INFLUENCE OF THE BYPASS RATIO ON LOW ALTITUDE NO_X EMISSIONS

H. Hemmer, T. Otten, M. Plohr, M. Lecht, A. Döpelheuer
German Aerospace Center (DLR), Institute of Propulsion Technology
Linder Höhe, 51147 Cologne
Germany

1. ABSTRACT

The goals defined by the ACARE Vision 2020, to reduce aircraft fuel consumption per passenger kilometer by 50%, NO_X production by 80% and to halve current perceived noise levels present a major challenge to aerospace industry.

The most important emission species are CO_2 and NO_x, both are contributing to the environmental impact of aircraft. Beside its effect on global climate the reduction of NO_x is also of special interest in the vicinity of airports due to its negative effects on airport air quality and health.

The scope of this study is to assess the influence of the bypass ratio of future engine concepts on low altitude engine NO_x emissions and fuel consumption. An overview of concepts achievable in near-term is given, by which realisation of ultra high bypass ratio cycles will become possible. These concepts include engines with a geared fan as well as with contra rotating fans and turbines.

Special emphasis is laid on the selection of the engine size for a given aircraft in order to fulfil all thrust requirements of a typical aircraft mission. Differences between this “engine-sizing” of today’s engines and future ultra high bypass ratio fan engines - so called UHB engines - are investigated by the use of detailed aircraft mission simulation based on existing data of aircraft/engine combinations and data derived for future engines. The trade-off effects and interdependencies of improved components with respect to the whole aircraft are considered, including engine weight and drag.

The CO_2 and NO_x emissions of today’s engines and UHB engines in the vicinity of airports are calculated using detailed takeoff and approach procedures. The effect of the thrust excess of the UHB engines on NO_x is discussed considering different aspects such as part load or steep takeoff. Several engines with different BPR are compared in order to quantify these effects. Beside the low altitude emissions, the resulting effects on the overall mission are presented.

2. NOMENCLATURE

ATA	Air Transport Association of America
BPR	Bypass ratio
C_D	Drag coefficient
CDA	Continuous descent approach
CR	Counter rotating
Dp	NO_x emitted during the ICAO LTO cycle
EI	Emission Index
FPR	Fan pressure ratio
F_{00}	Takeoff thrust
GF	Geared fan
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LPC	Low pressure compressor
LPT	Low pressure turbine
LTO	Landing and takeoff cycle
Ma	Mach number
OEI	One engine inoperative
OPR	Overall pressure ratio
SFC	Specific fuel consumption
SLS	Sea level static
t	Time
T	Temperature
TET	Turbine entry temperature
T/O	Take off
UHB	Ultra high bypass
v	Flight speed

3. INTRODUCTION

Due to the predicted rapid groth of air traffic over the next decades there is concern about its environmental impact. Therefore efforts have been made to reduce aircraft noise, NO_x emissions and fuel burn of which the latter is directly coupled with the emission of CO_2 by a constant factor.

Since its introduction in civil air transport the gas turbine jet engine propulsion technique has made a tremendous progress in thrust performance and in fuel efficiency. Increasing pressure and temperature of the gas turbine heat cycle as well as consequently following the design philosophy of a bypass ducted fan engine had been key elements of this development. On the one hand, for a fan engine, the reduction of fuel consumption and engine jet noise are favoured by increasing bypass ratio whereas on the other hand rising pressure and temperature levels of the engine heat cycle will lead to a decrease of fuel consumption and an increase of NO_x generation within the combustion process [1]. Therefore a variety of aspects has to be balanced with respect to the environmental friendliness of an aero engine.

Nevertheless the tendency for UHB engines may well dominate future developments and may bring another aspect into play. This is the lapse between thrust during takeoff and thrust during top of climb and cruise.

As the turbo components of an engine are ruled by air volume flow characteristics and the thrust is dominated by air mass flow there is a substantial effect of the air density with altitude level. Therefore bypass ratio, heat cycle loading and thrust performance have to be balanced with engine size concerning their effects on the emission characteristics between takeoff and cruise.

In this paper a trend of increasing engine bypass ratios has been anticipated and the effect of future UHB engines on flight performance, fuel consumption (CO_2) and the emission of NO_x will be investigated. The analysis of low-level NO_x emissions in conjunction with UHB engine concepts is emphasized in this study.

4. TECHNOLOGY

Different engine technology levels and architectures are investigated in this study.

The thermodynamic calculations are carried out with the one-dimensional engine performance calculation program VarCycle [4]. A more general thermodynamic description of a two spool bypass engine without detailed compressor and turbine performance mapping is used. The power equations of the high and the low pressure spool have to be fulfilled taking into account the mechanical losses. Furthermore, the pressure balance and the continuity of the mass flow are used for the iteration process.

4.1. Reference engine

The reference engine chosen in this study is representing current technology for larger engines, powering typical medium widebody twin-jets. In TAB 1 the basic engine data are given.

OPR (T/O)	35.7
T4 (T/O)	1665 K
BPR (T/O)	5.1
FPR (T/O)	1.87
Core mass flow	146 kg/s
SFC (cruise)	16.1 g/kN/s

TAB 1. Basic design data of the reference engine

4.2. New UHB engine concepts

Two engine concepts are investigated in this study, the geared fan and the counter rotating fan. Both concepts provide potential for high bypass ratios. In both cases three fan pressure ratios (1.4, 1.3 and 1.2) have been considered. Basic data of the engines investigated in this study are given in TAB 2 and TAB 3.

