The Supersonic Performance of High Bypass Ratio Turbofan Engines with Fixed Conical Spike Inlets

by

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ABSTRACT

The objective of this study is to understand how to integrate conical spike external compression inlets with high bypass turbofan engines for application on future supersonic airliners. Many performance problems arise when inlets are matched with engines as inlets come with a plethora of limitations and losses that greatly affect an engine's ability to operate. These limitations and losses include drag due to inlet spillage, bleed ducts, and bypass doors, as well as the maximum and minimum values of mass flow ratio at each Mach number that define when an engine can no longer function. A collection of tools was developed that allow one to calculate the raw propulsion data of an engine, match the propulsion data with an inlet, calculate the aerodynamic data of an aircraft, and combine the propulsion and aerodynamic data to calculate the installed performance of the entire propulsion system. Several trade studies were performed that tested how changing specific design parameters of the engine affected propulsion performance. These engine trade studies proved that high bypass turbofan engines could be developed with external compression inlets and retain effective supersonic performance. Several engines of efficient fuel consumption and differing bypass ratios were developed through the engine trade studies and used with the aerodynamic data of the Concorde to test the aircraft performance of a supersonic airliner using these engines. It was found that none of the engines that were tested came close to matching the supersonic performance that the Concorde could achieve with its own turbojet engines. It is possible to speculate from the results several different reasons why these turbofan engines were unable to function effectively with the Concorde. These speculations show that more tests and trade studies

need to be performed in order to determine if high bypass turbofan engines can be developed for effective usage with supersonic airliners in any possible way.

DEDICATION

To my family, my friends, and my professors; you are the ones who saw my potential, always supported and believed in me to achieve my goals, and drove me to always strive to accomplish more. Thank you for everything you have done to help me along with my journey.

ACKNOWLEDGEMENTS

Much of the work and tools needed for completion of the thesis was done thanks to former M.S. students Christopher Gedeon, Josh Dickman, and Ryan Palma who developed earlier versions of the NPSS model of the two-shaft turbofan engine and put in earlier efforts to study supersonic inlet performance.

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INTRODUCTION

Many engineers dream of a future with commercial supersonic flight. It has been more than 70 years since Chuck Yeager safely broke the sound barrier. Airliners that travel at supersonic speeds can greatly decrease the travel time required to fly long distances; this is a positive factor for passengers who need to take these journeys. Unfortunately, the dream of supersonic airliners has proven to be very slow and difficult to achieve; only a few designs ever reaching the production line. Only the BaE Concorde had some sort of commercial career, but none remain in use. It turns out that many problems arise in the designing process of an aerospace vehicle when one wishes to build a large scale supersonic aircraft, such as the aerodynamics of the design or the structures and materials used to build it. Propulsion is one of the main challenges aerospace engineers face when it comes to the development of supersonic airliners.

Large commercial aircraft need engines big enough to produce the thrust needed to overcome their drag under engine-inoperative conditions at takeoff; they also need to overcome drag at high-altitude, high-speed flight. Typical airliners usually have a maximum Mach number of around 0.8; they have engines optimized for subsonic flight. To fly at Mach numbers above 1.0 requires the engines to develop thrust across a range of speed and altitude well beyond that found on current commercial engines. In order to efficiently fly at supersonic speeds, engineers need to develop an engine that can produce high-altitude, high-speed thrust. In order to take off and land at commercial airports, engineers need to fit future supersonic aircraft with engines that are quiet enough to meet current and proposed noise-level standards for certification.

With the resurgence of interest in supersonic commercial flight found in press releases by Gulfstream[1], Aerion[2], and Boom Aerospace[3], it is notable the need to explore the “art-of-the-possible” in commercial supersonic propulsion systems. It is important to understand how to create a large-scale engine with the ability to generate enough thrust to allow an airliner to reach supersonic speeds and with a high enough bypass ratio to be quiet enough to be cleared to operate from real world airports.

While it is understood that a Mach 2.0 “higher-bypass ratio” turbofan has never achieved volume production, it is desired to determine if there are physical impossibilities that prevent this, or merely a lack of finance. To do so, one must examine a plethora of thermodynamic and fluid mechanic problems. Engines having insufficiently large inlets or too little compression may not be able to bring in enough air for the engine to operate at higher Mach numbers and altitudes. Engines having excessively large inlets may oversupply an engine with air and disrupt its ability to operate.

The work here will combine a two-shaft turbofan engine thermodynamic model (developed using NPSS[4]) with a complex aerodynamic inlet loss model (developed using basis data found in PIPSI[5,6,7,8]).

AERODYNAMICS OF PROPULSION: TURBOFAN ENGINES

To understand the importance of the type of jet engine used with an aircraft, one should have knowledge of what a turbofan engine is, how it works, and what properties define its effectiveness. Turbofan engines have been of general use with the aerospace industry since the 1960s and has become one of the most common jet engine designs used with aircraft. Most modern commercial aircraft use high bypass turbofan engines while most military aircraft use low bypass turbofan engines. While possessing some disadvantages to other jet engine designs, especially with regards to high speed flight, it is apparent that any modern day supersonic airliner would need to use high bypass turbofan engines to be considered viable for commercial use.

Basic Functionality

At its most simplified form, a turbofan engine is a gas turbine system that functions with just about all the same principles as any other jet engine design. All gas turbine engines run off the principles of the Brayton thermodynamic cycle which involves increasing pressure and temperature of a fluid through a system to generate work. The first stage of the cycle for the engine is air flows through the inlet and enters a compressor that increases the pressure of the air moving through the system. The next stage of the cycle has the now pressurized air flow enter a chamber known as a combustor or burner where fuel is added to the high-pressure air and ignited which results in a high temperature gas flow. The last stage of the cycle has the now high temperature and pressure gas flow enter a turbine where the flow is expanded and decreases in pressure which produces shaft work that the turbine uses to drive the compressor. Any remaining energy from the gas flow that is not used as shaft work by the turbine flows out of the engine through a nozzle as an exhaust gas which produces thrust. This turbine system is the simplest configuration of a jet engine and is called a turbojet engine.[9] A diagram of this thermodynamic process running through a gas turbine engine is presented in Figure 1.

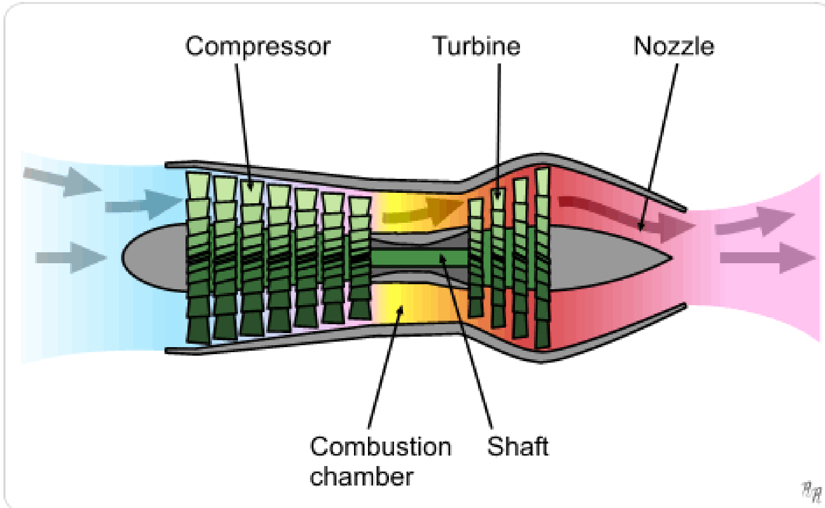

Figure 1. Diagram of Airflow Moving through a Turbojet System

A turbofan engine possesses all the same machinery as a turbojet engine but with one other mechanical system involved. A duct enclosed fan with a low-pressure compressor is placed in front of the main compressor of the system and is driven by either the main turbine driving the compressor or an independent turbine system. A two-spool configuration is where the fan and low-pressure compressor are connected to a low-pressure turbine that is located right behind the main turbine of the system. This means that the fan and low-pressure compressor are driven by the shaft work of the low-pressure turbine which is produced from the remaining energy of gas flow moving out of the main turbine. This configuration is one of the most common ones used with turbofan engines and the two-spool turbofan design is the only one used in this project.

