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Thrust Reverser for a Separate Exhaust High Bypass Ratio Turbofan Engine and its Effect on Aircraft and Engine Performance

Tashfeen Mahmood†, Anthony Jackson, Vishal Sethi, Pericles Pilidis
School of Engineering, Dept of Power and Propulsion,
Cranfield University, Cranfield, Bedford, MK43 0AL, UK
Email: t.mahmood@cranfield.ac.uk

ABSTRACT

This paper discusses thrust reversing techniques for a separate exhaust high bypass ratio turbofan engine and its effect on aircraft and engine performance. Cranfield University is developing suitable thrust reverser performance models. These thrust reverser performance models will subsequently be integrated within the TERA (Techno-economic Environmental Risk Analysis) architecture thereby allowing for more detailed and accurate representations of aircraft and engine performance during the landing phase of a typical civil aircraft mission.

The turbofan engine chosen for this study was CUTS_TF (Cranfield University Twin Spool Turbofan) which is similar to the CFM56-5B4 engine and the information available in the public domain is used for the engine performance analysis along with the Gas Turbine Performance Software, 'GasTurb 10' [1]. The CUTEA (Cranfield University Twin Engine Aircraft) which is similar to the Airbus A320 is used alongside with the engine model for the thrust reverser performance calculations. The aim of this research paper is to investigate the effects on aircraft and engine performance characteristics due to the pivoting door type thrust reverser deployment. The paper will look into the overall engine performance characteristics and how the engine components get affected when the thrust reversers come into operation. This includes the changes into the operating point of fan, booster, HP compressor, HP turbine, LP turbine, bypass nozzle and core nozzle. Also, thrust reverser performance analyses were performed (at aircraft/engine system level) by varying the reverser exit area by ± 5% and its effect on aircraft deceleration rate, deceleration time and landing distances were observed.

1. INTRODUCTION

From the early days of turbojet development (i.e. in the early 1950s) the safe landing distance requirement was very clear. With the landing speeds of jets ever increasing, the required landing distances were becoming prohibitively long. Especially during adverse weather conditions causing wet or ice on the runways, ship runways in naval application and where there is limited runway length, landing in the shortest time is very critical. Landing speeds are high for two reasons: firstly, aerodynamic reasons such as high wing loadings and low maximum lift coefficients and secondly, the necessity for making the final approach at relatively high engine speeds in preparation for a possible wave-off. These requirements lead to the concept of using brake plus a retarding force such as a parachute or a thrust reverser. The thrust reverser has the advantage of providing the required reverse thrust (at rated engine conditions) with assurance that full forward thrust can be regained rapidly if the need arises. A drag parachute can be used to reduce final approach speed by increasing drag but it must be cut loose in case of a wave-off and will not be available for the next attempted landing [2].

Thrust reversers for high bypass ratio engines are integrated into the engine nacelle and contribute to about 30% to the overall nacelle weight [3]. In civil applications no certification credit on landing distances is given for thrust reverser fitment; an aircraft landing distance will be determined by the use of anti-lock brakes and aerodynamic drag devices such as lift dumpers, airbrakes and parachutes [4]. However, thrust reversers are used universally on civil aircraft as they offer additional safety during aircraft landing and the use of thrust reversers can also be beneficial for extending the aircraft brakes life. On dry runways, the brake force and aerodynamic drag are the major decelerating forces. However, on a wet or icy runway, thrust reverser is a major contributor to safely decelerate the aircraft and helps to reduce the aircraft landing distance [Fig 1], and it dominates all the other decelerating forces [3]. There are mainly three types of thrust reversers in use today on civil aircraft namely: 1. cascade type thrust reverser 2. pivoting door type thrust reverser and 3. target type thrust reverser. Clamshell and bucket door type thrust reversers have been used in the past on military aircraft. The two most common thrust reverser designs in use for large civil aircraft engines are the cascade type thrust reverser using translating sleeve and the pivoting door type thrust reverser.

† PhD Student, Power and Propulsion, Cranfield University

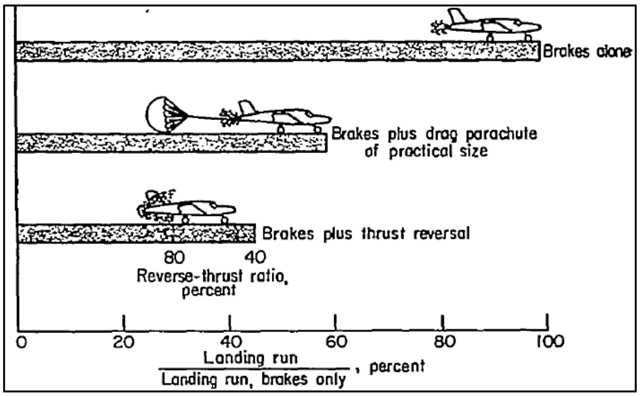

Figure 1: Landing run required when applying braking devices after touchdown [2].

A thrust reverser system is designed to operate mainly when the aircraft touches ground during landing. On large turbofan engines with separate exhausts, when thrust reversers get deployed they produce a rearward acting force using the fan-stream flow. This study is carried out on an engine model similar to the CFM56-5B4 engine which makes use of a pivoting door type thrust reverser as shown in Fig 2. On a pivoting door type reverser the four pivoting doors are movable structures during the reverse thrust. The pivoting doors deflect the exhaust airflow of the engine into the direction enforced by the door angle and the sharp edge (kicker plate) at the front end of the door. The re-direction angle of the flow when the thrust reverser is deployed depends on the engine; the CFM56-5B re-directs the flow at an angle of approximately 120 degrees [5].

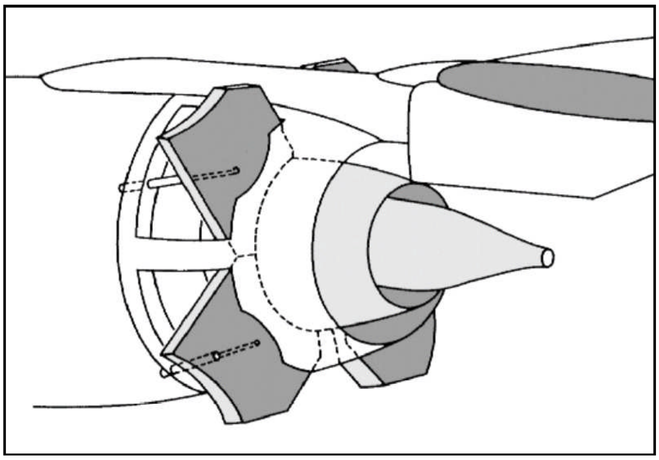
Figure 2: The thrust reverser of a CFM56-5B on an Airbus A320 with four pivoting doors in an open position [5].

Thrust reversers often make use of the fan stream only and this makes mechanical deflector components in the hot gas flow unnecessary. This results in simpler reverser kinematics with less weight and costs. Pivoting door type thrust reverser has fewer moving parts and simpler kinematics compared with the cascade type thrust reverser. Additionally, the required stiffness of the fixed structure can be achieved at a lower weight. It creates a higher drag in the reverse position and actuator loads are higher compared with the cascade type reverser of the same size. Pivoting door type thrust reverser was first used on the Airbus A320, and is also currently in use on the Airbus A340 with CFM56-5C engines and on the Airbus A330 with TRENT700 engines; both these engines have mixed exhaust. In the forward thrust position, the pivoting doors cover the openings in the fixed structure. The thrust reverser for the Airbus A320 employing the CFM56-5B engine has two blocker doors on each cowl. Actuation of the translating sleeves on pivot doors is either hydraulic or electrical and three separate locks are provided to ensure no thrust reverser deployment in flight occurs.

The thrust reverser lever is different from the throttle control lever [Fig 3]. The thrust reverser lever can be raised only when the forward thrust levers are in idle position. An interlock stop limits thrust to idle reverse while the reverser is in transit. The interlock also restrict the forward thrust lever from moving forward until reverse thrust levers are fully down and the reverse sleeves are no longer in transit. The EECs (Electronic Engine Control) control thrust limits during reverser operation. When the thrust reverser levers are pulled aft to the interlock position, the auto-throttle disengages and the auto-speed brakes deploy.