The NO_x emission levels of both concepts were estimated using well-known dependencies of the NO_x production rate on engine cycle parameters. This estimation was based on published emission data of today's best technology engines [2]. In the future, advanced combustor technology may significantly reduce NO_x emission levels of gas turbine engines. However, predicting the emission behaviour of such concepts is impossible without detailed geometry and/or measurement data. Therefore in this study the emissions were compared on a conventional technology basis only.

The component efficiencies of all UHB concepts considered are carefully selected on the basis of future trends shown in [3]. All UHB core engines have identical component efficiencies and pressure ratios. For the counter rotating fans an efficiency gain of two percent with respect to the corresponding geared fan is anticipated. This assumption is made since the counter rotating technology incorporates performance benefits due to the absence of a stator and higher rotor efficiencies. The different fan efficiencies lead to slightly higher bypass ratios in case of the counter rotating fan concepts. The maximum material temperature is assumed to be 40 Kelvin above the value for the reference engine. The maximum cooling air flow is limited because higher air flows cause lower turbine efficiencies. Hereby $T_{4,max}$ is limited. The overall pressure ratio is set to 45.

4.2.1. Geared fan

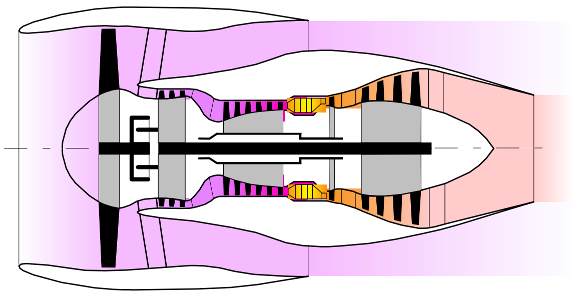

FIG 1. Geared fan [12]

The engine diameter is limited by the circumferential speed of the fan blades. Today's fans already run with a tip speed of Ma 1.4. A further increase of speed would lead to flow separation and negative aero-acoustic effects. Therefore an enlargement of the fan will lead to a reduction of the fan speed. This has negative effects on the turbine, which normally runs most efficiently at high speeds. A reduction of the turbine speed leads to a higher number of turbine stages, causing an increase of weight and size.

In order to run high bypass fans and low pressure turbines (LPT) at favorable speeds it becomes necessary to separate the rotational speeds of both.

One way of separating the rotational speed of the fan and the low pressure turbine is the introduction of a gearbox between the fan shaft and the low pressure compressor (LPC) shaft (FIG 1). A transmission ratio of around 3 allows the use of a compact high-speed turbine which is driving a low-speed fan with a large diameter.

Engine	GF14	GF13	GF12
OPR	45	45	45
T4max	1880 K	1880 K	1880 K
FPR	1.4	1.3	1.2
BPR	12.94	16.85	24.57

TAB 2. Basic design data of the UHB engines with geared fans

Besides the benefits concerning a high-speed LPT there are several other advantages. With low rotational speed, the fan will become more efficient and has - in combination with a low fan pressure ratio (FPR) - a great potential for the reduction of fan-related noise.

Due to a higher rotational speed and lower torque of the LPT, the diameter of the low pressure shaft can be reduced, easing its integration through the high pressure turbine and the corresponding shaft.

The availability of extremely reliable and lightweight gearboxes will be crucial for the success of this concept. A risk of increased engine failure probability will not be accepted by potential customers.

Integration and cooling of the gearbox pose further challenges. For medium sized engines, as regarded in this study, a mechanical loss of 1% causes a heat output of several hundred kilowatts demanding large (and heavy) coolers.

4.2.2. Counter rotating fan

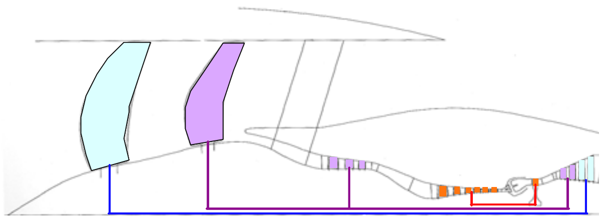

FIG 2. Counter rotating fan

A two-stage, counter rotating fan (CR fan, FIG 2) provides the opportunity of a higher flow velocity within the fan duct, so that a higher bypass mass flow can be achieved without increasing the fan diameter. Splitting the fan pressure rise in two steps allows fewer blades in each stage, thus decreasing the area ratio in the fan, i.e. increasing the possible axial flow velocity. The counter rotating fan makes a stator obsolete, so no losses are produced in the stator vanes. The counter rotating fans may be driven by a counter rotating, statorless turbine or by a gearbox and a high-speed turbine like the geared fan. Both techniques allow compact turbines. The use of two independent turbines is the easiest way to drive two fans, but has no advantages with respect to the turbine size.