The area of the fan is larger than the main turbine system which is referred as the core, which means that the air that flows through the inlet and then the fan not only flows through the core but around it as well. The work done on the air by the fan increases its kinetic energy, which increases the velocity of the airflow moving around the core. The air flow that moves around the core then exits the engine either separately from or mixed with the main flow of the gas turbine depending on the duct design of engine. The idea of this system is that the thrust of the engine is produced by a combination of the exhaust gas flowing from the gas turbine and the increased-speed air flow moving around the core and out the same direction as the exhaust gas. This means that the engine does not rely solely on the nozzle exit flow of the turbine to produce thrust and is therefore more efficient with fuel consumption. The amount of thrust that is produced by the airflow through the fan depends on the size of the fan compared to the size of the core as well as the rotational speed of the fan.[10] A diagram of airflow moving through a two-spool turbofan engine system is presented in Figure 2.

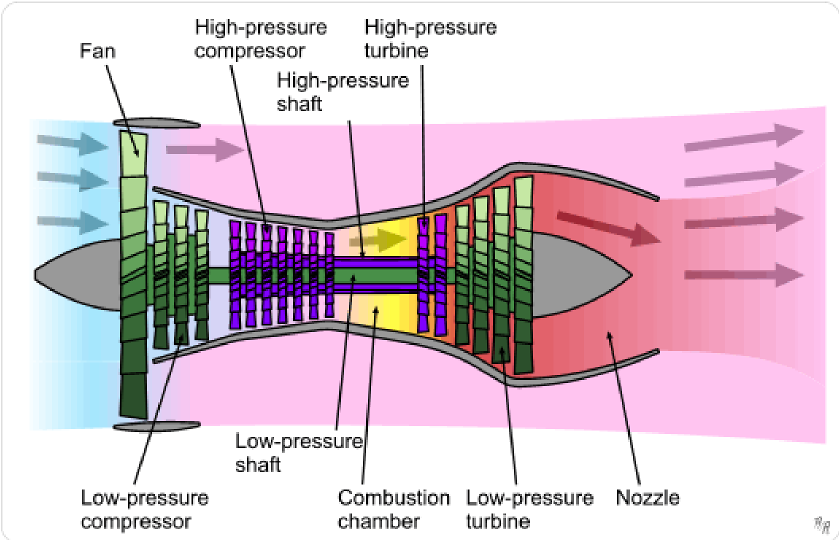

Figure 2. Diagram of Airflow Moving through a Two-Spool Turbofan System

As stated previously, turbofan engines are one of the most commonly used jet engines in the aerospace industry today. The reason for this comes from its effective thrust and thrust specific fuel consumption efficiency at high subsonic and low supersonic speeds. Having a portion of the thrust depend on the airflow through the fan means that less fuel needs to be burned in the turbine process to generate the necessary thrust for desired aircraft speed. Another crucial factor is the fact that the amount of airflow that moves around the core depending on the size of the fan, also known as the bypass flow, means that there is versatility to the design of a turbofan depending on desired performance. A turbofan engine with a larger bypass ratio would give an aircraft better range and fuel efficiency while a turbofan engine with a smaller bypass ratio would give an aircraft better thrust performance. Turbofan engines are also much quieter than other high-speed engines like the turbojet since the thrust it produces doesn't all come from the high velocity exhaust gas which means less jet noise is generated.

While advantageous for a wide range of aircraft designs, there are still disadvantages to using turbofan engines when compared to other jet engine designs. The size of turbofans is an obvious and one of the biggest disadvantages to the design. They are much larger than most other engine designs since the outer frame of the engine is the size of the fan to allow for the airflow to move over the core. This means a larger surface area which results in more drag accumulating around the engine which lead to loss in performance. This loss in performance due to drag is especially apparent when the turbofan reaches high supersonic speeds. Even though a high bypass turbofan engine could generate more thrust than a turbojet engine with its combined fan and jet thrust, the amount of drag that accumulates from its size more than offsets the greater amount of thrust that is produced. This means turbofan engines need a low bypass ratio in order to avoid the large amount of drag loss and have a performance similar to a turbojet engine at high speeds. The issue with using a smaller fan is now the engine is no longer as efficient with fuel consumption since it relies less on fan thrust.[11]

Important Design Parameters

Many different design parameters and properties are present throughout the various systems of a turbofan engine. The design parameters that will be focused on in the project are the ones that are adjustable for the simulations performed that generate propulsion data. These parameters are some of the most important aspects of a turbofan engine as they define the propulsion performance and limitations of the fan, the core, and the system as a whole.

The bypass ratio is one of the most important parameters when it comes to determining the performance of the thrust coming from the fan as well as TSFC of the entire system. BPR is the ratio of the mass flow rate of air moving around the core to the mass flow rate of air moving through the core. A visual representation of BPR is presented in Figure 3. This means that BPR is what determines the amount of air that flows through the fan and is the biggest factor in defining the size of the fan to the size of the core and therefore the size of the whole engine. A BPR value less than 1.0 means that more air flows through the core than through the fan and this is referred as low bypass. A BPR value above 1.0 means that more air flows through the fan than through the core and this is referred as high bypass. BPR is also the main design parameter in establishing the desired propulsion efficiency of an engine. A lower BPR value means that the engine is less TSFC efficient but produces higher exit flow velocity and less drag due to its smaller size which makes it effective for high supersonic speeds. A higher BPR value means the engine produces more thrust due to the combination of fan and jet thrust as well as higher TSFC efficiency which makes its effective for large aircraft flying great distances.[11]

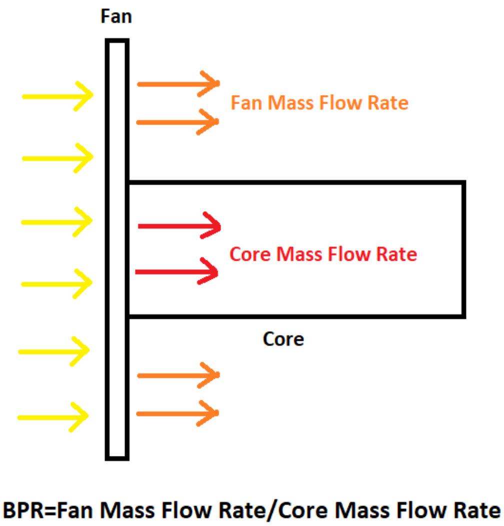

Figure 3. Diagram of Bypass Ratio in the Engine System

The fan pressure ratio is another important parameter when it comes to determining the performance of the thrust coming from the fan as well as TSFC of the entire system. FPR is the ratio of the total pressure of the fan outlet airflow to the total pressure at the exit of the engine inlet. A visual representation of FPR is presented in Figure 4. This means that FPR is what determines the increase in pressure of the fan airflow due to the work done by the fan and therefore the speed of the airflow moving around the core and the thrust it generates at the outlet. Since the work done by the fan on the bypass airflow in a two-spool configuration is powered by the shaft work of a turbine using the exhaust gas after the main turbine, this means less thrust is generated from the core as the fan power increases. Even though decrease in jet thrust occurs, the efficiency of the fan is usually enough to make the decrease minor and the fan thrust produced from the work done by the fan is more than enough to offset this loss of thrust. This indicates that an engine achieves higher thrust performance as the FPR value increases due to the increase in thrust from the fan airflow. Increasing FPR also leads to better TSFC performance since more thrust from the increased velocity of the fan airflow means more reliance on fan thrust and less fuel burned for jet thrust to achieve specific thrust values.[11]