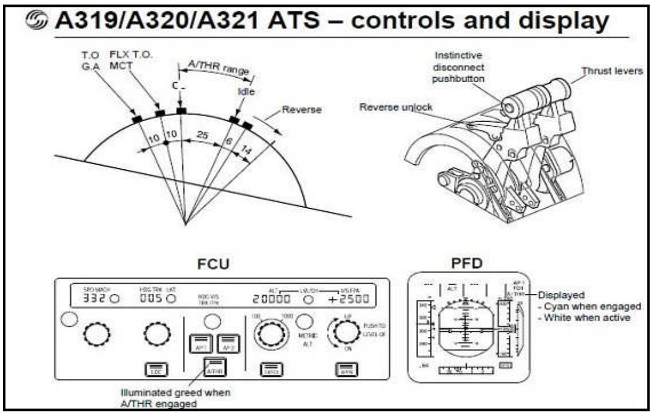

Figure 3: Airbus A320 controls and display [6].

If the total flight time for a civil aircraft is considered, the thrust reversers represent only a small fraction of the flight operating time. Even though the thrust reversers operating time is very limited, still they are considered a critical component as their installation on aircraft engines offers the safety of aircraft and the passengers. However, thrust reverser installation and use affects the nacelle design, propulsion weight, aircraft cruise performance, engine maintenance expenses, and also installation of a thrust reverser system can apparently increase the engine specific fuel consumption (s.f.c) by up to 1.0 per cent as a result of leakage and pressure drops [3]. Manufacturing and design of thrust reversers are mostly not carried out by the gas turbine manufacturers but are out sourced mainly to other companies whose prime purpose is to carry research and development, design, testing and manufacturing of such products. Some of the renowned suppliers in this market are *Hispano-Suiza, Aircelle, Goodrich* and *Honeywell.*

2. THRUST REVERSER DEPLOYMENT

A thrust reverser system is usually designed to operate when the aircraft touches ground during landing, although there are a few exceptions to this. During landing, the thrust reverser is deployed shortly after touchdown by selection of the pilot. The best braking effectiveness from a thrust reverser is achieved at higher speeds during the landing run because the *propulsive efficiency* for the reverse thrust has its highest values at the high forward speeds: as the aircraft speed decreases so does the reverse thrust. Thrust reversers are stowed back at speeds near 60 knots (30.9 m/s) to prevent the engine from F.O.D (foreign object damage). This method is the most efficient way to use the thrust reverser system in terms of fuel consumption and brake wear.

The thrust reverser, for most aircraft including the Airbus A320, can only be operated when both engine control units are operating with a running engine and the aircraft is on the ground. At this stage the thrust reverser will open ONLY, if both the air/ground sensors show the airplane in GROUND configuration and the computer detects the thrust lever angle in the reverser range and the thrust lever of the other engine in the idle range. After the thrust lever is placed in the reverser range, the EEC commands the hydraulic valves for the deploy operation. The hydraulic pressure releases the door latches first and then enters each actuator. When the pivoting doors reach the deployed position the airflow keeps the pivoting doors open. During the deployment of pivoting doors, the EEC keeps the engine at idle. After the EEC has detected that all the doors are fully deployed it accelerates the engine to the selected reverse thrust. During reverse thrust selection, the thrust lever can be moved directly to the desired power setting because it has no interlock stop. The interlock function to delay the engine acceleration is established in the software of the EEC [5].

The reverse thrust is cancelled by moving the reverser lever in the forward thrust region; the EEC then stows the pivoting doors by closing the reverser doors completely and switches off the hydraulic pressure. If all doors are locked correctly, then they remain in the stowed position. Otherwise, an unlocked door would be lifted a few degrees by the elastic seals and the air pressure [5]. Fig 4 shows the overall system.

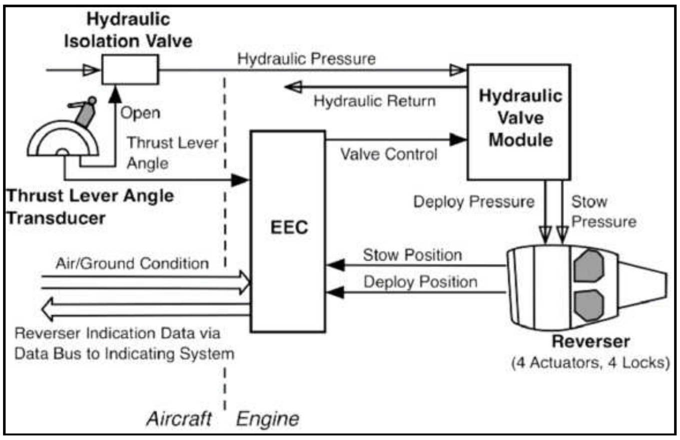

Figure 4: The Airbus A320 thrust reverser control system [5].

3. THRUST REVERSER UTILISATION

The typical aircraft brake system consists of an anti-skid system and an auto-brake system (ABS), each operating independent of the other. The function of the anti-skid system is to modulate the individual wheel brake pressure to achieve maximum brake effectiveness for the current runway condition. The anti-skid system senses wheel speed and adjusts brake pressure accordingly to prevent wheel lockup. The availability and/or use of thrust reversers have no impact at all on the design and function of the anti-skid system. The ABS system senses the aircraft deceleration rate and modulates brake system pressure to maintain a constant pre-selected deceleration rate. The application of reverse thrust results in reduced braking required from the ABS system. The availability of the thrust reverser indirectly affects the use of auto-brake system in that the braking action required for a given deceleration rate is reduced when thrust reverser are used. To save on brake wear some airlines instruct their pilots not to use ABS except during adverse weather conditions [3]. The use of ABS is recommended for landing on wet, slippery and contaminated runways or runways close to minimum runway length.

The normal landing speed for civil aircraft is between 120 and 145knots (61.7 and 74.6 m/s). The aircraft touches the ground at a high angle of attack at which point the brakes and the lift dumpers become effective; the pilot sets the thrust lever to idle and uses the reverse thrust lever to apply reverse thrust. The amount of reverse thrust depends on the circumstances such as the length of the runway, runway surface conditions, and the aircraft landing weight. The final decision on the amount of reverse thrust to be used is pilot dependent. Normally, when the thrust reversers are used on a dry runway, the pilot does not use ABS until the aircraft speed is reduced below 100 knots (51.4 m/s), and the reverse thrust is cancelled between the speeds of 80 and 60knots (41.2 and 30.9 m/s) to avoid the hot air/gas re-ingestion into the engine intake which could cause surge. At this stage, the thrust reversers are stowed and the engines are operated at idle power. The engine remains at idle power and the brakes are then used to decelerate the aircraft to a speed of 20knots (10.3 m/s) (normal taxi speed).

4. ENGINE PERFORMANCE

Initially, an engine *design point* study was carried out for the CUTS_TF engine at sea level static (SLS) condition i.e. maximum power; that is when it is operating at a particular speed, turbine entry temperature (TET), pressure ratio (P.R), and mass flow (W) for which the components were designed [Table 1].The variation of performance of the gas turbine over the complete operating range of speed and power output, normally referred to as the *off-design* engine performance, was also performed at take-off, cruise, landing, idle, and thrust reverser mode. The data available in the public domain was used for this study together with the performance software 'GasTurb 10'. Performance graphs for the fan, booster, HPC, HPT, LPT, bypass and core nozzles were then plotted. The design and off-design performance studies are beneficial as they allow a comparison of thrust reverser operation with other operating regions.

CUTS_TF Design Point Study at Sea level static (Operating at maximum power)	
Engine Mass Flow (kg/s)	406.8
Net Thrust (kN)	120.1
BPR	5.7
OPR	26.6
Fan RPM and Core RPM	5200 and 15183
$V_{(Bypass)}/V_{(Core)}$	0.695

Table 1: Design point variables at the SLS condition.

