	1
2	1
3	2
4	2
6	4

For the taxi-in phase, now instead of Equation 1, the following equation holds:

$$E_{ijk} = T_{In,jk} * FF_j * EI_{ij} * NE_{\mathrm{Re}duced,j}$$ **Equation 2**

Where:

$T_{In,\,jk}$ = Time of taxi-in phase, which equals the time that the measure is in effect;

$NE_{Reduced,\,j}$ = the number of engines that remain during EOT.

For taxi-out out the situation is more complicated. Since engines take approximately 4 to 5 minutes of warm-up time to reach thermal stability prior to take-off (see V. Kumar et al. [6]), single engine taxiing is only beneficial in the taxi-out phase when taxi times exceed at least 4 to 5 minutes. In the calculation, single engine taxiing is only applied to those flight movements in the traffic that have taxi times above a threshold value of 6 minutes. This threshold value is set to 6 minutes and covers 5 minutes of engine warm-up time and 1 minute of extra time. The extra minute is included because the effort of applying the measure is not worth while if only a reduction of emissions due to reduced engine taxiing during less than one minute is realized. A value higher than 1 minute could be chosen but since no data is available this minimum value has been picked to determine an upper boundary for emission reduction. Engine warm-up time is addressed in two ways:

- Short haul taxi-out movements are excluded from EOT;
- The time during which the reduced engine measure is applied, is given by the difference between the time of the taxi-out phase and the warm-up time.

For the taxi-out phase the equation is as follows:

$$E_{ijk} = \left(T_{Out,jk} - T_{WarmUp}\right) * FF_j * EI_{ij} * NE_{\mathrm{Re}duced,j}$$ **Equation 3**

Where:

$T_{Out,jk}$ = Time of taxi-out phase, which equals the time that the measure is in effect;

T_{WarmUp} = Time for the engines to stabilize prior to take-off, set to 5 minutes.

It is unknown if and if so to what extent, a higher thrust is applied to the remaining operating engines when not all engines are running if the thrust is compared to the case with all engines operating. If a higher thrust setting is applied this has two possible effects;

- The higher thrust would partially counteract the reduction in fuel burn and consequentially emissions;
- The higher thrust would have a positive effect on emissions of HC, CO and a negative effect on NO_x.

Aspects that hinder a quantitative assessment of the effects of EOT are:

- Uncertainty of thrust settings throughout the taxi-out phase such as differences between thrust for taxi idle and idle during line-up delay and push-back. Also the duration and amount of thrust applied for acceleration is unknown;
- Engine performance data (ICAO) only provides emission performance and fuel flow data for static conditions at sea-level at 7% thrust; This is a generally accepted standard value for local air quality modelling, detailed modelling of measures such as taxiing with a reduced number of engines require a more thorough and detailed assessment of the engine operation during taxiing. It is difficult to estimate the actual thrust since this estimation requires an extrapolation using the 7% thrust level. There is also uncertainty of the emissions indices at the lower thrust levels. CAEP guidance on this area is not yet available;
- There exist various combinations of aircraft type and engine type. Since the traffic only provides information about the aircraft type, it is not known what type of engine the aircraft used;
- For aircraft with 3, 4 and 6 engines several options are available to lower the number of operating engines during taxiing. For instance an aircraft with 3 engines can use 1 or 2 engines during taxiing.

According to the IATA fuel book [14], it is recommended for the Boeing 777 not to taxi with only 1 engine operating, however, since the goal is to calculate the maximum possible reduction in local emissions all aircraft are taken into account for the taxiing calculations. Also for aircraft with weights above maximum landing weight, the suitability of EOT can lead to problems. Again, this calculation gives an upper boundary and therefore does not take these limitations into account.

5.4.2 Towing

Towing the aircraft to/from the runway with all engines off is modelled in a similar way as EOT. The potential for emissions reduction is determined by calculating the emissions that occur in the base case situation minus the emissions that are prevented by not operating the engines while using an aircraft tractor. In the case of towing this reduction is partially countered by the fact that the aircraft tractor emits pollutants and the aircrafts APU must be operated.

The calculation of the emission reduction therefore has three main components, expressed in the following equation:

$$\Delta E_{Taxi,i} = E_{Tow,i} + E_{Truck,i} + E_{APU,i}$$ **Equation 4**

Where:

$\Delta E_{Taxi,i}$ = The potential for emission reduction of pollutant *i* during surface movement due to the towing measure;

$E_{Tow,i}$ = The total reduction in emissions of pollutant *i* by the aircrafts main engines in the situation where the engines are not operating during towing;

$E_{Truck,i}$ = The emissions of pollutant *i* by the aircraft tractor during towing;

$E_{APU,i}$ = The emissions of pollutant *i* generated by the APU during taxiing.

The following sections describe the method used for each of these components. The emission reductions of this measure are assessed for both the taxi-in as well as the taxi-out phase. Taxi-in and taxi-out require a slightly different approach; this is discussed in the following sections.

Reduction of emissions due to engines off

The reduction in emissions of the aircrafts main engines in the cases where towing is applied is as follows for taxi-out:

$$E_{Tow,i} = E_{BaseCase,i} - FB_j * EI_{ij} * (T_{jk} - T_{WarmUp}) * NE_j$$ **Equation 5**

$E_{BaseCase,i}$ = The total emissions of pollutant *i* by the aircraft main engines during taxi-out as calculated in the base case scenario (see paragraph 5.3, equation 1);

FB_i = Fuel burn during taxi-out phase for each engine of aircraft type *j*;

EI_{ij} = Emission index for pollutant *i* and engine corresponding with aircraft type *j* during taxi-out phase;

T_{jk} = Taxi-out time for aircraft *j* at airport *k*;

T_{WarmUp} = Time for the engines to stabilize prior to take-off, set to 5 minutes.

If the value of T_{jk} is smaller than the threshold value, the value of $E_{Tow,i}$ equals $E_{BaseCase,i}$.

During taxi-out, the period of warm-up time of 4 to 5 minutes (see V. Kumar et al. [6]) is required for the engines to reach thermal stability prior to take-off. This has two implications for the modelling of towing during the taxi-out phase:

- If the taxi time is shorter then the time required for engine warm-up, it is not possible to reduce emissions by towing. Therefore, a threshold value is determined to exclude the short haul taxi movements that do not yield any benefits in terms of emission reduction. This threshold value is set to 6 minutes and covers 5 minutes of engine warm-up time and 1 minute of extra time. The extra minute is included because the effort of applying the measure is not worthwhile if a reduction of aircraft engine emissions due to taxiing is realized for only a very short period of time. This value is likely to be larger than 1 minute but since no data is available this minimum value has been chosen to determine an upper boundary for emission reduction, aircraft type/ engine type;
- It is assumed that engines during warm-up produce sufficient power for taxiing. In the cases where towing is applied, the maximum time during which the aircrafts engines are not operating and the aircraft is towed, is the total taxi-out time minus the time required for engine warm-up.

For the assessment of the emission reductions by applying towing during the taxi-in phase these effects do not apply. In the case of taxi-in, Equation 5 is used and the warm-up time is set to zero. It is assumed that the aircraft will taxi 1 minute using its engines directly after the landing before it is connected to an aircraft tractor. If the taxi-in time is less than 2 minutes in total it is not considered useful to tow the aircraft to the gate. For that reason a threshold value of 2 minutes is applied similar to the threshold value that is applied for taxi-out surface movements.

Aircraft tractor emissions

Emissions from the towing truck E_{truck} emissions that occur during the towing of the aircraft and the emissions from the empty truck movement associated with the towing movement are included in the calculation. The emissions of the aircraft tractor are calculated as described in the IATA fuel book [14][2]. The method described in this study uses a deterioration factor of 1 to incorporate the increase in emissions due to aging of the GSE equipment. Since no airport specific data is available and this calculation is aimed at providing an upper boundary for the potential emission reductions (a high aging factor would increase the aircraft tractor emissions), this factor is disregarded.

$$E_{Truck,i} = FF_j * EF_{ij} * T_{tow}$$ **Equation 6**

Where:

FF_j = Fuel flow for engine type *j* and a load factor of 25% (the load factor is explained later on in this paragraph);

EF_{ij} = Emission factor for pollutant *i* and engine type *j*;

T_{Tow} = Time of operation of the aircraft tractor.

And

$$T_{tow} = \left(T_{jk} - T_{connect}\right) * F_v$$ **Equation 7**

Where:

T_{jk} = The average taxi time for aircraft type *j* at airport *k*;

$T_{connect}$ = The time between the aircraft leaving the runway after touchdown and the moment that the aircraft is connected to the aircraft tractor. For departures the aircraft tractor is connected at the gate and $T_{connect}$ is set to zero;

F_v = The towing speed. The towing speed is expected to be lower than taxi speed, resulting in a longer time of operation for the aircraft tractor. Since only very limited data is available on the towing times or speeds, the following rough estimations are made:

- For taxi-out F_v = 1.5; the time of operation of the aircraft tractor is estimated to be 1.5 times the corresponding taxi time of the aircraft in the situation with no towing;
- During taxi-in F_v = 1.5; the aircraft is lighter compared to taxi-out, towing time is assumed to be equal to the taxi time.

The following emission indices for diesel powered ground support equipment are used for the calculation of emissions of the aircraft tractors (see the IATA fuel book [14]):

Table 5-3: Emission indices for diesel powered ground support equipment

Pollutant	**NO_x**	**CO**	**HC**	**SO_x**	**PM10**
Emission index (g/Kg)	48.2	15.8	10.5	n.a.	5.7

Developments on diesel engines are expected to lead to a reduction of the emission indices for diesel powered ground support equipment. However, this is not incorporated in this study. ALAQS does not provide data on SO_x emissions of aircraft tractors and the literature gives a

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[2] Annex 2 Aircraft Handling Emissions, advanced approach

range of possible values for SO_x emission indices. For these reasons SO_x emissions of aircraft tractors are disregarded. From ALAQS data is available on two different categories of aircraft tractors: Narrow body aircraft tractors and wide body aircraft tractors. For both types a load factor of 25% is used, as listed in the IATA fuel book [14]. The load factor gives the average engine setting relative to the maximum available power. The reference does not indicate whether the load factor changes if aircraft tractors are used to tow aircraft to and from the runway instead of only pushing the aircraft from the gate. For future research it is suggested to investigate what values of the load factor are applicable to this case. Annex 2 provides a list of aircraft types and the corresponding type of aircraft tractors. The emission factors of diesel powered ground service equipment are derived from the IATA fuel book [14]. For the emission calculations the categories propeller aircraft, turboprop aircraft and business jets are disregarded.

APU emissions during towing

Without the main engines running during towing, the use of the aircrafts APU is required to power the aircrafts systems, the air-conditioning and to start the engines at the end of the towing phase. For the towing phase, the APU is assumed already started. The APU emissions are calculated using the methodology described in paragraph 5.3.2.

The APU operating mode ‘maxECS/normal running’ gives power for the aircraft systems and the air-conditioning. The TIM for this APU operating mode equals the time the aircraft is being towed without main engines operating. The APU is off during warm-up of the engines.

The engines are started using the ‘main engine start’ operating mode of the APU. The TIM for main engine start is the default TIM as used in APU emission calculations for aircraft at the gate (standard value in ALAQS).

5.4.3 Using electric ground power and PCAU instead of the APU

The APU is used for the start up of the engine, for powering aircraft systems and the supply of power for the air-conditioning. Part of the emissions of the APU can be attributed to starting up of the APU itself. With the exception of the engine start up, the APU can be replaced by electric ground power and a PCAU. Replacing the use of APU for powering the air-conditioning requires pre/conditioned air units powered by electric ground power. According to Aeroway Airport & Ground Support Equipment [15] it is possible to start the engine using an engine start-up unit. However, the use of these start-up units and their effect on local emissions is not considered in this study.

The potential for emission reductions by using electric ground power and PCAU instead of APU and GPU is assessed with information from ALAQS and CAEP/7-WP28 [12]. Standard values for APU and GPU fuel burn and emission indices are used. The potential for emission reductions is done by carrying out an upper boundary calculation. The upper boundary calculation is defined by the following presumptions:

- Electric ground power and PCAU substitutes the complete use of APUs and GPUs with the exception of engine start up;
- Availability of electric ground power is 100%.

Default values in ALAQS are used for the assessment. To determine the contributions of the different modes (engine start, air-conditioning & powering aircraft systems and idling) to the total emissions, calculations are performed for the different aircraft based on CAEP/7-WP28 [12].

Replacement of the APU by electric ground power and a PCAU is an effective measure for improving airport air quality since direct emissions on the airport are reduced. Applying ground power may cause emissions at the location of the power plant. These should be taken into account when looking at this measure in the context of regional air quality and-or global greenhouse gas emissions.

Data availability on APU use is limited, and operation of APUs and GPUs may vary strongly from one airport, airline or aircraft type to another.