Engine	CR14	CR13	CR12
OPR	45	45	45
T4max	1880 K	1880 K	1880 K
FPR	1.4	1.3	1.2
BPR	13.33	17.32	25.2

TAB 3. Basic design data of the UHB engines with counter rotating fans

In addition to the challenging development of a counter rotating, statorless turbine the CR fan has several disadvantages concerning engine noise. The incoming flow at the second fan stage will be disturbed by the wake of the first one, generating pressure fluctuations on the fan surface which propagate as a sound wave. This inherent disadvantage of the CR fan may be attenuated by special fan geometry which implies most advanced technology and highly sophisticated design tools.

4.3. Aircraft model

In order to simulate the engine operating conditions in a realistic way it is necessary to take the effects of real flight-missions into account.

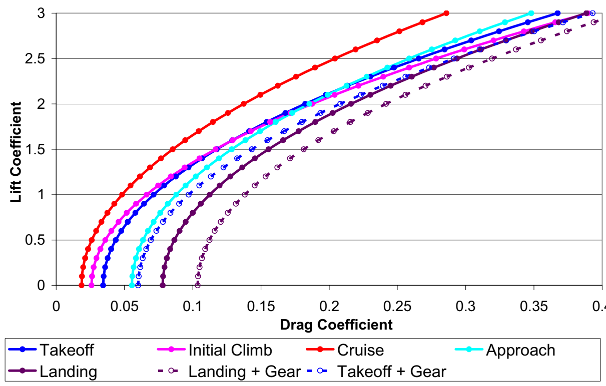

FIG 3. Aircraft drag polars[1]

For a detailed evaluation of the engines, flight missions are simulated with the mission calculation software VarFlight [4]. It allows a very flexible mission simulation. A typical medium sized widebody aircraft is selected as the reference aircraft. The aircraft data is derived from [5] and [6]. Detailed aircraft polars for different flap settings are used taking into account the extra drag of the landing gear (FIG 3).

5. THRUST REQUIREMENTS AND ENGINE SIZING

It is necessary to adopt the engine size for the given aircraft model.

First, the thrust requirements of the aircraft are investigated. These requirements have to be determined in an iterative process, because the engine itself has an effect on the aircraft's drag and thus on the thrust required.

The zero fuel weight of the aircraft is set to be constant for all regarded concepts. The different weight of the engines is considered by modifying the payload of the aircraft correspondingly to the engine weight.

The required thrust ratings are determined for different critical flight conditions taking into account the variable engine drags. Furthermore, the windmill and trim drags of one-engine-inoperative (OEI-) conditions are considered for the thrust requirements during takeoff where for each takeoff segment a minimum flight performance is defined by certification authorities. Furthermore, it is necessary to

[1] Produced with the EUROCONTROL Base of Aircraft Data (BADA). BADA is a tool owned by EUROCONTROL ©2006 All rights reserved. Aircraft performance data contained herein are based on data drawn from the EUROCONTROL Base of Aircraft Data (BADA). It is to be noted that the data contained in BADA have been developed by EUROCONTROL from a set of aircraft operational conditions available to EUROCONTROL. EUROCONTROL has validated BADA aircraft models only for those conditions and can therefore not guarantee the model's accuracy for operating conditions other then the reference conditions.

consider the different engine efficiencies due to their effects on fuel consumption.

5.1. Engine weight and drag estimation

The weight of conventional engines can be estimated by a simple correlation between engine weight and maximum takeoff thrust of existing engines. Thus the weight of today's engines can be calculated quite accurately.

For the geared fan, the smaller LPT and the lighter shaft is supposed to compensate for the additional weight of the gearbox. If we also assume a gearbox to drive the CR fan, the UHB engine weight can be approximated independently of the used fan concept by the correlation mentioned above.

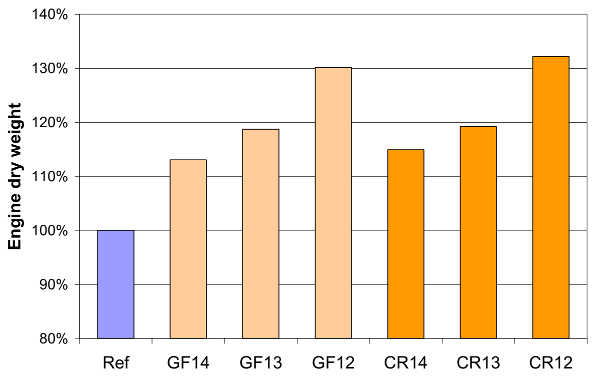

FIG 4. Engine dry weight relative to reference engine

It was found, that the new engine concepts come along with a weight penalty of 12-32% compared to the reference engine (FIG 4).

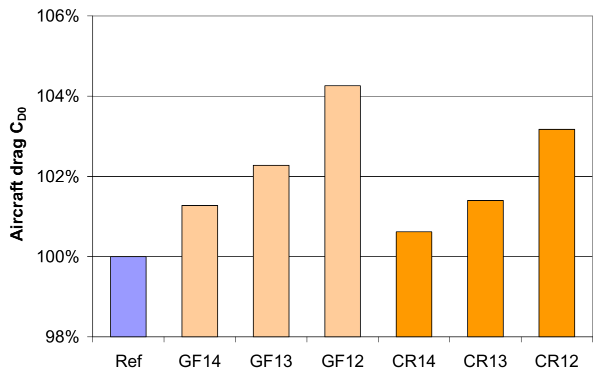

FIG 5. Aircraft drag coefficient C_{D0}

For an evaluation of the potential of an aircraft engine concept, the drag estimation is important. The high bypass ratios of the investigated engines cause larger engine diameters, although the highly effective core engines are smaller than the reference core. A constant engine drag coefficient c_D referring to the squared inlet diameter is assumed [7]. This assumption results in higher drag coefficients for the whole aircraft and is spoiling the benefits of the advanced engines up to a certain extent. FIG 5 shows the lift independent drag (C_{D0}) of the regarded aircraft in combination with the UHB engines relative to the aircraft equipped with the reference engine.