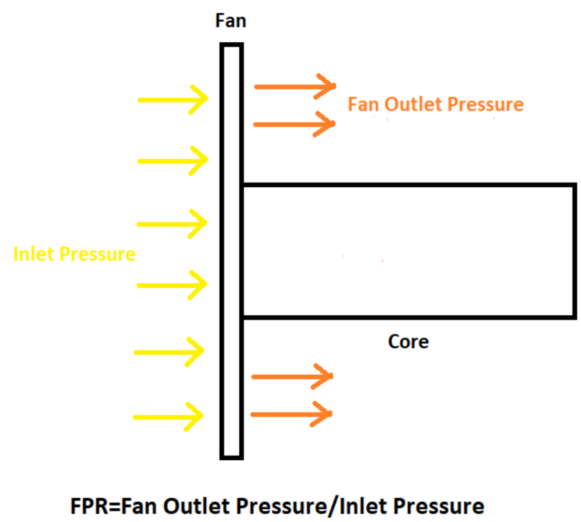

Figure 4. Diagram of Fan Pressure Ratio in the Engine System

The turbine inlet temperature is an important parameter when it comes to determining the performance of the thrust coming from the core as well as TSFC of the entire system. TIT is the temperature of the gas flow after it went through the combustor and right before it enters the main turbine of the system. A visual representation of TIT is presented in Figure 5. This means that TIT is what determines the amount of fuel that is burned in the combustor as well as the excess amount of air supplied to the combustor to generate the necessary amount of energy for the main turbine, fan turbine, and jet thrust.

The relation of thrust and TSFC efficiency is very simple when it comes to TIT. Since more fuel would need to be burned to generate more energy and therefore more thrust, higher TIT leads to higher thrust performance but worse TSFC performance. It should be noted that TIT cannot be continuously increased to increase jet thrust, there is a finite amount of energy that can be generated from air as it increases in temperature. This indicates that there is a point where the combustor is hot enough that no more energy can be generated from airflow even if more fuel was burned.[11]

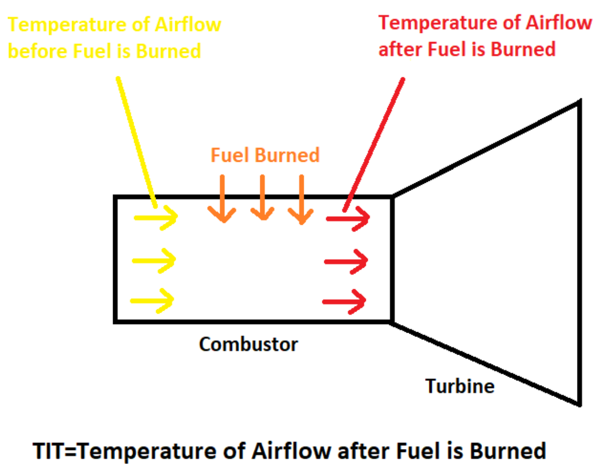

Figure 5. Diagram of Turbine Inlet Temperature in the Engine System

The overall pressure ratio is another important parameter when it comes to determining the performance of the thrust coming from the core as well as TSFC of the entire system. OPR is the ratio of the total pressure entering the combustor to the total inlet pressure of the engine. A visual representation of OPR is presented in Figure 6. This means that OPR is what determines the increase in pressure of the core airflow due to the main compressor and therefore the pressure of the airflow moving through the turbine system. An airflow at higher pressure leads to more work generated by the turbine and higher speed of exhaust gas due to larger difference of pressure inside the exit nozzle to pressure outside the exit nozzle. This indicates that as the OPR value of the engine is increased, the thrust that is generated by the exhaust gas of the core increases. Unlike most of the other design parameters that affect propulsion performance, increasing OPR also leads to better TSFC efficiency even though it also increases jet thrust. The reason for this comes from the fact that increased pressure also leads to increased temperature of the airflow as it is compressed by substantial amounts of force. This means that less fuel needs to be burned in the combustor to achieve a specific TIT value for the already hotter airflow or the same amount of fuel can be burned to achieve a higher TIT value and more energy. Combining this with the increase to jet thrust due to the increase in pressure leads to less fuel being used per unit of thrust generated which translates to better TSFC efficiency. Ideal Brayton cycle *T-s* diagrams of a lower OPR and a higher OPR engine system showing how increasing OPR affects work done by the system are presented in Figure 7. It should be noted that most of the limitations to OPR come from the compressor of the system. The reason for this is compressors get heavier as the OPR value is increased and the high temperature of the airflow as it is compressed creates a risk of the compressor machinery being damaged.[11]

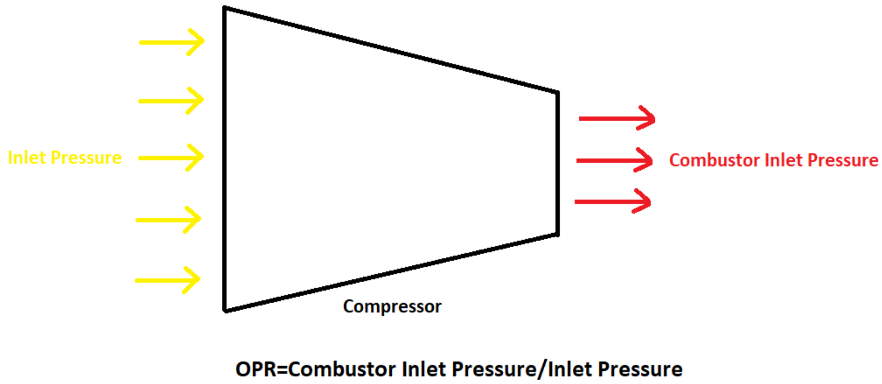

Figure 6. Diagram of Overall Pressure Ratio in the Engine System

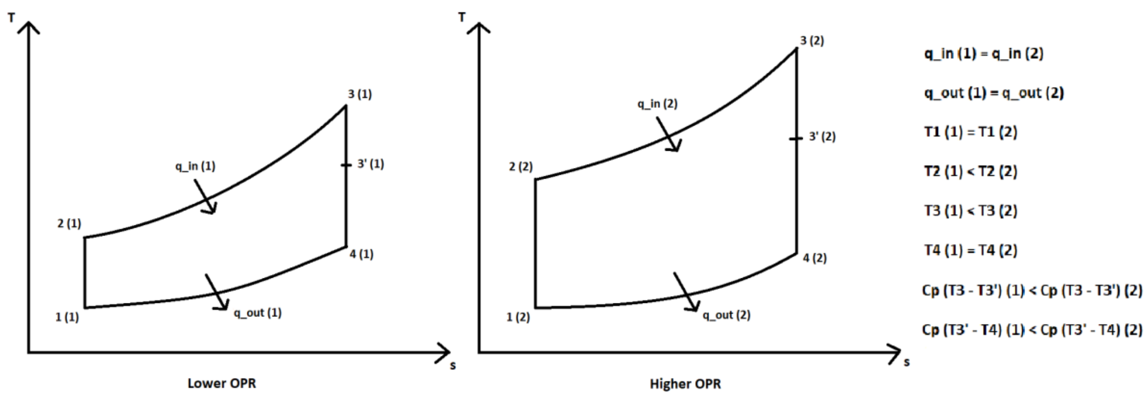

Figure 7. Ideal Brayton Cycle *T-s* Diagrams Showing the Effect of Increasing OPR