5.5 EFFECTS OF IMPROVEMENTS TO OPTIMIZE SURFACE MOVEMENTS

The OI steps described in paragraph 5.2.2 will optimize the taxi process, so that taxi and queuing times are minimized. When all proposed improvements of this group of OI steps are implemented, this results in an airport that is designed in an environmentally friendly way. Furthermore the traffic on the airport is managed in such a way that taxi delays are almost eliminated. For the calculation of the effect of these OI steps on the LAQ, it is assumed that this set of measures will reduce queuing times to zero. This way the calculations give an upper boundary on the possible reduction in local aircraft emissions due to these OI steps. The calculations are carried out for 20 airports (as described in paragraph 5.1).

6 OUTPUT DATA ANALYSIS

Paragraphs 6.2 and 6.3 of this chapter will outline the results of the calculations on the effects of the OI steps on the local aircraft emissions. The results are obtained with the methods described in chapter 5. For several OI steps and some groups of OI steps separate scenarios are developed so that it is possible to present the accumulated effect of (groups of) individual measures. A comparison of the results for different (groups of) OI steps and the constraints to accumulating the emission reductions from the implementation of the OI steps are discussed in paragraph 6.4.

6.1 CALCULATION RESULTS BASE CASE

As discussed in Episode 3 D2.4.4-02 [16], the emissions below 1000 ft have the largest impact on the LAQ. However, the KPIs are defined as emissions below 3000 ft. For this reason this paragraph shows the composition of local emissions below 1000 ft as well as below 3000ft.

Figure 6-1 shows the composition of aircraft emissions that are relevant to the local air quality. This includes the airborne emissions, the taxiing emissions of the aircraft and the usage of the APU. The emissions are presented in chronological order and are averages over the 20 busiest airports.

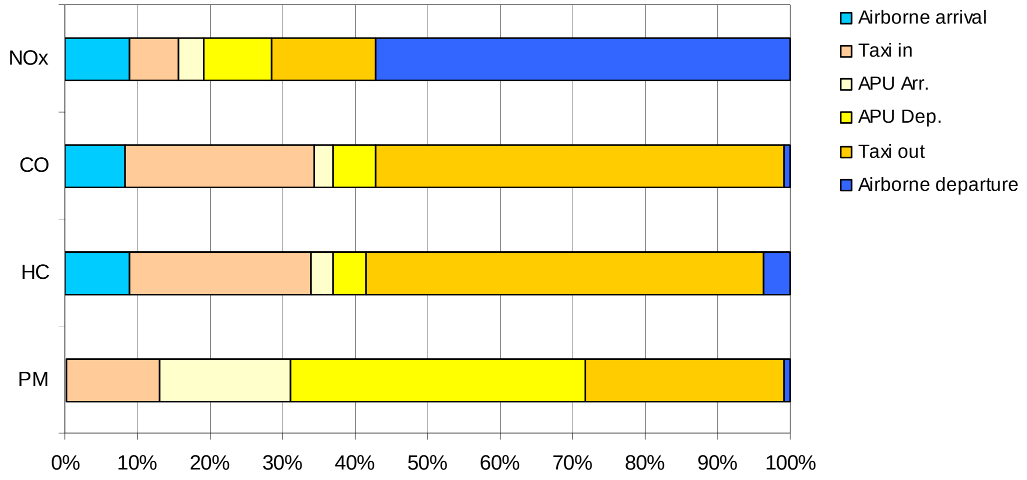

Figure 6-1: Composition of local aircraft emissions below 1000 ft.

The following observations are made regarding Figure 6-1:

- Taxi-in and taxi-out are responsible for approximately 80 to 90% of the CO and HC emissions below 1000 ft. Emissions of hydrocarbons and carbon monoxide are associated with incomplete combustion of fossil fuels. This typically occurs when the aircraft main engines are operated at low thrust settings. Since low thrust settings are applied during taxiing, the taxi phase results in the highest CO and HC emissions;
- NO_x emissions are dominated by the airborne departure phase, due to the high production of NO_x by the aircraft main engines during take-off and to a lesser extent during climb-out. Taxiing is a significant contributor to the remainder of the NO_x emissions. However, the relative contribution of the airborne phase for NO_x is much larger when compared to the relative airborne CO and HC emissions. This is in accordance with the differences in engine behaviour with respect to NO_x emissions

versus the engine behaviour with respect to CO and HC emissions at higher thrust settings;

- Regarding the PM10 emissions of the main engines, methods for measuring and modelling the emissions are under development in ICAO workgroup 3. In the absence of measured PM10 emission indices, these methods are based on smoke number. This method is considered to be provisional until suitable methods for measuring PM10 are developed. Figure 6-1 shows that the APU emissions are responsible for more than half of the PM10 emissions below 3000 ft and that the airborne phases have a limited contribution to these emissions;
- The SO_x emissions below 1000 ft are omitted in Figure 6-1 for two reasons. First of all the APU SO_x emissions are not calculated and secondly for the airborne phases SO_2 is calculated, this does not allow for a comparison with SO_x.

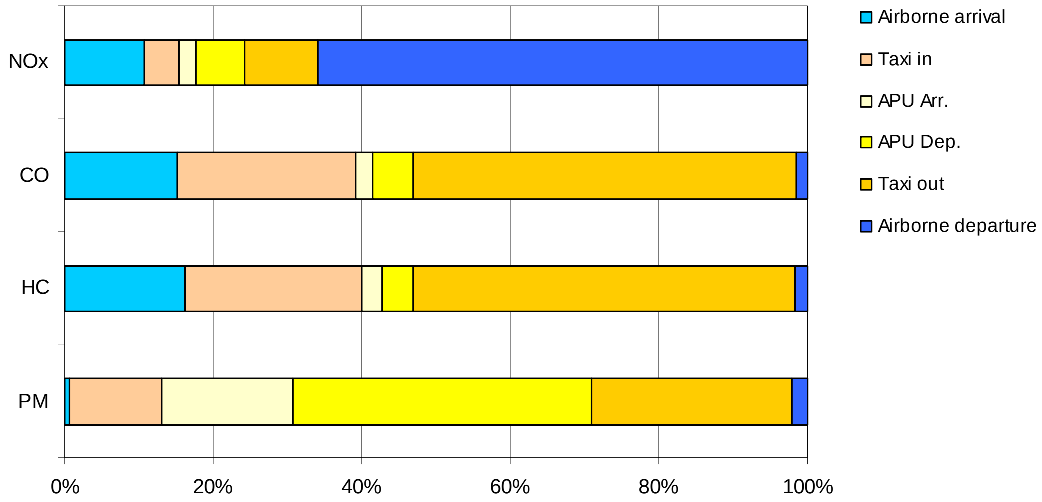

Figure 6-2: Composition of local aircraft emissions below 3000 ft

Figure 6-2 shows the composition of emissions below 3000 ft. The difference between Figure 6-1 and Figure 6-2 is that the latter shows increased airborne emissions because it takes emissions up to the increased height of 3000ft into account. Particularly CO and HC emissions during the airborne arrival phase are higher. This is a consequence of a longer period of time during which the aircrafts main engines are operated at the approach thrust setting. The emissions below 3000 ft are of interest since the KPIs are defined as the emissions below 3000 ft.

The results of the calculations are corrected for omissions of data (see Table 6-1) on fuel flow and emission indices in the engine database. However, omissions in the data are more abundant for turboprops and propeller aircraft, this will result in a small bias towards jet aircraft, i.e. jet aircraft are slightly over represented in the results.

Table 6-1: Data coverage of emission data

	NO_x and CO	HC	SO_x	PM10
Airborne emissions	100%	90%	n.a.	92%
Taxiing emissions	100%	100%	95%	92%
APU emissions	100%	100%	100%	100%

6.2 CALCULATION RESULTS FOR GROUND MOVEMENT TECHNIQUES

In this paragraph the results of three OI steps that are part of AUO-0802 (Ground movement techniques to reduce gaseous emissions and noise disturbance) are discussed.

6.2.1 Engine out taxiing

This chapter presents the results of the calculations of the maximum obtainable reduction in emissions for EOT. The red bars in Figure 6-3 to Figure 6-7 show the average value of the calculated reductions in emissions for NO_x, CO, HC, SO_x and PM10. This means that the figures show the average emission reduction for all flights at all considered airports. The shown reduction is the percentage of reduction relative to the total taxi emissions per pollutant.

The pattern is similar for the 5 investigated pollutants. The reduction of emissions are well below 45% due to the fact that single engine aircraft cannot taxi with a reduced number of engines and aircraft with 3 engines operate 2 in the operational improvement scenario. For application of the measure in the taxi-out phase an additional factor is the influence of the engine warm up time. The time needed for the warm up of the engine(s) that are not operating while the measure is in effect equals 5 minutes in the computations. The warm up time, during witch the measure cannot be applied reduces the potential for emission reduction and the reduction is consequentially lower than for arrivals.

In this study the time between the moment of arrival and the moment that one or more engines are switched off is set to one minute. The relative margin of arrivals over departures will decrease if a longer engine cool off period is modelled (R. Yamartino et al. [5] reports a recommended cool-off time of 3 minutes).

In order to give an impression of the variance in the results, the maximum and minimum reductions are shown in the graphs by the black interval indicators. The bars show the range between the results for the airports with the highest and the lowest emission reduction. The variance in Figure 6-3 to Figure 6-7 is proportional to the variance in the time of taxi-out and taxi-in phase. Taxi-out results vary between the 20 busiest European airports, this is caused by varying taxi times due to for instance the airport layout (this affects both taxi-in and taxi-out) and the levels of congestion (affecting predominantly taxi-out).

The bars show the emission reduction per flight for arrivals and departures separately and for all traffic. The bar with the total emission reduction per flight is always in between the emission reduction for departures and arrivals, since this bar gives the average reduction for all flights.

The aircraft engines only need to warm-up before take-off and not after landing. This results in differences in the variance of the results for arrivals and departures. The warm-up time has a larger impact on the relative emission reduction at airports with short taxi-out time than on airports with long taxi times. At airports with low taxi-out times, less aircraft movements are selected for the application of the measure because the taxi time minus engine warm up time needs to be higher than a designated threshold value. If the taxi-time does not exceed this threshold value, applying the measure is not feasible.

According to R. Yamartino et al. [5] EOT yields a 35% reduction of the aircraft LTO's HC emissions and a 4.7% reduction of NO_x emissions. For HC this corresponds with the results presented in this study. As expected, the results on potential NO_x reductions from this study are higher than in R. Yamartino et al. [5]. A possible reason for this difference is the fact that the study in R. Yamartino et al. [5] is based on a traffic consisting of 1992 aircraft. The 2006 traffic used in this study can be expected to have a better average performance in NO_x emissions. The current generation of engines is mainly designed to further increase fuel efficiency. These engines have higher by-pass ratios and operate at higher temperatures compared to engines from the 90s. Both favour the production of NO_x.

