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Master Thesis

Department Fahrzeugtechnik und Flugzeugbau

Efficient autonomous pushback and taxiing- a step forward to reducing costs and pollution

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Abstract

The current Pushback and Taxi procedures are very fuel inefficient these days. That is caused by the use of different airports and different types of airplanes. There are many different procedures and facilities. Therefore a low cost ground handling aircraft is going to be built. This is the purpose of the ALOHA project. All the changes will be done on an AIRBUS A320 while it is the most commonly used aircraft as low cost carriers, so a low cost and independent aircraft will be designed.

This paper will deal with the taxi and pushback procedure and not the other ground handlings like de-icing, energy supply, boarding in,…

To see if the integration of a new system is more efficient than the current-state-of-the-art, a detailed cost breakdown for ground operations and fuel consumption have to be carried out. Also all the ground handling procedure must be fully understood in order to minimize the time aspect and costs of them.

There are proposals done of making a full towing procedure or putting an electromotor in the nose gear, so the aircraft can drive autonomous. Of both proposals a procedure time schedule and a total cost calculation is made. This includes depreciation, fuel savings and maintenance cost. What also is taken in consideration is the extra DOC cost of the aircraft due to the extra weight.

Depending on the procedure there are time reductions and cost reductions.

An other issue of a shorter pushback and taxi procedure is the emission and noise reduction. It is logic that with a shorter use of the main engines that there is a lower pollution in and around the airport, what means an environmental improvement occurs.

As seen in the procedure schedules and conclusion, it will be made clear that an optimization of the procedure reduces the costs and pollution.

Hochschule für Angewandte Wissenschaften Hamburg
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DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Efficient Autonomous Pushback and Taxiing – A Step towards Reduced Costs and Pollution

Task for a *Project*

Background

Current pushback and taxiing procedures are very fuel-inefficient and noisy mission phases. Furthermore, the necessity of a pushback tractor and a controller clearance to perform the operations leads to undesirable time consumption. However, two solutions have been proposed for this problem so far: a) Full towing aircraft from apron to holding area, b) Electrical driven nose landing gear. According to Virgin Airlines, "Towing aircraft from a stand substantially can reduce the amount of time they need to taxi with their engines running and reduces the time spent queuing before take-off", but despite this operation has been used by some airlines, this improvement has not been clearly proven yet. On the other hand, it is claimed than an electrical driven nose landing gear may be the best solution for autonomous pushback and taxiing, but it is still under early development. This project is part of the aircraft design research project "ALOHA" (http://ALOHA.ProfScholz.de).

Task

The project task is to evaluate existing solutions as well as identify promising new solution for the efficiency improvement of the autonomous pushback and taxing operations. The task includes

- gathering information about the current state-of-the-art of technologies and operations,
- proposing new and innovative solutions for the problem,
- checking feasibility of proposed technologies by means of draft system layout and sizing,
- comparing proposed solutions with the current operation in order to evaluate the improvement,
- identifying the most suitable technologies and further developments.

The report has to be written in English based on German or international standards on report writing.

Declaration

This Thesis is entirely my own work. Where work has been used from others, it has totally been acknowledged and referenced.

Date Signature

June 30, 2008

Contents

List of pictures

List of Tables

List of Abbreviations

AC	Alternating current
APS	Autonomous Pushback System
APU	Auxiliary Power Unit
FTRR	Failure to repair ratio
DMC	Direct maintenance cost
DOC	Direct Operation cost
DOC_{sys}	Direct Operation Cost system
ME	Main Engines
MLG	Main Landing Gear
MTBF	Mean time between failures
MTBUR	Mean time between unscheduled failures
MTOW	Maximum Take Off Weight
PM	Particle Matter
RT	Repair time
TBL	Tow Less Bar
UHC	Unburned Hydro Carbons

List of Symbols

h	hour
hP	horsepower
km	kilometers
M_A	Moment around point A
min	minute
P	Power
sec	second
V	Volt

Greek Symbols

μ	friction of the tires
ρ	density

Explanation of terms and definitions

Tug

"A tug is an other word for a pushback truck“

Apron

“The airport ramp or apron is part of an airport. It is usually the area where aircraft are parked, unloaded or loaded, refueled or boarded. Although the use of the apron is covered by regulations, such as lighting on vehicles, it is typically more accessible to users than the runway or taxiway. However, the apron is not usually open to the general public and a license may be required to gain access” **(Wikipedia 2008)**

1 Introduction

1.1 Motivation

With the recent consumption society we live in, it is necessary to make everything as efficient as possible. An efficient autonomous pushback and taxiing can be dealt with either. The changes have an influence on the environment, less fuel consumption, less noise, less pollution. Here for a project called ALOHA is funded by Airbus, Airport Hamburg and HAW Hamburg. The task is to make a low fare autonomous aircraft.

1.2 Objectives

. The task is to evaluate the existing current-state-of-the-art technologies. This is done by making a theoretical standard procedure and calculating the current costs as well as to identify promising new solutions for the efficiency improvement of the autonomous pushback and taxing operations. The final results can only be found by gathering information about the current state-of-the-art of technologies and operations, proposing new and innovative solutions for the problem, checking feasibility of proposed technologies by means of draft system layout and sizing, comparing proposed solutions with the current operation in order to evaluate the improvement and at last identifying the most suitable technologies and further developments. With these results the ALOHA project is a step closer to reduce the ground handling costs and turn around time.

1.3 Report Structure

Chapter 2 contains all the information about the material that is necessary to perform the current pushback procedure with the associated costs. A theoretical case study of the current pushback and taxi procedure is made. Together with brief introduction about the ME and APU, ground handling costs and a detailed fuel consumption calculation.

Chapter 3 deals with the APS. The design concept is explained, the sizing is calculated and compared with other models. Also explanation of the APU which will feed the APS. Then a new procedure with only an autonomous pushback is introduced with the necessary calculations of fuel consumption and time aspects.

Chapter 4 has a change of the time aspect: procedure change. Here a full autonomous pushback and taxi procedure is proposed with the including charts and cost calculation of fuel consumption. Also the after landing aspect is mentioned.

Chapter 5 is about the full towing procedure. Tests and results of other paper are included and controlle calculations. All the necessary aspects are discussed and out of these a conclusion about this procedure is made.

Chapter 6 contains all the troubleshooting and explanation of the emission gasses which Increase or decrease on the airport due to the procedure changes. The effects on humans and the environment can be found and also a calculation of the proposed procedures.

Chapter 7 is a completion of the previous chapters in order to the cost aspect. Both DOC of an aircraft and DOC of the system are integrated. Depreciation and maintenance of the APS is also taken into account. Here a total cost schedule is set up.

Chapter 8 contains the conclusion of the paper. Every previous result is written down again and discussed. This includes further development and proposals in order to perfect the procedure and get better results.

2 Current state-of-the-art of technologies and operations

2.1 Equipment: Pushback and pushback truck

In airports the aircrafts can be parked in an external apron or at a gate. In both of these cases they have to be prepared for take-off.
When the airplane is standing in an airport gate, it stands with its nose to the building. When it is parked in the apron, it is further away of the airport building. The advantages of the gate are that it is easier to perform the ground handling and the people can board in on the airplane easier, because of the bridge that is attached to the aircraft.
First, all the basic ground handling procedures have to be done, all the people and/or cargo have to be on board and all the check ups have to be controlled. Then the pushback and taxi procedure of aircraft can start. This paper will deal with ground handling operations at the gate.

The aircraft can leave the gate by driving backwards with own power or an external power.
In the first case, the airplane can drive backwards using reverse thrust, called a power back, but due to the noise, and high fuel consumption it is eventually not good for the environment. Therefore it can be pushed backwards with an external power which is done by a pushback-tractor or tug. This procedure is an airport ground handling procedure and the one that will be dealt with in this paper.

There are 2 different kinds of pushback trucks, conventional trucks and tow bar less (TBL) ones. The conventional ones have a pushback bar between the car and the airplane. These types can push or pull the airplane and the truck is most of the times designed for these different set ups. The TBL does not have a pushback bar and the nose wheel of the plane fits in the truck. Some trucks can lift the front wheel, so the car can move the plain, what can result in time reduction.

Below, in **picture 2.1** the TBL truck, the gate, and ground personnel can be seen. Here there are 2 people walking and 1 person who controls the truck. Later on this aspect will be dealt with. The picture is taken at Zurich Kloten Airport by James Sullivan, who put a full travel guide on **(Airliners.net)**.

Picture 2.1 An A320 with TBL pushback truck at the gate, with the ground handling staff

2.2 Time: Pushback and taxiing procedure

Time is a big aspect of the procedures, every procedure takes time and can be reduced with proper study and changes. Some examples of ground handling procedures: de-icing, boarding in, standard check-up, connecting the tug ...The procedures that are being worked on here are the pushback and taxi procedure. It also includes the start up from the engines and the fuel consumption.

A full theoretical current procedure has been produced by means of real ground handling procedure videos available at the internet. But with guidance advice and help of a pilot and flight Director of Thomas Cook **(Raes 2008)**
The procedure is being explained in the next paragraphs.

2.2.1 Pushback procedure

"Pushback is an airport procedure during which an aircraft is pushed backwards away from an airport gate by external power, when there isn't enough room for the aircraft to turn around under its own power (which requires some degree of forward motion). Pushback procedures are carried out by special, low-profile vehicles called pushback tractors or tugs"
(**Wikipedia 2008)**

Every procedure takes a certain amount of time; some only take 10 seconds and others some minutes, but the importance of them have to be kept in consideration. So there are some steps in this procedure the pilot and ground handling staff have to follow.
These are important steps

- positioning and connecting the tug and bar
- moving the airplane
- disconnecting

Some of these are part of the critical path and others can be done while there are other necessary procedures going on. The whole procedure will be discussed now and also whether it is situated in the critical path.

First of all there must be a take off briefing, and there must be direct contact with the ground handling staff. During this time the tug and the bar are put connected, this can take about 2 minutes. This can be done while boarding in of the passengers or while loading, so this is not a time-consuming part. During this time the APU is in use.
Then when every passenger is in his seat, the doors are closed and all equipment is away of the plane, the moving-procedure can start. This takes average from 1 minute to 1 minute and 30 seconds, with a pushback speed of about 5 km/h.

Disconnecting the bar after the plane is not moving and when disconnected the tug can drive away. This procedure can take up to 2 minutes.

The chosen time for the pushback is 1 minute and 30 seconds.
So the whole pushback procedure, which includes the connection of the bar, takes approximately 4,5 to 5 minutes.

2.2.2 Taxi procedure

“Taxiing refers to the movement of an aircraft on the ground, under its own power.

An airplane uses taxiways to taxi from one place on an airport to another; for example, when moving from a terminal to the runway. The term "taxiing" is not used for the accelerating run along a runway prior to takeoff, or the decelerating run immediately after landing” **(wikipedia org 2004)**

After safely finishing the whole pushback procedure, the taxiing procedure can start.

This procedure is the driving on own power of the airplane, from the gate (after pushback) to the runway.
This procedure is nowhere the same, because every airport has different accommodations, shorter or longer runways. There are many different parameters that have an influence on it.

Some of the influences are:

- Bad weather conditions
- Unfamiliarity of the pilots with the airport
- Different taxiways and procedures
- Ground obstructions
- Traffic

So the whole taxi period depends on the airport, and that makes it hard to make a standard taxi-procedure.

For this study a theoretical procedure is made. It includes the times, the startups from the engines and the fuel consumption of both APU and head Engines. The procedure is already discussed. The Engines and costs will be dealt in the next paragraphs.
The whole table with the theoretical procedure is found in **APPENDIX A**. An 'x' means that the procedure mentioned in the column name is being executed.

Below a Gantt's table **(Picture 2.2)** and the timetable **(Table 2.1)** with just the procedures and engine use is shown. Note that the calculations in **APPENDIX A1** are done in seconds, but the Gantt's Table is just a figure to see the overview of the procedure.

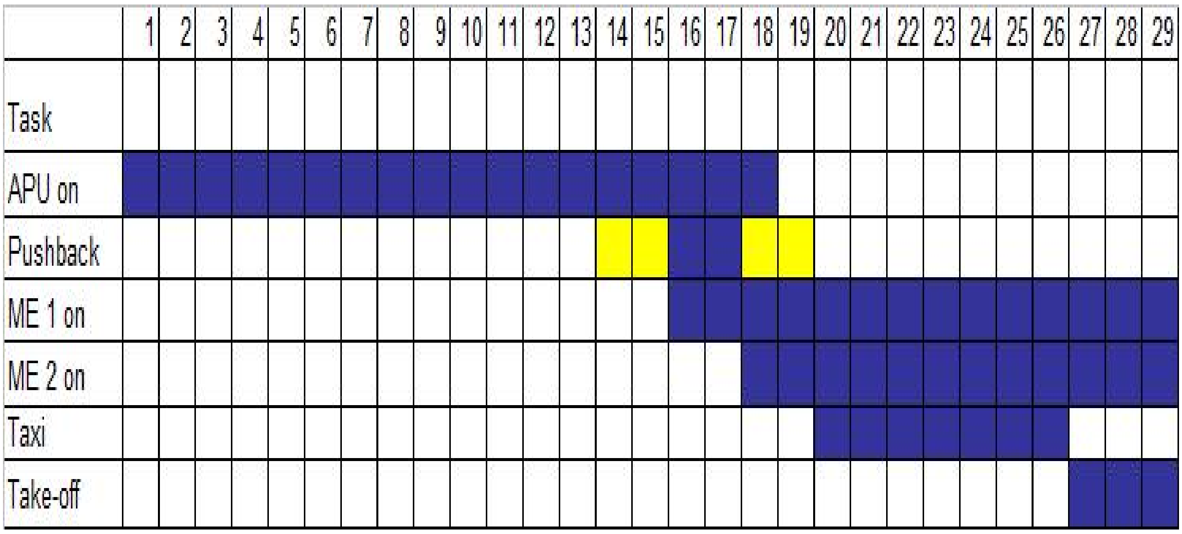
On the figure the blocks which are colored blue mean that the containing task is being performed.
The yellow blocks before the blue in the Pushback procedure mean the connection of the bar, which consumes 2 minutes and can be performed while boarding in, loading the luggage, fueling,… so it is not a critical time problem.
The yellow block after the pushback means the disconnecting of the bar and driving away the truck. This is a more critical time consuming procedure, because it has to be done before the taxi procedure can start.

The APU is used for starting ME1 and ME2, after that the APU is shut of. When the APU is shut off, the taxi procedure start for 7minutes and 20 seconds, followed by the actual take-off.

Here the time consuming issue in the theoretical study is the fact that the taxiing starts 2 minutes after disconnecting the bar for safety of ground handling staff.
The chosen taxi time for the theoretical is 7 minutes and 20 seconds.

Procedure 1 : current procedure			
Task	start (h,min,sec)	end (h:min:sec)	duration (h:min:sec)
APU on	0:00:00	0:17:50	0:17:50
Pushback	0:15:20	0:16:50	0:01:30
ME 1 on	0:15:40	0:30:00	0:14:20
ME 2 on	0:17:30	0:30:00	0:12:30
Taxi	0:19:40	0:27:00	0:07:20
Take-off	0:27:00	0:30:00	0:03:00

Table 2.1 values for Gantt's Table of the current procedure



Picture 2.2 Gantt's Table of the current procedure

Pushback time : 1 min 30 sec
Taxi time : 7 min 20 sec
Total time : 27 min 00 sec

2.3 Fuel consumption: Engines and their fuel consumption

2.3.1 Auxiliary Power Unit

On an airplane it is required to have several kinds of energy to run the systems on board.
Because it takes some time for starting the main engines and because of the high fuel consumption of them, an auxiliary power unit (APU) is installed. This engine can create pneumatic power to start the main engines,
The APU is a gas turbine engine, which is being used for the power supply to the electrical, pneumatic and hydraulic systems, when the main engines are not in use or do not function. But as said before an important function is to start to start up the main engines (ME) with pneumatic power.
On the Airbus A320 series there are 3 available APU's

- Honeywell 36-300 APU standard
- Honeywell 131-9(A)
- APIC APS 3200

As soon as the pilots get in the cabine, they start the APU. It is needed for the air conditioning and sometimes for the electrical supply for electrical systems on board. The APU uses 75 kg/h of jet fuel without any loads and 150 kg/h with full load **(Raes 08)**. In some cases the airplane takes electricity and pneumatic power from the airport. Together with air conditioning the APU can be on full load. For starting the main engines the APU is used. So the APU is always in full load. From the startup from the APU until shutdown, it takes approximately 25 minutes, and that at a fuel consumption of 150 kg/h.