4.1 Compressor Performance

In this section the performance of the fan, booster and HPC are discussed. The variation of mass flow and pressure ratio with rotational speed of the compressor is plotted in Figures 5, 6 and 7. The equilibrium running points for a series of speeds at SLS and cruise condition are plotted and joined up to form an equilibrium running line. Figures 5, 6 and 7 also show the proximity of the operating line or zone to the compressor surge line. The pressure ratios were obtained at various operating conditions and are presented in [Table 2]. The bleed values for off-design performance were set as per Ref [7].

Compressor Pressure Table				
Engine Operating Conditions	**Fan P.R.**	**Booster P.R.**	**HPC P.R.**	$V_{(Bypass)}/V_{(core)}$
Sea Level Static (max-power)	1.64	1.62	10.40	0.695
Take off (0.23 M)	1.63	1.61	10.30	0.700
Typical Cruise (0.8 M, 10,668 m)	1.68	1.71	10.80	0.61
Landing at 65% Engine Power (0.211 M, 140knots)	1.53	1.51	9.86	0.85
Idle thrust – landing at 17% Engine Power (0.211 M)	1.11	1.11	5.19	1.18
Rev. Thrust 80% engine power. Bypass nozzle area unchanged.	1.53	1.51	9.86	0.79
Rev. Thrust 80% engine power. Bypass nozzle area reduced by 5%.	1.54	1.53	9.88	0.80
Rev. Thrust 80% engine power. Bypass nozzle area increased by 5%.	1.52	1.50	9.70	0.77

Table 2: Pressure ratios at different operating conditions and the fully expendable velocity ratios of bypass stream/core stream.

The aircraft will normally take-off at maximum engine power. The *take-off* condition was considered at 0.23 M (V=150 knots, 170 mph, 77.2 m/s). From the compressor maps the take-off operating point is very close to the design point. At *cruise* the engine is operating at 10,668 m and at 0.8 M. Hence, there will be a ram pressure rise due to the high forward speed. The performance plot shows that during cruise the operating point for the fan and booster moves further away from the surge line and operates at higher non-dimensional flows; however, for the HPC the cruise operating point is still close to the design point. The engine net thrust during cruise was 25.04 kN.

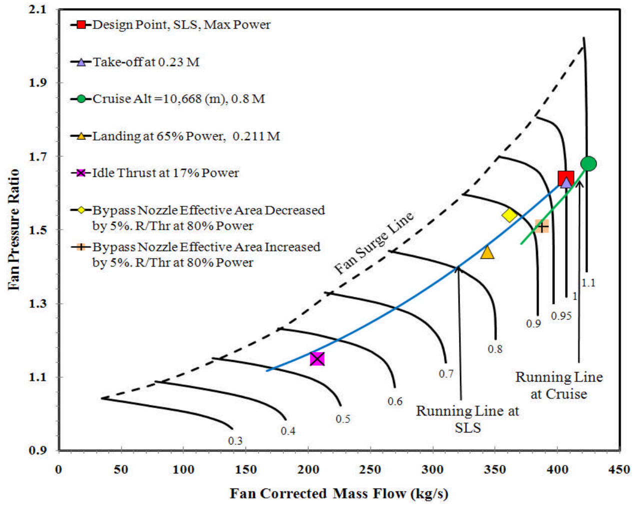

Figure 5: Fan PR against the corrected mass flow for different engine operating conditions.

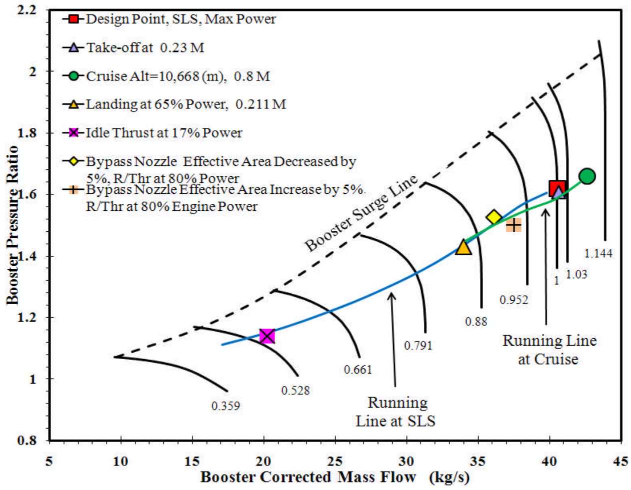

Figure 6: Booster PR against the corrected mass flow for different engine operating conditions.

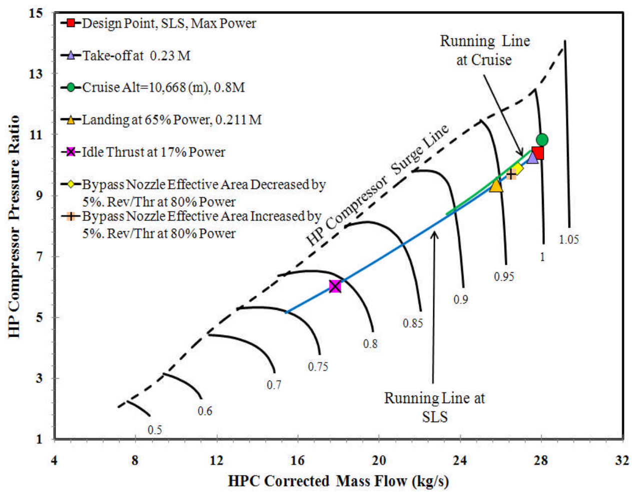

Figure 7: HP compressor PR against the corrected mass flow for different engine operating conditions.

For this study the aircraft landing takes place at 0.211 M (V=140 knots, 161 mph, 72 m/s) [8]. The engine power is set to 65% as shown in Figures 5, 6 and 7. The operating point at landing is close to the SLS running line. Once landed, after main gear touchdown, the pilot will ensure that the lift dumpers are deployed and brakes are effective. The pilot then reduces the engine thrust to ground idle for the thrust reverser deployment.

The determination of what idle thrust is reflects several engine issues, including combustor stability, engine temperatures and surge margin levels. In addition, certain applications impose their own particular requirements. The idle thrust at which the thrust reverser is selected is assumed to be about 17% engine power. During reverse thrust operation, the reverser effective area (pivoting door exit area) should be close to the bypass nozzle exit effective area; this is to ensure that the engine does not sense any change in the deployment cycle. The operating point at idle-setting is close to the engine running line at SLS; however, this will reduce the engine surge margin especially in the booster and the HPC as shown in the Figures 6 and 7. The pilot then changes the fan thrust into the reverse thrust by making use of the reverse thrust lever [Figure 3]. The change in thrust setting to idle will reduce the pressure ratio across the fan, booster and HPC [Table 2].

The pilot then increases the reverse thrust per the requirement for the aircraft. In this paper, the reverse thrust is assumed to be at 80% power; normally the case when the runway is short or contaminated by rain or ice. Three configurations are considered in the case of reverse thrust exit area. In the first case the reverser effective area is assumed to be the same as the bypass nozzle effective area, in the second case the reverser effective area is 5% less than the bypass nozzle effective area and in the final case the reverser effective area is 5% more than the bypass nozzle effective area. If the reverser effective area is the same as the bypass nozzle effective area then the reverser operating point will be on the engine running line at SLS for booster and HPC, and the fan will be close to its normal running line (the engine parameters will then be unaltered relative to their forward speed values at that throttle setting).

The 5% decrease in reverser effective area of the bypass nozzle will move the fan and booster thrust reverser operating point close to the surge line; the reduction in effective area will move the fan thrust reverser operating point closer to the surge line than that observed of the booster.

Nozzle Area During Reverse Thrust and Flight Conditions		
Nozzle Area	**Fan Nozzle Area (m^2)**	**Core Nozzle Area (m^2)**
All conditions other then rev. thrust	0.995	0.339
All conditions including rev. thrust	0.995	0.339
Reverser area 5% less than bypass nozzle area – During rev. thrust	0.945	0.339
Reverser area 5% greater than bypass nozzle area – During rev. thrust	1.045	0.339

Table 3: Variation in bypass nozzle area during reverse thrust operation.