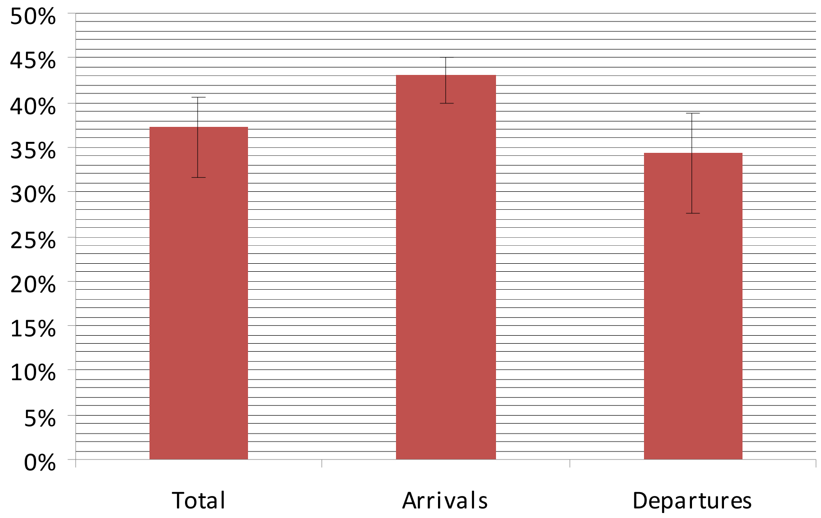

Figure 6-3: Reduction of NO_x taxi emissions due to EOT

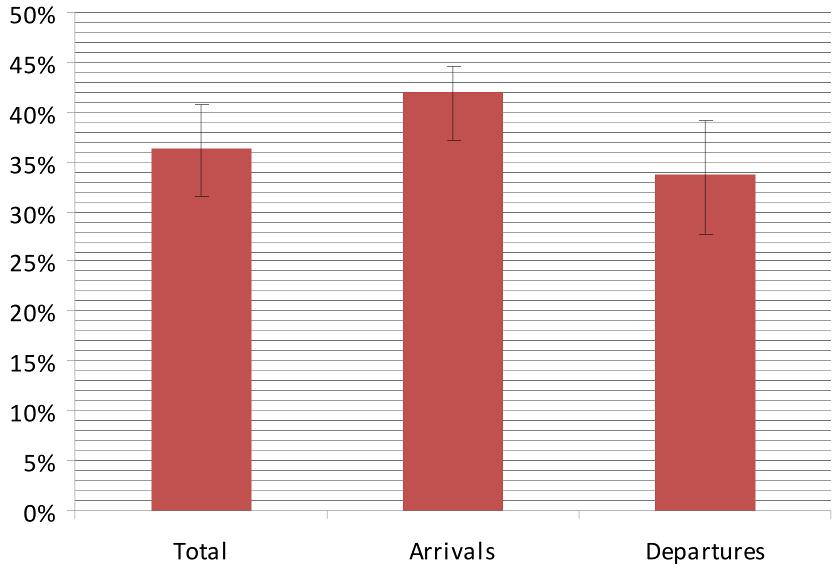

Figure 6-4: Reduction of HC taxi emissions due to EOT

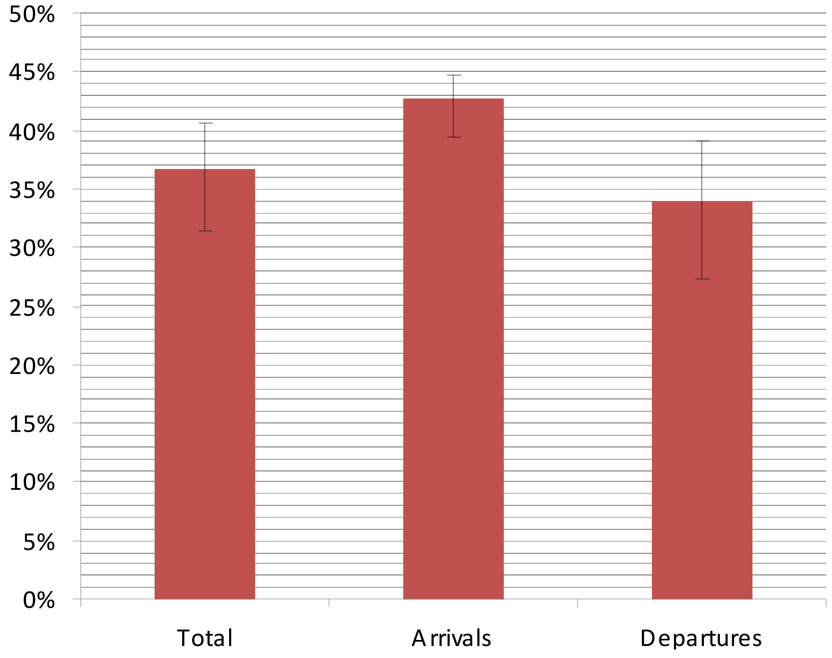

Figure 6-5: Reduction CO taxi emissions due EOT

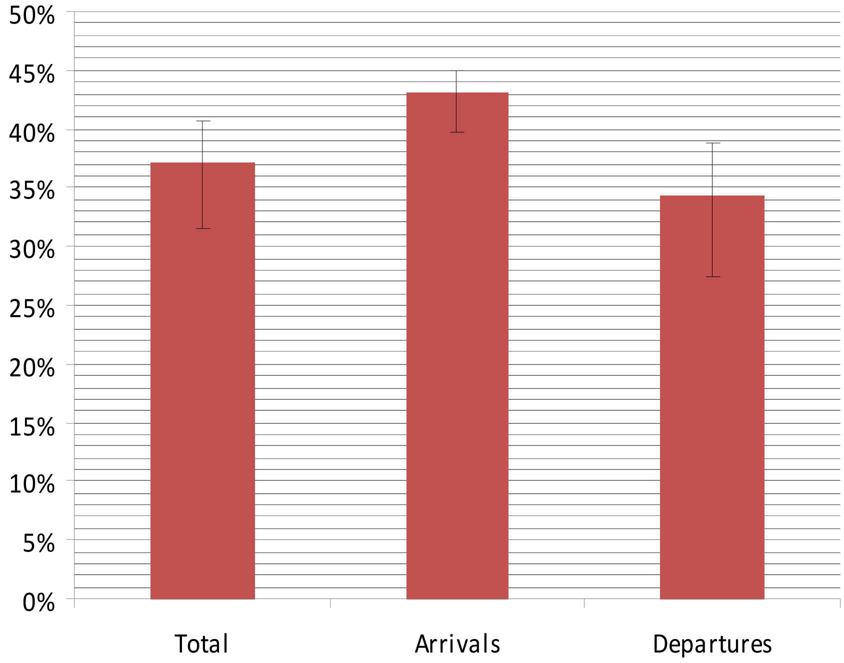

Figure 6-6: Reduction of SO_x taxi emissions due to EOT

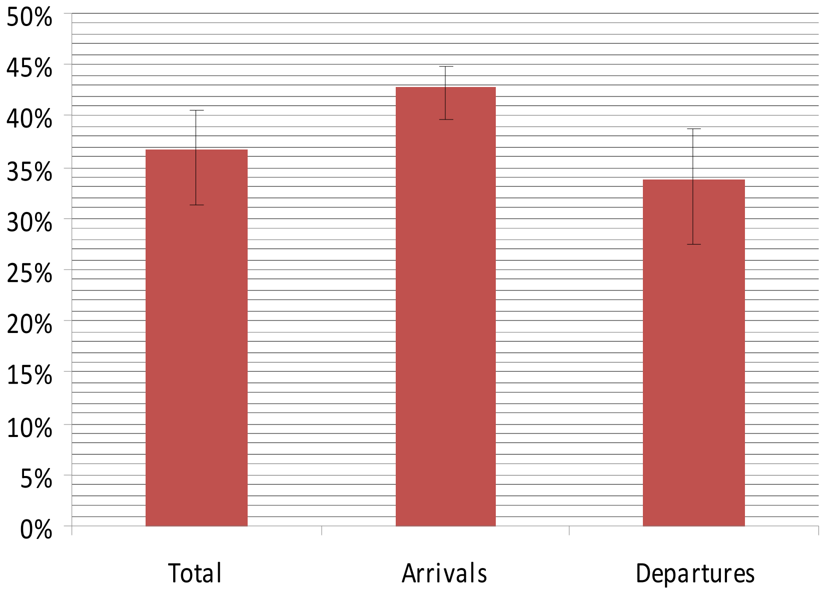

Figure 6-7: Reduction of PM10 emissions due to EOT

To calculate the maximum achievable emission reductions for EOT, the following assumptions are made:

- Thrust setting the operating engine(s) remains the same as for taxiing with all engines operating;
- Taxiing speed remains the same as for taxiing with all engines operating;
- All aircraft taxi with a reduced number of operating engines, both before take-off and after landing;
- No additional APU usage is taken into account.

These assumptions have several consequences for the obtained results. The effect on the thrust setting of the engine is unknown, however it is likely that the trust setting of the operating engine(s) increases if one or more engines are switched off. Due to the uncertainties of the modelled thrust, both for taxiing with all and with a limited number of operating engines, the effect of this assumption on the results cannot be estimated. If the taxi speed decreases due to the improvement, this can have another negative effect on emissions if for instance the APU is used during the taxiing phase. In this case the emissions will increase due to the fact that the APU is used for a longer period.

Since the calculations aim to provide an upper limit of the possible emission reduction, it is assumed that this improvement is applied by all taxiing aircraft. However, according to the IATA fuel book [14] this improvement might not be applicable to some aircraft types, and also the aircraft weight can be a limiting factor for the usage of this improvement, especially for departing aircraft. Also limitations to the feasibility of the improvement can be posed by the airport terrain. If the measure is to be implemented, the taxi route should not contain steep turns and uneven terrain. The last assumption is that no additional APU usage is required if an aircraft taxies with a lower number of operating engines, while in practice additional APU usage may be required, for instance to start-up the non operating engine(s).

All together, these assumptions indicate that the calculations of the emission reduction due to EOT give an overestimation of the achievable emission reduction. In practice not all aircraft will be able to make use of this improvement, especially during taxi-out and due to uncertainties in the thrust setting and the taxi speed, the accuracy of the calculation results is reduced.

6.2.2 Towing the aircraft to/from the runway

Figure 6-8, Figure 6-10, Figure 6-12 and Figure 6-14 show the average value of the calculated reductions in emissions of NO_x, PM10, HC and CO when towing is applied. The figures give the average emission reduction at all considered airports. The shown reduction is the percentage of reduction relative to the total emissions per pollutant during the taxi phase, i.e. taxi-in for arrivals and taxi-out for departures.

The effect of towing differs for investigated pollutants, primarily because the reduction of emissions of the aircrafts main engines are partially or completely counteracted by the emissions of the aircraft tractor and the additional APU usage needed to power the aircraft systems and air conditioning. Figure 6-9, Figure 6-11, Figure 6-13 and Figure 6-15 show the contributions of the aircraft main engines, aircraft tractor and APU emissions to the total emissions of NO_x, PM10, HC and CO when towing is applied. The SO_x emissions are not shown since the contribution of the aircraft tractors and APU are unknown.

The maximum reduction in emissions as a percentage of the initial taxi NO_x emissions during taxiing (Figure 6-8) is larger for the arrivals because this measure does not lead to a reduction in emissions during engine warm-up. The absolute emission reductions in Figure 6-9 indicate that applying towing to departures has a greater potential. The higher amount of emissions of departing aircraft is caused by longer taxi times and the fact that it is assumed that no taxi delays occur for arriving traffic.

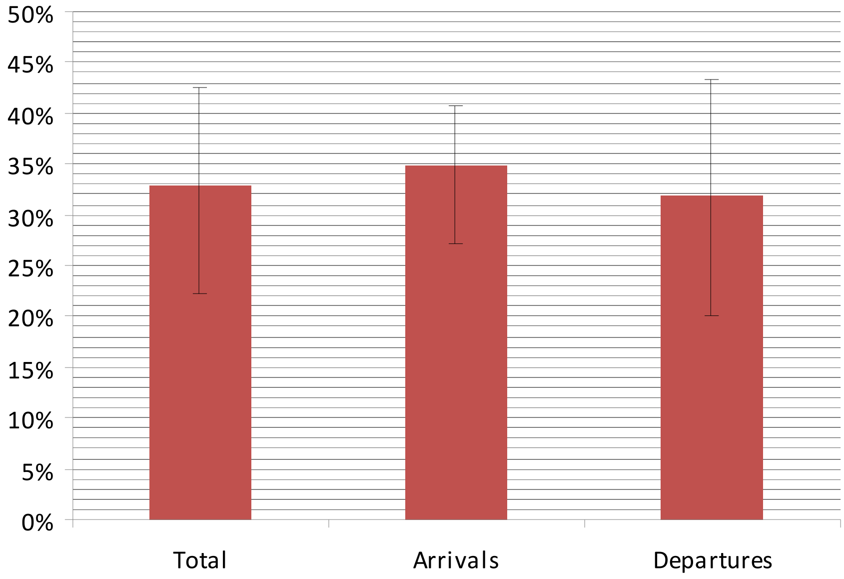

Figure 6-8: Relative reduction of NO_x emissions for towing

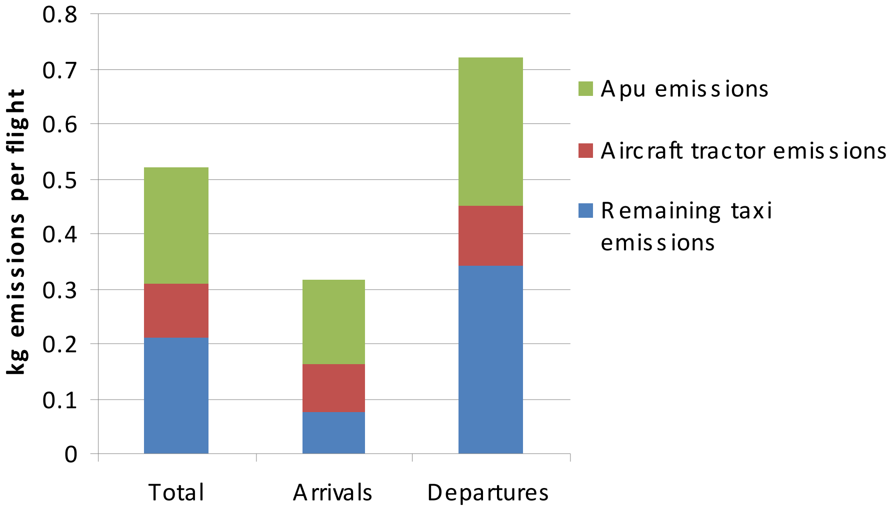

Figure 6-9: Different sources of NO_x emissions during towing

The PM10 emissions are dominated by the APU and aircraft tractor PM10 emissions (see Figure 6-11). The increase of emissions from the APU and aircraft tractor results in a negative net effect on the average relative reduction (see Figure 6-10). In other words: towing results in an increase in PM10 emissions.