For the theoretical case study, see **[APENDIX A1] and (Table 2.1),** this means the APU is on for almost 17 minutes.
There is not a specific rule on how to use the APU for these systems.

In the theoretical case the APU is started up and used for the Air-conditioning system and Electrical supply. Then it is used during the pushback for starting ME1 and after the procedure or at the end of the pushback for starting ME2. When both ME's are running the APU is shut of immediately. **(Raes 08)**
The fuel costs are being explained in the next paragraph.

2.3.2 Main Engines

An A320 has 2 main engines on board, 2 CFM556-5 from CFM International.

"A CFM56-5 is a high bypass turbofan; coaxial front fan/booster driven by multistage
low pressure turbine, multi-stage compressor with one-stage
high pressure turbine and annular combustor."
(U.S. DOT 98)

The first Main Engine starts up while the pushback is busy. During pushback, one engine runs autonomous and at the end of the pushback, the pilots are busy starting the second one. Once the engine's are started they have each a fuel consumption of 275kg/h, value of General Electric CFM56.
In the theoretical example the fuel consumption calculation stops before the take off, because it isn't a part of the Taxi procedure.

2.4 Costs

First of all there has to be said that all the costs which are calculated here are for 1 procedure before the take-off.
Also this part of calculation is for the standard current theoretical procedure of picture 2.2 and shown in **APPENDIX A1**
Since the fuel consumption during taxi is only a smart fracture of the total fuel consumption during the whole flight, a simple calculation is used. For evaluation with the later on following proposals the DOC method will be integrated and explained for the total costs of the procedures.

Because money has to be saved, only the costs that can be changed will be dealt with. So in this case it is only the fuel consumption and the ground handling costs, so pushback truck and ground handling staff, which are charged by the airport.

The ground handling costs depend on the airport. Or the airport charges for the ground handling costs or the ground handling is arranged by an external ground handling company, which works together with the airport. In the table below there are some examples of the fees charged by some airports in Spain, Italy and Switzerland.
(Aena 99)

Airport	handling	cost €
Salzburg Airport	towing truck	79,3
	headset and pushback control	36,1
	manpower per person	18,1
	Total cost	133,5
Tallinn Airport	pushback	63,27
	Tow bar	22,37
	manpower per person	15,98
	Total cost	101,62
Aena Spanish Airports	Communication with pushback or start up staff	8,17
	Equipment for communication	8,17
	Pushback bar	22,07
	Push back operation	84,19
	Total cost	122,6

Table 2.2

The average ground handling cost of these airport charges is 119,24€. In the theoretical procedure, the Spanish Aena-cost is used because it is close to the average.

A problem in calculation can occur because some Airports have 1 Airport price which includes all handlings, power supply and services.

For the rest of the calculations, the ground handling costs are converted to $. The rate can be found below.
The fuel consumption costs of both APU and Main Engines depends on how much the fuel costs, the characteristic fuel consumption (kg/h) of the engines and total mass of fuel consumed during the procedure.
At the moment of writing the price for jet fuel A is **3.0840 $/gallon**.
(IATA 2007)

The jet fuel's density **ρ = 0.8 kg/l**
The exchange rate of dollar and € at the moment of writing is

$$1€ = 1.5898\$$$

A detailed fuel cost calculation in an Excel sheet depending on the procedure can be found in **APPENDIX A1**

In the **Table 2.3** below the characteristic fuel consumption of both APU and 1 ME can be found. Note that the fuel consumption of ME is only for 1 engine, so in the table there is a column for each engine.

The Excel sheet calculation works like this; an 'x' means that the procedure mentioned in the column name is being executed for the time that stands next to it. Then with the sum of all the times, the total fuel consumption is used. Since the APU and Main Engines use the same fuel, the calculation is easy. The total time that the APU is used times the specific fuel consumption gives the fuel consumption of the APU. The same is done for the main engines.

With the values of **Table 2.3**, the ground handling cost of 122,6€ (which is converted to $ in the calculations) and the procedure according to **APPENDIX A**, the total cost of ground handling and fuel consumption can be calculated. This result is figured in Table 2.4.

Engine	load	fuel consumption (kg/h)
APU	normal	75
	full	150
ME	normal	275
	full	/

Table 2.3

RESULTS		
Fuel consumption	138,19	kg
Total ground handling costs	194,90948	($)
FUEL costs	140,734909	($)
TOTAL CHANGEABLE COSTS	335,6444	($)

Table 2.4

The total fuel consumption of this procedure is 138,19 kilogram per flight.
The total costs that can be saved on are 335,64 $.

Note: this is only the basic cost calculation. In the next chapters other costs like depreciation, aircraft DOC and maintenance will be included.

3 Change of Equipment

The goal is to improve the pushback procedure and make it more efficient. So a choice has been made to put an electrical engine in the NLG.
Basically if solutions want to be figured out, it can be done on the following parameters: equipment, time or fuel consumption reduction. In this chapter the equipment change will be worked out and the out of that following procedure changes and costs.

3.1 Introduction: APS

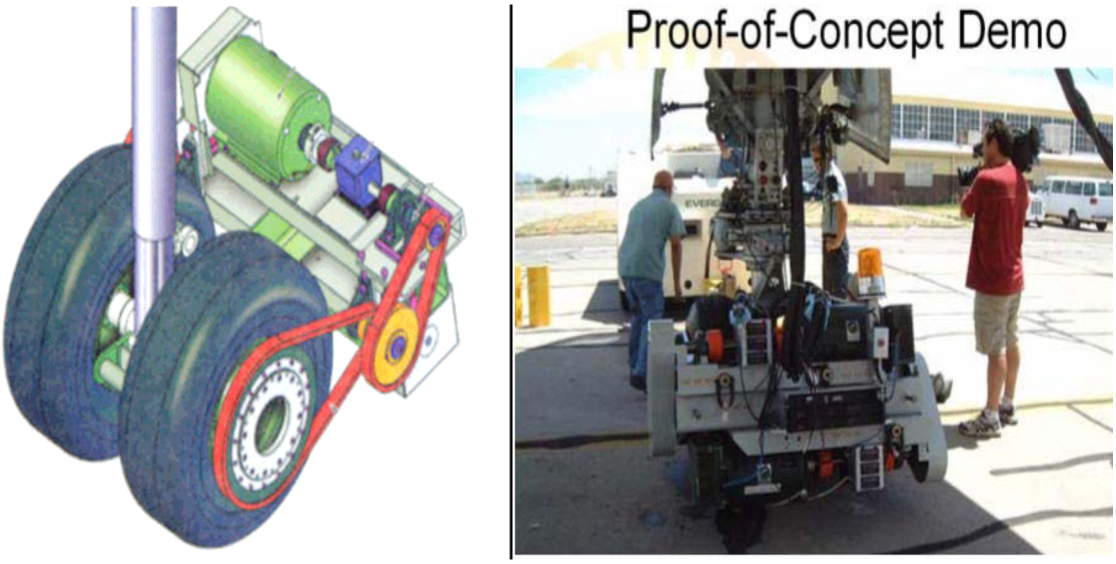
For specific procedure changes, some changes in both system and procedure have to be made. An independent aircraft has to be build or an existing airplane has to be adapted.
Going out of the principle that no external power (the tug) has to be used and the aircraft can drive on its own with the APS, a new procedure is figured out and explained.

3.2 Electrical Driven Nose gear

A change of equipment can lead to a more efficient pushback. Because the current pushback procedure takes a lot of time and costs about 122€ on equipment that has to be rented every time before take-off.
The following change might be a solution: putting an electromotor in the nose gear, so the airplane can drive on own power.

There is already a model made and load tests are done. This part of the design is handled with in the thesis of Mr. Kuntner. **(Kuntner 2007)**

In **picture 3.1** on the left side the test setup of the firm Wheeltug **(Wheeltug 2007)** and on the right side the proof of the test setup.



Picture 3.1 The theoretical production unit of the Firm Weeltug **(Weeltug 2007)**

In real life this is not realizable, so an integrated system has to be made. At the moment of writing this paper, there is already a prototype of an integrated electromotor in the rims of the NLG. There is a design of an integrated electromotor in the rims.

3.3 Auxiliary Power Unit

The energy to supply the electromotor has to come from somewhere. The main engines use to much fuel, so the other energy supplier on the airplane is the APU.

The auxiliary power unit (APU) is a gas turbine engine, which is being used for the power supply to the electrical, pneumatic and hydraulic systems, when the main engines are not on. For the Airbus A32O series there are 3 APU's available **(Jane's 2007)**

- Honeywell 36-300 APU standard
- Honeywell 131-9(A)
- APIC APS 3200

The APU feeds the electrical generator which on his turn will feed the new electromotor. The estimated power needed for the electromotor is 50 kW. The generator can give 90 kVA, so with a good and efficient use of the APU it is possible to feed the APS.
All the procedures are made considering that the amount off power needed, can be delivered by the APU.

"The primary electrical system powered by two Hamilton Sundstrand 90 kVA constant frequency generators, providing 115/200 V three-phase AC at 400 Hz; third generator of same type, directly driven at constant speed by APU, can be used during ground operations and, if required, during flight" **(Jane's 2007)**

3.4 Mechanical calculations

To know how powerful this electromotor has to be, the reaction forces have to be calculated. There are different ways to calculate this, first it is done pure mechanical, then with a preliminary power table of Boeing 737 and at last with estimation made based on an other master thesis **(Kuntner 2008)**. Each part will be explained thoroughly.

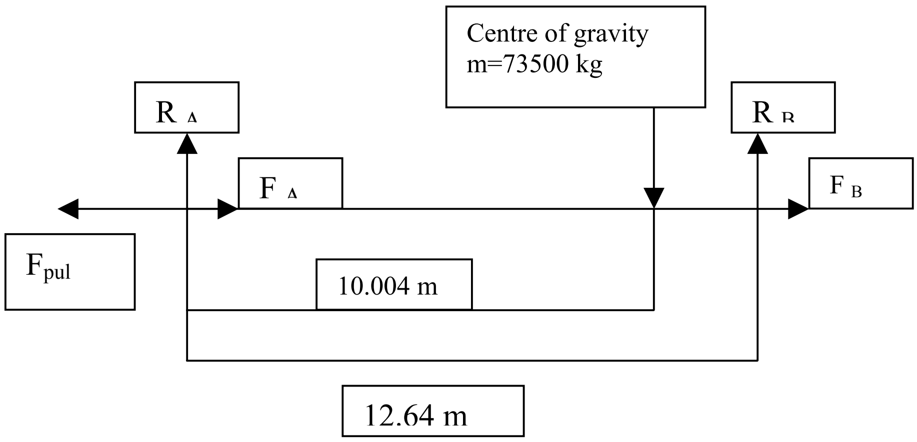
The 1st method is a pure mechanical basic calculation.

This method is based on the balance and moment of forces and it is for static systems. There can be assumed that the system is static since the plane has to start riding from standing still until a maximum taxi speed of 5 km/h. This calculation does not include changes of friction while driving, torque and dynamic changes. It is made to have an idea about the necessary power.

The forces related to the system are the weight of the airplane, the friction forces and resistance of the wheels and the power necessary from the tow bar to pull the airplane.

The sizing of the A320 can be found in **APPENDIX B**
The CG is being estimated, it lays at 25% of the mean aerodynamic chord of the wing, so from the NLG to CG there is a distance of 10,004m.

The schedule for the balance of the forces are shown on **picture 3.1**



Picture 3.2

The NLG is point A and the MLG is point B.
The reaction forces R_a and R_b and the necessary F_{pull} are unknown.

$$m = 73500$$
$$\mu = 0,05$$
$$F_x = 0$$
$$F_y = 0$$
$$M_A = 0$$
$$F_{pull} = \mu \cdot (R_A + R_B)$$

μ= friction of the tires, some examples of typical values: 0.02 for snow, 0.08 for dry concrete **(Raymer 2006)**
m= mass, here for the maximum take of weight (MTOW) is used

With these formulas a needed pull force

$$F_{pull} = 36051,8N$$

However knowing only the force is not enough, while for sizing an electromotor the power is needed. The power needed depends on the velocity v the aircraft has to drive. So the formula for power:

$$P = F \cdot V \qquad [N*m/s]$$

In **table 3.1** for the following speeds, the respectively powers are:

Speed (km/h)	Power (kW)	power (hP)
20	200288	268
10	100144	135
5	50072	70

Table 3.1

These results can be interpreted now: if an engine of 268 hP wants to be used, a big place is needed, because an engine of such a power is quite large. A 70 hP is acceptable, but it has to be checked. The result will follow in the 2^{nd} method.

What has to be considered is, can an engine, powerful enough so it can drive up to 30km/h, be designed into the nose gear system?

In this case the engine only needs to be powerful enough for the pushback. As said before the pushback speed is only 5km/h, thus an engine of 70 hP is enough.

2^{nd} method

As we know, the current pushback is done by a pushback truck. There are a lot of different aircrafts which are different in size and mass. So there are tables to see what force (power) is needed.
With the preliminary design tables, which can be found in **APPENDIX B** the force needed to pull the airplane can be configured.
For the same circumstances as in method 1 a force of approximately 2900kg ~= 30kN is needed. It can be seen that it is almost the same needed force as method 1.

3rd method

There are currently more people working on this design phase, so there is information available. Based on the thesis: "Integration eines Fahrwerkantriebes zum Manövrieren des Flugzeuges am Bodensimple" the following results can be found as a check up for the previous methods. There is need of 40 kW mechanical, so because of the efficiency of energy converting, there has to be an electrical power of 50 kW and a torque of 11kNm **(Kuntner 2008)**

The calculated powers are 50 kW in the first method, 41,6 kW in the second and as comparison 50 kW in the 3rd method. Keep in mind that tests have to be done on the possible speed and circumstances like slopes, rain, acceleration,…

3.5 Procedure change

Theoretically there is an aircraft with the APS, which will indirectly be fed with energy from the APU. So there will be a different use of the MEs and APU.
An extra estimated 25kg/h fuel consumption of the APU is used to feed the electromotor. **(TU Delft 2007).** This estimation has been made looking to the air-conditioning system which has a similar overall power and thus same fuel consumption.
The cost of the extra fuel used for the electromotor is estimated to be lower then the dropout of the ground handling costs.

The next procedure is the same as in chapter 2, but the APU has now a consumption of 175kg/h when it performs the pushback procedure. due to the extra power needed for the APS system. During normal procedures and standing still, the same consumption of 150 kg/h is used. So only when the pushback is performed, there is a higher overall APU fuel consumption.
Going out of the same time consumptions as the current procedure (taxi time of 7 minutes 20 seconds and a pushback of 1 minute and 30 seconds), due to the keeping of the same pushback and taxi speed, the following procedure is made and is shown in **Table 3.2**. and **picture 3.1**.
Note that the picture is not as accurate as the numbers shown in table 3.2.
The total schedule can be seen in **APPENDIX A2**

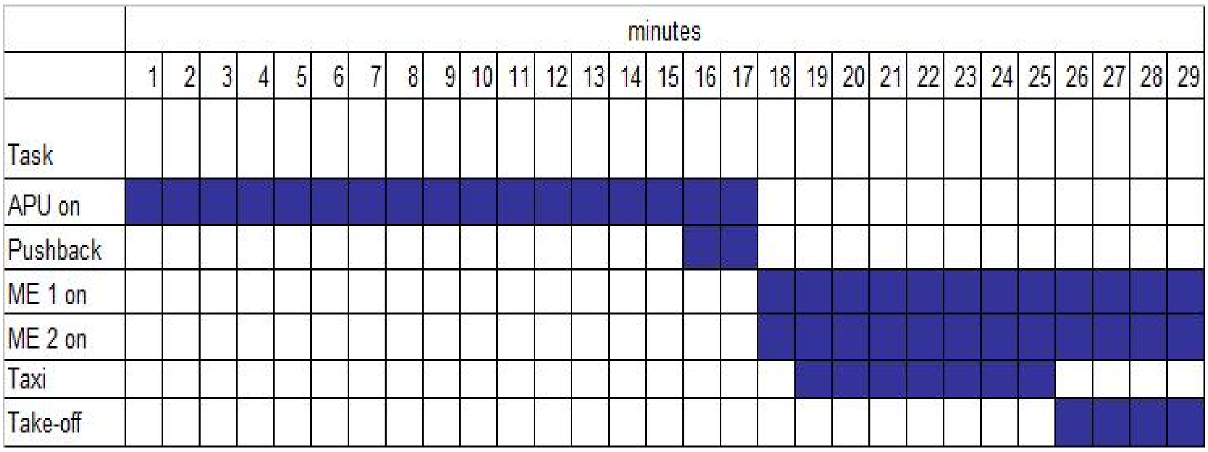
The procedure will be explained now. The APU is on for the same time as in procedure 1 before the start of the pushback procedure. Here also it is used for the supply of electrical and air-conditioning system and consumes 150kg/h. There has been estimated that the APU is powerful enough for the normal use (electrical power and air-conditioning) and pushback. Then when the pushback starts the APU uses 175kg/h.