However, the area change will not affect the HPC operating point. The pressure ratio across the fan, booster and HPC will increase slightly to that of the landing configuration [Table 2]. The 5% increase in bypass nozzle reverser effective area will not affect the thrust reverser operating point for the HPC. The fan and booster, however, will see the beneficial effects as they will now have more surge margin than before. The increase in reverser effective area will also cause a slight reduction in pressure ratio across the fan, booster and HPC [Table 2]. Therefore, the increase in reverser effective area will allow a better surge margin and an increase in fan thrust as shown in the latter part of the paper. The 5% increase in reverser effective area is beneficial as the change in thrust to idle and back to maximum will provide a greater surge margin for the engine to operate safely.

4.1.1 Compressor Surge Margin

The surge margin provides a measure of how close an operating point is to surge. The power or thrust level at which the minimum surge occurs will vary. The required surge margin at ISA, SLS and maximum rating varies greatly, being dependent upon acceleration and deceleration times required, engine configuration, whether centrifugal or axial compressors are applied, whether bleed valve or VSVs (variable stator vanes) are employed at part load, etc. The first order guide for a civil aero engine could be as follows: fan (10 – 15%), booster (15 – 20%) and HP compressor (20 – 25%); for a fan the biggest single contributor to the requirement is inlet distortion where up to 5% surge margin must be allowed [9]. The compressor surge margin (S.M) is found using [Equation 1].

$$SM = 100 \times \frac{(PR_{surge} - PR_{working\ line})}{PR_{working\ line}} \text{ @ constant flow [Equation 1]}$$

Compressor Surge Margin			
Operating conditions	Fan S.M	Booster S.M	HPC S.M
SLS **(Design Point)**	17.14	23.46	21.27
Take-off (0.23 M)	17.79	24.22	20.98
Cruise (10668 m, 0.8 M)	19.76	24.1	23.84
Landing (0.21 M)	15.97	22.38	25.53
Idle thrust (0.21 M)	13.04	13.16	24.58
Reverse Thrust – Bypass nozzle area unchanged	15.7	22.52	22.4
Reverse Thrust – Bypass nozzle area 5% decrease.	12.01	20.26	22.22
Reverse Thrust – Bypass nozzle area 5% increase.	22.52	25	22.68

Table 4: Shows surge margin at different off-design conditions.

Table 4 shows that the surge margin for fan, booster and HPC are within the first order guide for civil aero engine. The required surge margin for the fan and booster at idle power may not be sufficient and the use of bleed valves and VSVs will be made. The CUTS_TF booster is a three stage axial compressor and incorporates the ring of bleed doors which allows core airflow to escape into the fan duct at low power settings. The CUTS_TF HPC is a nine stage compressor with the first four stator rows variable. It is assumed that the use of bleed doors and VSVs at low power setting will increase the surge margin. Also, the 5% increase in reverser area beneficially increases the S.M for both the fan and the booster during thrust reverser operation. The increase in reverser area is beneficial especially for the fan as the inlet distortions during reverse thrust operation can reduce the fan S.M by up to 5%.

4.2 Turbine Performance

The design flow characteristics of a turbine must be carefully matched with those of the compressor to achieve efficiency and performance targets. If the turbine components allow too low a maximum flow, then a back pressure would build up in the engine causing the compressor to surge. Conversely, too high a flow would cause the compressor to choke, where the total gas flow entering the compressor is greater than its working capacity due to imbalance between the two systems. Either condition would induce a loss in engine efficiency and performance. Every design is a compromise and the design methodologies used often require a lengthy iteration process to achieve the best overall solution. This series of iterative loops is required because of each component's inter-relationship with its neighboring components [4]. Once the turbine geometry has been fixed at the design point then the turbine map may be generated to define its performance under all off design conditions. It is often found in practice that turbines do not exhibit any significant variation in non-dimensional flow with non-dimensional speed, and in most cases the turbine operating region is severely restricted by another component downstream [10]. The turbine map is represented by a series of curves as shown in Figure 8 and 9. The map also shows a running line at SLS and at cruise. There is no surge line in the turbine as surge does not occur in the accelerating flow.

Table 5, shows the pressure ratios across the HPT and LPT at different engine operating conditions. It is noticed that the HPT remains choked and the pressure ratio remains constant for all the operating conditions apart from the idle thrust where it is reduced slightly. As long as the LPT turbine is choked the HPT turbine will operate at the fixed non-dimensional point of PR ≈ 3.84 – 3.87 [Figure 8]. The pressure ratio across the LPT will vary as shown in the [Table 5], however, the LPT turbine remains choked for all the engine operating conditions apart from idle thrust at which it operates unchoked [Figure 9]. The maximum pressure ratio across the LPT is controlled by intake capacity of the core nozzle.

Turbine Pressure Table		
Engine Operating Conditions	HPT P.R	LPT P.R
Sea Level Static (SLS) – 100% Power	3.87	4.53
Take-off - 0.23 M	3.87	4.58
Typical Cruise - 10,668 (m), 0.8 M	3.87	5.01
Landing at 65% engine power – 0.211 M	3.84	3.8
Idle thrust at 17% engine power – 0.211 M	3.42	2.14
R/Thrust bypass nozzle area unchanged.	3.86	4.17
R/Thrust bypass nozzle area reduced by 5%.	3.86	4.14
R/thrust bypass nozzle area increased by 5%.	3.86	4.21

Table 5: Variation in pressure ratio across the HPT and LPT.

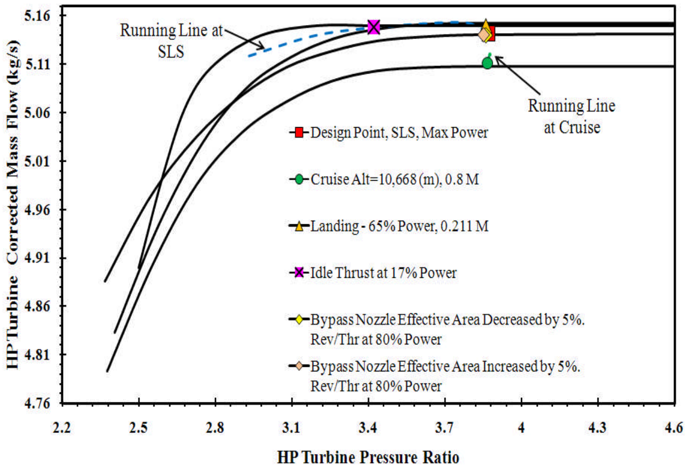

Figure 8: Pressure ratio across the HP turbine at different operating conditions.

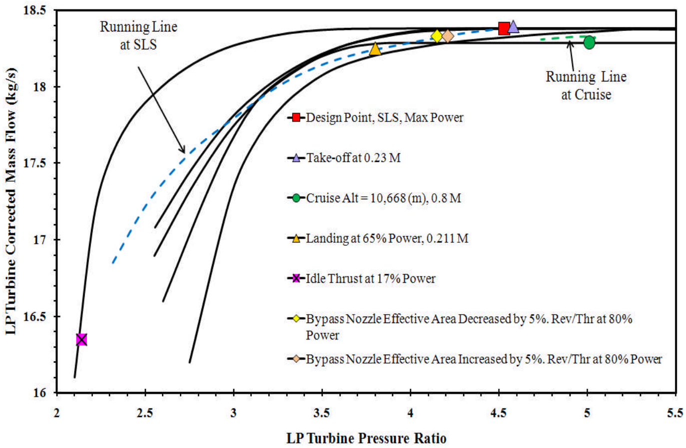

Figure 9: Pressure ratio across the LP turbine at different operating conditions.