Similar to the results of EOT, also for towing the largest effects on emissions are obtained for arriving traffic. This is caused by the fact that the engines of departing traffic need to warm-up.

The calculated results for the PM10 emissions should be interpreted with caution for the following reasons:

- Methods for measurement and modelling particulates from aircraft engines and APUs are still under development (see also paragraph 6.2.1). This means that the uncertainties in the calculations for PM10 are larger than for the calculations of other pollutants;
- Emission indices for diesel engines of GSE are derived from the ICAO Airport Air Quality Guidance Manual [3], emission performance of GSE is likely to vary between different types of vehicles and different load factors.

PM10 for particulates only addresses the abundance of particulates in terms of mass; it does not adequately address the characteristics of PM in terms of particle chemistry and size distribution. When considering health aspects, volatile components are of importance but volatile components are not represented adequately. This is relevant in the context of this measure because the size, mass and chemical distributions are different for the three types of emission sources under consideration.

Figure 6-10: Relative reduction of PM10 emissions for towing

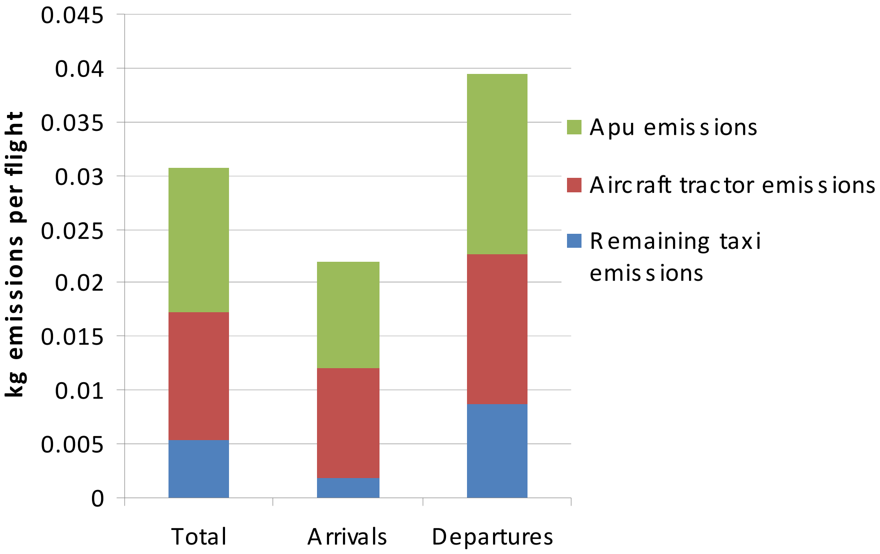

Figure 6-11: Different sources of PM10 emissions during towing

Figure 6-12 to Figure 6-15 show the calculation results of the HC and CO emissions. Both types of emissions show similar patterns with respect to relative reduction of emissions and the build up of different emission sources that remain when the measure is applied. The figures make clear that the measure is effective in the sense that it results in a reduction of the HC and CO emissions, in the order of 65% to 70%.

Again, applying this measure on arriving traffic has more potential for a reduction in emissions due to the effect of engine warm-up time. The differences between the effect of the improvement on CO and HC emissions are caused by differences in emission characteristics of aircraft tractors and APUs. Similar to the NO_x emissions, the absolute PM10 taxi emissions are larger for departing aircraft.

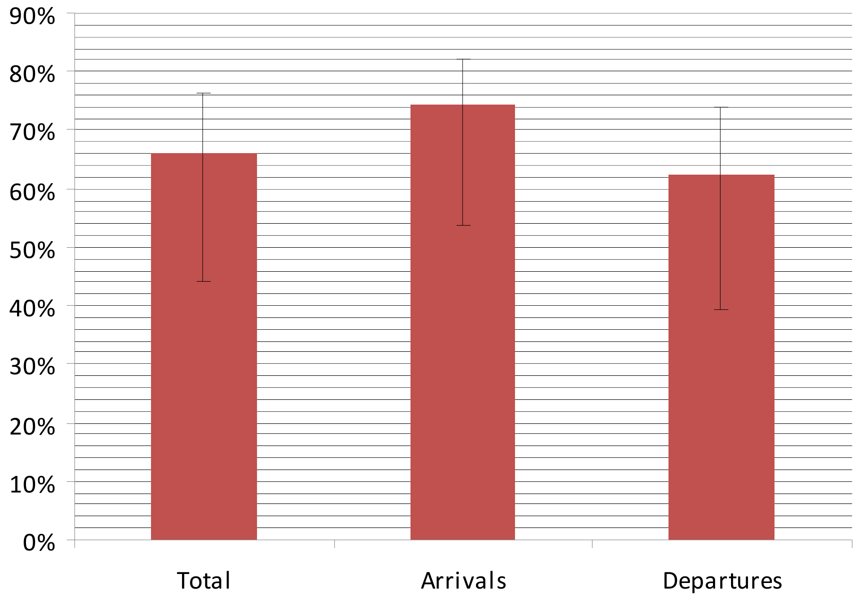

Figure 6-12: Relative reduction of HC emissions for towing

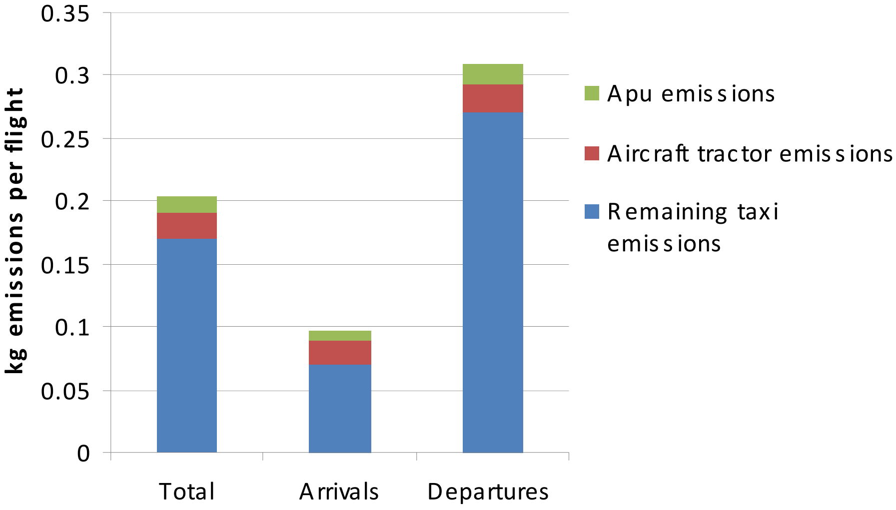

Figure 6-13: Different sources of HC emissions during towing

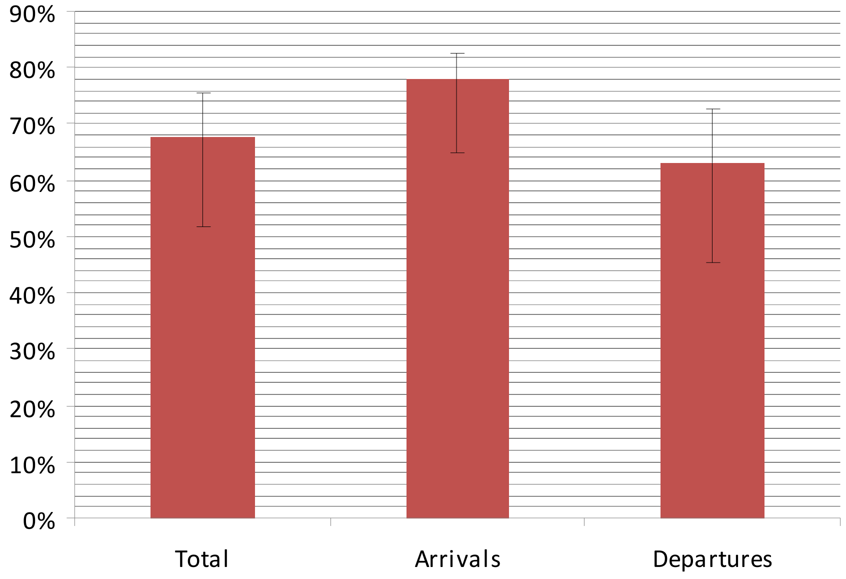

Figure 6-14: Relative reduction of CO emissions for towing

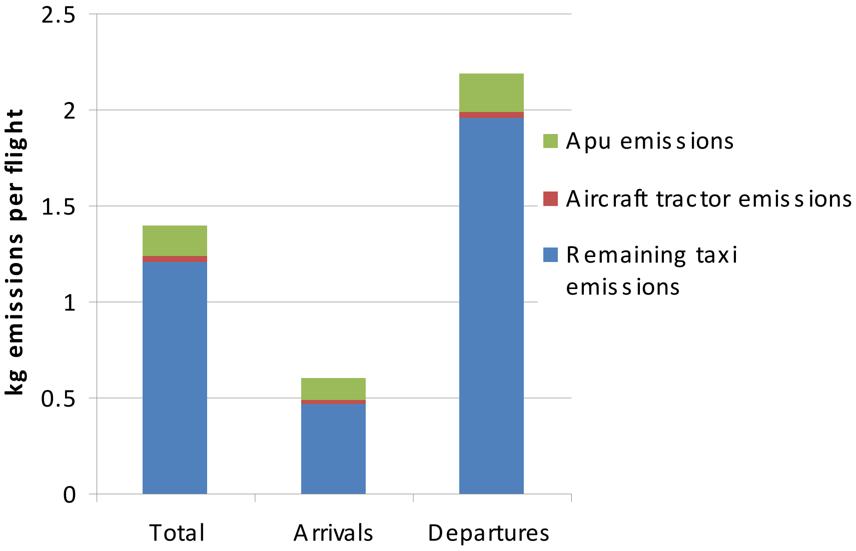

Figure 6-15: Different sources of CO emissions during towing

Several choices have to be made for the calculation of the departure emissions and these choices influence the final results.

In the current study it is assumed that the aircraft remains connected to the tractor during the engine warm-up and during queuing. Furthermore it is assumed that the engine warm-up starts 5 minutes prior to departure. The warm-up time is included as time on top of the time of the taxi-out phase, i.e. in the modelling the engine warm-up takes place during the taxiing or during line up delay. This is in line with the idea that it is not efficient to conduct the engine warm-up at a location at the start of the runway after taxiing/towing and possible line up (see R. Yamartino et al. [5]).

Not only for the warm-up time, but also for the values for towing speeds, load factors, emission indices of aircraft tractors and threshold values assumptions are made. To obtain more accurate values for these parameters, more research is needed. This implies that the results contain errors due to incorrect input values. Due to the number of input values and the fact that the cumulative error that they induce is unknown, the error margin for the calculations cannot be estimated.

If this OI step is to be implemented, several practical problems should be solved. The improvement will require a redesign of the aircraft landing gear and the airport infrastructure must be extended in such a way that aircraft the additional tractor movements can be accommodated. If the taxi speed becomes lower due to towing, this might have operational consequences since aircraft need more time to travel between the runway and the gate.

6.2.3 The use of electric ground power and PCAU instead of APU

As described in section 5.4.3, the APU is used for starting the engine, for powering aircraft systems and the supply of power for the air-conditioning. Electric ground power and pre-conditioned air can replace the APU for the most part. However, the APU is still required for starting the aircraft engines. In the calculations it is assumed that the emissions due to electric ground power and PCAU are emitted at a different location than the airport and do not contribute to the LAQ.

After arrival the APU is no longer required when electric ground power and PCAU are used. An arriving aircraft is assumed to taxi to the gate where electric ground power and a PCAU are connected to the aircraft. In the case of a departing aircraft the APU is only used for starting the aircraft engines. However, some aircraft engines can also be started with an (electric) ground unit. The calculations for the current operational improvement do not consider this ground unit for starting aircraft engines.

Since in this case the APU is no longer required, the emission reduction for CO, NO_x, HC and PM10 equals 100%. For departures, the average reduction of emissions per aircraft movement for 20 airports varies between 54% and 94% of the total APU emissions at the gate. The time in mode for arriving and departing aircraft follow from the input data. These databases provide information for both arriving and departing traffic. If one aircraft lands and takes off from an airport on the same day, this means that two data records exist for this aircraft; one for each flight movement.

Figure 6-16, Figure 6-17, Figure 6-18 and Figure 6-19 show the average value of the calculated reductions in emissions for NO_x, HC, CO and PM10. The figures show three bars each. The ‘Total’ bar indicates the average emission reduction for arrival and departure together. The ‘Arrivals’ bar shows the average emission reduction per arrival, which is 100% for this operational improvement. The ‘Departures’ bar shows the average emission reduction per departure. The averages are calculated based on traffic for the 20 largest airports in Europe. The blue margin bars indicate the upper and lower average reduction for the 20 airports.