Because using the APU at full power already and then starting the main engines is impossible, with pneumatic power is used to start the main engines. So after the pushback procedure of 1 minute and 30 seconds and a rest of 10 seconds, ME1 is started. Then after half minute ME2 is started. Then the APU is shut off. Because of the startup time of the main engines the taxi procedure can only start after 1 minute.
Almost 1 minute after the start-up of ME2 the taxi procedure starts for 7 minutes and 20 seconds.

In this case there is no time necessary for the connecting and disconnecting of the tug and that gives the time profit. The total procedure takes 25 minutes and 50 seconds.

Procedure 2 :APS			
Task	start (h,min,sec)	end (h:min:sec)	duration (h:min:sec)
APU on	0:00:00	0:17:50	0:17:50
Pushback	0:15:20	0:16:50	0:01:30
ME 1 on	0:17:00	0:30:00	0:13:00
ME 2 on	0:17:30	0:30:00	0:12:30
Taxi	0:18:30	0:25:50	0:07:20
Take-off	0:25:50	0:30:00	0:04:10

Table 3.2



Picture 3.3 Gantt's Table of the APS

Pushback time	:	1 min 30 sec
Taxi time	:	7 min 20 sec
Total time	:	25 min 50 sec

The whole procedure has a time profit of 1 min 10 sec due to the earlier possibility to start the taxiing and this procedure also has a fuel reduction. In the next paragraph the fuel reduction and costs will be explained.

3.6 Costs APS

The same method as in chapter 2 is used, with the difference that the ground handling does not have to be included. The calculation is for 1 flight.

At the moment of writing the price for jet fuel A is **3.0840 $/gallon**.
The exchange rate of dollar and € at the moment of writing is

$$1€ = 1.5898\$$$

The jet fuel's density **ρ = 0.8 kg/l**
A detailed fuel cost calculation depending on the procedure can be found in **APPENDIX A**
An 'x' means that the procedure is being performed for the containing time. Depending on that time the fuel consumption for APU, ME1 and ME2 are calculated and so the total fuel consumption is known.

In the **Table 3.3** below the characteristic fuel consumption of both APU and 1 ME can be found.
With the values of **Table 3.3** and the procedure according to **APPENDIX A** and **Table 3.2**, the total cost of fuel consumption can be calculated. This result is figured in **Table 3.4**.

Engine	Load	fuel consumption (kg/h)
APU	Full	150
	full + APS	175
ME	Normal	275
	Full	/

Table 3.3

RESULTS		
Fuel consumption	123,89	kg
Total ground handling costs	0,00	($)
FUEL costs	126,17	($)
TOTAL CHANGEABLE COSTS	126,17	($)

Table 3.4

The total fuel consumption of this procedure is 123.89 kilogram per flight, so a reduction of 14.31 kg compared with the current procedure, which can be seen in chapter 2.4 Costs.
If only the fuel savings are taken in consideration and the ground handling costs are excluded, there is a cost reduction of 14.57 $ per flight. The total costs for the current procedure are 335.64$, so now with a total cost of 126.17$ there is a reduction of 209,48 $.

Note: this is only the basic cost calculation. In the next chapters other costs like depreciation, the aircraft DOC, and maintenance will be included.

4 Procedures

A seen in previous chapter the fuel savings for the APS alone do not have a big influence on the total savings. Maybe if there is a change of the procedures, more fuel can be saved. Proposals for an APS in combination with an autonomous taxi procedure are made. This procedure will be worked out in the next paragraph.
Another idea is to tow the aircraft from the gate to the take-off place or just in front of the runway. That is for the next chapter.

4.1 Autonomous pushback and taxi

With an electrical engine which is powerful enough to drive with a velocity of 20km/h, what is approximately the same as the current taxi speed, the whole taxi procedure can be done with the APS. Speeds and regulations are the same as in chapter 2.

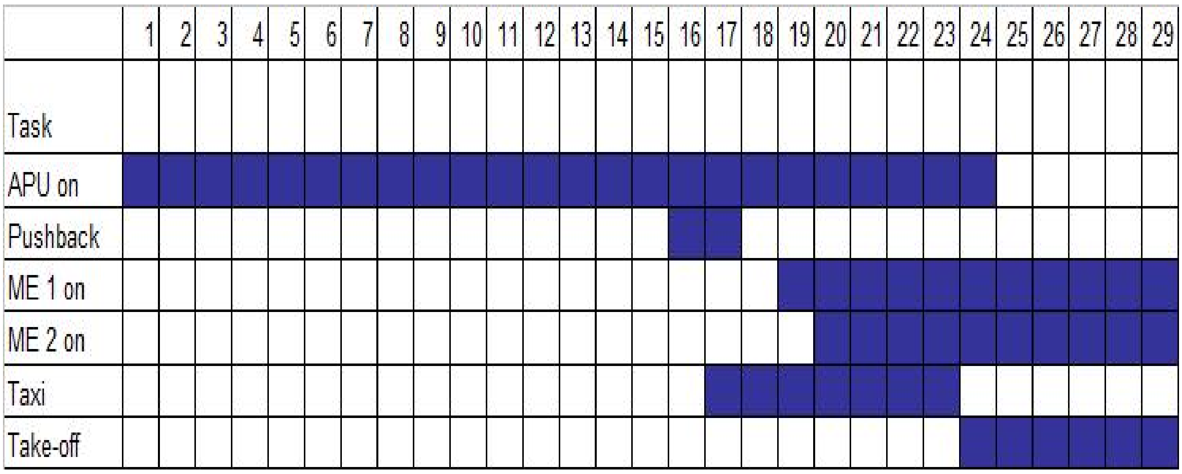
The following procedure can be set up, although the same taxi time of 7 minutes and 20 seconds as in previous procedures is used. Exactly the same pushback time of 1 minute and 30 seconds. Although we have to include a 5-minute startup time of the main engines. The procedure is shown in **Table 4.1** and **picture 4.1**

The procedure works as follows:
The APU is functioning for the electrical supply and air-condition system at a fuel consumption of 150 kg/h. When the pushback procedure or taxi procedure are performed it uses the estimated 175 kg/h. We go out of the principle that the APU is powerful enough to start the MEs while it is used for the taxi procedure. Also because there are proposals of integrating a fuel cell APU there might be a possibility of integrating a more powerful APU and/or generator.

The pushback starts at the same time as in procedure 1 and 2. There is no time needed after this pushback procedure for connecting and disconnecting the tug. So after the pushback the airplane stands still for 20 seconds. Now it has to drive forwards for the taxi-procedure.
Because of the polarity of the electromotor, the plane can drive in 2 directions. After these 20 seconds of waiting, which in considered to be the time to change the direction of rotation of the electromotor.
Now the taxi-procedure can start. If the airplane can drive up to 25km/h, the same taxi-time as in previous procedures can be kept. During the taxiing ME1 respectively ME2 is started 5 minutes before take-off. The pilots have drive the aircraft only using the APU to feed the electromotor, because of the lower fuel consumption compared to the main engines. As soon as the taxiing stops the APU is shut off. At 24 min 30 seconds the take-off starts.

Procedure 3: APS and taxi			
Task	start (h,min,sec)	end (h:min:sec)	duration (h:min:sec)
APU on	0:00:00	0:24:30	0:24:30
Pushback	0:15:20	0:16:50	0:01:30
ME 1 on	0:19:10	0:30:00	0:10:50
ME 2 on	0:19:30	0:30:00	0:10:30
Taxi	0:17:10	0:24:30	0:07:20
Take-off	0:24:30	0:30:00	0:05:30

Table 4.1



Picture 4.1 Gantt's Table of the APS+ Taxi

Pushback time : 1 min 30 sec
Taxi time : 7 min 20 sec

Total time : 24 min 30 sec

The whole procedure has a time profit of 2 min 30 sec due an even earlier possibility to start the taxiing. In the next paragraph the fuel reduction and costs will be explained.

4.2 Costs Autonomous pushback and taxi

The same method for calculating as in chapter 2 and 3 is used, with the difference that the ground handling does not have to be included and that there is a longer use of the APU. The calculation is for 1 flight.

At the moment of writing the price for jet fuel A is **3,0840 $/gallon**.
The jet fuel its density **ρ = 0.8 kg/l**
The exchange rate of dollar and € at the moment of writing is

$$1€ = 1.5898\$$$

A detailed fuel cost calculation depending on the procedure can be found in **APPENDIX A3**

In the **Table 4.2** below the characteristic fuel consumption of both APU and 1 ME can be found.
With the values of **Table 4.2** and the procedure according to **APPENDIX A3** and Table 4.1, the total cost of fuel consumption can be calculated. This result is figured in **Table 4.3**.

engine	Load	fuel consumption (kg/h)
APU	Full	150
	full + APS+Taxi	175
ME	Normal	275
	Full	/

Table 4.2

RESULTS		
Fuel consumption	112,29	kg

Total ground handling costs	0,00	($)
FUEL costs	114,36	($)
TOTAL CHANGEABLE COSTS	114,36	($)

Table 4.3

The total fuel consumption of this procedure is 112.29 kilogram per flight, so a reduction of 25.90 kg per flight.

If only the fuel savings are taken in consideration and the ground handling costs are excluded, there is a cost reduction of 26.4 $ per flight. And with the ground handling costs included, so compared with the 335.64$ of the current procedure a reduction of 221.9$

The fuel consumption savings are seemingly higher then the normal APS procedure.
A logic result is, the longer the taxi time, the more duel is saved. This is easy to calculate as follows. 1 minute driving with the APS, but the main engines are not on yet, consumes **2.917 kg**. The taxiing with the main engines on, like in the current procedure, is **9.167 kg**.
That is a reduction of 68.2% per minute that the main engines are off.

Note: this is only the basic cost calculation. In the next chapters other costs like depreciation, the aircraft DOC, and maintenance will be included.
The practical part will be discussed in the conclusion of chapter 8.

4.3 After Landing Taxiing

The same procedure change can be done for when the aircraft landed. In the current official procedure 1 engine has to be shut down, for noise reduction and unnecessarily air pollution.
Then the APU can be started again.
As known from previous procedures that every minute of using the APU instead of the main engines there is a fuel reduction of 68.2%
Note that this is calculated for 2 engines. In the normal procedure there is only 1 engine running, that means a cost reduction of 50%.
The total savings are thus 34.1%.
It is unnecessary to make a schedule, while it is a fact that there is a fuel reduction and emission reduction.

Things that have to be taken in consideration are:

- Will there be a time problem, thus will the critical path be an issue?

- Is the fuel reduction worth of the work?
- Do the pilots have time to make a change of procedure?

5 Full Towing

5.1 Research

Another idea to get the aircraft from the apron or gate to the runway is to push/pull it with a pushback truck, which has been worked out in sight of reducing fuel consumption, but more because of reduction of the air pollution.
The Dutch Ministerie van Verkeer en Waterstaat (Ministry of Traffic and Water state) already tested this issue together with Virgin Atlantic Airways (VAA) and British Airport authority.
On these tests this chapter is written **(MVW 2007)**

The current pushback procedure with a pushback truck has been explained in chapter 2, so for the new full towing procedure the same setup and equipment can be used.
In the current procedure the airplane starts its engines during or after the pushback, because they need to heat up for minimum 1 minute before the taxi can start and 5 minutes before take-off. During heating up the engines, the airplane taxies the resting time/distance to the takeoff place on the runway. Then it is ready for take-off.

Instead of pushing the airplane backward to the starting grid where the airplane can start up his engines and drive on own power to the runway and takeoff place, the pushback truck will push/pull the airplane to the take-off place on the runway.

5.2 Demands for full towing

To perform this whole operation there are some arguments that have to be considered. Because in most cases theoretical and practical information mostly do not match.
So the following arguments that has to be dealt with:

- Infrastructure of the airport

- Material, pushback truck
- Organization

Infrastructure of the airport must be adapted to the requirements of the new full towing procedure, because the runway must be free for take offs and landings, there must be enough starting grids or some areas where the pushback truck can be disconnected. For some airports this is impossible because of a lack of available space. Additional lanes or space for a save return of the trucks is also necessarily.

The material required is an amount problem. The pushback takes approximately 5 minutes, in that time the connecting, pushback and disconnecting is included. So the truck can be reused after 10 minutes.
The taxi-speed is also slower then when the airplane drives on own power.
The problem now is that the truck is operative for double the time if it does the taxiing. Like in the theoretical examples with a taxi-time of 7 minutes and 20 seconds, a pushback of 1 minute and 20 seconds, a few minutes of connection time and extra time due to the slower driving then normal taxi-speed it takes between 10 and 15 minutes. But the truck has to return to the apron for the next airplane, so it's only standby after 20 to 30 minutes.

With investments from the airport or ground-handling firms for new trucks this is acceptable. A doubling or even tripling of the amount of trucks, which cost 800'000 € each, will be enough to provide every airplane the full towing procedure.

The nose gear is not designed for long mechanical external forces according to Boeing/Airbus and no data about any tests can be provided. Adaptations to the nose gear must be done in order to suite to the new procedure.

The organization of traffic has to be completely changed. With the extra trucks driving around and the tight schedules, it's even a harder job then the current state of operating.

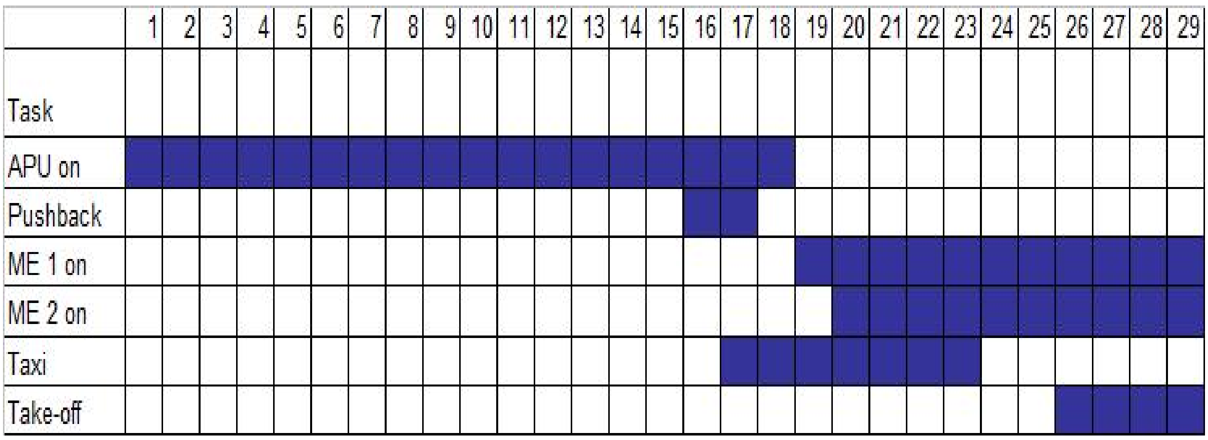
5.3 Procedure schedule

This procedure is almost the same as the current procedure. The APU is on with a consumption of 150 kg/h. Then while standing at the gate, during other ground handling procedures the tug can be connected. After that the pushback procedure starts at the same moment as the other previous procedures. After that, the taxiing can start immediately. 5 minutes before take off the engines have to be on, because they have to warm up. The tug has to be disconnected, so after 1 or 2 minutes the aircraft is ready for take off.