4.3 Nozzle Performance

The performance analyses, carried out for both the bypass and the core nozzles, and the variation in pressure across the nozzles at different engine operating conditions are shown in Table 6. The propelling nozzle area for a jet engine is determined from the design point calculations, and once the nozzle size has been fixed, it has a major influence on the off-design operation. During take-off conditions it was observed that the pressure ratios across the two nozzles are slightly higher than that at SLS. The jet engine, of course is intended for flight at high speeds and it is necessary to consider the effect of forward speed on the component equilibrium running lines. It is most convenient to express the forward speed in terms of Mach number for the matching calculations, and this can readily be converted to velocity for calculation of the momentum drag and thrust. At cruise the forward speed produces a ram pressure ratio which is a function of both flight Mach number and intake efficiency. This ram effect will give rise to an increase in compressor delivery pressure, which leads to higher pressure before the propelling nozzle, thereby increasing the nozzle pressure ratio. Once the nozzle is choked, however, the nozzle non-dimensional flow will reach its maximum value and will then be independent of the nozzle pressure ratio and forward speed. The significance of this is that the HP and LP turbine operating points will then also be unchanged, because of the requirement for compatibility of flow between the turbine and the nozzle. It follows that as long as the exhaust nozzle is choked the turbine operating points will be fixed independent of flight speed. Any increase in overall expansion ratio across the nozzle due to increasing ram effect will therefore result in an increase in overall nozzle pressure ratio with the turbine pressure ratio unaffected [10]. Both the core and bypass nozzles are choked at cruise. The turbine capacity, expansion ratio and hence work parameter of the HPT and LPT can be approximated to remain constant. Also, when the nozzles are choked, there will be an additional pressure force due to static pressure in the exit plane being greater than the ambient pressure acting upon the equal area at the front of the engine.

Thus, in our case the nozzle is unchoked during SLS, take-off, landing and thrust reverse operation. Although, the civil aircraft engine spends most time at cruise with the nozzles choked, it is important to consider the effect of low forward speed on the running line under conditions where the nozzle is unchoked because it is at low rotational speeds that the running line is in close proximity to the surge line [Figures 5, 6 and 7]. It should be noted that increasing the Mach number pushes the equilibrium running line away from the surge line at low compressor speeds. Fundamentally, this is because the ram pressure rise allows the compressor to utilise a lower pressure ratio for pushing the required flow through the nozzle.

During landing configuration, both the bypass and the core nozzles will be unchoked; in order to deploy the thrust reverser, the thrust will be reduced to idle at which point the pressure ratios across both the nozzles will be significantly reduced. Once the thrust reverser is deployed, the engine thrust will be increased, thus increasing the nozzle pressure. As previously discussed the beneficial effects of increasing the bypass nozzle effective area during reverse thrust operation will give a better surge margin for the fan and booster [Table 4]. The effect of decreasing the bypass nozzle effective area by 5% and also the effect of increasing the bypass nozzle effective area by 5% relative to its datum value are shown in Tables 3, 4 and 6 and in Figure 10.

Increasing the bypass nozzle effective area decreases the pressure ratio across the bypass nozzle and no change in core nozzle pressure ratio will be observed [Table 6]. At a fixed value of N_H, any increase in bypass nozzle effective area will cause an increase in N_L, the physical reason being that the LP turbine power stays essentially constant at fixed N_H; thus to have constant fan power the reduced fan pressure ratio must be compensated by an increase in mass flow and hence fan speed. This will also cause an increase in engine mass flow and an increase in total gross thrust as shown in the next section. Thus, increase in bypass nozzle area is not only beneficial for increasing the surge margin for the fan and booster, but also has a favourable effect of increasing the reverse thrust.

Nozzle Pressure Table		
Engine Operating Condition	Bypass NPR	Core NPR
Sea Level Static (SLS) – 100% Power	1.58	1.39
Take-off - 0.23 M	1.63	1.41
Cruise – 0.8 M	2.50	2.15
Landing at 65% engine power – 0.211 M	1.44	1.20
Idle thrust at 17% engine power – 0.211 M	1.16	1.04
Rev. thrust at 80% engine power. Bypass nozzle area Unchanged – 0.211 M	1.52	1.28
Rev. thrust at 80% engine power. Bypass nozzle area reduced by 5%. – 0.211 M	1.54	1.27
Rev. thrust at 80% engine power. Bypass nozzle area increased by 5%. – 0.211 M	1.51	1.28

Table 6: Variation in pressure ratio across the bypass and core nozzles at different operating conditions.

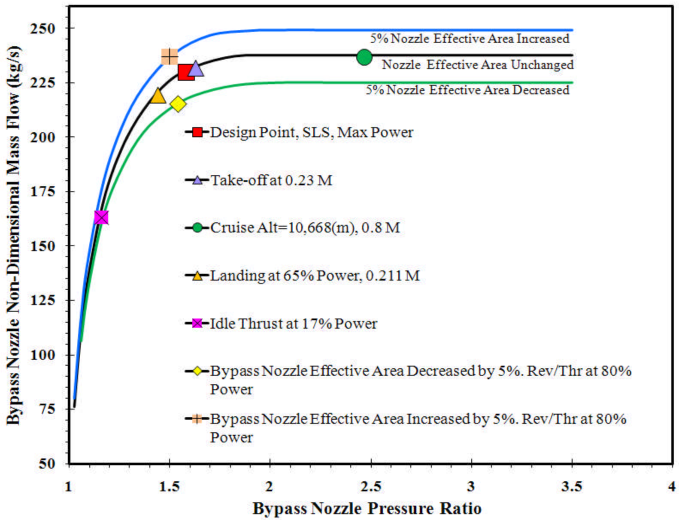

Figure 10: Variation in Pressure ratio across the bypass nozzle at different operating conditions.

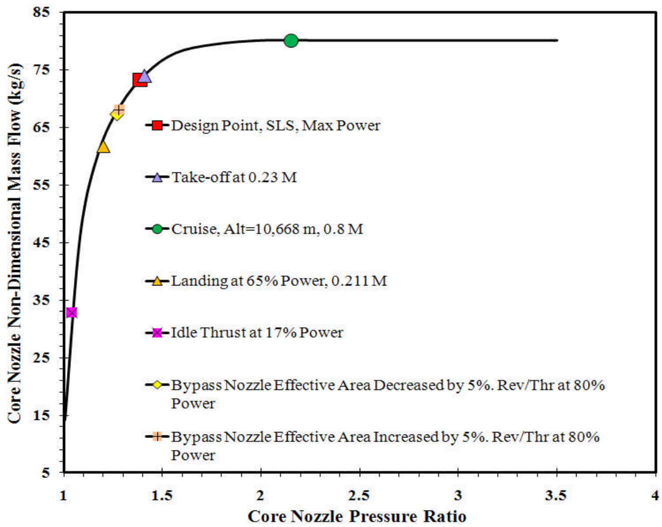

Figure 11: Variation in pressure ratio across the core nozzle at different engine operating conditions.

5 THRUST REVERSER PERFORMANCE

Part of the thrust reverser design optimisation process includes ensuring that the hot air/gases neither impinge on the aircraft wing or fuselage nor are re-ingested into the engine intake, which could cause engine surge and F.O.D. It is also important to minimize any lift component from the thrust reverser in order to maximize braking efficiency. In this section the performance of the thrust reverser is carried out at different landing speeds, and in different configuration angles of the pivoting door to get the maximum reverse thrust, to minimize the landing distance.

The majority of each Airbus A320 landing takes place at *Auto-throttle* setting [11]. At landing the pilot deploys the thrust reversers once the lift dumpers and brakes can be effective. It takes 1.5 seconds for the lift dumpers to be aerodynamically effective for landing configuration; the total time for the brakes and lift dumpers to become effective is about 2 seconds [Table 7]. In the next 1.5 seconds the pilot reduces the engine thrust to idle.

Time Period for Landing Procedure	
Procedure	**Time (s)**
From main gear touchdown to lift dumpers effective	1.8
From main gear touchdown to brakes effective	2
From main gear touchdown to ground idle	3.5

Table 7: Time required for the lift dumpers and brakes to be effective, and to reduce the engine thrust to idle [12].