Figure 6-16 presents the average reduction for NO_x. For departures a reduction of almost 94% NO_x emissions is possible. The remaining 6% is emitted during start up of the APU and the subsequent aircraft engine start where the APU is required. The time in mode for both APU modes used (APU start-up and jet engine start) are considerable lower than the time in mode for the APU mode that is replaced by electric ground power and PCAU. Therefore the reduction of NO_x emissions is close to 100%.

As explained above, during arrival, the taxi-in phase and deplaning at the gate the APU is not required. The reduction in NO_x emission is therefore 100%. This also holds for HC, CO and PM10 emissions.

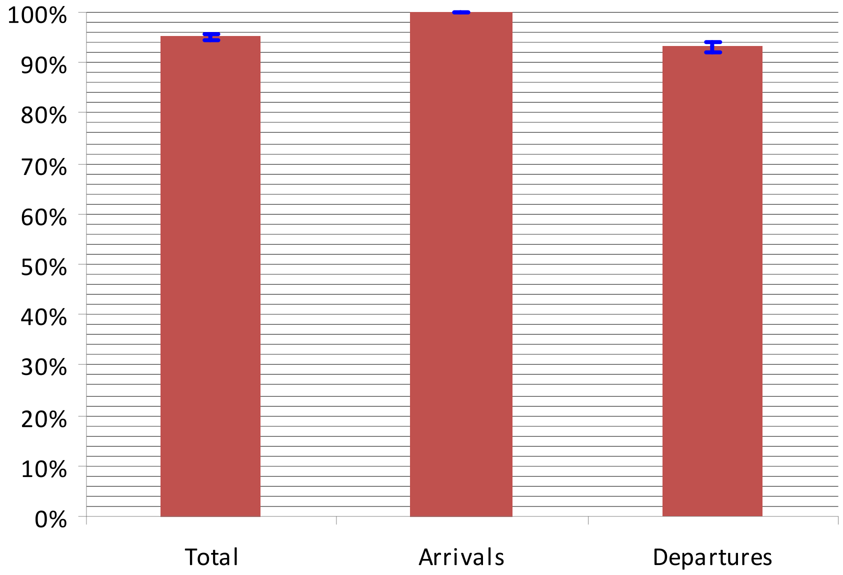

Figure 6-16: Relative reduction of NO_x emissions due to reduced APU usage

Figure 6-17 shows the average reduction for HC. The average reduction of the HC emissions at the gate equals almost 82%. The average HC emission reduction is smaller than for NO_x. This is caused by the fact that relatively more HC is emitted during APU start-up than during the mode in which the APU is used for powering aircraft systems and the supply of power for the air-conditioning. For arrivals, the average HC emission reduction is again 100%.

The upper and lower average reduction margin bars indicate that there are large differences between airports. This is mainly caused by differences in fleet. An airport with relatively more large aircraft will benefit more from the electric ground power and PCAU operational improvement than an airport with only small aircraft. This is because the time the APU is used for powering aircraft systems and the supply of power for the air-conditioning is much larger for large aircraft than for small aircraft. Large aircraft benefit more than small aircraft due to their longer turnaround times.

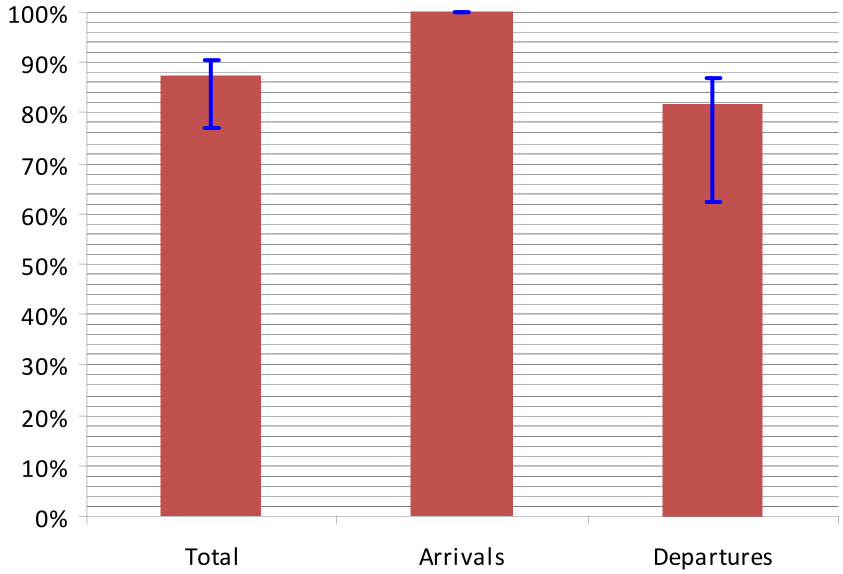

Figure 6-17: Relative reduction of HC emissions due to reduced APU usage

Figure 6-18 shows the calculated upper limit of the average reduction of CO emissions. For arrivals the reduction is 100%. The use of electrical ground power and PCAU results in an average reduction of the CO emissions of the APU at the gate with 54%. This reduction is lower than for NO_x and HC. This is caused by the fact that during the start-up of the APU and aircraft engines relatively more CO is emitted by the APU than in the other modes. Similar to the reductions of HC emissions, the bandwidth between upper and lower average reduction is caused by differences in fleet.

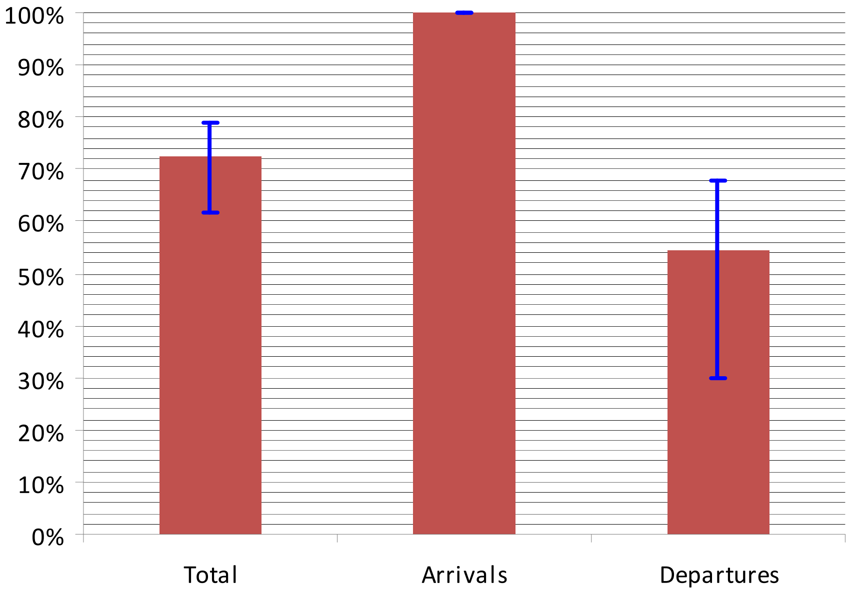

Figure 6-18: Relative reduction of CO emissions due to reduced APU usage

Figure 6-19 presents the average reduction of PM emissions. The average reduction for departures equals 94% and for arrivals the reduction is 100%. The APU mode for powering aircraft systems and supplying power for the air-conditioning has the largest contribution to the PM10 emissions. Only a relatively small amount of PM10 is emitted in the other APU modes. Therefore the average reduction for PM10 emission is high for this operational improvement. The small margin between upper and lower average PM10 emission reduction is caused by the fact that the amount of PM10 emitted per hour is the roughly the same for the different generic APU types (emissions are calculated with 8 APU classes, see section 5.3.2). Therefore, variations in fleet mix within the 20 largest airports do not have a large impact on the variation in average PM10 emission reduction.

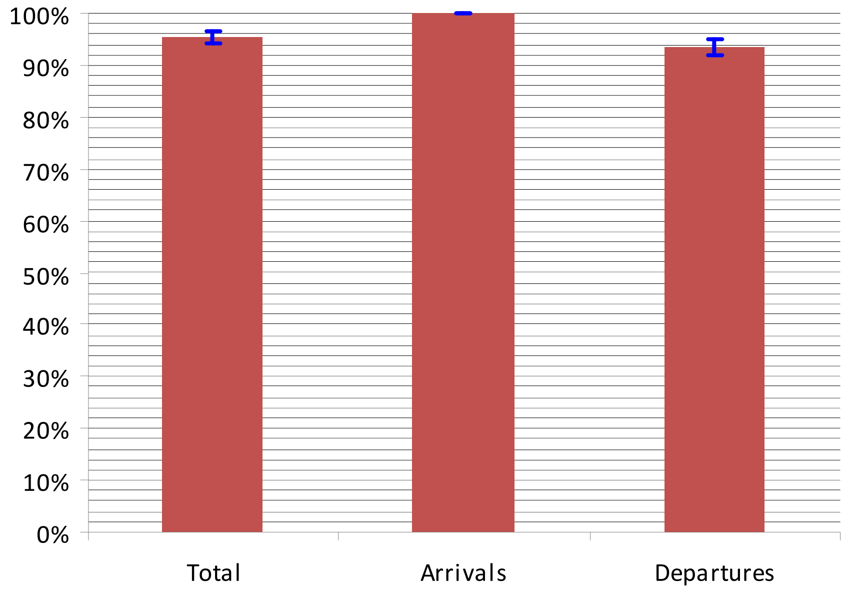

Figure 6-19: Relative reduction of PM10 emissions due to reduced APU usage

6.3 CALCULATION RESULTS FOR THE OPTIMIZATION OF SURFACE MOVEMENTS

The OI steps from this group are described in paragraph 5.2.2. These improvements will optimize the taxi process, so that taxi and queuing times are minimized. To model the effects of these improvements the queuing times are set to zero. This way the calculations give an upper boundary on the possible reduction in local aircraft emissions due to these OI steps.

Since it is assumed that the taxi delay is zero for arriving aircraft, these measures will not result in emission reductions for arriving traffic. Another difference with the previous paragraphs is the fact that the relative effect of this group of OI steps is almost equal for all of the pollutants (NO_x, CO, HC, SO_x and PM10). This can be explained with the fact that the emission reduction is only caused by a decrease in taxi time. Since the emission indices remain the same, the net effect per pollutant is the same. The relative reductions per pollutant vary with at most 0.16%. The small differences between the results can by explained by the fact that emission indices differ per aircraft category. If the traffic consists of a larger number of jets than propeller aircraft, this means that a larger reduction in jet emissions is achieved with the improvements.

The calculations show that all taxi emissions on the airport surface decrease by 16% if the optimization of surface movements reduces the queuing time to zero. In other words, for the investigated airports, the queuing emissions equal 16% of the total taxiing emissions.

For the calculation of the emission reductions due to the optimization of surface movements, it is assumed that the queuing delays are reduced to zero due to the OI steps. In practice, reducing the taxi delays to zero is not possible for instance due to unforeseen events such as an aborted take-off that leads to an unexpected long runway occupancy time. Furthermore, the reduction of the queuing time can lead to an increase in the waiting time at the gate which induces additional APU emissions if no measures are taken to remove the APU emissions at the gates. Finally the effect of possible APU usage during taxiing is not taken into account. If aircraft use their APU during the taxiing phase, this means that reducing the taxiing times leads to a larger emission reduction, since also these APU emissions are reduced. These assumptions result in an underestimation of the APU emissions.

6.4 IMPACT OF THE INVESTIGATED OPERATIONAL IMPROVEMENT STEPS

Paragraphs 6.2.1 to 6.2.3 presented the upper limits for the potential reduction of emissions for a number of individual improvements and for grouped measures. To assess the effect of implementation of a combination or all of these measures in relation to the defined KPIs, the following constraints need to be taken into account:

- Any reduction of delays during taxi-out affects the results of EOT and towing in two ways:
  - The number of aircraft movements to which the measures can be applied is reduced because less aircraft movements exceed the threshold value above which applying the measure is infeasible (see paragraph 5.4.1 and 5.4.2);
  - Mitigation of delays reduces the time during which the measure is applied and consequentially this decreases the reduction in emissions.
- Applying towing with no engines operating and taxiing with a reduced number of engines at the same time is not possible.

However, it is possible to combine some OI steps. Implementing the optimization of surface movements and towing or taxiing with a reduced number of operating engines at the same time is possible. Though the total effect is not as large as the sum of the reductions caused by the improvements separately, combining the improvements still gives a larger reduction in emissions compared to a single improvement.

Figure 6-20 to Figure 6-24 show the upper limits for the emission reductions due to the investigated OI steps compared to the total emissions of the baseline scenario including airborne emissions up to 3000 ft, APU and taxi emissions. The bars represent the upper limit of the reduction of NO_x, CO, HC, SO_x and PM10 emissions per aircraft movement. The figures present the reductions in terms of percentage relative to the total baseline emissions below 3000 ft. This way the figures show the effect of the OI steps on the KPIs.

The figures show that the effect of the measures varies with regard to the reduction in the emissions of different pollutants. For NO_x (Figure 6-20), the upper limits of the maximum potential emissions reductions do not exceed 10%. This reduction is low in comparison to the other pollutants due to the relatively high NO_x emissions that occur during the airborne phases. The measure with the highest upper limit for mitigating NO_x emissions is the application of ground power and PCAUs instead of APUs.