The whole procedure has a time profit of 50 sec so it is not a very profitable procedure according to the time aspect. In the next paragraph the fuel reduction and costs will be explained.

Procedure 1 : Full Towing			
Task	start (h,min,sec)	end (h:min:sec)	duration (h:min:sec)
APU on	0:00:00	0:19:10	0:19:10
Pushback	0:15:25	0:16:55	0:01:30
ME 1 on	0:18:55	0:26:10	0:07:15
ME 2 on	0:19:40	0:26:10	0:06:30
Taxi	0:17:10	0:24:40	0:07:30
Take-off	0:26:10	0:30:00	0:03:50

Table 5.1



Picture 5.1 Gantt's Table of the Full Towing procedure

Pushback time : 1 min 30 sec
Taxi time : 7 min 20 sec
Total time : 26 min 10 sec

5.4 Costs Full Towing

The same method as in previous chapters is used, but here again we have to integrate the ground handling costs. The calculation is for 1 flight.

At the moment of writing the costs for jet fuel A is **3.0840 $/gallon**.
The jet fuel its density ρ = 0.8 kg/l
A detailed fuel cost calculation depending on the procedure can be found in **APPENDIX A4**

In the **Table 5.2** below the characteristic fuel consumption of both APU and 1 ME can be found.
With the values of **Table 5.2** and the procedure according to **APPENDIX A4** and **Table 2.2**, the total cost of fuel consumption and ground handling can be calculated. This result is figured in **Table 5.3**.

Engine	load	fuel consumption (kg/h)
APU	normal	75
	full	150
ME	normal	275
	full	/

Table 5.2

RESULTS		
Fuel consumption	113,23	kg
Total ground handling costs	194,90948	($)
FUEL costs	115,310688	($)
TOTAL CHANGEABLE COSTS	240,9947	($)

Table 5.3

The total fuel consumption of this procedure is 113.23 kilogram per flight, so a reduction of 24.97 kg per flight compared with the current procedure.
In this case the ground handling has to be paid so there is a **cost reduction of 25.42 $ per flight**.

Note: this is only the basic cost calculation. In the next chapters other costs like depreciation, the aircraft DOC, and maintenance will be included.

There are some extra factors that have an influence on this cost calculation. The price of the ground handling is just the normal one. In this case the Tug is used for 30 minutes instead of 5 to 10. So the airport will probably charge more.
If we just double the current price for the use of all ground handling equipment, because the time that the truck is operating, has tripled. Then we would see an even higher end price. The amount of fuel saved then does not cover the extra tug cost

5.5 Pollution

With engine data it can be calculated that every flight 1.5ton of CO_2 gas is saved. This is the major and only advantage of the full towing procedure.
Other gases are reduced, but the truck brings extra pollution **(Finn air 2007).** With taxi times longer then 10 minutes the environmental advantages become better.

5.6 Conclusion

As seen in **Table 5.3** the fuel savings are not enough to cover the expenses of the pushback truck.

The costs and changes that the airports have to make are too complicated and not efficient enough to introduce the full towing for big airplanes.

There are also test done on the Boeing747 in London Airports, but because of too many operational and practical problems this has been cancelled. They did not give detailed information and just informed that it was not operational enough.

Other problems that have to be taken care of and these are also reasons not to do the full towing are:

- If the aircraft has Engine startup problems, the airplane has to be taxied back for reparation
- The engines have to start up to full power while the tug and personnel is close to the aircraft, so according to safety rules is forbidden.
- Some trucks can not ride as powerful in 2 directions.

This is not a good proposal and does not have to be taken in consideration for future projects.

6 Emission gasses and pollution

6.1 Research

Every engine its exhaust contains certain emission gasses and each in a certain amount. Some of the emission gasses are poisenous or cause direct or indirect effect on the environment. One of the popular problems nowadays is global warming. There are rules and norms and due to the global warming these rules get stronger and stronger every year. Because of the big increase of CO and NOx gasses
The Committee on Aviation Environmental Protection (CAEP) and current international standard (ICAO, 1998a) have set some goals for reduction of emissions. These have to be met with an extra 40 percent margin for nitrogen oxide (NOx), carbon oxide (CO), hydrocarbon (CxHy) and smoke.

6.2 Problems involving Emission gasses

The discussed procedures occur in the airport and so the emission gasses have influences on both people and the environment close to the airport. These are the effects that occur:

“Health effects due to pollutants may be divided into two classes: those due to acute exposures and those due to chronic exposures. Acute health effects are experienced immediately or within a few hours of the exposure. Health effects due to chronic exposure may only become apparent after an extended period of time, typically months or
years.

Environmental effects can also be divided into three broad categories: ecological effects (effects on plants and animals other than humans), damage to materials (soiling, etc.) and visibility (effects on transmission of light through the atmosphere).” **(EPA420 1999)**

Airports try to reduce the amount of emissions because on a year-basis every type occurs in amounts of tons. In **Table 6.1** the emissions from Finn airs ground equipment at Helsinki-Vantaa Airport from 2001 through 2003 are given **(Finnair 2003)**

	2003/tonnes	2002/tonnes	2001/tonnes
Carbon dioxide (CO2)	5 090	3 300	4 900
Carbon monoxide (CO)	29	32	34
Hydrocarbons (HC)	7.6	8.4	8.5
Nitrogen oxides (NOx)	23	27	27
Particles	3.7	3.9	3.8

Table 6.1

Picture 6.1 shows the effects of several kinds of emission gasses on people.
Picture 6.2 shows the effects of several kinds of emission gasses on the environment.

Pollutant	*Representative Health Effects*
Ozone	Lung function impairment, effects on exercise performance, increased airway responsiveness, increased susceptibility to respiratory infection, increased hospital admissions and emergency room visits, and pulmonary inflammation, lung structure damage.
Carbon Monoxide	Cardiovascular effects, especially in those persons with heart conditions (e.g., decreased time to onset of exercise-induced angina).
Nitrogen Oxides	Lung irritation and lower resistance to respiratory infections
Particulate Matter	Premature mortality, aggravation of respiratory and cardiovascular disease, changes in lung function and increased respiratory symptoms, changes to lung tissues and structure, and altered respiratory defense mechanisms.
Volatile Organic Compounds	Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment.

Picture 6.1

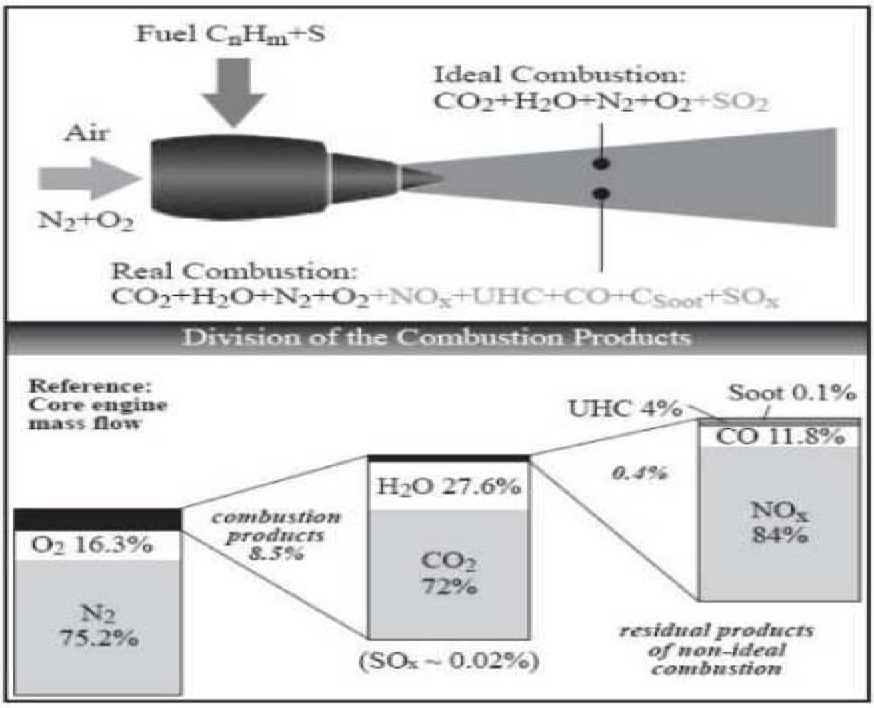
Pollutant	*Representative Environmental Effects*
Ozone	Crop damage, damage to trees and decreased resistance to disease for both crops and other plants.
Carbon Monoxide	Similar health effects on animals as on humans.
Nitrogen Oxides	Acid rain, visibility degradation, particle formation, contribution towards ozone formation.
Particulate Matter	Visibility degradation and monument and building soiling, safety effects for aircraft from reduced visibility.
Volatile Organic Compounds	Contribution towards ozone formation, odors and some direct effect on buildings and plants.

Picture 6.2

All the procedures in and around the airport that are more fuel efficient or that reduce the amount of emission have to be used, because of the increasing norms.

6.3 Emission gasses

A modern jet engine has a fuel and air inlet and the outlet contains multiple gasses according to **picture 6.3**. This is a picture used in the project of TU Delft. **(TU Delft)** As seen on the combustion products the emission gasses are only a small part, but that does not mean they are not important.



Picture 6.3 the principle of a combustion engine and its exhaust gasses

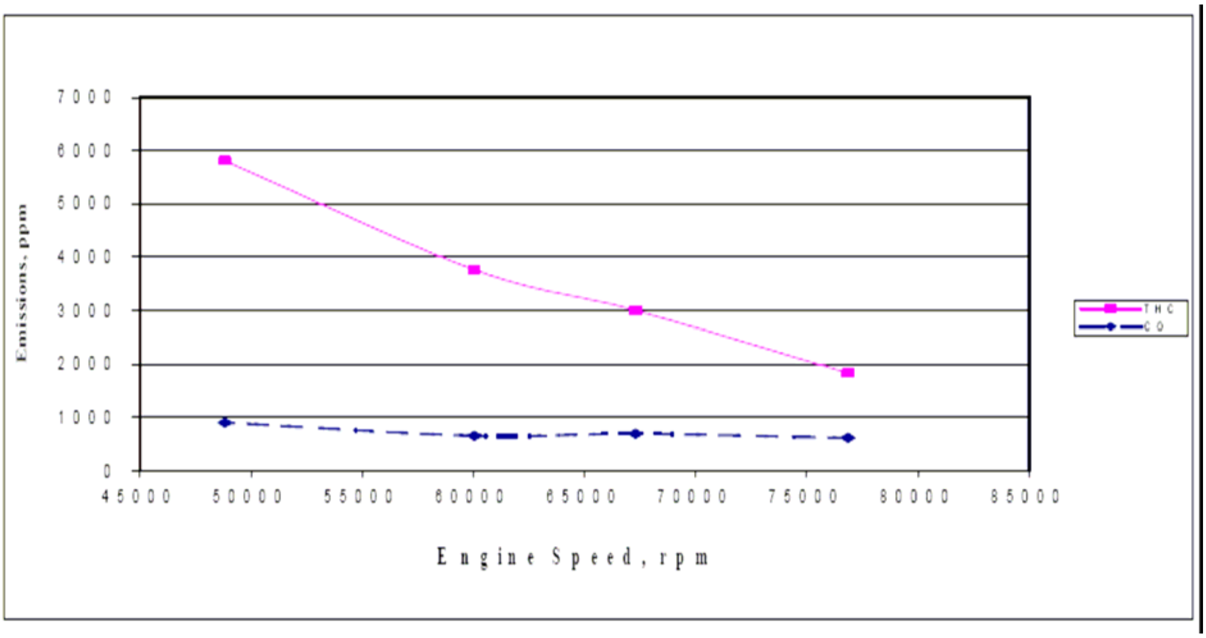
The following exhaust gasses and material can occur:

- Carbon dioxide CO_2
- Carbon oxide CO
- Nitrogen oxide NO_x
- Unburned Hydrocarbon (UHC) C_xH_y
- SO_2
- Smoke
- Particular matters
- …

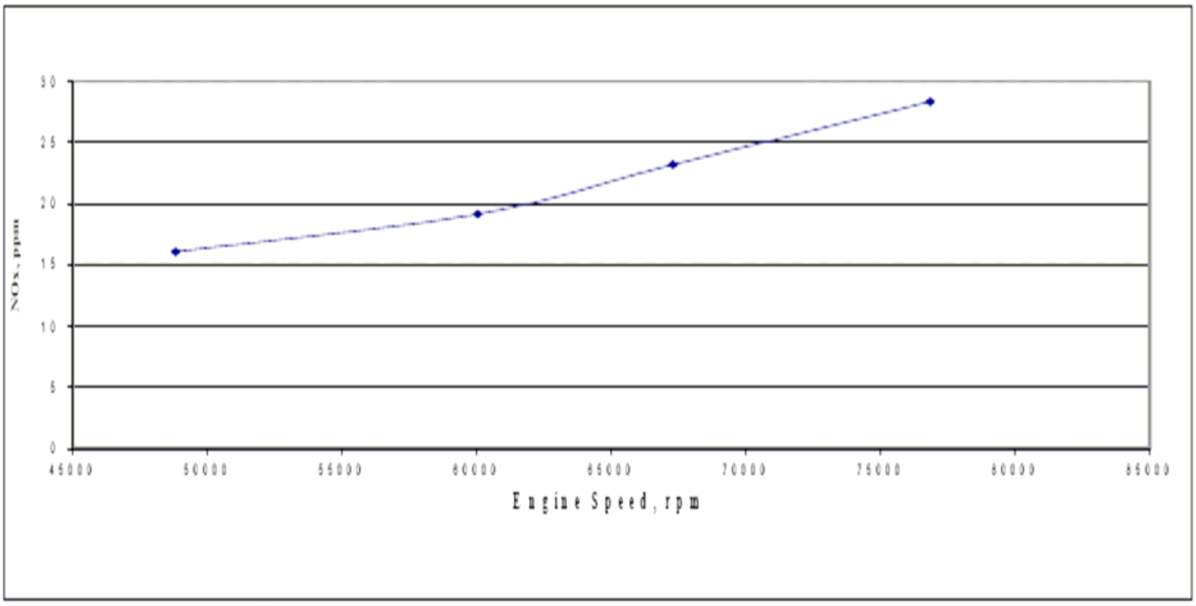
Some of these are really important to reduce for example the most 'popular' ones are CO and NOx.
In the tables with the emissions in function of the engines speed, the following results can be seen.

In **picture 6.4** the unburned hydro carbonates (UHC) which decrease with increasing rotating speed of the jet engine and the approximately constant CO.

In **Picture 6.5** the increasing NOx in function of the increasing engine speed.
(ASME 2003)



Picture 6.4 UHC and CO in function off the engine speed



Picture 6.5 NOx in function of the engine speed

Emission gasses also change according to different cruise altitude, but that is not evident for this paper. In the case of this project we have a low engine speed, because of the taxiing so the amount of UHC is important. So the taxi procedure and take

Calculations can be made if the emission amount in kilogram per time the engines are running is given. A report is made by the united states Environmental protection Agency **(EPA420 1999)**The values have been taken from the table in **APPENDIX C** where the emission gasses per flight phases are given and which come from the same report mentioned above. These values and are shown in **Table 6.2** below.

task	emission gas (kg/min)			
	HC	CO	NOx	SO_2
take of	0,0290	0,1135	3,1026	0,0681
climb	0,0238	0,0931	2,0275	0,0559
approach	0,0140	0,0873	0,2794	0,0189
idle	0,0170	0,0170	0,0485	0,0066

Table 6.2

For each procedure the amount of emission gasses is calculated in **Table 6.3** below.