5.2. Engine performance requirements

For an aircraft with two engines, the certification standards define minimum climb gradients for takeoff which must be fulfilled with only one engine operative.

In the first takeoff segment a positive rate of climb is required. During the second segment a gradient of 2.4% is defined as a minimum. The engine is allowed to run at maximum takeoff thrust. During the final segment a gradient of 1.2% is needed while the engine is running at maximum continuous thrust [9].

All these requirements are based on ISA-conditions at maximum takeoff weight with only one engine operative, resulting in additional drag of the failed engine (windmill drag) as well as the additional drag of the side-rudder and ailerons (trim drag). These effects are calculated according to [8].

Another important thrust requirement is the ability of the aircraft to reach a realistic cruise altitude. Because of the thrust lapse this requirement becomes more and more important for UHB engines.

With the assumption of ISA-conditions and maximum takeoff weight (minus fuel already burned to reach cruise altitude) an initial service ceiling at 35000ft, Ma 0.83 was defined as the requirement for top of climb. Service ceiling is the density altitude where an aircraft in clean configuration at airspeed for best rate of climb and with all engines operating at maximum continuous power is able to conduct a 100 feet per minute (0.5 m/s) climb (v = 246 m/s => angle of climb = 0.116°).

The maximum continuous thrust is limited mainly by the turbine entry temperature and is about 20% lower than max. takeoff thrust (at sea level static conditions) which is only allowed for five minutes during takeoff (10 minutes with one engine inoperative).

With high bypass concepts the top of climb thrust is assumed to be reached with the TET for max. continuous thrust. For cruise conditions TET is reduced so that the turbine temperature is below the max. continuous limit and the engine is operated near the SFC minimum. For medium and long-range aircraft, this operating condition is very important in order to reach the lowest fuel burn possible. All engines in this study have been designed to reach their efficiency optimum at the same cruise thrust.

5.3. Results of the engine sizing

The sizing of the engines is depending on their characteristics. Hence the operating conditions throughout the whole flight mission have to be considered in order to fulfil all thrust requirements.

FIG 6 shows the thrust levels provided by the regarded engines. The hatched bars visualize the thrust excess. The solid bars represent the thrust levels to cope with the required climb angles. They only show minor variations for the different engines since the effects of changing engine weight and drag on the total required thrust level is small. During takeoff one engine is assumed to be inoperative whereas at top of climb both engines are in operation.

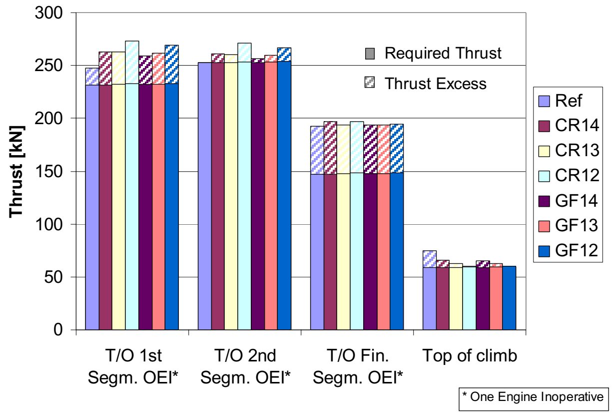

FIG 6. Thrust requirements

For low altitude and low speed operation (first takeoff segment) the UHB engines come along with a clear difference between provided and required thrust levels. This difference increases with the bypass ratio and decreases with the fan pressure ratio respectively. The counter rotating fans show a stronger thrust excess than the geared fans, since the fan efficiencies are higher.

The second takeoff segment is the dimensioning flight phase for the reference engine. The required climb gradient can be just met with the given thrust of the reference engine. The UHB engines provide more thrust and show qualitatively the same effects as in the first takeoff segment.

The final takeoff segment is characterised by a strong thrust excess for all regarded engines. It is nearly of the same magnitude for all of them (about 30%). At this flight condition the thrust lapse of the UHB engines compensates for the massive thrust excess at sea level static conditions. For increasing flight speed and altitude the reference engine provides more thrust than the UHB engines due to a smaller thrust lapse.