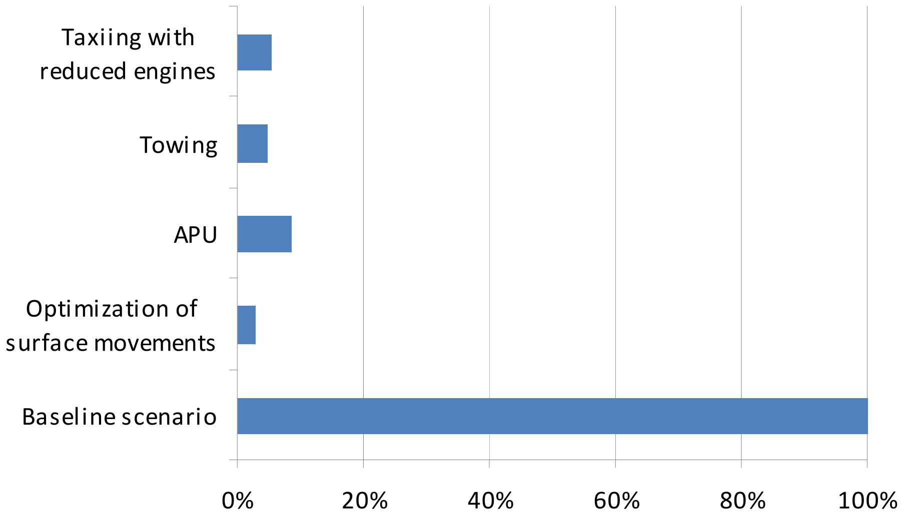

Figure 6-20: Baseline NO_x emissions and upper limits of the reduction per OI step

The patterns observed for CO (Figure 6-21) and HC (Figure 6-22) are comparable with respect to the relative emission reduction of different measures. Towing and EOT mitigates CO and HC emissions by reducing the time that aircraft main engines operate at low thrust settings. At low thrust settings the combustion process is sub-optimal, which leads to an increase of products of incomplete combustion. For CO and HC emissions upper limits are highest for towing, followed by taxiing with a reduced number of engines, optimization of surface movements and finally the application of ground power and PCAUs instead of APUs.

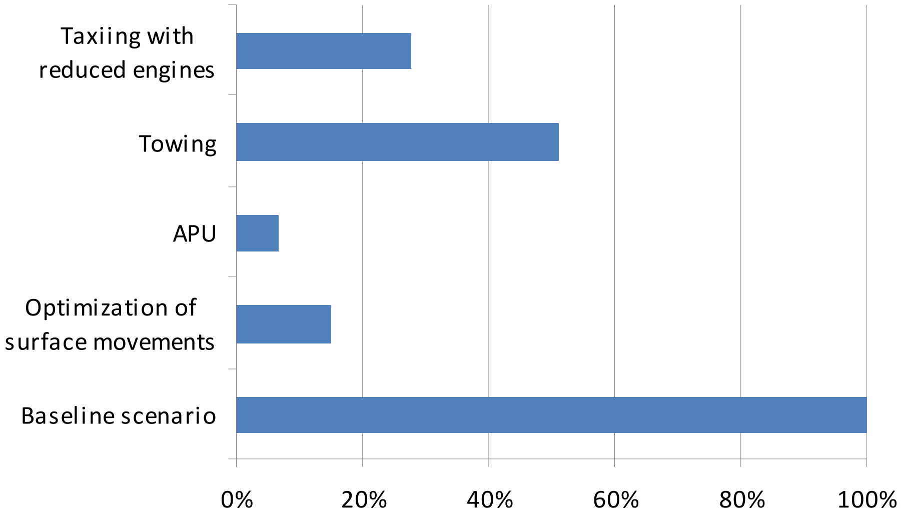

Figure 6-21: Baseline CO emissions and upper limits of the reduction per OI step

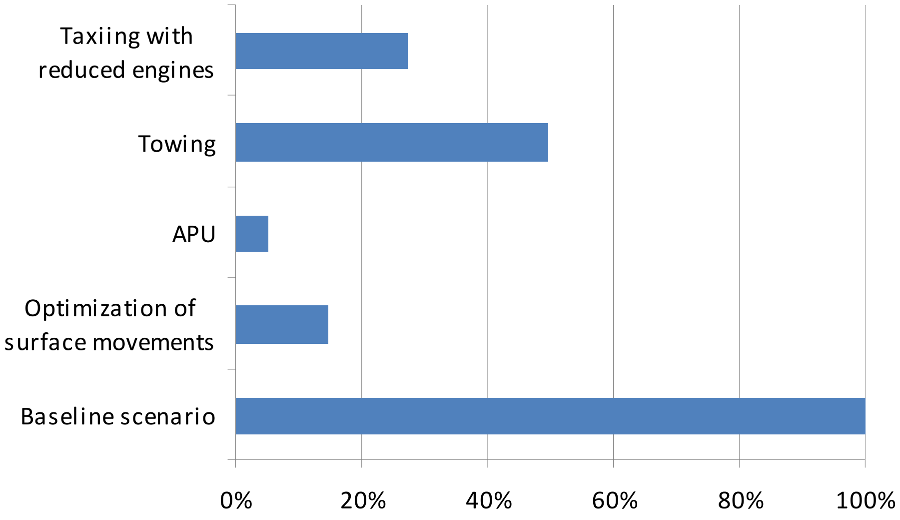

Figure 6-22: Baseline HC emissions and upper limits of the reduction per OI step

The SO_x emissions of APUs are not calculated due to a lack of input data and SO_x emissions of the airborne phases are not calculated since LEAS-iT only provides SO_2 emissions. These emissions are therefore not included in the baseline scenario. As a consequence the emission reductions are inflated.

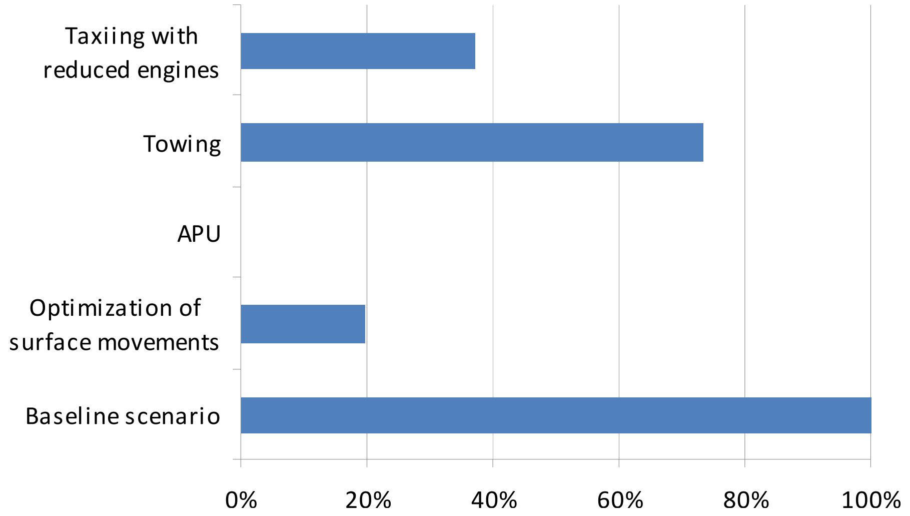

Figure 6-23: Baseline SO_x emissions and upper limits of the reduction per OI step

Reducing the APU emissions by applying ground power and PCAUs has the largest upper limit for potential reduction of PM10 emissions, followed by EOT and optimization of surface movements. Towing yields a negative upper limit due to the PM10 emissions of the aircraft tractor and of the operation of APUs when the main engines of the aircraft are off.

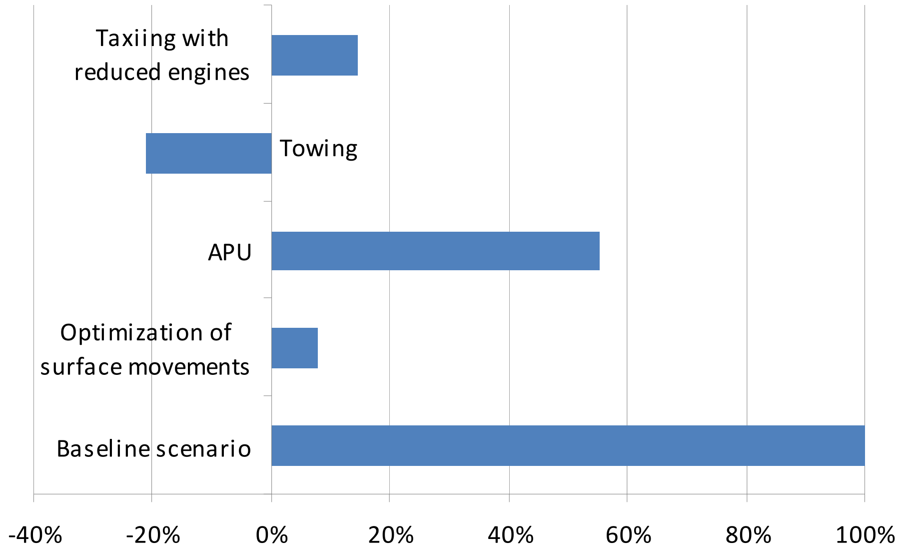

Figure 6-24: Baseline PM10 emissions and upper limits of the reduction per OI step

According to the calculations EOT and towing are the most effective measures to reduce the local emissions of CO and HC. Also for SO_x emissions these measures show the best results, however, no APU and aircraft tractor SO_x emissions are calculated due to a lack of data. Using electrical ground power and PCAUs instead of APUs results in the largest reduction of NO_x and PM10 emissions. The optimization of surface movements leads to a reduction of the emissions of all considered pollutants.

7 STUDY RESULTS AND RECOMMENDATIONS

This chapter gives conclusions and recommendations. The assumptions used for the calculations are discussed and the results are summarized in this chapter.

7.1 CONCLUSIONS

The goal of this report is to provide insight into both the used methodology and the obtained results of the study on emission reductions due to the different (groups of) OI steps. The used methodology is described in chapters 2 to 5 and chapter 6 gives the results of the research.

The calculated results give the upper limit of the emission reductions due to the different (groups of) OI steps. This means that in practice the implementation of the OI steps lead to an equal or lower reduction of emissions. This is discussed in more detail later in this paragraph. Chapter 6 summarizes the calculation results for four (groups of) OI steps:

- Engine out taxiing (EOT);
- Towing;
- The use of electrical ground power and PCAU instead of the APU;
- Optimization of surface movements.

The total emissions below 3000 ft are build up from APU emissions at the gate, taxiing emissions and airborne aircraft emissions of NO_x, CO, HC, SO_x and PM10. The emissions below 3000 ft are of interest since the KPIs for local emissions are defined as emissions below 3000 ft. The airborne emissions are not affected by the investigated OI steps. They do however contribute to the LAQ and therefore are included in the KPIs. The figures indicate that the taxi emissions have the largest contribution to the total emissions of NO_x, CO and HC below 3000 ft and that the APU emissions at the gate have the largest impact on PM10 emissions below 3000 ft.

The calculations for EOT show a reduction in the emission of all considered pollutants (NO_x, CO, HC, SO_x and PM10) during taxiing. Since the number of operating engines is always at least half of the total number of engines, the theoretical maximum reduction never exceeds 50% of the emissions. The calculations show that this result is not achieved at any of the considered airports for the following reasons:

- A certain time is required for the aircrafts engines to reach thermal stability before take off, during which EOT will not be possible;
- Short haul taxi movements and small aircraft are excluded from the measure;
- Aircraft fitted with three engines taxi use two operating engines during taxiing, so that the maximum obtainable reduction is reduced.

According to the calculations towing leads to a reduction of NO_x, CO and HC emissions during taxiing. Due to a lack of data the SO_x, emissions could not be calculated. The calculations indicate that the PM10 emissions increase due to towing. The fact that the APUs and aircraft tractors combined emit more PM10 during towing than the aircraft engines during taxiing is the reason for this increase.

The use of electrical ground power and PCAU instead of the APU reduces the APU emissions at the gate. For arriving traffic these emissions are completely eliminated. Departing aircraft still need the APU to start up their engines, which leads to emissions. Still this measure leads to a reduction of NO_x, CO, HC, and PM10 emissions.

The results for the optimization of surface movements show a reduction in the emission of all considered pollutants (NO_x, CO, HC, SO_x and PM10) during taxiing. For the calculation it is assumed that the implementation of a group of measures aimed at optimizing surface movements leads to a reduction of the excess time during the taxi-out phase, i.e. the delay time, to zero. Potential benefits due to the shortening of the unimpeded taxi time (such as stands closer to the runway) have not been taken into account.