Note that this is done with the values of the take-off of the entire aircraft. This is done because the engine's warming up and the increasing of the engine while getting closer in time to the actual take-off is not done at 1 certain speed. This makes that average emission pollution is close to the values of the actual take-off values. This is estimated keeping in mind that the differences between the values are being made. And that there is also the linearity of the graphs, so the used results vary linear. With this the difference in emission pollution depending on the type of procedure can be estimated/seen

task	emission gas (kg/year)			
	HC	CO	NOx	SO_2
Current procedure	1377,8300	5391,1575	147357,0371	3234,8845
APS	1309,3664	5123,2739	140034,9483	3074,1449
APS and taxi	1095,4176	4286,1376	117153,4208	2571,8336
Full towing	706,0309	2762,5496	75509,0408	1657,6271

Table 6.3

As seen the amount of UHC, CO, NO_x and SO_2 are going down, this due to the lower time use of the main engines. For the APU this is probably the same. But the point is made clear that with a more efficient procedure the Emission amount decreases.

6.4 Conclusion

Every time reduction gives an emission change. Depending on the amount of flights the amount can be calculated in kg/year.
These values are under a certain norm. If the values decrease in such a big amount there can even be made new standards. These can lead to lower environment taxes given by the government or Airport.

The ME's have to warm up and be on 5 minutes before take-off. In this case we have a Taxi time of 7 minutes so 2 minutes time profit on fuel saving and emission reduction. The longer the taxi time takes, the more reduction we have. It can not be more reduced then 5 minutes per engine. So the Emission rate stays at that constant amount.

7 Costs

To make an evaluation of the total costs, some cost calculation systems have to be used.
Every change in an aircraft has its direct and indirect cost changes. In this case a new system has been added, so a cost schedule has to be made. Some parts of the costs are more important then the other. So there has to be dealt with every part. Only the costs that are changed will be handled, because not all of the aircraft costs change.
The following parts have an influece on the total cost: ground handling, fuel cost, depreciation of the APS system, maintenance of the APS system, change of the aircraft DOC.

For the new system there has to be dealt with following points

- weight
- price
- maintenance
- fuel consumption
- compability of the system
- functionality of the system

7.1 Ground Handling

The ground handling costs were discussed in chapter 2 topic 2.4 Costs.
For the ground handling costs only the pushback costs are used. Not the entire convenient DOC for aircrafts.
The problem with this kind of costs is, that not in every airport the costs are the same.
Some airports ask money separatly for pushback procedure and manpower, but other airports charge 1 price for the whole ground handling. That price includes the pushback procedure, but it is hardly impossible to change the airport fees. Further details and proposals will follow in the next chapter.

7.2 Fuel costs

Due to a different use of both main engines and APU, there is a fuel consumption reduction depending on the procedures mentioned in chapter 4. Because of the small amount of fuel compared to the fuel use for a whole flight, only the fuel costs for the procedures are used. The fuel used for the taxi and pushback procedures in the previous chapters is between 4,7 % and 7,9% of the total mission fuel mass according to the Aircraft DOC.

Going out of specific fuel consumption (kg/h) and the used time for the procedures the fuel mass can be calculated as in chapter 2. With a known price of 3,0840$/gallon the price in $ is known. In the **table 7.1** below the fuel price for all of the 4 procedures is given.
Each separate cost is calculated in the chapters 3.6 Cost savings APS, 4.2 Costs Autonomous Pushback and taxi, 5.4 Costs Full Towing

procedure	mass of consumed fuel (kg)	Price ($)
Procedure 1 :standard procedure	138,19	140,73
procedure 2: APS	123,89	126,17
procedure 3: APS and Taxi	112,29	114,36
procedure 4: full towing	113,23	115,31

Table 7.1

The APS has a fuel reduction of 10.4%
The APS and Taxi a reduction of 18.75%
The full Towing procedure has a reduction of 18.1%

The extra fuel used because of the extra weight of the electro motor during the whole flight will be calculated in a next paragraph.

7.3 Aircraft DOC

It is not enough to just calculate the fuel cost and the depreciation of the APS. Due to the extra weight, which is 100 kg **(Kuntner 2008)**, the aircraft will use more fuel to carry the extra weight. So the whole aircraft cost has to be recalculated. This can easily be done with the **(AEA 1989 DOC**) calculation methods.

Since this is part of a whole project, the ALOHA project, with weight reduction and addition of new parts, the whole aircraft DOC has to be recalculated. This is beyond the scope of this paper. Thus the following calculation is proposed. In the conclusions later on, there are problems discussed which deal with the payload change in case of cargo and/or passenger transport. This has an influence on the revenue, so for the whole weight change this is important..
In this paper only the electro motor its weight is added, to show that the DOC changes.

To know how much the extra costs per flight are, one has to know the amount of flights per year (yearly flight cycles), the ‘normal aircraft DOC costs’ without the APS and the DOC costs with the APS. The difference between these last two gives the cost per flight.

Now the question is: in which weight parameter does the 100 kg has to be added.
If the MTOW is changed, there is more power needed, thus bigger main engines. Or structural adjustments have to be done.
If the 100 kg is added to the Empty Operation Weight (OEW) the payload decreases. The comparison between DOC and payload is made and can be calculated with the revenue rate FR $_{TKO}$ **(Scholz 2008)**

$$F.R._{TKO} = 0,6€ / tokm$$

This means with 100 kg and 1000 km averaged per flight, an increase of **60€/flight**. This is a high cost, so there is chosen to change the MTOW.
Further explanation will be given in the conclusions.

The 100 kg extra weight is added to the Maximum Take Off Weight (MTOW)!
First the ‘normal’ aircraft DOC is being calculated with the normal values of the A320 low fare flights.

Since in this paper it is not the goal of calculating an aircraft DOC, pre chosen values are taken from a preliminary design and DOC tool, in Microsoft Excel, from the AERO group of the HAW Hamburg. These values are kept in mind, because further cost calculations are bond to them.

In **Table 7.2** the main input values for the Excel worksheet for AEA 1989 DOC are shown and explained. The left Table is the ‘normal’ DOC cost, the left table is the one with the APS system.

Main Input		Unit	A320-200	A320-APS
Average Stage Lenght	R	km	1025	1025
Cruise speed	Vc	km/h	871,2	871,2
Flight time	tf	h	1,176538108	1,176538108
Block time	tb=tf+0.25	h	1,426538108	1,426538108
Yearly Flight Time	Ku1	h	3750	3750
Block time supplement per flight	Ku2	h	0,75	0,75
Annual Aircraft Utilization Ua,f	Ua,f	h	2290,127502	2290,127502
Annual Aircraft Utilization Ua,b	Ua,b	h	2457,810358	2457,810358
Yearly Flight Cycles (based on block time!)	nt,a	-	1722,919523	1722,919523
MTOW		kg	75500	75600
OEW		kg	41310	41310
MZFW		kg	60500	60500
Number of passengers	nPAX	-	179	179
SLS Engine Thrust	T	kN	111,7	111,7
Number of enginers	nE	-	2	2

Table 7.2 Input Data aircraft DOC

The rest of the calculation table is listed in **APPENDIX D**

There is chosen for a **'useful service life' of 14 years**. We know that we need the amount of **per** year. In **Table 7.2** there can be seen that it are **1722.92 flights a year**. This value is based on the block time and calculated with the next formula

$$U_{a,f} = t_f \cdot \frac{k_{u1}}{t_f + k_{U2}}$$

k_{U1} yearly flight time

t_f block time supplement per flight (total procedure time)

k_{U2} turnaround time

Then as can be seen in **table 7.2** in yellow an extra weight of 100 kg is added to the MTOW, so now there is an MTOW of 75600 kg, and calculated again. The result is shown in **Table 7.3** below.

cost type	A320-200($)	A320 APS ($)
DOC	20760847,56	20764546,75
DOC/SEATS	115982,3886	116003,0545
DOC/SEATTRIP	67,31735697	67,32935167
DOC/TRIP	12049,8069	12051,95395
Δ DOC/TRIP	2,147051002	

Table 7.3

The difference between the 2 calculations is the DOC cost per flight.
This makes that the **aircraft DOC has a difference of 2.147 $/flight**. This number has to be taken in account with procedure 2: APS and procedure 3: APS and Taxi.

7.4 Depreciation

"Depreciation is a term used in accounting, economics and finance with reference to the fact that assets with finite lives lose value over time. " **(wikipedia 2008)**

This means that when a machine, system or any other consumption product is bought and used, that it loses its value while using it. So this value has to be used in the total cost calculation.

The factors which have an influence are the actual purchase price, the residual and the amount of years the machine, system or other consumption product will be used or is expected to be used.
In this case, the price of the system is estimated on 100'000 $

The depreciation can be calculated by inserting an extra cost in the total DOC, which is explained above. But here is chosen to deal with it separately.

The depreciation is calculated in the normal depreciation case. This means a residual value of 10% and a life cycle of 14 years. This number of years is the assumed amount of years for a low fare aircraft according to the AEA DOC method **(AEA 1989a).** This in order to make the whole calculation of the total cost the same.

$$Depr_{sys} = \frac{Price - Residual}{N} = \frac{Price \cdot \left(1 - \frac{Residual}{Price}\right)}{N}$$

So the depreciation cost according to the following formula is 6071.43 \$/year
The depreciation per flight is a more useful value, so with 1723 flights a year, the depreciation per flight is **3,52\$/flight**

7.5 Maintenance

As known in the mechanical industry electro motors are well designed and good working machines. They are made in a solid housing and do not need a lot of maintenance. For example there is a maintenance guide that proofs that after 10'000 working hours only the oil has to be changed. This will be shown later.
But to make a schedule between maintenance and costs, some theories or calculations methods have to be used. Here is chosen for the DOC system method. **(Scholz 1998)**

This is the method for calculating the DOC

The total maintenance costs consist of direct and indirect costs.

$$TMC = DMC + IMC$$

TMC	Total Maintenance Costs
DMC	Direct Maintenance Costs (durch das Flugzeug verursachte Kosten)
IMC	Indirect Maintenance Costs (durch die Wartungsumgebung verursacht)

Only the direct costs are calculated for the DOC costs.

$$DMC = \left(MMH_{on} + MMH_{off}\right).LR + MC$$

MC	Material Costs, which have to be estimated
LR	Labour rate: For creating a worst case scenario the most expensive price is taken, the LR with "overhead" at a rate of 69 \$/FH (Flight Hour)
MMH	Maintenance Man Hour
MMH_{on}	Line Maintenance (on the aircraft)
MMH_{off}	Shop Maintenance (off the aircraft)

Here for FH, the actual amount of time that the engine is running is taken. This can easily be calculated by taking the yearly flight cycles from chapter 7.3 Aircraft DOC and multiply it with time the engine is working. This depends on the procedure that is used, and so a calculation is made for every procedure. Each calculation can be found in **APPENDIX E**

The hours that need to be worked on the machine have to be calculated, these depend on the time between 2 failures of the same system/machine, the failure rate (how much maintenance it needs) and the flight hours, which have been calculated already.
This leads to the following procedure:

$$MTBUR = FTRR \cdot MTBF$$

MTBF Mean Time Between Failures, this value has to be estimated
FTRR Failure To Removal Ration, see table 7.4, here is chosen for **0.7**
MTBUR Mean Time Between Unscheduled Removals

Table 7.4 shows the Failure To Removal Ratio (FTRR)

System FTRR	Failure rate
Elektronik	0,3…0,4
Elektrik	0,6…0,7
Hydraulik	0,8…0,9
Mechanik	1,0

Table 7.4

The amount of yearly waiting-results are calculated with MTBUR

$$n_M = \frac{FH}{MTBUR}$$

This number together with the man hours and the time needed to repair the system/parts/machine give the maintenance man hours

$$MMH_{on} = RT_{on} \cdot n_M$$
$$MMH_{off} = RT_{off} \cdot n_M$$

$RT_{on/off}$ Repair Time on/off the system

For the MTBF there has been looked to a maintenance manual of an electromotor from the company Nord. In the manual of the common electromotor **(Nord 2004)** there is referred to follow the procedure for a fireproof gearbox.
The following **Picture 7.1** gives the procedure of the maintenance that has to be done on the fireproof gear motor. **(Nord 2004)**

Service and Maintenance Intervals	Service and Maintenance Work
weekly or every 100 hours of operation	– visual inspection for leaks – check gearbox for unusual running noise and/or vibrations – **For transmission with cooling cover:** Visual inspection temperature adhesive label
Every 2500 operating hours, at least six-monthly	– Check oil level – Visual inspection of rubber buffer – Visual inspection of hose – Visual inspection of temperature-resistant adhesive label – Remove dust (applicable only to Category 2D) – Check coupling (applicable only to Category 2G and IEC/NEMA standard motor mounting) – Re-grease (applicable only to free drive shaft / Option W and on agitator bearings / Option VLII / VLIII)
Every 5000 operating hours, at least annually (applicable only to IEC/NEMA standard motor mounting)	– replace automatic lubricant dispenser
Every 10000 operating hours, at least bi-annually	– Change oil – Check the cooling spiral for contamination.
Interval as indicated on rating plate MI = operating hours, at least every 10 years (applicable only to Categories 2G and 2D)	– General overhaul

Picture 7.1

For each procedure, both APS and APS + Taxi, it has been calculated.
The total Excel sheets can be founding **APPENDIX E**

Here an example for procedure 2: APS

There is each time a use of the electromotor for 5 minutes. That together with the yearly flight cycles from paragraph 7.3, which are 1723 flights there are **143,5766 working hours**, called in this example FH.

After **100 working hours** only a visual check has to be done,
The repair time, which is just a visual control, is estimated on 5 minutes = **0.1 h**

	100 working hours
e	visual control

MTBF	100	[h]
FTRR	0,6	[/]
FH	143,5766	[FH]
RT on	0,1	[h]
RT off	0	[h]
LR/FH	69	[$/FH]
	0	[$]
MTUBR	60,00	[h]
nm	2,392944	[FH/h]
MMHon	0,239294	[h]
	16,51131	[$]
MMHoff	0	[h]
	0	[$]
DMC	16,51131	[$]

Table 7.5

For the complete calculation there is an extra material cost of 1500$ included. The repair times are estimated and can be seen in the complete calculation in **APPENDIX E**
In both cases an extra material cost of 1500$ is included.
The total cost is for 10000 working hours (FH) and that is equal to approximately 70 years in the case of procedure 1: APS.
For procedure 2: APS the cost per flight is **0.0127$/flight**
For procedure 3: APS + Taxi the maintenance cost per flight is **0.0522$/flight**

As predicted these costs are not high compared with the other costs. Though they have to be included.

7.6 Total costs

Now that all the separate costs are calculated and discussed, an overview cost schedule can be made. This part contains other prices then previously calculated, due to the fact that all the costs are included.

cost	procedure 1: current procedure	procedure 2 : APS	procedure 3 : APS + Taxi	procedure 4 : Full Towing
ground handling	194,9095	0,0000	0,0000	194,9095
Fuel costs per flight	140,7349	126,1664	114,3560	115,3107
depreciation		3,5239	3,5239	
maintenance		0,0127	0,0522	
AircraftDOC		2,1471	2,1471	
total costs	335,6444	131,8500	120,0791	310,2202
money profit per flight compared to current procedure		203,7943	215,5653	25,4242

Table 7.6 Table with the total cost per procedure

These are just the cost calculations for the theoretical procedures. An analyse is made in the next chapter.
The results are quite clear; the cost savings are mostly due to the disappearing of the ground handling costs. If the Taxi-procedure is included and extra cost saving occurs. This cost saving is the fuel saving that is variable with different taxi times.
The full towing only has a fuel profit of 25$, but as mentioned in the chapter dealing with Full Towing, there are too many external influences and costs.

8 Overview

8.1 Conclusion

Due to the APS system the ground handling costs can be eliminated, this is the biggest part of the cost savings. The procedure gets more efficient with longer taxi times. Since the main engines have to start 5 minutes before take-off, it get more profitable if the Taxi procedure is longer then that time. Every minute has a fuel efficiency of 68%
The same analogy counts for the Emission gasses.

8.2 Comparison of results

To see if the proposed method is good and/or correct, comparising with other methods have to be used. A company called Wheeltug made the theoretical test structure (see chapter 3.2 Electrical Driven Nose Gear).