Once the thrust reversers are deployed, the reverse thrust is established on the fan stream [Figure 12]. This thrust is different from that coming out from a convergent propelling nozzle which, in subsonic civil aircraft, is essentially axial. As shown in [Figure 12], the 3D reverse thrust has force components in all the three axes; an axial component, F_x, a vertical component F_y, and a side force component, F_z. The pivoting doors are normally designed and installed in a nacelle at an angle that will maximize the reverse thrust and will cause the minimum interference with the wing surface. Also, it should be such that the reverse flow will not be re-ingested in the engine as it will induce pressure and temperature distortions along with the F.OD. The reverse (gross) thrust force is expressed as [13]:

$$F = F_{Resultant} = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad \text{[Equation 2]}$$

In the above equation, $F_{Resultant} = F$, and is regarded as the resultant force. F_y, is the vertical component of the reverse thrust, F_x, is the horizontal component of the reverse thrust and F_z, is the side component of the reverse thrust. The individual gross thrust forces will be calculated as follows:

$$F_y = F_{resultant} \times \cos\theta \qquad \text{[Equation 3]}$$
$$F_x = F_{resultant} \times \sin\theta \times \sin\emptyset \qquad \text{[Equation 4]}$$
$$F_z = F_{resultant} \times \sin\theta \times \cos\emptyset \qquad \text{[Equation 5]}$$

In the calculation of this paper, the above equations will be simplified to 2D [Figure 12]. The reverser thrust will be calculated as a 2D force, as the angle $\emptyset$ will only be provided by the manufacturer or calculated from the aerodynamic and/or CFD model. The force, $F_{resultant}$ [Equation 6], is the fan gross thrust. However, for reverse thrust calculation this value is reduced by 5% due to the blocker door leakage during reverse thrust operation.

$$F = F_{Resultant} = \sqrt{F_x^2 + F_y^2} \qquad \text{[Equation 6]}$$
$$F_x = F_{resultant} \times \cos\theta \qquad \text{[Equation 7]}$$
$$F_y = F_{resultant} \times \sin\theta \qquad \text{[Equation 8]}$$

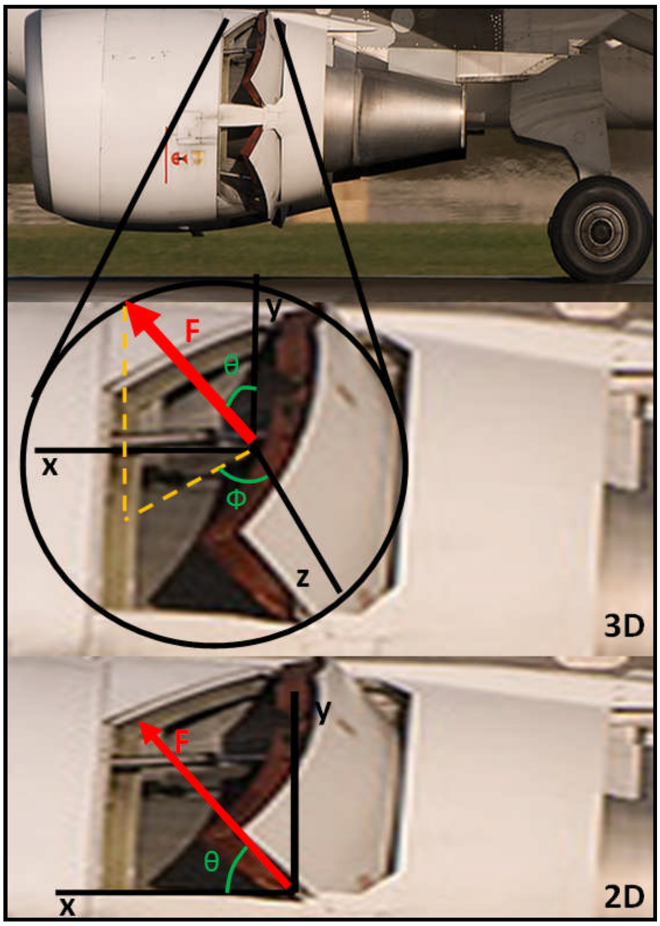

Figure 12: Reverse thrust force components. [14]

5.1 Overall Thrust Reverser Effectiveness

The *overall thrust reverser effectiveness*, η_{rev}, is defined as:

$$\eta_{rev} = F_A / F_{Total} \qquad \text{[Equation 9]}$$

where F_{Total}, is defined as the total nozzle net forward gross thrust (fan + core) that is produced at corresponding core and fan nozzle pressure ratios. The axial force, F_A, is the force during reverse thrust operation and is defined as the difference between the reverse gross thrust and the core nozzle gross thrust:

$$F_A = F_x - F_{core} \qquad \text{[Equation 10]}$$

F_x, is defined as the *gross reverser thrust* and can also be written as, F_{rev}. The core nozzle gross thrust is F_{core}. The typical value of η_{rev} is between 0.31 and 0.58 [13].

5.2 Fan Reverser Effectiveness

The term fan reverser effectiveness is defined as:

$$\eta_{fan} = F_{rev}/F_{fan} \qquad \text{[Equation 11]}$$

In the above equation, F_{rev}, is the gross reverser thrust. F_{fan}, is the fan nozzle forward gross thrust. A reasonable value of η_{fan}, should be > 0.54. The calculations were performed for reverse thrust at different Mach numbers starting from 0.211 M, 0.15 M, and 0.1M. The calculations were not performed for values less than 0.1 M as below this speed the reverser thrust will be cancelled and pilot will make use of the brakes to decelerate the aircraft.

6 AIRCRAFT PERFORMANCE

6.1 Aircraft Landing

Figure 13 shows a plot where the aircraft lands at 65% power at a speed of 0.211 M (140 knots, 72 m/s) and then engages into reverse thrust at 80% power. The pilot cancels the reverse thrust at 0.1 M (66 knots, 34 m/s). At 0.09 M (60 knots, 31 m/s) the pilot changes the reverser thrust into forward idle thrust; this is the normal speed at which the reverser thrust is changed into forward idle. Therefore, the reverser thrust is operated between the speeds of 0.211 M and 0.1M.

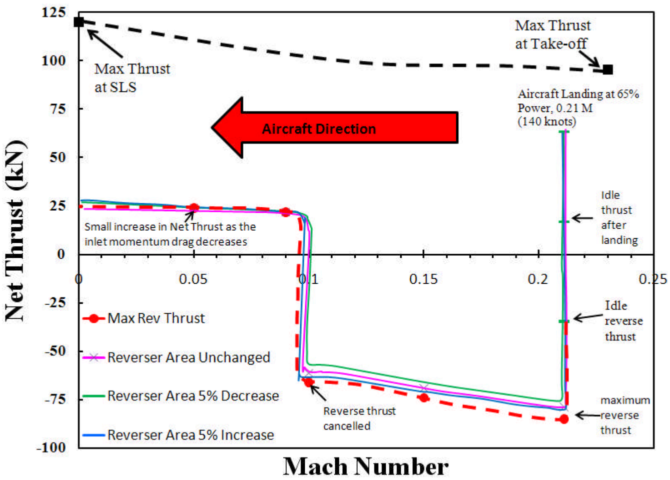

Figure 13: Engine thrust profile during aircraft landing.

Table 8 and Figure 13 show how the calculations were performed. Firstly a reverser exit effective area same as the bypass nozzle effective area was considered. The reverser effective area was then reduced by 5% and finally it was increased by 5%. The calculations were performed for various pivoting door angles, ranging from 25 – 50 degrees to the axial direction. It was observed, reducing the reverser effective exit area reduces reverse thrust whereas increasing the reverser effective exit area increases the reverse thrust. The higher the reverse thrust the greater will be the aircraft deceleration and less will be the stopping time and distance. The reverse thrust is cancelled at 0.09 M and the aircraft is taxing at idle thrust [Figure 13 and Table 8]. However, the net thrust will increase as the aircraft decelerate from 0.09 M to 0.05 M (31 m/s to 17 m/s); this is because as the aircraft decelerates the inlet momentum drag decreases from (6.02 to 3.32 kN).