Finally a group of OI steps with measures to optimize airport and airspace operations is defined. This group contains measures that lead to an improvement of the LAQ by improving airport and airspace operations. The largest beneficial effect of these OI steps on the LAQ is obtained by increasing the airport capacity. The increase in capacity leads to a reduction in delay times, which is beneficial for the emissions per flight. If the runway capacity increases, more aircraft can take-off and land at the runway that is optimal with respect to emissions. Since the main effect of these measures is an increased capacity, these measures are most effective at high density airports where capacity is a limiting factor for the airport operations.

The effect of an OI step on the LAQ is difficult to quantify if the main effect of the OI step is an increase in capacity, due to the fact that the increased capacity has an indirect effect on the LAQ. Therefore this report does not quantify the potential reduction in local aircraft emissions due to these measures.

For the calculations a traffic sample of three days is used. This means that the number of aircraft per day and the fleet mix are not representative for the traffic during a complete year. However, this study aims to determine the differences in emissions due to OI steps, and this is still possible using the available fleet mix data.

The fact that the considered airports have higher delay times than the smaller airports means that the ECAC wide effects of improvements that decrease queuing delays are overestimated when the results of the 20 busiest airports are considered to be representative for all other European airports. It is likely that the implementation of measures aimed at reducing line up delay does not prove useful at small airports due to the lack of queuing delays.

The calculations of the emission reductions due to the OI steps produce upper limits for the emission reductions. This means that in practice the actual benefits of the measures are expected to be lower than the calculated values.

7.2 RECOMMENDATIONS

This report describes an approach for the assessment of effects of a new ATM concept on the LAQ. This method can be used as a basis for future assessments during the development phase of new ATM concepts. There are several possibilities to improve the presented approach. This paragraph discusses several possible improvements and gives suggestions for further research. The following improvements and suggestions for further research are addressed:

- Investigate the operational constraints and consequences of towing, EOT and the reduction of APU emissions in more detail;
- Investigate OI steps from optimization of surface movements separately. In this study generic data at European airports on delay times is used, while for a detailed assessment data is needed on the current operational situation with regard to ground movements at different airports;
- Improve the results by performing calculations using more traffic data or airport data. Also using more accurate input data of the OI steps and more accurate taxi data will improve the study results;
- Validate the results from this study.

Several options exist to improve the quality of the calculation results. First of all the calculations in this study were carried out using traffic for three days in the summer period. Since the number of flights is not constant over the year, the used traffic does not represent the average traffic over a year. In general the number of flights in the summer period is higher compared to the average number of flights. This means that the study results still give a good indication of the effects of the investigated OI steps relative to the base case, but that the absolute values contain larger uncertainties and calculated reductions are likely to be higher than the yearly average values due to the large amount of traffic.

Secondly the number of airports used for the study can be increased. To obtain results representing the effects of OI steps in the whole ECAC-region, preferably all airports in this region should be used.

A third option to improve the results is the use of more accurate input data. After the revision of the Episode 3 DOW [18], the number of fast time simulations decreased. Due to this revision less detailed information about the effects of the different OI steps was available for the LAQ assessment. In order to do a detailed assessment of new ATM concepts in the future, it is desirable to make sure that sufficient information is available about the effects of the new concept on all parameters that are relevant for the LAQ assessment. This means that the effects on taxi times and delay times should be known so that the effect on the LAQ can be modelled in more detail.

The fourth possible way to perform more detailed calculations is to use more detailed taxi data. In the dataset used for this study the cause of the taxiing delays is not specified. It is not known which part of the total delay is caused by waiting for other traffic, de-icing or line-up delay. If an OI step is investigated that only reduces line-up delays for instance, this can be modelled more accurately.

In order to validate the results from this study, simulations or testing OI steps on an actual airport should be considered. This way the quality of the results is verified and the effects of assumptions from this study can be taken into account.

For this study only limited input data was available, for this reason only the maximum possible reduction in local emissions for the different (groups of) OI steps were calculated instead of calculating the actual effect of each (group of) OI step(s). One of the possibilities for future research is to use more detailed input data to investigate the OI steps in more detail. This should not only produce upper limits of emission reductions, but also more detailed estimations of the emission reductions.

This study provides calculation on the optimization of surface movements. These calculations give results for a group of OI steps. The use of more detailed input data gives the possibility to investigate these OI steps separately so that the calculations show the effects per individual OI step.

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1 Annex: results of screening and scoping

The starting point of this study is a set of operational improvement steps, identified by Episode 3 D2.4.4-02 [16]. The selection of the improvement steps is based on their potential to reduce aviation emissions in relation to local air quality.

1. AO-0704 (optimized design and procedures for airport manoeuvring areas to reduce gaseous emissions and noise disturbance). This OI step improves the environment by designing taxiways in such a way that the queuing and taxi times are minimized;
2. AO-0701 (Effective collaboration between ATM stakeholders supported by environmental management systems). The goal of this OI step is to develop the airport in such a way that the environmental impact of the airport is reduced to a minimum;
3. AUO-0802 (Ground movement techniques to reduce gaseous emissions and noise disturbance). The goal of this OI step is to decrease the emissions per flight by using new procedures;
4. AO-0207 (Surface management integrated with DMAN and AMAN). To optimize the airport throughput surface, departure and arrival management are combined. This leads to a reduction in taxi and queuing times;
5. AO-0402, AO-0403, AUO-0701, AUO-0702 and AUO-0703 combined (Using runways configurations to full potential). These OI steps increase the runway capacity, which in turn leads to lower queuing times;
6. TS-0301 and TS-0304 combined (managing interactions between departure and arrival traffic). These OI steps increase the runway capacity;
7. TS-0201, TS-0202, TS-0203 and TS-0306 combined (departure traffic synchronisation). Synchronising the departure traffic reduces the queuing and taxi times;
8. DCB-0201 (Interactive network capacity planning). This OI step increases the capacity of an airport, which indirectly is beneficial for the queuing times;
9. AO-0602 (Collaborative pre-departure sequencing). This OI step leads to a reduction in queuing times;
10. TS-0102, TS-0103, TS-0104, TS-0106, TS-0303 and TS-030 combined (arrival traffic synchronisation). These OI steps increase the runway capacity.

2 Annex: Aircraft tractors

This annex describes the type of aircraft tractor per aircraft.

Table A1: Aircraft and corresponding tug types

Aircraft type	Tug type	Aircraft type	Tug type	Aircraft type	Tug type
A109	Narrow-body	AS32	Narrow-body	B742	Wide-body
A124	Wide-body	AS55	Narrow-body	B743	Wide-body
A140	Narrow-body	AS65	Narrow-body	B744	Wide-body
A306	Wide-body	ASTR	Narrow-body	B74S	Wide-body
A30B	Wide-body	AT43	Narrow-body	B752	Narrow-body
A310	Wide-body	AT44	Narrow-body	B753	Narrow-body
A318	Narrow-body	AT45	Narrow-body	B762	Wide-body
A319	Narrow-body	AT72	Narrow-body	B763	Wide-body
A320	Narrow-body	ATLA	Narrow-body	B764	Wide-body
A321	Narrow-body	ATP	Narrow-body	B772	Wide-body
A332	Wide-body	B06	Narrow-body	B773	Wide-body
A333	Wide-body	B105	Narrow-body	BA11	Narrow-body
A342	Wide-body	B190	Narrow-body	BE10	Narrow-body
A343	Wide-body	B212	Narrow-body	BE19	Narrow-body
A345	Wide-body	B350	Narrow-body	BE20	Narrow-body
A346	Wide-body	B412	Narrow-body	BE23	Narrow-body
A3ST	Narrow-body	B461	Narrow-body	BE30	Narrow-body
A6	Narrow-body	B462	Narrow-body	BE33	Narrow-body
A748	Narrow-body	B463	Narrow-body	BE35	Narrow-body
AA5	Narrow-body	B703	Narrow-body	BE36	Narrow-body
AC11	Narrow-body	B712	Narrow-body	BE40	Narrow-body
AC50	Narrow-body	B720	Narrow-body	BE55	Narrow-body
AC90	Narrow-body	B721	Narrow-body	BE58	Narrow-body
AC95	Narrow-body	B722	Narrow-body	BE60	Narrow-body
AEST	Narrow-body	B732	Narrow-body	BE76	Narrow-body
ALO3	Narrow-body	B733	Narrow-body	BE95	Narrow-body
AN12	Narrow-body	B734	Narrow-body	BE99	Narrow-body
AN24	Narrow-body	B735	Narrow-body	BE9L	Narrow-body
AN26	Narrow-body	B736	Narrow-body	BE9T	Narrow-body
AN28	Narrow-body	B737	Narrow-body	BN2P	Narrow-body
AN30	Narrow-body	B738	Narrow-body	BN2T	Narrow-body
AN32	Narrow-body	B739	Narrow-body	C101	Narrow-body
AN72	Narrow-body	B741	Wide-body	C10T	Narrow-body

Aircraft type	Tug type	Aircraft type	Tug type	Aircraft type	Tug type
C130	Narrow-body	C750	Narrow-body	ETAR	Narrow-body
C135	Narrow-body	C77R	Narrow-body	F1	Narrow-body
C152	Narrow-body	C82R	Narrow-body	F100	Narrow-body
C160	Narrow-body	CL2T	Narrow-body	F15	Narrow-body
C17	Narrow-body	CL30	Narrow-body	F16	Narrow-body
C172	Narrow-body	CL60	Narrow-body	F18	Narrow-body
C177	Narrow-body	CN35	Narrow-body	F260	Narrow-body
C182	Narrow-body	CRJ1	Narrow-body	F27	Narrow-body
C206	Narrow-body	CRJ2	Narrow-body	F28	Narrow-body
C207	Narrow-body	CRJ7	Narrow-body	F2TH	Narrow-body
C208	Narrow-body	CRJ9	Narrow-body	F4	Narrow-body
C210	Narrow-body	D228	Narrow-body	F406	Narrow-body
C212	Narrow-body	D328	Narrow-body	F5	Narrow-body
C25A	Narrow-body	DA42	Narrow-body	F50	Narrow-body
C25B	Narrow-body	DC10	Wide-body	F60	Narrow-body
C295	Narrow-body	DC86	Narrow-body	F70	Narrow-body
C303	Narrow-body	DC87	Narrow-body	F900	Narrow-body
C310	Narrow-body	DC93	Narrow-body	FA10	Narrow-body
C335	Narrow-body	DC95	Narrow-body	FA20	Narrow-body
C337	Narrow-body	DH8A	Narrow-body	FA50	Narrow-body
C340	Narrow-body	DH8B	Narrow-body	G115	Narrow-body
C404	Narrow-body	DH8C	Narrow-body	G222	Narrow-body
C414	Narrow-body	DH8D	Narrow-body	GA7	Narrow-body
C421	Narrow-body	DHC6	Narrow-body	GALX	Narrow-body
C425	Narrow-body	DR40	Narrow-body	GLEX	Narrow-body
C441	Narrow-body	E110	Narrow-body	GLF2	Narrow-body
C5	Narrow-body	E120	Narrow-body	GLF3	Narrow-body
C500	Narrow-body	E121	Narrow-body	GLF4	Narrow-body
C501	Narrow-body	E135	Narrow-body	GLF5	Narrow-body
C525	Narrow-body	E145	Narrow-body	H25A	Narrow-body
C550	Narrow-body	E170	Narrow-body	H25B	Narrow-body
C551	Narrow-body	E3CF	Narrow-body	H25C	Narrow-body
C560	Narrow-body	E3TF	Narrow-body	H47	Narrow-body
C56X	Narrow-body	E400	Narrow-body	H53	Narrow-body
C650	Narrow-body	EC35	Narrow-body	H60	Narrow-body
C680	Narrow-body	EC45	Narrow-body	HAR	Narrow-body
C72R	Narrow-body	EC55	Narrow-body	HAWK	Narrow-body

Aircraft type	Tug type	Aircraft type	Tug type	Aircraft type	Tug type
IL18	Narrow-body	MU2	Narrow-body	RJ70	Narrow-body
IL62	Narrow-body	MU30	Narrow-body	RJ85	Narrow-body
IL76	Wide-body	N262	Narrow-body	S601	Narrow-body
IL86	Narrow-body	NIM	Narrow-body	S61	Narrow-body
IL96	Wide-body	P180	Narrow-body	S65C	Narrow-body
J328	Narrow-body	P210	Narrow-body	S76	Narrow-body
JS20	Narrow-body	P28A	Narrow-body	SB20	Narrow-body
JS31	Narrow-body	P28B	Narrow-body	SB39	Narrow-body
JS32	Narrow-body	P28R	Narrow-body	SBR1	Narrow-body
JS41	Narrow-body	P28T	Narrow-body	SC7	Narrow-body
K35E	Narrow-body	P3	Narrow-body	SF34	Narrow-body
K35R	Narrow-body	P32R	Narrow-body	SH36	Narrow-body
L101	Wide-body	P32T	Narrow-body	SR20	Narrow-body
L188	Narrow-body	P46T	Narrow-body	SR22	Narrow-body
L200	Narrow-body	P66T	Narrow-body	SW2	Narrow-body
L29B	Narrow-body	P68	Narrow-body	SW3	Narrow-body
L39	Narrow-body	PA23	Narrow-body	SW4	Narrow-body
L410	Narrow-body	PA24	Narrow-body	T134	Narrow-body
LJ25	Narrow-body	PA27	Narrow-body	T154	Narrow-body
LJ31	Narrow-body	PA30	Narrow-body	T204	Narrow-body
LJ35	Narrow-body	PA31	Narrow-body	TB30	Narrow-body
LJ45	Narrow-body	PA32	Narrow-body	TBM7	Narrow-body
LJ55	Narrow-body	PA34	Narrow-body	TOBA	Narrow-body
LJ60	Narrow-body	PA44	Narrow-body	TOR	Narrow-body
LNC2	Narrow-body	PA46	Narrow-body	TRIN	Narrow-body
M20P	Narrow-body	PAY1	Narrow-body	TRIS	Narrow-body
M20T	Narrow-body	PAY2	Narrow-body	TUCA	Narrow-body
M339	Narrow-body	PAY3	Narrow-body	VC10	Narrow-body
MD11	Wide-body	PAY4	Narrow-body	WW24	Narrow-body
MD81	Narrow-body	PC12	Narrow-body	YK40	Narrow-body
MD82	Narrow-body	PC9	Narrow-body	YK42	Narrow-body
MD83	Narrow-body	PRM1	Narrow-body	YS11	Narrow-body
MD87	Narrow-body	PUMA	Narrow-body	Z43	Narrow-body
MD88	Narrow-body	R722	Narrow-body		
MD90	Narrow-body	R90R	Narrow-body		
MIR2	Narrow-body	RF6	Narrow-body		
MRF1	Narrow-body	RJ1H	Narrow-body		

3 Annex: Aircraft APU class

This annex describes the APU class per aircraft. The table shows that not all aircraft types have an APU.