"WheelTug is a fully integrated ground propulsion system for airdraft. Built into the hubs of the nose wheels, it will give aircraft of all sizes full ground mobility(forward and reverse with steering) without turbines or external tugs. It will not require airframe modifications. It will be powered by the APU which, while technically a turbine, is designed for this sort of application." **(Wheeltug 2007)**

They also have an online Financial Benefits Calculator, which works for several types of aircrafts and also the A320.
Their procedure is the closest to the pushback+Taxi procedure of chapter 4. If we use the results of this paper and put them in the site of wheeltug, a comparison can be seen.
The following parameters that were used during the whole paper are used.

- a ground taxi time of 7 minutes.
- A fuel price of 3.0840$/gl
- A turnaround saving of 2.5 minutes
- 4.72 flights per day (depending on the yearly flight cycles)

A screenshot is taken from the site and shown in **Picture 8.1**

Basic Variables Select an aircraft model and modify the below figures to match your airline's specific application.			
Aircraft	Airbus A320 The most popular Airbus aircraft, the A320 is a competitor to the somewhat smaller 737.		 Photo � Bruno David
Ground Taxi Time	7	Minutes	Includes time from gate to runway and back. The industry average is 25 minutes. This calculator will factor in the 5 minutes that the engines will need to be running prior to takeoff.
CO_2 Credit Value	$ 33.50	/Metric Tonne	This is only relevant to airlines in Kyoto signatory countries. $33.50/metric tonne was the value as of Febuary 3rd, 2006.
Fuel Price	$ 3.084	/Gallon	$1.649 was the average price paid from Jan-Nov 2005.
Turnaround Savings	2.5	Minutes	This is the number of minutes that would be saved by using WheelTug. Savings would be realized by not having to wait for a tug push-back from the gate.
Turnaround Savings Calc Method	◉ Less Time/Flight ○ More Seat Miles/Day		The average aircraft in a fleet would have less flying time for the same number of flights. The average aircraft in a fleet would enjoy more flying minutes without additional operational time. See sources and assumptions for more information.
Cycles/Day	4.72		The industry average is 3.55. Southwest does 6.7.
	Calculate		

Financial Benefits of a Single WheelTug system on a Airbus A320		
	Per Flight	Per Year
Fuel	$20	$34,052
Maintenance	$10	$17,056
Carbon Credits	$2	$3,531
Turnaround Benefits	$110	$188,823
Total	$142	$243,462
NPV	$2,295,095	Present value of benefits. Doesn't include purchase price. Assumes 10% cost of capital and 30-year life of plane.

Picture 8.1 input and results of www.wheeltug.com

As seen the method of the site is about the same, they seem to have aproximatly the same fuel reduction. The maintenance price is bigger, but this is due to the whole system and electric they have. prices are aproximatly the same. This paper has a total reduction of aproximatly 215$ in total, so it is quite the same.

In **table 8.1** the comparison between the 2 calculations are shown.

Cost	Calculation $	Wheeltug $
Fuel saving	26	20
Maintenance	0.052	10
benefits	110	194
Total cost	142	221

Table 8.1 comparison with Wheeltug

8.3 Further development

This is only the theoretical case study. For integration in the whole aircraft the following procedures and tasks have to be worked on.

- If the aircraft is used for 1 flight route then an airport depending procedure to optimize the procedure can be made. This in means of exact taxi times and thus optimal use of both main engines in combination with the APU.
- For overall use an optimalization of the systems can be done, so the procedures are easier to perform on different airports.
- A total cost saving calculation in terms of the aircraft DOC. All the weight changes for making the low fare aircraft might have an effect on the amount of passengers. And thus the DOC has to be changed.
- Depending on the transport of cargo or persons, there are critical cost changes. As said in chapter 7.3, when the OEW changes, the payload changes. And that cooperates with the revenue factor. In the case of cargo transport, there are large losses of about 60€/flight.
- If the MTOW is changed, there have to be structural modifications or an increase of power. This can make the costs higher and thus has to be worked on.
- A new calculation of fuel savings due to the possible use of a Fuel Cell APU.

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APPENDIX A1

Current procedure : Pushback and Taxiing										
time		APU start	Pushback start	engine 1 start	engine 2 start	Taxi start	engine full power	APU fuel consumption kg	Main engine Fuel Consumption kg	Total fuel consumption
0:00:00	0:15:10	x						37,91667		37,92
0:15:10	0:15:20	x						0,20833		0,21
0:15:20	0:15:30	x	x					0,20833		0,21
0:15:30	0:15:40	x	x					0,20833		0,21
0:15:40	0:15:50	x	x					0,20833		0,21
0:15:50	0:16:00	x	x	x				0,20833	0,7639	0,97
0:16:00	0:16:10	x	x	x				0,20833	0,7639	0,97
0:16:10	0:16:20	x	x	x				0,20833	0,7639	0,97
0:16:20	0:16:30	x	x	x				0,20833	0,7639	0,97
0:16:30	0:16:40	x	x	x				0,20833	0,7639	0,97
0:16:40	0:16:50	x	x	x				0,20833	0,7639	0,97
0:16:50	0:17:00	x		x	x			0,20833	1,5278	1,74
0:17:00	0:17:10	x		x	x			0,20833	1,5278	1,74
0:17:10	0:17:20			x	x				1,5278	1,53
0:17:20	0:17:30			x	x				1,5278	1,53
0:17:30	0:17:40			x	x				1,5278	1,53
0:17:40	0:17:50			x	x				1,5278	1,53
0:17:50	0:18:00			x	x				1,5278	1,53
0:18:00	0:18:10			x	x				1,5278	1,53
0:18:10	0:18:20			x	x				1,5278	1,53
0:18:20	0:18:30			x	x				1,5278	1,53
0:18:30	0:18:40			x	x				1,5278	1,53
0:18:40	0:18:50			x	x				1,5278	1,53
0:18:50	0:19:00			x	x				1,5278	1,53
0:19:00	0:19:10			x	x				1,5278	1,53
0:19:10	0:19:20			x	x				1,5278	1,53
0:19:20	0:19:30			x	x				1,5278	1,53
0:19:30	0:19:40			x	x				1,5278	1,53
0:19:40	0:19:50			x	x	x			1,5278	1,53
0:19:50	0:20:00			x	x	x			1,5278	1,53
0:20:00	0:20:10			x	x	x			1,5278	1,53
0:20:10	0:20:20			x	x	x			1,5278	1,53
0:20:20	0:20:30			x	x	x			1,5278	1,53
0:20:30	0:20:40			x	x	x			1,5278	1,53
0:20:40	0:20:50			x	x	x			1,5278	1,53
0:20:50	0:21:00			x	x	x			1,5278	1,53
0:21:00	0:21:10			x	x	x			1,5278	1,53
0:21:10	0:21:20			x	x	x			1,5278	1,53
0:21:20	0:21:30			x	x	x			1,5278	1,53
0:21:30	0:21:40			x	x	x			1,5278	1,53
0:21:40	0:21:50			x	x	x			1,5278	1,53
0:21:50	0:22:00			x	x	x			1,5278	1,53

0:22:00	0:22:10			x	x	x			1,5278	1,53
0:22:10	0:22:20			x	x	x			1,5278	1,53
0:22:20	0:22:30			x	x	x			1,5278	1,53
0:22:30	0:22:40			x	x	x			1,5278	1,53
0:22:40	0:22:50			x	x	x			1,5278	1,53
0:22:50	0:23:00			x	x	x			1,5278	1,53
0:23:00	0:23:10			x	x	x			1,5278	1,53
0:23:10	0:23:20			x	x	x			1,5278	1,53
0:23:20	0:23:30			x	x	x			1,5278	1,53
0:23:30	0:23:40			x	x	x			1,5278	1,53
0:23:40	0:23:50			x	x	x			1,5278	1,53
0:23:50	0:24:00			x	x	x			1,5278	1,53
0:24:00	0:24:10			x	x	x			1,5278	1,53
0:24:10	0:24:20			x	x	x			1,5278	1,53
0:24:20	0:24:30			x	x	x			1,5278	1,53
0:24:30	0:24:40			x	x	x			1,5278	1,53
0:24:40	0:24:50			x	x	x			1,5278	1,53
0:24:50	0:25:00			x	x	x			1,5278	1,53
0:25:00	0:25:10			x	x	x			1,5278	1,53
0:25:10	0:25:20			x	x	x			1,5278	1,53
0:25:20	0:25:30			x	x	x			1,5278	1,53
0:25:30	0:25:40			x	x	x			1,5278	1,53
0:25:40	0:25:50			x	x	x			1,5278	1,53
0:25:50	0:26:00			x	x	x			1,5278	1,53
0:26:00	0:26:10			x	x	x			1,5278	1,53
0:26:10	0:26:20			x	x	x			1,5278	1,53
0:26:20	0:26:30			x	x	x			1,5278	1,53
0:26:30	0:26:40			x	x	x			1,5278	1,53
0:26:40	0:26:50			x	x	x			1,5278	1,53
0:26:50	0:27:00			x	x	x			1,5278	1,53
0:27:00	0:27:10						x			
0:27:10	0:27:20						x			
0:27:20	0:27:30						x			
0:27:30	0:27:40						x			
0:27:40	0:27:50						x			

APPENDIX A2

only autonomous pushback											
time		APU start	Pushback start	engine 1 start	engine 2 start	Taxi start	engine full power	APU fuel consumption kg	Head engine Fuel Consumption kg	Total fuel consumption
0:00:00	0:15:10	x						37,91667		37,92
0:15:10	0:15:20	x						0,41667		0,42
0:15:20	0:15:30	x	x					0,48611		0,49
0:15:30	0:15:40	x	x					0,48611		0,49
0:15:40	0:15:50	x	x					0,48611		0,49
0:15:50	0:16:00	x	x					0,48611		0,49
0:16:00	0:16:10	x	x					0,48611		0,49
0:16:10	0:16:20	x	x					0,48611		0,49
0:16:20	0:16:30	x	x					0,48611		0,49
0:16:30	0:16:40	x	x					0,48611		0,49
0:16:40	0:16:50	x	x					0,48611		0,49
0:16:50	0:17:00	x						0,41667		0,42
0:17:00	0:17:10	x		x				0,41667	0,7639	1,18
0:17:10	0:17:20	x		x				0,41667	0,7639	1,18
0:17:20	0:17:30	x		x				0,41667	0,7639	1,18
0:17:30	0:17:40	x		x	x			0,41667	1,5278	1,94
0:17:40	0:17:50	x		x	x			0,41667	1,5278	1,94
0:17:50	0:18:00			x	x				1,5278	1,53
0:18:00	0:18:10			x	x				1,5278	1,53
0:18:10	0:18:20			x	x				1,5278	1,53
0:18:20	0:18:30			x	x				1,5278	1,53
0:18:30	0:18:40			x	x	x			1,5278	1,53
0:18:40	0:18:50			x	x	x			1,5278	1,53
0:18:50	0:19:00			x	x	x			1,5278	1,53
0:19:00	0:19:10			x	x	x			1,5278	1,53
0:19:10	0:19:20			x	x	x			1,5278	1,53
0:19:20	0:19:30			x	x	x			1,5278	1,53
0:19:30	0:19:40			x	x	x			1,5278	1,53
0:19:40	0:19:50			x	x	x			1,5278	1,53
0:19:50	0:20:00			x	x	x			1,5278	1,53
0:20:00	0:20:10			x	x	x			1,5278	1,53
0:20:10	0:20:20			x	x	x			1,5278	1,53
0:20:20	0:20:30			x	x	x			1,5278	1,53
0:20:30	0:20:40			x	x	x			1,5278	1,53
0:20:40	0:20:50			x	x	x			1,5278	1,53
0:20:50	0:21:00			x	x	x			1,5278	1,53
0:21:00	0:21:10			x	x	x			1,5278	1,53
0:21:10	0:21:20			x	x	x			1,5278	1,53
0:21:20	0:21:30			x	x	x			1,5278	1,53
0:21:30	0:21:40			x	x	x			1,5278	1,53
0:21:40	0:21:50			x	x	x			1,5278	1,53
0:21:50	0:22:00			x	x	x			1,5278	1,53

0:22:00	0:22:10			x	x	x			1,5278	1,53
0:22:10	0:22:20			x	x	x			1,5278	1,53
0:22:20	0:22:30			x	x	x			1,5278	1,53
0:22:30	0:22:40			x	x	x			1,5278	1,53
0:22:40	0:22:50			x	x	x			1,5278	1,53
0:22:50	0:23:00			x	x	x			1,5278	1,53
0:23:00	0:23:10			x	x	x			1,5278	1,53
0:23:10	0:23:20			x	x	x			1,5278	1,53
0:23:20	0:23:30			x	x	x			1,5278	1,53
0:23:30	0:23:40			x	x	x			1,5278	1,53
0:23:40	0:23:50			x	x	x			1,5278	1,53
0:23:50	0:24:00			x	x	x			1,5278	1,53
0:24:00	0:24:10			x	x	x			1,5278	1,53
0:24:10	0:24:20			x	x	x			1,5278	1,53
0:24:20	0:24:30			x	x	x			1,5278	1,53
0:24:30	0:24:40			x	x	x			1,5278	1,53
0:24:40	0:24:50			x	x	x			1,5278	1,53
0:24:50	0:25:00			x	x	x			1,5278	1,53
0:25:00	0:25:10			x	x	x			1,5278	1,53
0:25:10	0:25:20			x	x	x			1,5278	1,53
0:25:20	0:25:30			x	x	x			1,5278	1,53
0:25:30	0:25:40			x	x	x			1,5278	1,53
0:25:40	0:25:50			x	x	x			1,5278	1,53
0:25:50	0:26:00						x			
0:26:00	0:26:10						x			
0:26:10	0:26:20						x			
0:26:20	0:26:30						x			
0:26:30	0:26:40						x			

APPENDIX A3

New procedure : Autonomous Pushback and Taxiing										
time		APU start	Pushback start	engine 1 start	engine 2 start	Taxi start	engine full power	APU fuel consumption kg	Head engine Fuel Consumption kg	Total fuel consumption
0:00:00	0:15:10	x						37,91667		37,92
0:15:10	0:15:20	x						0,41667		0,42
0:15:20	0:15:30	x	x					0,48611		0,49
0:15:30	0:15:40	x	x					0,48611		0,49
0:15:40	0:15:50	x	x					0,48611		0,49
0:15:50	0:16:00	x	x					0,48611		0,49
0:16:00	0:16:10	x	x					0,48611		0,49
0:16:10	0:16:20	x	x					0,48611		0,49
0:16:20	0:16:30	x	x					0,48611		0,49
0:16:30	0:16:40	x	x					0,48611		0,49
0:16:40	0:16:50	x	x					0,48611		0,49
0:16:50	0:17:00	x						0,41667		0,42
0:17:00	0:17:10	x						0,41667		0,42
0:17:10	0:17:20	x				x		0,48611		0,49
0:17:20	0:17:30	x				x		0,48611		0,49
0:17:30	0:17:40	x				x		0,48611		0,49
0:17:40	0:17:50	x				x		0,48611		0,49
0:17:50	0:18:00	x				x		0,48611		0,49
0:18:00	0:18:10	x				x		0,48611		0,49
0:18:10	0:18:20	x				x		0,48611		0,49
0:18:20	0:18:30	x				x		0,48611		0,49
0:18:30	0:18:40	x				x		0,48611		0,49
0:18:40	0:18:50	x				x		0,48611		0,49
0:18:50	0:19:00	x				x		0,48611		0,49
0:19:00	0:19:10	x				x		0,48611		0,49
0:19:10	0:19:20	x		x		x		0,48611	0,7639	1,25
0:19:20	0:19:30	x		x		x		0,48611	0,7639	1,25
0:19:30	0:19:40	x		x	x	x		0,48611	1,5278	2,01
0:19:40	0:19:50	x		x	x	x		0,48611	1,5278	2,01
0:19:50	0:20:00	x		x	x	x		0,48611	1,5278	2,01
0:20:00	0:20:10	x		x	x	x		0,48611	1,5278	2,01
0:20:10	0:20:20	x		x	x	x		0,48611	1,5278	2,01
0:20:20	0:20:30	x		x	x	x		0,48611	1,5278	2,01
0:20:30	0:20:40	x		x	x	x		0,48611	1,5278	2,01
0:20:40	0:20:50	x		x	x	x		0,48611	1,5278	2,01
0:20:50	0:21:00	x		x	x	x		0,48611	1,5278	2,01
0:21:00	0:21:10	x		x	x	x		0,48611	1,5278	2,01
0:21:10	0:21:20	x		x	x	x		0,48611	1,5278	2,01
0:21:20	0:21:30	x		x	x	x		0,48611	1,5278	2,01
0:21:30	0:21:40	x		x	x	x		0,48611	1,5278	2,01
0:21:40	0:21:50	x		x	x	x		0,48611	1,5278	2,01
0:21:50	0:22:00	x		x	x	x		0,48611	1,5278	2,01