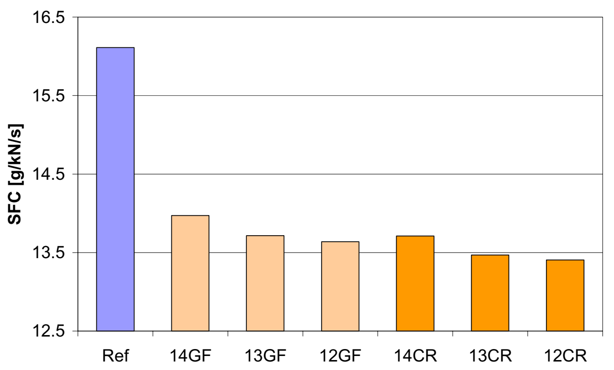

FIG 7. Optimum cruise SFC (35000ft, Ma 0.83)

This effect is shown by the bars for the top of climb flight condition. This is the dimensioning operating condition for the UHB engines with a fan pressure ratio of 1.2. They do not provide any excess thrust. In case of increasing fan pressure ratio (1.3 and 1.4) and decreasing bypass ratio respectively the thrust excess increases.

In FIG 7 the minimum cruise SFC values are given for the regarded engines. All engines are designed to reach their SFC optimum during cruise conditions at the same thrust level. The better core efficiency of the UHB engines as well as the higher propulsive efficiency lead to a much lower fuel consumption than the reference engine. The differences between the UHB engines root in the change in fan pressure ratio. The lower fan pressure ratio is directly leading to higher propulsive efficiencies.

	Ref	GF14	GF13	GF12	CR14	CR13	CR12
Takeoff-Thrust [kN]	304,7	345,3	363,6	400,7	351,3	365,3	407,4
Max Cont. Thrust [kN]	268,6	304,4	320,5	353,2	309,7	322,0	359,1

TAB 4. Resulting engine design thrust (SLS-conditions)

In TAB 4 the maximum takeoff and the maximum continuous thrust levels for SLS conditions are shown for the considered engines. Due to the design criteria (climb gradients for the different takeoff segments and top of climb, fixed thrust level for optimum cruise SFC) and the dependence of the thrust lapse on the fan pressure ratio the maximum takeoff thrust levels spread up to 34% (reference engine compared to CR12).

6. ICAO LTO

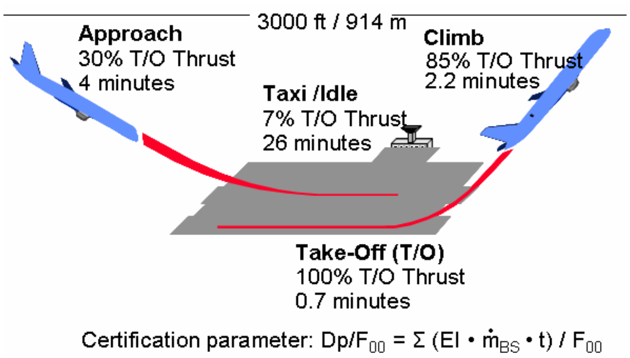

FIG 8. ICAO LTO cycle

The ICAO Landing and Takeoff (LTO) cycle is a standardized approach to create a comparable basis for evaluation and certification of aero engines. In this cycle the operating conditions below 915 meters (3000 feet) are simulated by a sequence of thrust settings at sea level static conditions. FIG 8 illustrates the ICAO LTO cycle.

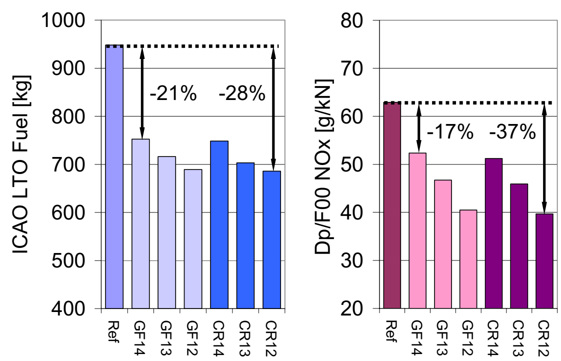

FIG 9. ICAO LTO fuel consumption and NO_x emissions

FIG 9 shows the fuel burned during one ICAO LTO cycle for one engine. The reference engine burns about 950 kg of fuel for the cycle, whereas the UHB engines provide a fuel reduction of 21% up to 27% in case of the geared fans and 21% up to 28% in case of the counter rotating fans.

The amount of NO_x (normalized with the maximum takeoff thrust) emitted during the ICAO LTO cycle is also shown in FIG 9**.** The geared fans produce a 17% up to 36% decrease in total NO_x emissions compared to the reference engine. The counter rotating fans show a reduction of 19% up to 37%.

If the amount of ICAO LTO NO_x is referred to the payload, the differences between the UHB engines with geared fans and those with counter rotating fans decrease. A reduction of NO_x emissions per kg payload of 4% to 12% is achieved for both engine types. This effect results from the higher engine weight and thus less payload in case of the UHB engines.

7. FLIGHT MISSION CALCULATION

Obviously an evaluation of the concepts based on cruise SFC and ICAO-LTO only is not sufficient. A more detailed analysis is necessary, considering the results of the weight and drag analysis as well as the different engine characteristics. Detailed flight mission calculations have been performed for 6000 km range to evaluate the impact of the different engine types on the fuel consumption and NO_x emissions of a whole mission.