Thrust Reverser Performance						
Operating Conditions	M	m (kg/s)	Total Gros/Thr (kN)	Gross Rev/Thru (kN)	θ Deg	Net Thrust (kN)
SLS	0.0	406.8	120.1	-	-	120.1
Take-off	0.23	407.4	128	-	-	95.5
Cruise	0.8	163.1	63.7	-	-	25.04
Landing	0.21	343.8	88.5	-	-	63.4
Fwd-Idle landing	0.21	207.1	32	-	-	16.9
Rev-Idle	0.21	207.1	32	21.24	35	-34.76
Fwd-Idle Taxi	0.09	196.6	27.62	-	-	21.63
Fwd-Idle Taxi	0.05	195.3	27.08	-	-	23.79
R/ Area(m^2)	Reverser Area Unchanged – 80% Power					
0.995	0.21	374.8	105.7	54.12	50	-64
0.995	0.21	374.8	105.7	59.54	45	-69.42
0.995	0.21	374.8	105.7	64.5	40	-74.38
0.995	0.21	374.8	105.7	68.9	35	-78.85
0.995	0.21	374.8	105.7	72.9	30	-82.8
0.995	0.21	374.8	105.7	76.3	25	-86.19
R/ Area(m^2)	Reverser Area Decreased by 5% - 80% Power					
0.945	0.21	361.4	102.9	52.6	50	-61.7
0.945	0.21	361.4	102.9	57.8	45	-66.9
0.945	0.21	361.4	102.9	62.7	40	-71.8
0.945	0.21	361.4	102.9	67	35	-76.2
0.945	0.21	361.4	102.9	70.8	30	-79.9
0.945	0.21	361.4	102.9	74.1	25	-83.3
R/ Area(m^2)	Reverser Area Increased by 5% - 80% Power					
1.045	0.21	387.6	108.1	55.32	50	-65.7
1.045	0.21	387.6	108.1	60.86	45	-71.2
1.045	0.21	387.6	108.1	65.93	40	-76.3
1.045	0.21	387.6	108.1	70.5	35	-80.8
1.045	0.21	387.6	108.1	74.5	30	-84.9
1.045	0.21	387.6	108.1	78	25	-88.3
1.045	0.15	386.3	104.7	53.49	50	-56.21
1.045	0.15	386.3	104.7	58.85	45	-61.56
1.045	0.15	386.3	104.7	63.75	40	-66.47
1.045	0.15	386.3	104.7	68.17	35	-70.9
1.045	0.15	386.3	104.7	72.07	30	-74.8
1.045	0.15	386.3	104.7	75.42	25	-78.1
1.045	0.1	385.5	102.8	52.45	50	-48.8
1.045	0.1	385.5	102.8	57.7	45	-54.02
1.045	0.1	385.5	102.8	62.5	40	-58.8
1.045	0.1	385.5	102.8	66.85	35	-63.2
1.045	0.1	385.5	102.8	70.7	30	-67
1.045	0.1	385.5	102.8	73.9	25	-70.3

Table 8: Variation of engine net thrust at different reverser nozzle area and reverser cascade angles.

6.2 Aircraft Deceleration time

During landing the pilot applies reverse thrust to shorten the landing distance. The reverse thrust exhaust is inclined at the pivoting door angle (θ) to the normal flight. If the aircraft is powered by (n) engines, and assuming the average drag on the airplane during landing is, D_{av}, then the time necessary to decelerate the airplane from touchdown speed (V_{TD}) to any value (V) is given by[15]:

$$t = -\frac{m}{n\dot{m}_a}\, ln\frac{V + V_j \cos\theta + (D_{av}/n\dot{m}_a)}{V_{TD} + V_j \cos\theta + (D_{av}/n\dot{m}_a)} \quad \text{[Equation 12]}$$

where

m: aircraft total mass at landing

$\dot{m}_a$: mass flow rate of air entering or leaving one engine (negligible fuel mass flow rate)

V_j : reverse flow exit velocity

θ : reverser cascade angle, taken as 35°

$$D = D_{av} = \frac{1}{2}\,\rho\, V^2\, S\, C_D \quad \text{[Equation 13]}$$

As mentioned previously, the aircraft configuration used for this calculation is similar to that for an Airbus A320, called CUTEA (Cranfield University Twin Engine Aircraft) and the information available in the public domain was used for the calculations. A reasonable estimated value for the aircraft landing weight was taken as W=55,225kg, aircraft touchdown speed of 0.211 M (140knots), the average aircraft drag was calculated from [Equation 13]. The pivoting door angle was taken as 35 degrees. The calculations were performed to find the total time for which the thrust reverser is deployed and the aircraft deceleration rate.

Table 9 shows that the increase in reverser effective area increases the reverse thrust, therefore, reduces the aircraft speed in minimum time. It can also be seen that although the thrust reversers are universally used by all the airlines, their use is only for a very short period of time. A survey was carried out by British Airways at London Heathrow Airport where they measured the thrust reverser deployment time for various aircraft on a dry runway. In the survey, 32 landings of the Airbus A320 were observed out of which 60% of the landings were carried out using the reverse thrust greater than idle and average time for use of the reverse thrust was noted to be about 18 seconds [16]. The value is very close to the calculations that were performed in this paper [Table 9]. The aircraft deceleration time with thrust reverser for the 5% increased area is about 18.79 seconds, this matches very well with the survey carried out by the British Airways. The rate of deceleration between the three configurations varied slightly. Although, thrust reversers are used for a very short duration when compared with the overall flight time, it should be remembered that thrust reverser malfunction and late deployment in the past has caused catastrophic fatalities, therefore, care must be taken during all phases of thrust reverser design as it is a critical component and offers safety for both passenger and aircraft.

Reverser Area Unchanged					
Aircraft mass (kg)	**V (knots)**	$\dot{m}_a$ **(kg/s)**	**Drag (N)**	$V_j \cos\theta$	**Time (sec)**
55,225	140	374.8	34,957	225.6	1.09
55,225	130	374.8	30,180	225.6	2.26
55,225	120	374.8	25,671	225.6	3.44
55,225	110	374.8	21,602	225.6	4.68
55,225	100	373.6	17,815	225.6	5.94
55,225	90	373.6	14,456	225.6	7.14
55,225	80	373.6	11,670	225.6	8.62
55,225	70	373.6	8,739	225.6	10.01
55,225	60	373.6	6,438	225.6	19.17
		Total time (sec)			**19.17**
Adding 3.5 seconds for the T/Rev Deployment					**22.67**
Aircraft Deceleration rate (m/s^2)					**-2.14**

Reverser Area Decreased by 5%					
Aircraft mass (kg)	**V (knots)**	$\dot{m}_a$ **(kg/s)**	**Drag (N)**	$V_j \cos\theta$	**Time (sec)**
55,225	140	361.4	34,957	228.5	1.13
55,225	130	361.4	30,180	228.5	2.3
55,225	120	361.4	25,671	228.5	3.52
55,225	110	361.4	21,602	228.5	4.8
55,225	100	360.1	17,815	228.5	6.09
55,225	90	360.1	14,455	228.5	7.32
55,225	80	360.1	11,669	228.5	8.83
55,225	70	360.1	8,739	228.5	10.26
55,225	60	360.1	6,438	228.5	19.64
		Total time (sec)			**19.64**
Adding 3.5 seconds for the T/Rev Deployment					**23.14**
Aircraft Deceleration rate (m/s^2)					**-2.09**

Reverser Area Increased by 5%					
Aircraft mass (kg)	**V (knots)**	$\dot{m}_a$ **(kg/s)**	**Drag (N)**	$V_j \cos\theta$	**Time (sec)**
55,225	140	387.6	34,957	222.5	1.08
55,225	130	387.6	30,180	222.5	2.21
55,225	120	387.6	25,671	222.5	3.36
55,225	110	387.6	21,602	222.5	4.58
55,225	100	386.3	17,815	222.5	5.83
55,225	90	386.3	14,455	222.5	7.00
55,225	80	386.3	11,669	222.5	8.45
55,225	70	386.3	8,739	222.5	9.82
55,225	60	386.3	6,438	222.5	18.79
		Total time (sec)			**18.79**
Adding 3.5 seconds for the T/Rev Deployment					**22.29**
Aircraft Deceleration rate (m/s^2)					**-2.18**

Table 9: Total time and deceleration rate during reverse thrust for the three different reverser area configurations.