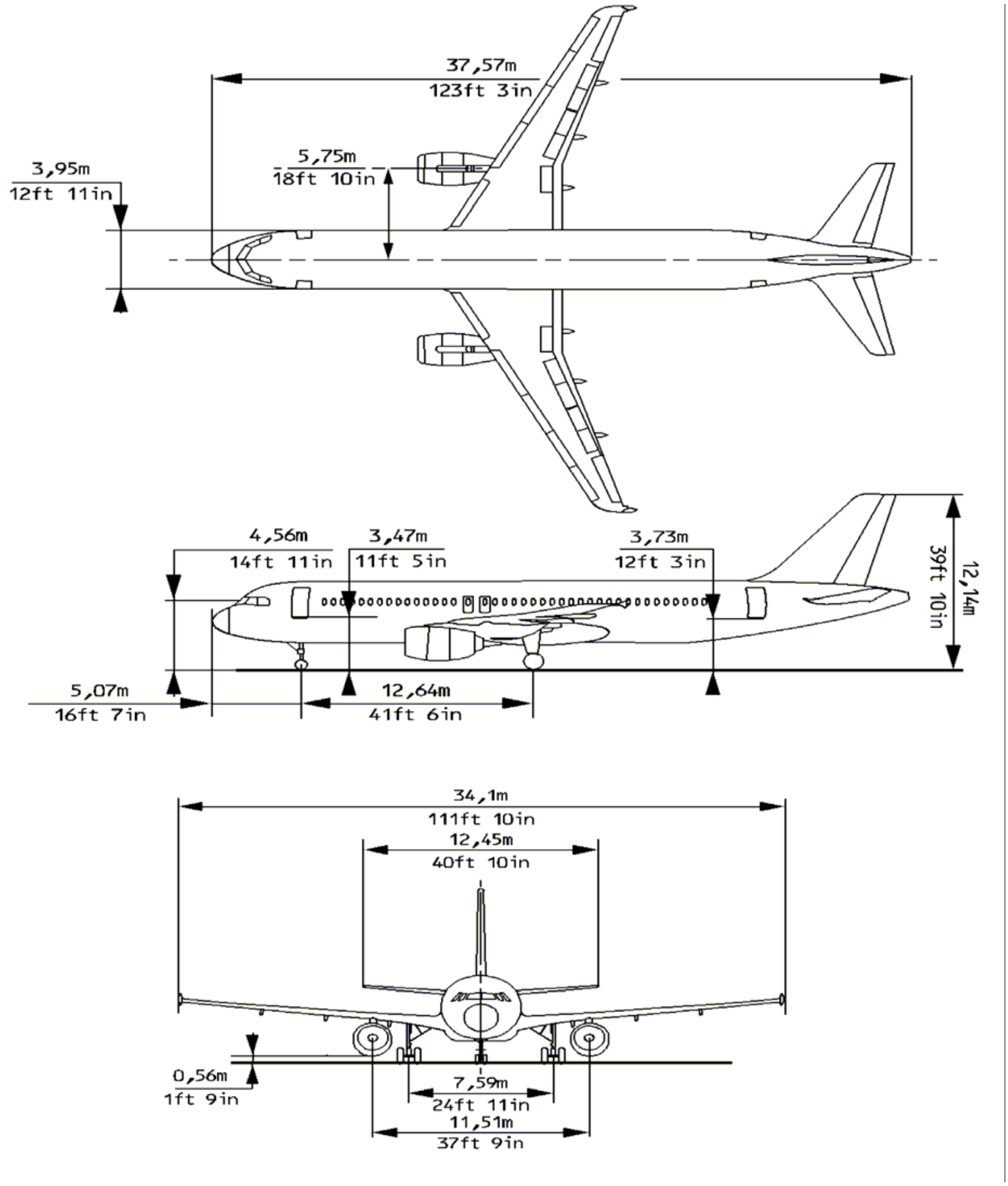
0:22:00	0:22:10	x		x	x	x		0,48611	1,5278	2,01
0:22:10	0:22:20	x		x	x	x		0,48611	1,5278	2,01
0:22:20	0:22:30	x		x	x	x		0,48611	1,5278	2,01
0:22:30	0:22:40	x		x	x	x		0,48611	1,5278	2,01
0:22:40	0:22:50	x		x	x	x		0,48611	1,5278	2,01
0:22:50	0:23:00	x		x	x	x		0,48611	1,5278	2,01
0:23:00	0:23:10	x		x	x	x		0,48611	1,5278	2,01
0:23:10	0:23:20	x		x	x	x		0,48611	1,5278	2,01
0:23:20	0:23:30	x		x	x	x		0,48611	1,5278	2,01
0:23:30	0:23:40	x		x	x	x		0,48611	1,5278	2,01
0:23:40	0:23:50	x		x	x	x		0,48611	1,5278	2,01
0:23:50	0:24:00	x		x	x	x		0,48611	1,5278	2,01
0:24:00	0:24:10	x		x	x	x		0,48611	1,5278	2,01
0:24:10	0:24:20	x		x	x	x		0,48611	1,5278	2,01
0:24:20	0:24:30	x		x	x	x		0,48611	1,5278	2,01
0:24:30	0:24:40						x			
0:24:40	0:24:50						x			
0:24:50	0:25:00						x			
0:25:00	0:25:10						x			
0:25:10	0:25:20						x			

APPENDIX A4

Full Towing											
time		APU start	Pushback start	engine 1 start	engine 2 start	Taxi start	engine full power	APU fuel consumption kg	Head engine Fuel Consumption kg	Total fuel consumption
0:00:00	0:15:10	x						37,91667		37,92
0:15:10	0:15:25	x						0,62500		0,63
0:15:25	0:15:40	x	x					0,62500		0,63
0:15:40	0:15:55	x	x					0,62500		0,63
0:15:55	0:16:10	x	x					0,62500		0,63
0:16:10	0:16:25	x	x					0,62500		0,63
0:16:25	0:16:40	x	x					0,62500		0,63
0:16:40	0:16:55	x	x					0,62500		0,63
0:16:55	0:17:10	x						0,62500		0,63
0:17:10	0:17:25	x				x		0,62500		0,63
0:17:25	0:17:40	x				x		0,62500		0,63
0:17:40	0:17:55	x				x		0,62500		0,63
0:17:55	0:18:10	x				x		0,62500		0,63
0:18:10	0:18:25	x				x		0,62500		0,63
0:18:25	0:18:40	x				x		0,62500		0,63
0:18:40	0:18:55	x				x		0,62500		0,63
0:18:55	0:19:10	x		x		x		0,62500	1,1458	1,77
0:19:10	0:19:25			x		x			1,1458	1,15
0:19:25	0:19:40			x		x			1,1458	1,15
0:19:40	0:19:55			x	x	x			2,2917	2,29
0:19:55	0:20:10			x	x	x			2,2917	2,29
0:20:10	0:20:25			x	x	x			2,2917	2,29
0:20:25	0:20:40			x	x	x			2,2917	2,29
0:20:40	0:20:55			x	x	x			2,2917	2,29
0:20:55	0:21:10			x	x	x			2,2917	2,29
0:21:10	0:21:25			x	x	x			2,2917	2,29
0:21:25	0:21:40			x	x	x			2,2917	2,29
0:21:40	0:21:55			x	x	x			2,2917	2,29
0:21:55	0:22:10			x	x	x			2,2917	2,29
0:22:10	0:22:25			x	x	x			2,2917	2,29
0:22:25	0:22:40			x	x	x			2,2917	2,29
0:22:40	0:22:55			x	x	x			2,2917	2,29
0:22:55	0:23:10			x	x	x			2,2917	2,29
0:23:10	0:23:25			x	x	x			2,2917	2,29
0:23:25	0:23:40			x	x	x			2,2917	2,29
0:23:40	0:23:55			x	x	x			2,2917	2,29
0:23:55	0:24:10			x	x	x			2,2917	2,29
0:24:10	0:24:25			x	x	x			2,2917	2,29
0:24:25	0:24:40			x	x	x			2,2917	2,29
0:24:40	0:24:55			x	x				2,2917	2,29
0:24:55	0:25:10			x	x				2,2917	2,29
0:25:10	0:25:25			x	x				2,2917	2,29

0:25:25	0:25:40			x	x				2,2917	2,29
0:25:40	0:25:55			x	x				2,2917	2,29
0:25:55	0:26:10			x	x				2,2917	2,29
0:26:10	0:26:25			x	x		x		2,2917	2,29
0:26:25	0:26:40						x			
0:26:40	0:26:55						x			
0:26:55	0:27:10						x			
0:27:10	0:27:25						x			

APPENDIX B1

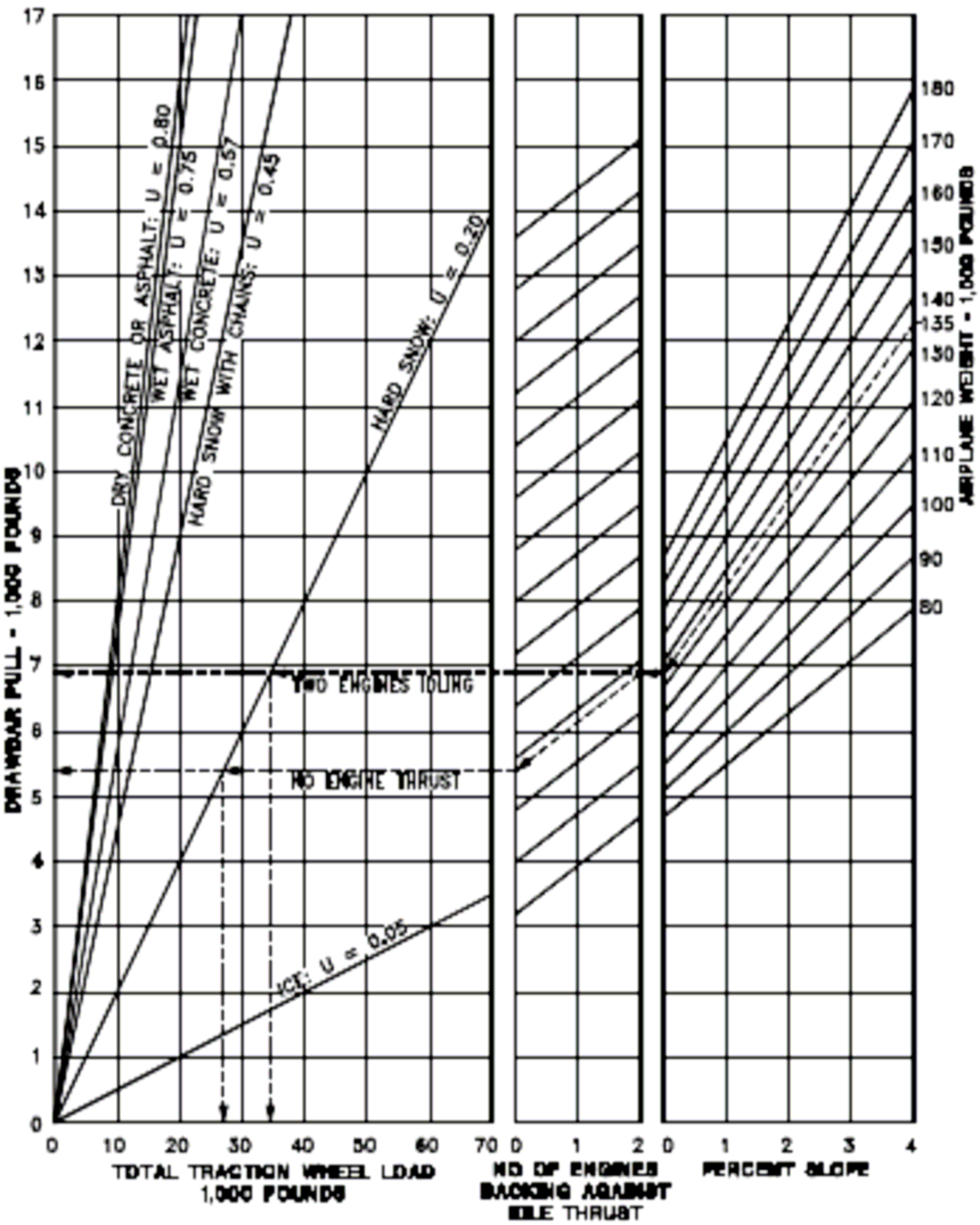


37,57m
123ft 3in
5,75m
18ft 10in
3,95m
12ft 11in
4,56m
14ft 11in
3,47m
11ft 5in
3,73m
12ft 3in
12,14m
39ft 10in
5,07m
16ft 7in
12,64m
41ft 6in
34,1m
111ft 10in
12,45m
40ft 10in
0,56m
1ft 9in
7,59m
24ft 11in
11,51m
37ft 9in

APPENDIX B2

PRELIMINARY INFORMATION

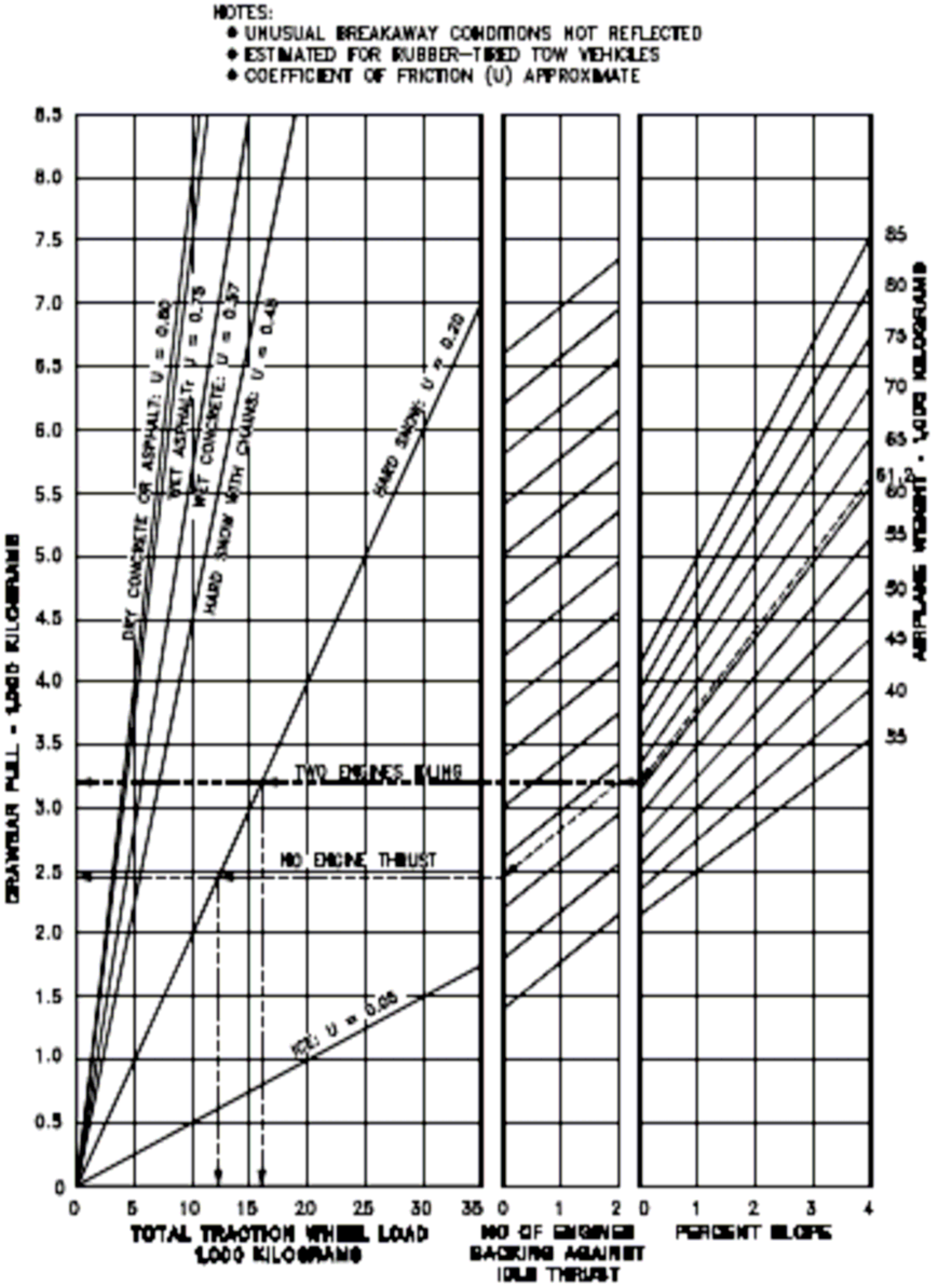
NOTES:
- UNUSUAL BREAKAWAY CONDITIONS NOT REFLECTED
- ESTIMATED FOR RUBBER-TIRED TOW VEHICLES
- COEFFICIENT OF FRICTION (U) APPROXIMATE