The overall size of the engine is an important parameter when it comes to determining the raw propulsion performance of the whole engine as well as the loss of performance due to the inlet. In the case of the engine simulations performed in this project, the overall size refers to the fan diameter of the turbofan configuration. A diagram showing how the fan diameter essentially defines the size of a turbofan engine is presented in Figure 8. Out of all the other design parameters that are focused on in the project, fan diameter is one of the only ones that is not independently changed for each engine test. The reason for this is the input files used in the simulations adjust the fan diameter according to the set parameters of BPR, FPR, TIT, and OPR. This means that the size of the engine depends on the desired performance of the fan and core system. One of the biggest factors that the fan diameter affects when it comes to propulsion performance is the size of the inlet. More detail about inlet sizing and performance will be discussed later, but it is important to know that inlet matching defines the functionality of an engine at specific flight conditions. Inlets too small lead to engines not having enough airflow to function at higher speeds and altitudes and inlets too large lead to the engines losing performance at lower speeds and altitudes due to drag loss.

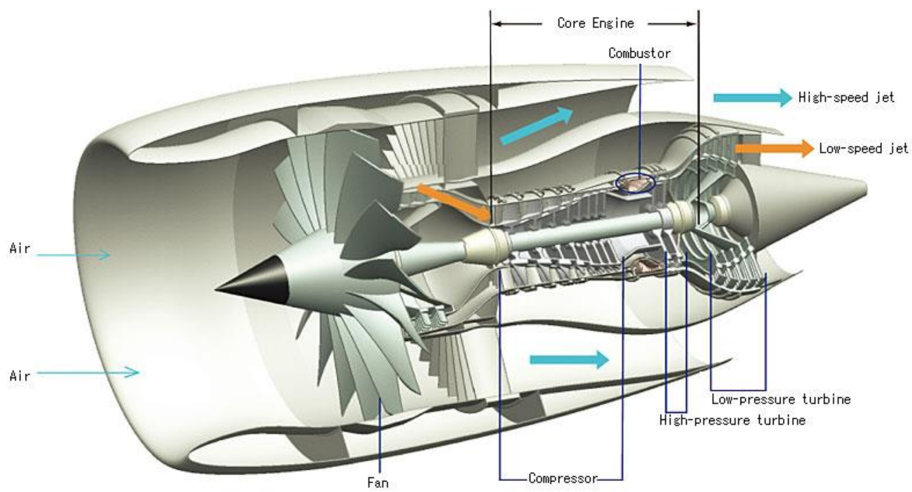

Figure 8. Diagram of Turbofan Engine Showing its Size due to Fan Diameter

The sea-level static thrust rating is another important parameter when it comes to determining the effective propulsion performance of the entire engine system. SLS thrust rating refers to the thrust performance of the engine over a range of power settings while the engine is stationary and at sea level. The maximum possible thrust at each power setting for the engine is always at SLS so the values obtained from the SLS thrust rating define the maximum thrust the engine can possibly achieve. Similar to the fan diameter of the engine, SLS thrust rating depends on the other parameter values when performing the propulsion simulations for each engine. While it cannot be independently adjusted initially, the entire thrust performance can be put through a process of normalization after initial engine simulations in order to set the SLS thrust rating to the desired value. Normalization is performed by dividing the desired maximum static thrust value by the maximum static thrust value calculated from the simulation and multiplying every thrust value from the simulation by that ratio. The mass flow ratio that is calculated for each flight condition of the engine will also be multiplied by this ratio to account for the increase/decrease in airflow needed for the increased/decreased thrust. A section of propulsion data at SLS that was normalized to have a maximum thrust value of 10,000 lbf is presented in Figure 9. An important factor of the normalization process for the project is it allows one to set it so that every engine tested has the same maximum thrust value. The reason for doing this is it allows for more accurate comparisons of the thrust and TSFC performance of each engine at different flight conditions, since every engine would now have the same SLS thrust rating and therefore the same thrust capabilities. Normalization of each engine to a specific maximum thrust value also makes it easier to scale up the thrust performance of the engine so that certain thrust-to-weight ratios can be met when testing aircraft performance.

Mach	Altitude	PLA	Thrust	TSFC	Wair	Ram Drag	Thrust New
0	0	-20	1622	0.30859	107	0	1842.13515
0	0	-10	2288.7	0.29285	126.9	0	2599.318569
0	0	0	3040.5	0.28885	145.9	0	3453.151618
0	0	10	3907.4	0.29156	165	0	4437.705849
0	0	20	4968.7	0.29966	185.4	0	5643.043725
0	0	30	6258.3	0.30923	207.2	0	7107.666099
0	0	40	7748.5	0.3212	229.3	0	8800.113572
0	0	50	8805	0.3327	243.3	0	10000

Figure 9. Sea Level Static Thrust Rating put through Normalization Process

AERODYNAMICS OF PROPULSION: INLET THEORY

To understand the process of matching an engine with an inlet, one should have knowledge on how inlets function and why limitations to engine performance exist in the first place.

Inlets are complex; like any system that requires a perfect design to function efficiently, but their designs are based on simple principles. Inlets supply the air needed for engines to function; because of that, inlets are one of the main contributors to inefficient propulsion system performance. This loss of performance due to inlets is not always large, since gas turbine engines can run very efficiently when they are flying at subsonic speeds, but it is when they reach supersonic speeds that these losses can become very significant.

Aerodynamics become very different when airflow is supersonic and causes many problems such as shocks and boundary layers that lead to bad airflow through the inlet which can lead to the engines not being able to operate. These issues must be addressed when developing engine systems that are meant to fly at supersonic speeds and many of these problems that can stop engines from functioning have been solved with the creation of specific inlet designs. While these inlet designs make it possible for engines to function effectively above Mach 1.0, the aspects of their designs that help deal with supersonic airflow have drawbacks that can lead to loss in engine performance or even the ability for the engine to function at certain speeds or altitudes. It is because of these drawbacks due to inlet designs that inlet matching must be performed on engines to determine their actual propulsion performance and if the engine can feasibly function

External Compression Inlets

In order for turbofan engines to operate efficiently, the air that enters the compressor must be moving at subsonic speeds. This factor makes it more difficult to develop such engines for supersonic flight. While a supersonic inlet compressor is theoretically possible, the shocks that would form around the blades of the compressor would lead to very inefficient propulsion performance.

One design method that allows turbofan engines to function efficiently in supersonic flow is an external compression inlet design. This type of inlet allows for subsonic flow to reach the compressor in supersonic conditions by having shocks form on the external surface of the inlet such as a conical spike. The shocks that form on the exterior of the inlet would decelerate the air that enters the inlet enough to no longer be supersonic and as well as compress the air to increase its total pressure for the compressor. This combination of subsonic flow and increased air pressure allows for the turbofan propulsion system to run effectively in flow regimes it normally would not. One or multiple shocks can form on the external surface and the shock can be normal or oblique, it all depends on the design of the inlet.