6.3 Calculation of Aircraft Ground Roll Distance

As the aircraft touches down there will be a period of rotation which introduces a slight delay before the wheel brakes can become effective. The typical rate of rotation is about 3 degrees per second; there will be some deceleration during the delay period, even though the brakes have not yet become effective. In a typical touchdown case the speed falls by about 1.5% per second [17]. The ground roll time (t) in which the lift dumpers and brakes become effective is about 3 - 4 seconds for large airplanes [15]. The next stage is applying the reverse thrust for some 600 to 700 m. Finally, the thrust reverser is stowed prior to final stop. Thus, the three landing distances will be calculated here. Only the main equations are presented. Detailed derivation is shown in [15] and [17]. The landing distance may then be written as:

$$S_{Total} = S_1 + S_2 + S_3 \qquad \text{[Equation 14]}$$

Where the free roll distance is

$$S_1 = S_{fr} = tV_{TD} \qquad \text{[Equation 15]}$$

$$S_2 = \frac{m}{2} \frac{V_{TD}^2 - V_{brake}^2}{[T_{rev} + D + \mu_{r1}(W - L)]_{0.7V_{TD}}} \qquad \text{[Equation 16]}$$

Here the lift and drag forces are calculated at an average speed equal to seventh-tenth of the touchdown speed. The value for reverse thrust, T_{rev}, are obtained from [Table 8] at a reverser cascade angle of 35^o.

The third segment is when the brakes are applied and the thrust is again in the axial direction but at idle condition. Here the lift and drag forces are calculated at an average speed equal to thirty five percent of the touchdown speed.

$$S_3 = \frac{m}{2} \frac{V_{brake}^2}{[-T + D + \mu_{r2}(W - L)]_{0.35V_{TD}}} \qquad \text{[Equation 17]}$$

where:

T_{rev}: (difference between the reverse thrust axial component and the core thrust)

μ_{r1}: runway rolling coefficient of friction

μ_{r2}: braking coefficient of friction

m: aircraft landing weight (55,225 kg)

L: aircraft lift

W: aircraft downward force

V_{TD}: the touchdown speed.

Table 10 shows the landing distance for five different cases. In all the calculations, the reverse thrust was taken at 80% engine power. In the case of maximum reverse thrust it was assumed that the pilot is using the engine at 100% power. The values for reverse thrust were obtained from Table 8.

Aircraft Landing Distance							
V_{TD} (m/s)	V_{TD2} (m/s)	V_B (m/s)	m (k/g)	Net Rev/T (kN)	S_1 (m)	S_2 (m)	S_3 (m)
Reverser Area Unchanged – Pivoting Door Angle 35^o							
72	69.84	27.9	55,225	140.5	248	676	65
				S_{Total} =	**989 m (3,245 feet)**		
Reverser Area Decreased by 5% – Pivoting Door Angle 35^o							
72	69.84	27.9	55,225	135.4	248	696	65
				S_{Total} =	**1,009 m (3,311 feet)**		
Reverser Area Increased by 5% – Pivoting Door Angle 35^o							
72	69.84	27.9	55,225	143.9	248	663	65
				S_{Total} =	**976 m (3,202 feet)**		
Reverser Thrust at MAX Power – Pivoting Door Angle 35^o							
72	69.84	27.9	55,225	149.7	248	641	65
				S_{Total} =	**953 m (3,127 feet)**		
Reverser Thrust set at Idle power – Decelerating with Brakes and lift dumpers							
72	69.84	27.9	55,225	29.15	248	1,174	65
				S_{Total} =	**1487 m (4,879 feet)**		

Table 10: Stopping distance with thrust reversers at different configurations on a dry runway.

As shown in Table 10 and Figure 14, landing with thrust reverser operating could considerably reduce the landing distance. In the last case [Table 10] the pilot sets the reverse thrust at idle power and decelerates the aircraft only with brakes and lift dumpers: the landing distance of 1,487 m (4,879 feet) is similar to that given in [18] for the Airbus A320 where the distance of 1,490 m is given at maximum landing weight. This shows that the landing distances are given by aircraft manufacturers without taking the effects of thrust reverser into account. Comparison is made between the case where the pilot decides to set the reverse thrust to idle and decelerate the aircraft only by brakes and lift dumpers, with the case when the pilot uses maximum reverse thrust. There is the difference of 534 m (1,752 feet) which is substantial and could be extremely beneficial in case of emergency landing or landing at the airports where the runways could be contaminated due to wet or icy conditions.

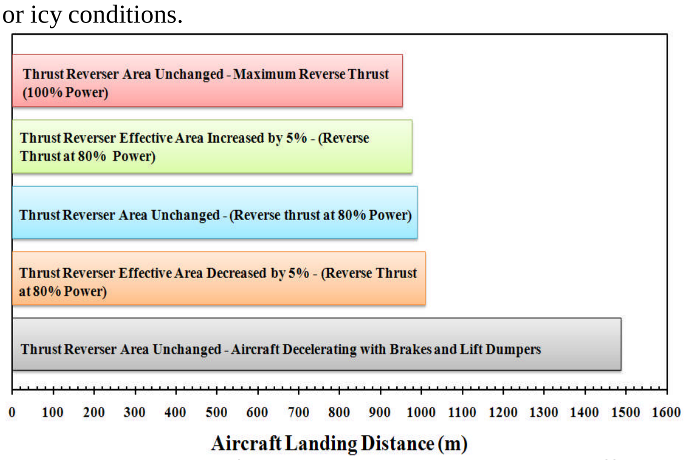

Figure 14: Aircraft stopping distances at different configurations on a dry runway.

CONCLUSIONS

Three cases were studied; first, the reverser exit area was assumed to be the same as the bypass nozzle exit area; in the other two cases the reverser area was reduced by 5% and increased by 5%. It was observed, increasing the reverser area by 5% could be beneficial in increasing the fan and booster surge margin. Also, the reverser with an exit area of 5% greater than the bypass nozzle area will be beneficial as it will produce more reverse thrust than the other two configurations. Analyses for time estimation and landing distances were performed using a 35^{o} pivoting door angle for the three thrust reverser configurations. The reverser with an increased area achieved the shortest time, highest deceleration rate and minimum landing distance. It was observed that on a dry runway the use of thrust reversers can reduce the landing distance on average by more than 487 m (1600 feet).

The best reverser angle is theoretically the smallest angle relative to the axial direction. However, practical problems limit the value to about 35 degrees.

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NOMENCLATURE

ABS	Auto brake system.
CUTS_TF	Cranfield University Twin Spool Turbofan.
CUTEA	Cranfield University Twin Engine Aircraft.
C_D	Drag coefficient.
D	Aircraft drag, N.
D_{av}	Average Drag, N.
EEC	Electronic Engine Control.
F.O.D	Foreign Object Damage.
F_A	Axial force during reverse thrust, N.
F_{core}	Core nozzle gross thrust, N.
F_{fan}	Fan nozzle forward thrust, N.
$F_{Resultant}$	Resultant reverser force, N.
F_{rev}	Gross reverse thrust, N.
F_{Total}	Total gross forward thrust i.e. fan + core, N.
F_x	Reverse thrust axial force component, N.
F_y	Reverse thrust vertical force component, N.
F_Z	Reverse thrust side force component, N.
HPC	High pressure compressor.
HPT	High pressure turbine.
LPT	Low pressure turbine.
L	Aircraft lift, N.
m	Aircraft mass, kg.
$\dot{m}_a$	Mass flow, kg/s.
M	Mach No
n	Number of engines
N_H	Rotational speed for HP rotor
N_L	Rotational speed for LP rotor
OPR	Overall pressure ratio
PR	Pressure ratio
S	Aircraft wing area, m^2.
s.f.c	Specific fuel consumption
t	Time, seconds.
T	Thrust, N.
T_{rev}	Difference between net reverse thrust axial component and the core thrust, N.
TET	Turbine entry temperature, K.
V_{Brake}	Velocity at braking point, m/s.
V_j	Jet Velocity, m/s.
V_{TD}	Aircraft touchdown velocity, m/s.
W	Aircraft downward force, N.
V	Velocity, m/s.
ρ	Density at sea level, kg/m^3.
θ	Pivoting door angles relative to axial, degrees.
η_{fan}	Fan reverser effectiveness
η_{rev}	Overall thrust reverser effectiveness
μ_{r1}	Runway rolling coefficient of friction
μ_{r2}	Braking coefficient of friction

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