7.1. Flight mission

7.1.1. Departure and approach

For the mission calculation a 15 minute taxi is assumed in this study. The required thrust is based on realistic drag assessments. A ICAO-A takeoff procedure was used. After takeoff the gear is retracted and the aircraft climbs with v_2 (1.2 times stall speed) to 457 meters (1500 feet) above ground level. At this altitude the thrust level is reduced to maximum continuous thrust and the climb is continued with v_2. After passing 915 meters (3000 feet) the flaps are retracted to the initial climb position and an accelerated climb is conducted up to 128.6 m/s (250 knots). Above 3050 meters (10000 feet) there is no speed limit and the aircraft is climbing to initial cruising altitude and accelerating to cruising speed after retracting the flaps to clean configuration.

A continuous descent approach (CDA) is simulated. The aircraft follows a flight path with a constant three degrees angle of descend. This low noise flight procedure was found to produce less emissions compared to conventional procedures with level flight sections at defined procedure altitudes [11].

7.1.2. Reserve fuel

The amount of reserve fuel is calculated according to ATA67 (Air Transport Association of America) for flights over 3000 nm without alternate [9]. This regulation requires an amount of extra fuel which enables the aircraft to continue the basic flight profile for two hours.

The aircraft landing weight is assumed to be zero fuel weight plus reserve fuel. The payload is set to be 80% of the maximum payload. The payload is comprised in the zero fuel weight.

7.2. Results for whole mission

The trajectories of the climb phase show the first major differences between the considered engines (FIG 10). An aircraft equipped with the reference engine is reaching cruise altitude after 250 km whereas an aircraft with FPR 1.2 engines needs more than 400 km to reach this altitude despite the much higher takeoff thrust of these engines.

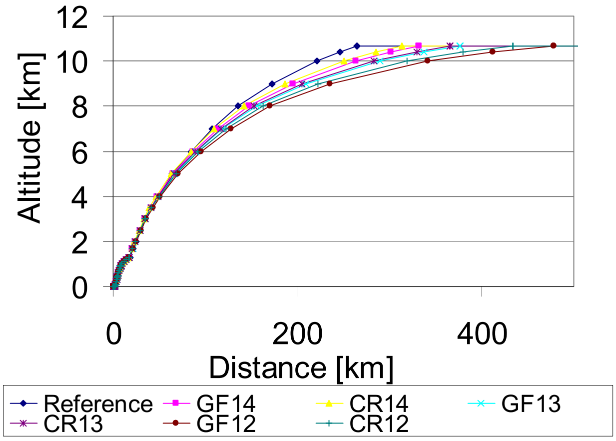

FIG 10. Climb trajectories

This thrust lapse is spoiling the advantages of the ultra high bypass engines, but nevertheless at long missions the climb distance is comparatively small.

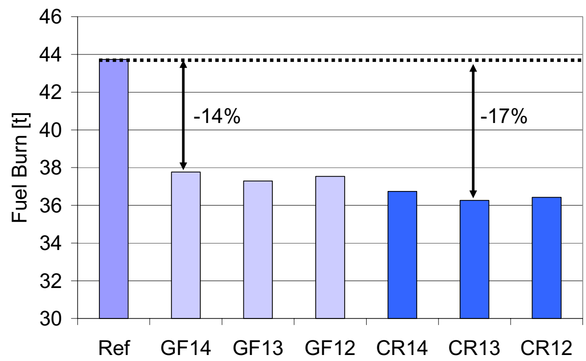

FIG 11. Fuel burn on 6000km mission

The better propulsive efficiency as well as the better thermodynamic efficiency is resulting in a lower total fuel burn on the whole flight mission (FIG 11) for all UHB engines. Although the FPR 1.2 engines have better cruise SFC-values (FIG 7) than the FPR 1.3 engines, their higher drag is spoiling these advantages and is leading to a slightly higher fuel consumption. The counter rotating fans have slight advantages over the geared fans due to their lower drag and their higher fan efficiencies. The CR13 engine shows lowest fuel burn for the regarded mission (17% less fuel than the reference engine).

Because the increased weight of the UHB engines is resulting in a lower payload, it becomes necessary to investigate the fuel burn per passenger-kilometer (100 kg is assumed for the passenger weight incl. luggage). For better comparability there is no cargo considered. Hence the payload is composed by passengers only.

FIG 12 shows, that the increased weight of the FPR 1.2 engines is further spoiling their SFC advantages, so that the FPR 1.4 engines have a lower fuel burn than the FPR 1.2 engines. Still, the FPR 1.3 engines have the lowest fuel burn per passenger with 15% less fuel than the reference engine in case of the CR engine.

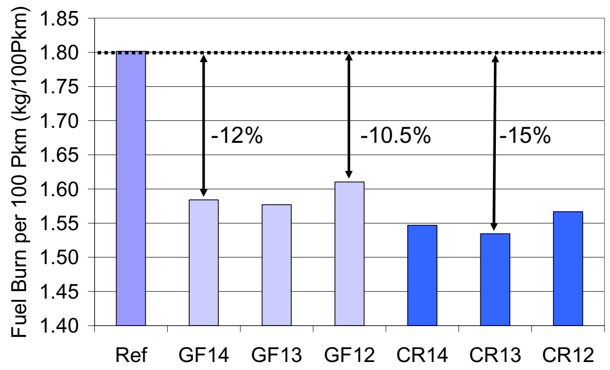

FIG 12. Fuel burn on 6000 km mission per 100 Pkm

The higher temperatures and pressures of all UHB engines result in higher emission indices. On the other hand the fuel savings benefit the NO_x values.