While able to function in supersonic flow regimes, engines with external compression inlets still run into limitations as the shocks formed to reduce flow speed can begin to deflect flow away from the inlet at higher Mach numbers. A demonstration of subsonic flow through an external compression inlet is presented in Figure 10. This figure shows that air flows normally through the inlet and remains subsonic as shocks only form when an aircraft reaches supersonic speeds. A demonstration of an external compression inlet at its supersonic limit is presented in Figure 11. This figure shows that an oblique shock forms from the tip of the spike to the tip of the cowl lip and any supersonic airflow that passes through the shock into the inlet is reduced to subsonic speeds. A demonstration of low supersonic flow through an external compression inlet is presented in Figure 12. This figure shows that a shock still forms at the tip of the spike but no longer connects to the cowl lip which causes some of the subsonic airflow to move above the lip instead of in the inlet. While air in the inlet is still decelerated to subsonic speeds for the compressor, the air that is spilling on the lip is causing drag that decreases the engine's performance.[12]

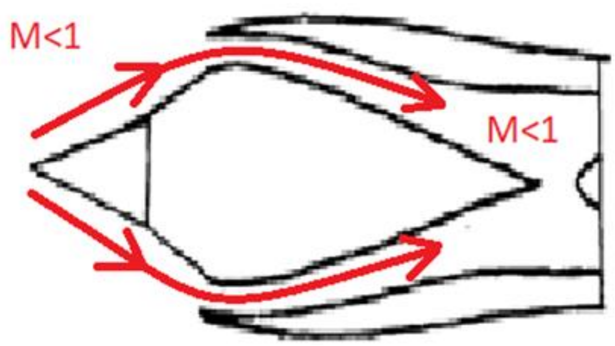

Figure 10. Flow Through an Inlet Moving at Subsonic Speeds

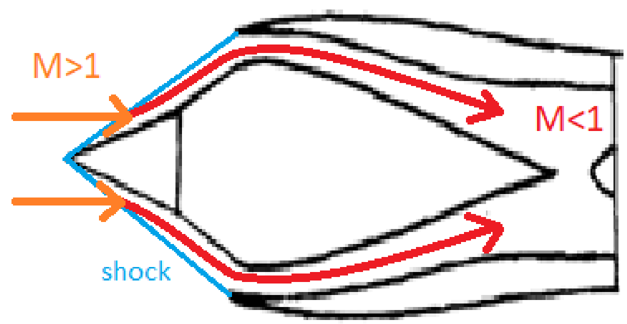

Figure 11. Flow Through Inlet Moving at the Supersonic Limit for External Compression

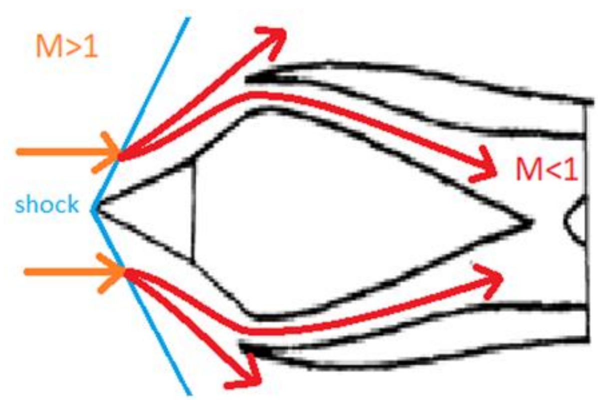

Figure 12. Flow Through Inlet Moving at Low Supersonic Speeds

Normalized Supersonic Inlet Performance Data

Inlets are the main source of air that flows through the engine and powers the propulsion system, so their designs greatly affect how well the engine performs. For the most part the effects of inlet designs on engine performance are limitations and losses to performance; they become really noticeable when the aircraft reaches supersonic speeds.

One important value in determining the performance of an inlet is the pressure recovery, which is the ratio of total air pressure entering the compressor of a gas turbine engine compared to freestream air pressure outside the engine. Pressure recovery generally characterizes the inlet efficiency of the engine which defines how much air the inlet is able to bring in from freestream airflow.

The power of an engine's propulsion system is dependent on the air pressure that enters the compressor. This means that the closer the pressure recovery value is to 1, the higher the inlet efficiency is and the more thrust the engine is able to produce. Pressure recovery is affected by many factors including the design of the inlet, the speed of the aircraft, and the airflow needed for the engine to function, but these effects all depend on the flow regime of the aircraft. When it comes to subsonic conditions, pressure recovery provides very little issues to the performance of an engine as the value is almost always close to 1 no matter the necessary mass flow ratio of air or the design of the inlet. It is not until an aircraft reaches supersonic speeds that pressure recovery becomes greatly affected by the conditions of Mach number, mass flow ratio, and inlet design.

As the freestream Mach number increases above 1.0, it becomes more difficult for air to flow through the inlet to the compressor and reaching faster speeds require more air to flow through the engine so the propulsion system functions properly. This combination of bad air flow and need for more air at supersonic speeds establishes the general relation that increasing Mach number and mass flow ratio leads to loss in pressure recovery and therefore loss in thrust performance.[12]

The distortion and buzz limit are also important inlet data values that help to determine the effective performance of an engine. Distortion limit occurs at supercritical operations which is when the mass flow ratio of the system is above 1 and usually occurs at low supersonic and high subsonic speeds. What happens at this limit is the compressor needs more air than the inlet is providing which leads to the engine being unable to function effectively. Buzz limit occurs at subcritical operations which is when the mass flow ratio of the system is below 1 and only occurs at supersonic speeds. What happens at this limit is more air than that is needed for the compressor is brought in from the inlet and the excess air causes disruptions in the airflow to the engine which can lead it to no longer operate properly. Both distortion and buzz limit change with regards to Mach number and vary depending on the inlet used so these values essentially define the maximum and minimum values of mass flow ratio the engine can operate at when flying at certain speeds. A visual representation of the relation of mass flow ratio and pressure recovery as well as their limits are presented in Figure 13.

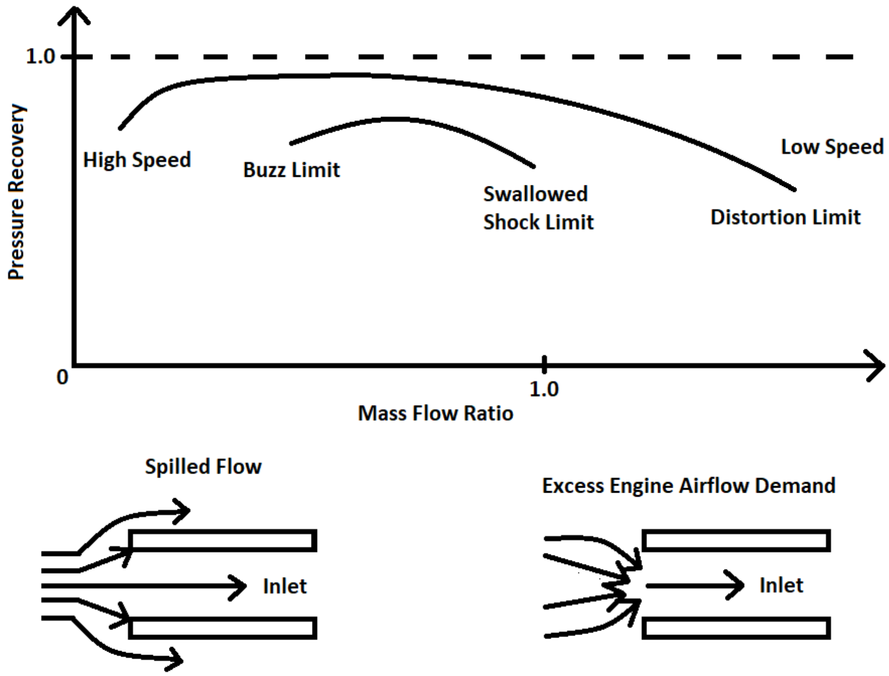

Figure 13. Inlet Limitations with Regards to Mass Flow Ratio and Pressure Recovery

Propulsion/Inlet Matching Problem

One of the major issues of developing high bypass ratio engines that give large aircraft the ability to reach supersonic speeds is finding an inlet design that allows these powerful engines to function effectively. Raw propulsion data from simulations in not enough to accurately model the performance of an aircraft using the engine as the propulsion system is only half of the engine design. Air flow is the most important factor when it comes to a jet propulsion system's ability to operate and the inlet governs the amount and speed of air that flows through the engine.