5.8.1 GROUND TOWING REQUIREMENTS - ENGLISH UNITS

MODEL 737-600, -700, -800, -900

PRELIMINARY INFORMATION



5.8.2 GROUND TOWING REQUIREMENTS - METRIC UNITS

MODEL 737-600, -700, -800, -900

APPENDIX C

Table F-3. Engine Modal Efs (kgs/min)		TK	TK	TK	TK	CB	CB	CB	CB
Body Type		THCef	COef	NOXef	SO2ef	THCef	COef	NOXef	SO2ef
AIRBUS	A300-600	0.02168	0.16106	10.64828	0.16725	0.01999	0.12992	5.71140	0.13491
AIRBUS	A300-B4	0.17287	0.12348	7.65584	0.13336	0.14415	0.10296	5.39516	0.11120
AIRBUS	A310-200	0.04067	0.14487	10.57316	0.13725	0.02689	0.10965	7.07537	0.11172
AIRBUS	A310-300	0.03396	0.03135	7.02743	0.14107	0.03427	0.03641	4.86239	0.11567
AIRBUS	A320-200	0.02901	0.11351	3.10258	0.06811	0.02379	0.09310	2.02745	0.05586
BEECH	18(CARG)	0.00000	0.00000	0.00000	0.00001	0.00000	0.00000	0.00000	0.00001
BEECH	B. 99A	0.00000	0.00642	0.05014	0.00347	0.00000	0.00726	0.04234	0.00327
BOEING	B707-300B	1.12705	0.42264	3.40933	0.15215	0.44736	0.62631	2.21445	0.12079
BOEING	B707-300C	1.12705	0.42264	3.40933	0.15215	0.44736	0.62631	2.21445	0.12079
BOEING	B727-100	0.06935	0.25961	3.04604	0.09615	0.07046	0.28287	1.97659	0.07886
BOEING	B727-100(CARG)	0.07053	0.26521	3.05925	0.09630	0.07209	0.28928	1.97814	0.07896
BOEING	B727-200	0.05736	0.18889	3.35563	0.09768	0.05206	0.19858	2.10413	0.07880
BOEING	B737-100	0.03545	0.13785	2.40397	0.06984	0.03467	0.13291	1.49600	0.05655
BOEING	B737-200	0.03545	0.13785	2.40397	0.06984	0.03467	0.13291	1.49600	0.05655
BOEING	B737-200(CARG)	0.05589	0.13227	2.61690	0.07452	0.05202	0.13051	1.62092	0.05988
BOEING	B737-200C	0.05669	0.13267	2.61345	0.07452	0.05260	0.13171	1.62033	0.05988
BOEING	B737-300	0.00456	0.11405	2.45839	0.06843	0.00495	0.09482	1.75953	0.05689
BOEING	B737-400	0.00456	0.11405	2.45839	0.06843	0.00495	0.09482	1.75953	0.05689
BOEING	B737-500	0.00415	0.12463	2.86657	0.07478	0.00458	0.10303	2.03776	0.06182
BOEING	B747	0.11721	0.11721	18.51956	0.31647	0.09598	0.09598	12.28567	0.25915
BOEING	B747(CARG)	0.15604	0.20805	23.92613	0.28087	0.12701	0.16935	14.56373	0.22862
BOEING	B747-200	0.12482	0.13475	19.05529	0.31435	0.10306	0.10814	12.51082	0.25670
BOEING	B747-400	0.01099	0.16906	14.49670	0.22823	0.01216	0.13901	9.48739	0.18766
BOEING	B747-SP	0.15022	0.19443	23.11515	0.28621	0.12236	0.15834	14.22202	0.23320
BOEING	B747F(CARG)	0.12675	0.17918	20.91499	0.30454	0.10258	0.13938	13.27545	0.24729
BOEING	B757-200	0.00896	0.07609	5.90570	0.10088	0.00883	0.06300	3.86390	0.08302
BOEING	B757-200(CARG)	0.00804	0.18880	10.58901	0.11886	0.00292	0.18300	6.08740	0.09680
BOEING	B767-200	0.06106	0.21283	8.21013	0.14136	0.05892	0.18995	5.89160	0.11730
BOEING	B767-300	0.02166	0.16093	9.53518	0.16712	0.01998	0.12986	5.72864	0.13485
BRITAIRCOR	BAE-111-200	0.00258	0.01289	0.58142	0.02321	0.00188	0.00887	0.37446	0.01915
BRITAIRCOR	BAE-146-1	0.00516	0.02578	1.16283	0.04641	0.00376	0.01773	0.74892	0.03830
CONVAIR	CV 640	0.00000	0.05623	0.10991	0.01380	0.00000	0.06120	0.07956	0.01102
DE HAVILLAND	DHC-6	0.00651	0.02374	2.04463	0.03186	0.00536	0.02323	1.43773	0.02653
FAIRCHILD	FH-227	0.02136	0.06835	0.11962	0.01153	0.02072	0.06594	0.08478	0.01017
FOKKER	F-27 SERIES	0.02136	0.06835	0.11962	0.01153	0.02072	0.06594	0.08478	0.01017

APPENDIX D

By Francisco Gomez Carrasco

Main Input		Unit	**A320-200**	**A320-APS**
Average Stage Lenght	R	km	**1025**	**1025**
Cruise speed	Vc	km/h	**871,2**	**871,2**
Flight time	tf	h	**1,176538108**	**1,176538108**
Block time	tb=tf+0.25	h	1,426538108	1,426538108
Yearly Flight Time	Ku1	h	3750	3750
Block time supplement per flight	Ku2	h	0,75	0,75
Annual Aircraft Utilization Ua,f	Ua,f	h	**2290,127502**	**2290,127502**
Annual Aircraft Utilization Ua,b	Ua,b	h	**2457,810358**	**2457,810358**
Yearly Flight Cycles(based on block time!)	nt,a	-	**1722,919523**	**1722,919523**
MTOW		kg	**75500**	**75600**
OEW		kg	**41310**	**41310**
MZFW		kg	**60500**	**60500**
Number of passengers	nPAX	-	**179**	**179**
SLS Engine Thrust	T	kN	**111,7**	**111,7**
Number of enginers	nE	-	**2**	**2**

Depreciation cost				
Useful service life	nDEP	years	14	14
Devilery price MTOW based	Pdev1	USD	37750000	37800000
Devilery price OEW based	Pdev2	USD	35526600	35526600
Devilery price nPAX based	Pdev3	USD	47435000	47435000
Chosen delivery price(from above)	Pdev	USD	**37750000**	**37750000**
Residual Ratio	Pres/Pdev	-	0,1	0,1
Engine Price	PE	USD	3595759,947	3595759,947
Airframe Price	PAF	USD	30558480,11	30558480,11
AF spare contribution	Ks,af	-	0,1	0,1
Engine spare contribution	Ks,e	-	0,3	0,3
Spare Prices	Ps	USD	5213303,979	5213303,979
Total Price	Ptotal	USD	42963303,98	42963303,98
Depreciation cost	**CDEP**	**USD**	**2761926,684**	**2761926,684**

Interest cost				
Interest rate	p	-	0,08	0,08
Interest rate + 1	q		1,08	1,08
Payment years	nPAY	years	14	14
Residual value of outside capital	kn/ko	-	0,1	0,1
Average Interest Rate	pav	-	0,052881453	0,052881453
Interest cost	**CINT**	**USD**	**1996274,861**	**1996274,861**

Insurance cost				
Insurance parameter	kINS	-	0,005	0,005
Insurance cost	**CINS**	**USD**	**188750**	**188750**

Fuel cost				
TSFC	TSFC	1/h	0,6	0,6
Aerodinamic efficiency	E	-	19,439	19,439

Breguet Range Factor	B	km	28225,428	28225,428
Cruise mass ratio		-	0,964336699	0,964336699
Engine start mass ratio		-	0,99	0,99
Taxi mass ratio		-	0,99	0,99
Take off mass ratio		-	0,995	0,995
Climb mass ratio		-	0,98	0,98
Descent mass ratio		-	0,99	0,99
Landing mass ratio		-	0,992	0,992
Total mass ratio		-	0,905096962	0,905096962
Breguet regression factor	f	-	1,200681879	1,200681879
Corrected Cruise mass ratio		-	0,957334432	0,957334432
Mass ratio(choose corrected or total)		-	**0,905096962**	**0,905096962**
TOW		kg	66843,6671	66843,6671
Mission fuel mass	m_F	kg	6343,667099	6343,667099
Fuel price(check IATA)	P_F	USD/kg	0,76	0,76
Fuel cost	**C_F**	**USD**	**8306517,199**	**8306517,199**

Maintenance cost

Maintenance man hour	LM	USD	65	65
Engine mass(check manufacturer)	mE	kg	**3500**	**3500**
Installation correction	K_eK_{thr}	-	1,357	1,357
Engine installation mass	ME,inst	-	9499	9499
Airframe mass	MAF	kg	31811	31811
Bypass Ratio	BPR	-	4,8	4,8
Overall Average Pressure Ratio	OAPR	-	27,4	27,4
MMH AF per flight hour	MMH/FH	1/h	8,548951247	8,548951247
AF maintenance cost per FH	$C_{M,M,AF,f}$	USD/h	176,3161694	176,3161694
Engine correction 1	k_1	-	0,996297828	0,996297828
Engine correction 2	k_2	-	1,002277624	1,002277624
Engine correction 3	k_3	-	1,018	1,018
Engine correction 4	k_4	-	0,57	0,57
Number of compressor stages	n_c	-	14	14
Number of shafts of the engine	n_s	-	2	2
MMH E per flight hour	MMH/E	1/h	2,454151987	2,454151987
E maintenance cost per FH	$C_{M,M,E,f}$	USD/h	21,8899771	21,8899771
Annual mean inflation rate	p_{INF}	-	0,033	0,033
Years from 1989	n_Y	years	**18**	**18**
Inflation factor	k_{INF}	-	1,793931217	1,793931217
Maintenance cost	**C_M**	USD	**3321555,559**	**3321555,559**

Staff cost

Cockpit crew	n_{CO}	-	2	2
Cabin crew	n_{CA}	-	5,114285714	5,114285714
Cockpit crew mean hourly rate	L_{CO}	USD	246,5	246,5
Cabin crew mean hourly rate	L_{CA}	USD	81	81
Staff cost	**C_C**	**USD**	**2229866,003**	**2229866,003**

Fees and charges

Landing parameter	k_{LD}	USD/kg	0,0078	0,0078
Landing fee	**$C_{FEE,LD}$**	**USD**	**1820171,6**	**1822582,424**
Navigation parameter	k_{NAV}	USD/kmkg^.5	0,0022356	0,0022356
Navigation fee	**$C_{FEE,NAV}$**	**USD**	**1946086,866**	**1947375,239**
Handling parameter	k_{GND}	USD/kg	0,05	0,05

Handling fee	**$C_{FEE,GND}$**	**USD**	**2965621,753**	**2965621,753**

cost type	A320-200($)	A320 APS ($)
DOC	25536770,53	25540469,72
DOC/SEATS	142663,5225	142684,1884
DOC/SEATTRIP	82,80335823	82,81535293
DOC/TRIP	14821,80112	14823,94817
Δ DOC/TRIP	2,147051002	

APPENDIX E

	amount of flights (see DOC costs)			1722,92					
just pushback	engine time per flight			5					
			FH	0,083333	[min]				
		100 working hours		2500 working hours		5000 operating hours		10000 operating hours	
						replace lubricant			
		visual control		visual + romove dust		dispenser		change oil	
mean time between failure	MTBF	100	[h]	2500	[h]	5000	[h]	10000	[h]
failure to removal ratio	FTRR	0,6	[ ]	0,6	[ ]	0,6	[ ]	0,6	[ ]
flight hours a year	FH	143,5766	[FH]	143,5766	[FH]	143,5766	[FH]	143,5766	[FH]
repair time on plane	RT on	0,1	[h]	0,5	[h]	1	[h]	1	[h]
repair time off plane	RT off	0	[h]	0	[h]	0	[h]	0	[h]
labor rate per flight hour	LR/FH	69	[$/FH]	69	[$/FH]	69	[$/FH]	69	[$/FH]
material costs		0	[$]	0	[$]	500	[$]	1000	[$]
	MTUBR	60,00	[h]	1500,00	[h]	3000,00	[h]	6000,00	[h]
Mean time bewteen unscheduled removals									
	nm	2,392944	[FH/h]	0,095718	[FH/h]	0,047859	[FH/h]	0,023929	[FH/h]
line maintenance	MMHon	0,239294	[h]	0,047859	[FH]	0,047859	[FH]	0,023929	[FH]
price		16,51131	[$]						
shop maintenance	MMHoff	0	[h]	0		0		0	
		0	[$]						
Direct maintenance cost	DMC	16,51131	[$]	3,302262	[$]	503,3023	[$]	1001,651	[$]
Total costs	1524,766968								
total costs per flight	0,012706391								

pushback and taxi	amount of flights (depending on DOC costs PACO)					1723			
	engine time per flight					20	[min]	0,333333	[h]
		100 working hours		2500 working hours		5000 operating hours		10000 operating hours	
						replace lubricant			
		visual control		visual + romove dust		dispenser		change oil	
mean time between failure	MTBF	100	[h]	2500	[h]	5000	[h]	10000	[h]
failure to removal ratio	FTRR	0,6	[ ]	0,6	[ ]	0,6	[ ]	0,6	[ ]
flight hours a year	FH	574,3333	[FH]	574,3333	[FH]	574,3333	[FH]	574,3333	[FH]
repair time on plane	RT on	0,05	[h]	0,5	[h]	1	[h]	1	[h]
repair time off plane	RT off	0	[h]	0	[h]	0	[h]	0	[h]
labor rate per flight hour	LR/FH	69	[$/FH]	69	[$/FH]	69	[$/FH]	69	[$/FH]
material costs		0	[$]			500		1000	
Mean time bewteen unscheduled removals	MTUBR	60,00	[h]	1500,00	[h]	3000,00	[h]	6000,00	[h]
	nm	9,572222	[FH/h]	0,382889	[FH/h]	0,191444	[FH/h]	0,095722	[FH/h]
line maintenance	MMHon	0,478611	[h]	0,191444	[FH]	0,191444	[FH]	0,095722	[FH]
price		33,02417	[$]						
shop maintenance	MMHoff	0	[h]	0		0		0	
		0	[$]						
Direct maintenance cost	DMC	33,02417	[$]	13,20967	[$]	513,2097	[$]	1006,605	[$]
Total costs	1566,048333								
total costs per flight	0,052201611								

APPENDIX E

This appendix contains the CD with the pdf file and excel worksheets.