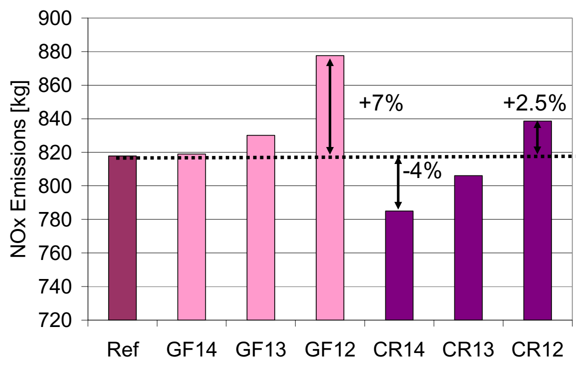

FIG 13. NO_x emissions on 6000 km mission

Comparing the NO_x emissions of the UHB engines for the considered FPRs it can be found that engines with lower FPRs create higher emissions (FIG 13**)**. This is the result of the thrust lapse of UHB engines which is leading to higher temperatures. The total NO_x emissions of the CR engines are lower than the emission level of the GF engines with the corresponding FPRs due to the better fan efficiencies. The emission levels of both concepts are in the same order of magnitude compared to the reference engine. The engines with a FPR of 1.2 produce more NO_x than the reference engine (7% in case of the GF, 2.5% for the CR). The CR fan with a FPR of 1.4 is able to save 4% NO_x compared to the reference engine.

It is important to keep in mind that the absolute values of NO_x are not generally representative for the UHB engines, because no new NO_x-reducing techniques are considered in this study. Nevertheless, the trend of higher NO_x with higher bypass ratios is most likely unaffected by these techniques.

Taking the reduced payload of the aircraft with UHB engines into account (FIG 14), the NO_x emissions per 100 passenger kilometres show slightly higher differences compared to the total NO_x emissions, the GF12 engine is producing 12% more NO_x than the reference while the benefit of the CR14 engine is reduced to 2%.

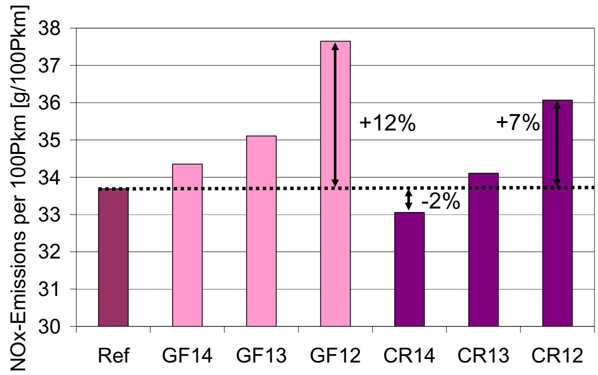

FIG 14. NO_x Emissions on 6000km mission per 100 Pkm

7.3. Results for takeoff and approach

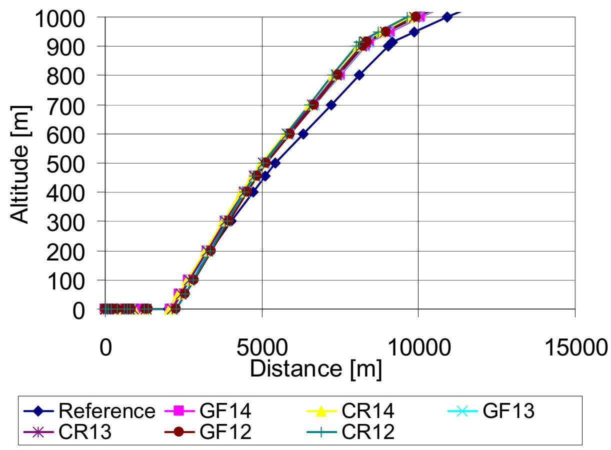

FIG 15. Low level takeoff-trajectory

The higher takeoff thrust of the UHB engines is resulting in higher climb gradients at takeoff (FIG 15). The aircraft with UHB engines is capable of reaching 3000ft about 1km (10%) earlier than the aircraft with reference engines. Since the engines with the high BPR (FPR 1.2) are losing their thrust excess over the FPR 1.4 engines already at low speeds (see FIG 6), there are only small differences between the flight paths of the aircraft equipped with UHB engines.

There are different possibilities to make use of this thrust-excess during takeoff. It is possible to use the full thrust and climb steeper than the aircraft with reference engines. Another possibility is a derated thrust takeoff. Here the thrust settings of the engines are selected in a way, that the aircraft follows the same flight path as with reference engines.

In FIG 16 the fuel burn below 3000ft is shown. As mentioned before, for all regarded aircraft-engine-combinations the same takeoff and descend procedures have been assumed (speed, flap setting, angle of descent). All UHB engines consume significantly less fuel than the reference engine. The GF14 engine is saving 27% compared to reference while the best engine (CR12) is saving 37% (fully rated takeoff). The derated takeoff is generating a lower fuel burn of about 1%.