Since inlets control the flow of air that propulsion systems need to operate, inlets apply many limitations and losses to the performance of the engine depending on their design. One such limitation is the pressure recovery of the engine system, as mass flow ratio and Mach number increases the pressure recovery decreases which leads to a loss of engine thrust and performance. The buzz and distortion limit of inlets are also major limitations to engines as mass flow ratios below the buzz limit indicates too little air flow to function and mass flow ratios above the distortion limit indicates too much air to function. A visual representation of pressure recovery and buzz and distortion limit in relation to mass flow ratio and Mach number are presented in Figure 14.

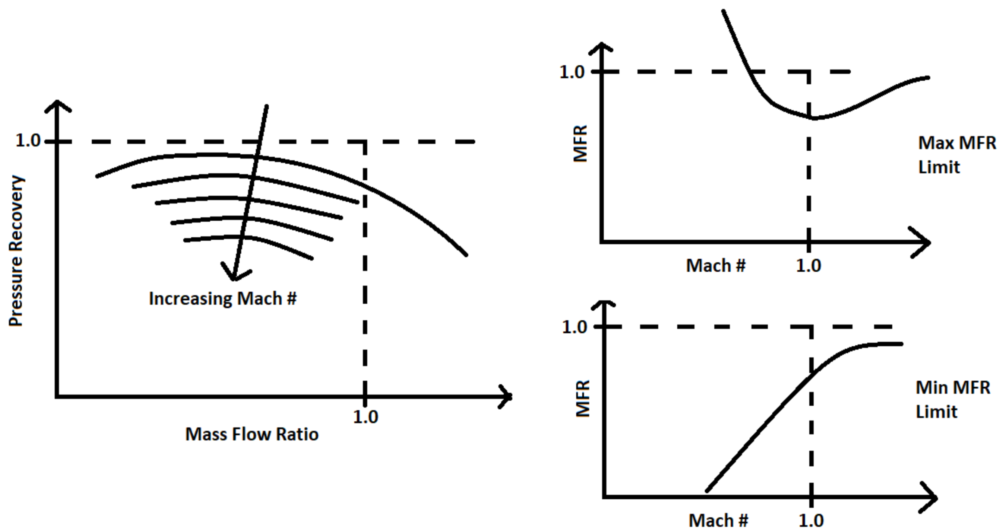

Figure 14. Expected Pressure Recovery Trends

As noted in the section describing the properties of external compression inlets, when supersonic flow gets high enough the shocks that form on the external surface of the inlet can cause air to be deflected from the inlet onto the outside end of the cowl lip. This airflow that spills onto the outer section of the inlet creates a drag force referred to spill drag which can greatly affect the performance of the engine.

Spill drag can occur at just about any Mach number or altitude but its effect on the propulsion system is usually minimum to none at subsonic and even low supersonic speeds and does not occur in supercritical operations. Its hindrance to engine performance becomes well apparent when the aircraft reaches high supersonic speeds and the mass flow ratio becomes very close to the buzz limit of the inlet.[12] A visual representation of how spillage drag increases with regards to Mach number and mass flow ratio is presented in Figure 15.

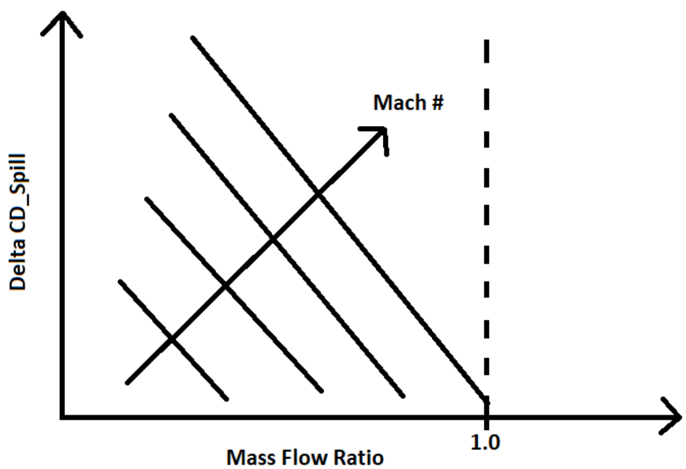

Figure 15. Expected Spill Drag Trends

Another issue engines run into when travelling at supersonic speeds is the boundary layers that form around the opening of the inlet. Boundary layers can separate from the inlet at these high speeds and cause unstable shocks to form around the inlet which can decrease pressure recovery and hinder the performance of external compression inlets that require stable shocks to function in supersonic flow. One way external compression inlets are able to mitigate this issue is by using bleed ducts that line the channel of inlet.

Bleed ducts are essentially openings in the walls of the inlet that are designed to lead the boundary layers away as they form in order keep them from building up and causing disturbances in the airflow.

While bleed ducts are necessary to keep the boundary layers thin and shocks stable in supersonic flow, they also affect the efficiency of the engine's propulsion system. The boundary layers that are removed from the bleed ducts are usually dumped out of the engine which leads to a drag force known as bleed drag. This drag force only becomes noticeable when the aircraft reaches speeds near Mach 1.0 and increases as Mach number increases. The bleed ducts can also slightly decrease the mass flow ratio of the air moving through the inlet due to them removing the air that forms the boundary layers.

Though they dampen thrust performance, the need for bleed ducts for steady flow at supersonic speeds is a greater concern than the drag that is caused by them. An alternative to dumping the boundary layers is to return them to the airflow moving to the compressor, which leads to a minor increase in mass flow ratio depending on the aircraft's speed.[12] A visual representation of how bleed ducts affect, engine performance is presented in Figure 16.

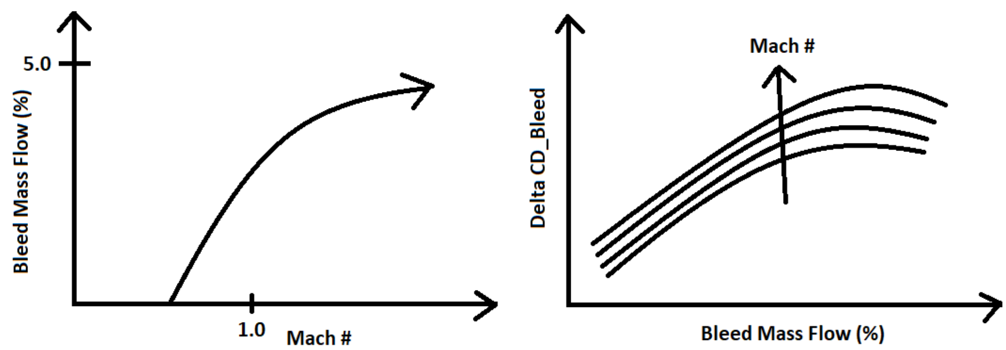

Figure 16. Expected Boundary Layer Bleed Drag Trends

As previously stated, engines moving at high Mach numbers run into the issue of air not flowing into the inlet and spilling onto the outer edges of the cowl lip; this hinders propulsion performance due to a loss of mass flow ratio and an increase in drag. One solution that was developed for engines to help deal with the problems of spilled air and need for more airflow at high speeds are adjustable vents in front of the engine face known as bypass doors. Bypass doors allow more air to enter the inlet by opening to a desired amount and essentially increase the effective area of the inlet's mouth by reducing spillage.