Table A2: Aircraft used in this study with corresponding APU classes

Aircraft type	Aircraft group	APU class
A109	HELICOPTER HEAVY	No APU
A124	JET LARGE	APU Jet Large Older Types (>300 Seats)
A140	TURBOPROP	APU Turboprop
A306	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
A30B	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
A310	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
A318	JET SMALL	APU Jet Small Newer Types (100-200 Seats)
A319	JET SMALL	APU Jet Small Newer Types (100-200 Seats)
A320	JET SMALL	APU Jet Small Older Types (100-200 Seats)
A321	JET SMALL	APU Jet Small Older Types (100-200 Seats)
A332	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
A333	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
A342	JET LARGE	APU Jet Large Older Types (>300 Seats)
A343	JET LARGE	APU Jet Large Older Types (>300 Seats)
A345	JET LARGE	APU Jet Large Newer Types (>300 Seats)
A346	JET LARGE	APU Jet Large Newer Types (>300 Seats)
A748	TURBOPROP	APU Turboprop
AC90	TURBOPROP	APU Turboprop
AEST	PROPELLER	No APU
AN12	TURBOPROP	APU Turboprop
AN24	TURBOPROP	APU Turboprop
AN26	TURBOPROP	APU Turboprop
AN72	JET REGIONAL	APU Jet Regional (<100 Seats)
ASTR	JET BUSINESS	APU Jet Business (<100 Seats)
AT43	TURBOPROP	APU Turboprop
AT45	TURBOPROP	APU Turboprop
AT72	TURBOPROP	APU Turboprop
ATP	TURBOPROP	APU Turboprop
B190	TURBOPROP	APU Turboprop
B350	TURBOPROP	APU Turboprop
B461	JET REGIONAL	APU Jet Regional (<100 Seats)
B462	JET REGIONAL	APU Jet Regional (<100 Seats)
B463	JET REGIONAL	APU Jet Regional (<100 Seats)

Aircraft type	Aircraft group	APU class
B703	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
B712	JET REGIONAL	APU Jet Regional (<100 Seats)
B720	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B721	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B722	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B732	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B733	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B734	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B735	JET SMALL	APU Jet Small Older Types (100-200 Seats)
B736	JET SMALL	APU Jet Small Newer Types (100-200 Seats)
B737	JET SMALL	APU Jet Small Newer Types (100-200 Seats)
B738	JET SMALL	APU Jet Small Newer Types (100-200 Seats)
B739	JET SMALL	APU Jet Mid-Range (200-300 Seats)
B741	JET LARGE	APU Jet Large Older Types (>300 Seats)
B742	JET LARGE	APU Jet Large Older Types (>300 Seats)
B743	JET LARGE	APU Jet Large Older Types (>300 Seats)
B744	JET LARGE	APU Jet Large Older Types (>300 Seats)
B74S	JET LARGE	APU Jet Large Older Types (>300 Seats)
B752	JET SMALL	APU Jet Mid-Range (200-300 Seats)
B753	JET SMALL	APU Jet Mid-Range (200-300 Seats)
B762	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
B763	JET MEDIUM	APU Jet Large Older Types (>300 Seats)
B764	JET MEDIUM	APU Jet Large Newer Types (>300 Seats)
B772	JET LARGE	APU Jet Large Older Types (>300 Seats)
B773	JET LARGE	APU Jet Large Newer Types (>300 Seats)
BE20	TURBOPROP	APU Turboprop
BE30	TURBOPROP	APU Turboprop
BE40	JET BUSINESS	APU Jet Business (<100 Seats)
BE58	PROPELLER	No APU
BE60	PROPELLER	No APU
BE99	TURBOPROP	APU Turboprop
BE9L	TURBOPROP	APU Turboprop
C10T	VARIOUS	No APU
C130	TURBOPROP	APU Turboprop
C17	JET LARGE	APU Jet Large Older Types (>300 Seats)
C182	PROPELLER	No APU
C206	PROPELLER	No APU

Aircraft type	Aircraft group	APU class
C208	TURBOPROP	APU Turboprop
C212	TURBOPROP	APU Turboprop
C25A	JET BUSINESS	APU Jet Business (<100 Seats)
C25B	VARIOUS	APU Jet Business (<100 Seats)
C303	PROPELLER	No APU
C335	PROPELLER	No APU
C340	PROPELLER	No APU
C404	PROPELLER	No APU
C421	PROPELLER	No APU
C441	TURBOPROP	APU Turboprop
C500	JET BUSINESS	APU Jet Business (<100 Seats)
C501	JET BUSINESS	APU Jet Business (<100 Seats)
C525	JET BUSINESS	APU Jet Business (<100 Seats)
C550	JET BUSINESS	APU Jet Business (<100 Seats)
C551	JET BUSINESS	APU Jet Business (<100 Seats)
C560	JET BUSINESS	APU Jet Business (<100 Seats)
C56X	JET BUSINESS	APU Jet Business (<100 Seats)
C650	JET BUSINESS	APU Jet Business (<100 Seats)
C680	JET BUSINESS	APU Jet Business (<100 Seats)
C750	JET BUSINESS	APU Jet Business (<100 Seats)
C82R	PROPELLER	No APU
CL30	VARIOUS	APU Jet Business (<100 Seats)
CL60	JET REGIONAL	APU Jet Business (<100 Seats)
CRJ1	JET REGIONAL	APU Jet Regional (<100 Seats)
CRJ2	JET REGIONAL	APU Jet Regional (<100 Seats)
CRJ7	JET REGIONAL	APU Jet Regional (<100 Seats)
CRJ9	JET REGIONAL	APU Jet Regional (<100 Seats)
D228	TURBOPROP	APU Turboprop
D328	TURBOPROP	APU Turboprop
DA42	VARIOUS	No APU
DC10	JET LARGE	APU Jet Large Older Types (>300 Seats)
DC86	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
DC87	JET MEDIUM	APU Jet Mid-Range (200-300 Seats)
DH8A	TURBOPROP	APU Turboprop
DH8B	TURBOPROP	APU Turboprop
DH8C	TURBOPROP	APU Turboprop
DH8D	TURBOPROP	APU Turboprop

Aircraft type	Aircraft group	APU class
DHC6	TURBOPROP	APU Turboprop
E120	TURBOPROP	APU Turboprop
E135	JET BUSINESS	APU Jet Business (<100 Seats)
E145	JET BUSINESS	APU Jet Business (<100 Seats)
E170	JET REGIONAL	APU Jet Regional (<100 Seats)
EC35	HELICOPTER HEAVY	No APU
F100	JET REGIONAL	APU Jet Regional (<100 Seats)
F27	TURBOPROP	APU Turboprop
F2TH	JET BUSINESS	APU Jet Business (<100 Seats)
F50	TURBOPROP	APU Turboprop
F70	JET REGIONAL	APU Jet Regional (<100 Seats)
F900	JET BUSINESS	APU Jet Business (<100 Seats)
FA10	JET BUSINESS	APU Jet Business (<100 Seats)
FA20	JET BUSINESS	APU Jet Business (<100 Seats)
FA50	JET BUSINESS	APU Jet Business (<100 Seats)
GALX	JET BUSINESS	APU Jet Business (<100 Seats)
GLEX	JET REGIONAL	APU Jet Business (<100 Seats)
GLF2	JET BUSINESS	APU Jet Business (<100 Seats)
GLF3	JET BUSINESS	APU Jet Business (<100 Seats)
GLF4	JET BUSINESS	APU Jet Business (<100 Seats)
GLF5	JET REGIONAL	APU Jet Business (<100 Seats)
H25B	JET BUSINESS	APU Jet Business (<100 Seats)
H25C	JET BUSINESS	APU Jet Business (<100 Seats)
IL76	JET LARGE	APU Jet Mid-Range (200-300 Seats)
IL86	JET LARGE	APU Jet Large Older Types (>300 Seats)
IL96	JET LARGE	APU Jet Mid-Range (200-300 Seats)
J328	JET BUSINESS	APU Jet Business (<100 Seats)
JS41	TURBOPROP	APU Turboprop
L101	JET LARGE	APU Jet Mid-Range (200-300 Seats)
L188	TURBOPROP	APU Turboprop
L29B	BUSINESS JET	APU Jet Business (<100 Seats)
L410	TURBOPROP	APU Turboprop
LJ31	JET BUSINESS	APU Jet Business (<100 Seats)
LJ35	JET BUSINESS	APU Jet Business (<100 Seats)
LJ45	JET BUSINESS	APU Jet Business (<100 Seats)
LJ55	JET BUSINESS	APU Jet Business (<100 Seats)
LJ60	JET BUSINESS	APU Jet Business (<100 Seats)

Aircraft type	Aircraft group	APU class
M20T	PROPELLER	No APU
MD11	JET LARGE	APU Jet Large Older Types (>300 Seats)
MD81	JET SMALL	APU Jet Small Older Types (100-200 Seats)
MD82	JET SMALL	APU Jet Small Older Types (100-200 Seats)
MD83	JET SMALL	APU Jet Small Older Types (100-200 Seats)
MD87	JET SMALL	APU Jet Small Older Types (100-200 Seats)
MD88	JET SMALL	APU Jet Small Older Types (100-200 Seats)
MD90	JET SMALL	APU Jet Small Older Types (100-200 Seats)
P180	TURBOPROP	APU Turboprop
P210	PROPELLER	No APU
P28A	PROPELLER	No APU
P28T	PROPELLER	No APU
P46T	TURBOPROP	APU Turboprop
PA31	PROPELLER	No APU
PA32	PROPELLER	No APU
PA34	PROPELLER	No APU
PA46	PROPELLER	No APU
PAY2	TURBOPROP	APU Turboprop
PAY3	TURBOPROP	APU Turboprop
PC12	TURBOPROP	APU Turboprop
PRM1	JET BUSINESS	APU Jet Business (<100 Seats)
R722	VARIOUS	No APU
RJ1H	JET REGIONAL	APU Jet Regional (<100 Seats)
RJ70	JET REGIONAL	APU Jet Regional (<100 Seats)
RJ85	JET REGIONAL	APU Jet Regional (<100 Seats)
S601	JET BUSINESS	APU Jet Business (<100 Seats)
SB20	TURBOPROP	APU Turboprop
SF34	TURBOPROP	APU Turboprop
SH36	TURBOPROP	APU Turboprop
SR22	VARIOUS	No APU
SW2	TURBOPROP	APU Turboprop
SW3	TURBOPROP	APU Turboprop
SW4	TURBOPROP	APU Turboprop
T134	JET REGIONAL	APU Jet Regional (<100 Seats)
T154	JET SMALL	APU Jet Small Older Types (100-200 Seats)
T204	JET SMALL	APU Jet Mid-Range (200-300 Seats)
TOBA	PROPELLER	No APU

Aircraft type	Aircraft group	APU class
WW24	JET BUSINESS	APU Jet Business (<100 Seats)
YK40	JET BUSINESS	APU Jet Business (<100 Seats)
YK42	JET REGIONAL	APU Jet Regional (<100 Seats)

END OF DOCUMENT