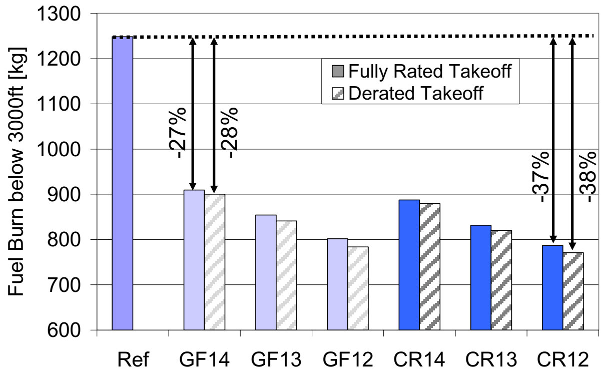

FIG 16. Low altitude fuel burn (<3000ft)

The NO_x emissions below 3000ft are shown in FIG 17. All UHB engines produce significantly lower NO_x emissions than the reference engine. The GF14 is lowering the NO_x emissions by 20% while the CR12 engine is capable of lowering the emitted NO_x by 32% (fully rated takeoff).

The derated takeoff is capable of reducing the NO_x emissions even further. For FPR 1.4 engines, a reduction of additional 8% is calculated (relative to reference), while for the FPR 1.2 engines a additional 11% reduction is detected.

This NO_x reduction is caused by two effects: On the one hand the fuel consumption is reduced, witch influences the amount of emitted NO_x directly, and on the other hand the combustor is operated at lower temperatures, which leads to a reduction of the emission index.

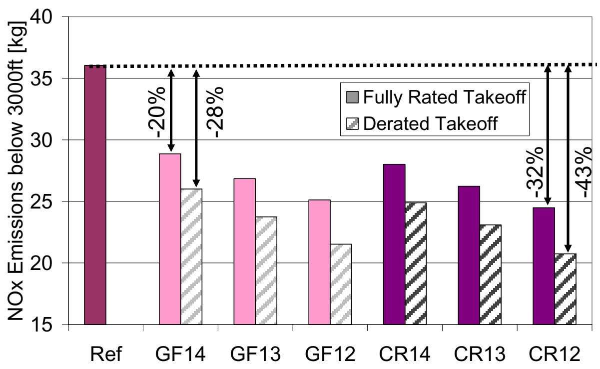

FIG 17. Low altitude NO_x-Emissions (<3000ft)

The NO_x production below 3000ft shows completely different results than on the whole mission (FIG 13), where it is increased with higher BPR. Compared to the reference engine the amount of NO_x emitted during a derated takeoff with the UHB engines can be reduced by 28% in case of the geared fan with FPR 1.4 and by 43% in case of the counter rotating fan with FPR 1.2. This shows the potential of UHB technology for low altitude NO_x emission reduction.

The derated takeoff of aircraft with GF engines is likely to provide a noise reduction during takeoff relative to an aircraft with reference engines in addition to the lower NO_x and CO_2 emissions. The noise level on counter rotating fans is supposed to be highly dependant on the applied technology.

8. SUMMARY AND CONCLUSIONS

To figure out the effect of ultra high bypass engines on low altitude NO_x emissions, a study of the impact of different engine concepts with different bypass ratios has been performed. The effects of the engine concept and BPR on the engine weight and drag have been considered. Special emphasis was placed on the determination of the suitable engine size for a reference aircraft, in consideration of detailed engine characteristics and certification requirements for the aircraft system.

A means of achieving a further reduction in fuel consumption is to increase propulsive efficiency by decreasing the fan pressure ratio while rising the bypass ratio. Two concepts that facilitate a significant bypass ratio increase have been investigated, the counter rotating and the geared fan. Both concepts allow for a considerable reduction in fuel consumption, but to the cost of increased engine weight and size.

To investigate the effects of reduced fuel consumption, increased engine weight and size as well as different engine characteristics on the whole aircraft efficiency, flight mission calculations have been performed.

It was found out, that with rising bypass ratio the specific fuel consumption is decreasing while the engine weight and drag is increasing.

The flight mission calculations showed that for the highest bypass ratios considered in this study (FPR 1.2, BPR 25) the negative effects on weight and drag outbalance the positive SFC effects, leading to higher mission fuel consumption than an engine with a lower bypass ratio.

On a flight mission, the NO_x emissions per passenger kilometer of the UHB engines increase with rising bypass ratio because the thrust lapse of the engines is requiring higher temperatures in the combustor during cruise flight.

During takeoff and approach (< 3000 ft), the UHB engines showed a significant NO_x reduction with rising bypass ratios. This effect is opposed to the results for the whole flight mission, where higher NO_x levels were found.

To meet all thrust requirements, the UHB engines have a high excess thrust on the ground. This excess thrust can be used in different ways. A full power takeoff is leading to higher climb gradients, reducing the flight time below 3000ft. A reduced power takeoff becomes possible without reducing the angle of climb compared to today's engines. This allows for a further NO_x reduction as well as more silent takeoffs because of the lower power setting.

The results show, that UHB engines are suitable to lower the NO_x emissions in the vicinity of airports while the CO_2 emissions can be reduced on the overall mission.

Because of airport air quality issues there is special interest to reduce NO_x in the vicinity of airports. In other parts of the mission the reduction of CO_2 emissions is most important due to the high climate effectiveness. UHB engines may be one possible engine concept to achieve a substantial reduction in low altitude NO_x emissions while the development of low NO_x combustor technology remains the key to reduce the overall NO_x emissions [14].

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