The position of the bypass doors also allows for the air that spills onto the exterior of the cowl lip to flow back into inlet to be used for the propulsion system. This extra airflow brought in through the bypass doors can prove to be essential in giving the engine the air it needs to operate efficiently at high Mach numbers as well as reduce the spill drag that increases with speed. The problem with bypass doors is when they are open they add extra geometry to that of the inlet which of course leads to more drag on the engine. Since bypass doors have adjustable geometries to account for the airflow needed at a given moment, more open doors lead to more bypass drag that results in a loss in propulsion performance. A visual representation of how bypass drag increases with regards to Mach number and mass flow ratio is presented in Figure 17.

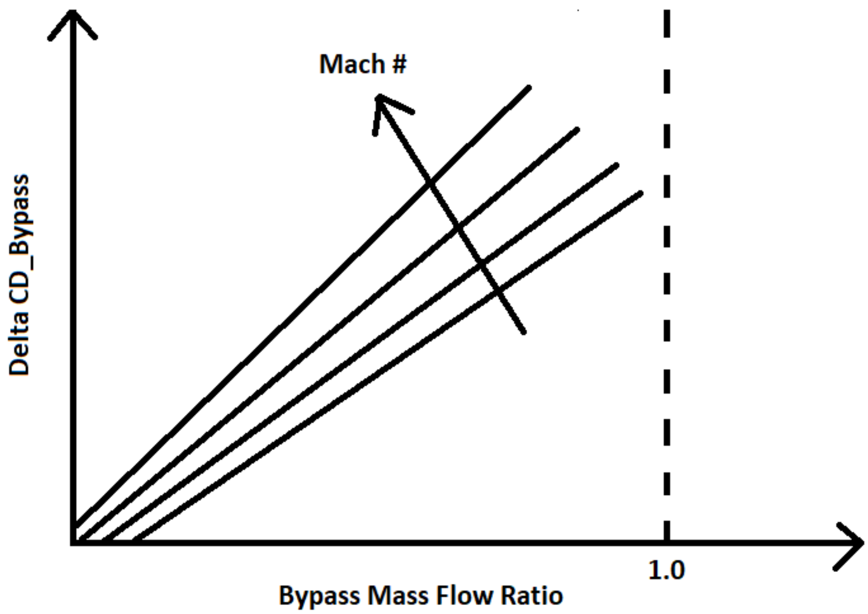

Figure 17. Expected Bypass Drag Trends

With an understanding of how inlets need to be designed to properly function and what limitations arise from their designs, it easy to identify the challenge of matching inlets with engines to produce efficient performance. Mass flow ratio through the inlet is one of the important values when it comes to the performance and operation of the engine as too much and too little air at given speeds can cause the engine to cease to function.

Bleed ducts and bypass doors can increase the airflow which can greatly benefit the engine at high Mach numbers but both systems cause drag that affects propulsion performance. Bypass doors also need to be adjusted in a certain way at each Mach number as it is possible for their negative effects to be greater than their positive effects. With how bypass doors are designed to reduce air spillage, this means that one needs to figure out if performance at each condition is best when there is more spill drag or bypass drag. In the end, thrust and TSFC are the most important performance values to get out of the inlet and engine matching process as they determine how well the engines will function at each desired condition. Thrust will decrease due to the bleed, bypass, and spill drag that the inlet causes and TSFC relies on thrust, so it would decrease in efficiency as well.

Knowing this, it is necessary to choose the right engine and inlet designs so that the thrust is able to overcome the limitations that the inlets create.

ANALYSIS TOOLS AND METHODS

In order to perform tests and complete the project, a variety of engineering computer codes, whether created by hand or official programs, were used to achieve the necessary results. The integration system Numerical Propulsion System Simulation (NPSS)[4] was used to simulate the propulsion performance of specified engines and create preliminary five column data. An inlet matching tool was created in Excel/VBA using the inlet data from a specific inlet configuration in the Performance of Installed Propulsion Systems Interactive or PIPSI Volumes 1 to 4[5,6,7,8] in order to calculate the true five column data of the engines using the inlet. The legacy Fortran code Empirical Drag Estimation Technique (EDET)[13] was used to calculate the aerodynamic performance values of the aircrafts desired to be used with the engines. Finally, a point performance tool[14] was also created in Excel/VBA to combine the aerodynamic and propulsion performance values from the previous codes to calculate performance values over a range of speeds and altitudes.

Numerical Propulsion System Simulation (*NPSS*)

NPSS is an integration system originally developed by NASA to model propulsion and thermal power systems with a lumped modeling environment that keeps track of flow rates and thermodynamic states to determine performance.[4] For the purpose of an aircraft propulsion system, NPSS is able to simulate the usage of the engine at a range of Mach numbers, altitudes, and power level angles to calculate the performance values of thrust and thrust specific fuel consumption at each parameter. The three parameter values and two performance values make up the initial five column propulsion data of the engine before it is sized with the desired inlet.

For the preliminary testing of the analysis tools, the engine propulsion system that was simulated through NPSS was a low bypass turbofan engine with an afterburner. The set parameters and geometry for this turbofan test was a BPR of 0.5, an FPR of 1.8, a TIT of 2700 °R, an OPR of 30.0, and a fan diameter of 25.632 in. In order to set up a proper five column propulsion data to test aircraft performance with an afterburner, three different simulations need to be run through NPSS to generate three different propulsion data sets to be combined together in one five column data set with a later analysis tool. The first simulation is the engine running with no power to the afterburner, the second is the engine running with the afterburner set to its minimum power, and the third is the engine running with the afterburner set to its maximum power.

For the actual testing that will be performed for the project, various high bypass turbofan engine designs will be simulated through NPSS to observe for certain results. Each propulsion system tested will be varied is some specific way to test how the different engine parameters affect the performance of the engine. The engines that will be tested for the project will only be simulated with the engine running with no fuel flow to the afterburner, meaning these engines will not have afterburner capabilities. This decision to develop these engines without afterburners will be explained later on when discussing preliminary results.

Performance of Installed Propulsion Systems Interactive (*PIPSI*)

In order to calculate the true performance of the engine and create the necessary five column propulsion data for analysis, an inlet matching tool was developed to apply the limits and effects of an external compression inlet used with the specified engine. The data of inlet limitations that was applied to the raw engine data in the tool was acquired from the PIPSI Volumes 1 to 4.[5,6,7,8] PIPSI is a compendium of generic tests of inlet performance data that was put together by Boeing to be initially used by the United States Air Force. Its purpose was to provide sufficient inlet data for effective usage in trade studies that would apply raw engine data to various inlet designs in order to test the installation effects of the inlet on the performance of the engine.

The data that was used from the specified inlet design in PIPSI includes bleed drag, bypass drag, spill drag, bleed schedule, pressure recovery, distortion limit, and buzz limit. These values are inputted into the tool and calculated for each parameter value through interpolation to determine the thrust and mass flow ratio limitations the inlet put on the engine.

The relationship of pressure recovery with mass flow ratio at specific Mach numbers is presented in Figure 18. This Figure shows that pressure recovery is mostly constant and close to 1 as expected for subsonic speeds. It also shows that as the supersonic Mach number and mass flow ratio increases, the pressure decreases at an exponential rate. This demonstrates the issue of inefficient engine performance when the aircraft is travelling at high speeds and its engine needs more airflow to function.

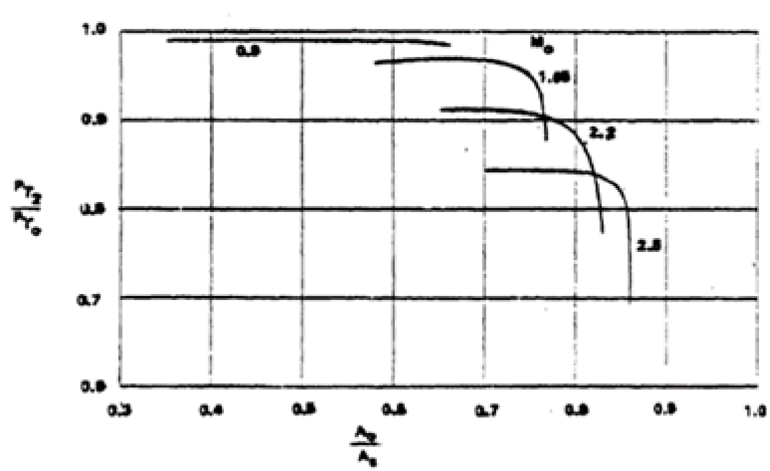

Figure 18. Relation of Pressure Recovery to Mass Flow Ratio and Mach Number

The range of maximum and minimum mass flow ratio values governed by the distortion and buzz limit is presented in Figure 19. The gold area of the figure shows that in the subsonic flow regime, there is no issue of the inlet bringing in enough air for the engine to function and the issue of bringing in too much air will only occur past Mach 0.4. The gold area also shows that as the Mach number increases the gap between maximum and minimum mass flow ratio becomes smaller, which means it is harder for the inlet to get the necessary amount of airflow for the engines to function as the aircraft flies faster.

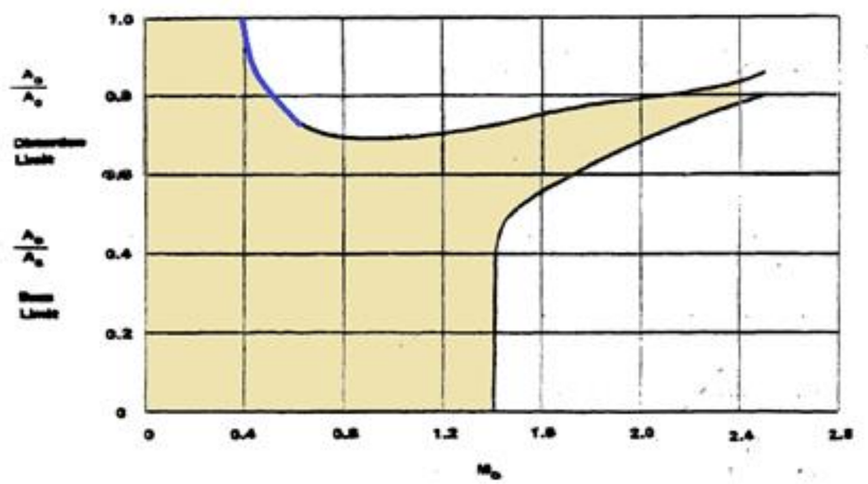

Figure 19. Achievable Mass Flow Ratios Due to Distortion and Buzz Limits

The relationship of coefficient of spill drag to mass flow ratio at various Mach numbers is presented in Figure 20. This figure shows that spill drag has mostly a linear relation to mass flow ratio no matter the Mach number of the aircraft where spill drag increases as mass flow ratio decreases. It also shows that little to no spill drag occurs when the aircraft is flying at subsonic speeds. Another important thing to note is that spill drag increases as Mach number increases and the engine is only able to function over a certain range of mass flow ratios when flying at specific Mach numbers.

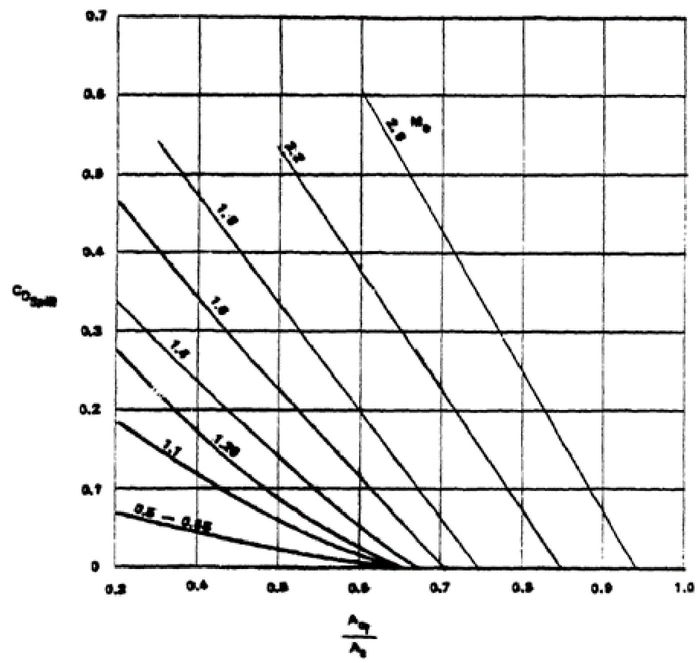

Figure 20. Relation of Spill Drag Coefficient to Engine Mass Flow Ratio and Mach Number

The relationship of coefficient of bleed drag to mass flow ratio through the bleed ducts at various Mach numbers is presented in Figure 21. This figure shows that bleed drag has a mostly exponential relation to mass flow ratio no matter the Mach number of the aircraft where bleed drag increases as mass flow ratio increases. It also shows that as the Mach number increases, so does the mass flow ratio needed to reach the same bleed drag value. This indicates that bleed drag has less of an effect on an engine when the aircraft is traveling at supersonic speeds and the amount of air flowing through the bleed ducts is low.

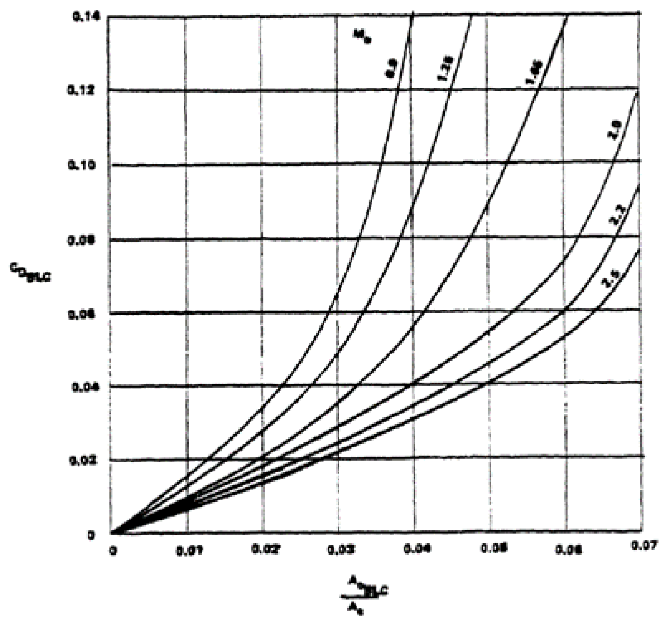

Figure 21. Relation of Bleed Drag Coefficient to Bleed Mass Flow Ratio and Mach Number

The relationship between mass flow ratio through the bleed ducts and mass flow ratio through the engine at various Mach numbers is presented in Figure 22. This figure shows that no air flows through the bleed ducts when the engine mass flow ratio is 1 then increases linearly as the engine mass flow ratio decreases for all Mach numbers. This indicates that the bleed ducts bring in more air from the boundary layers on the inlet when less air flow enters the engines. The figure also shows that the amount of air that flows through the bleed ducts increases as the Mach number increases and that the bleed ducts are not used or have very little air flow through them below Mach 1.0.

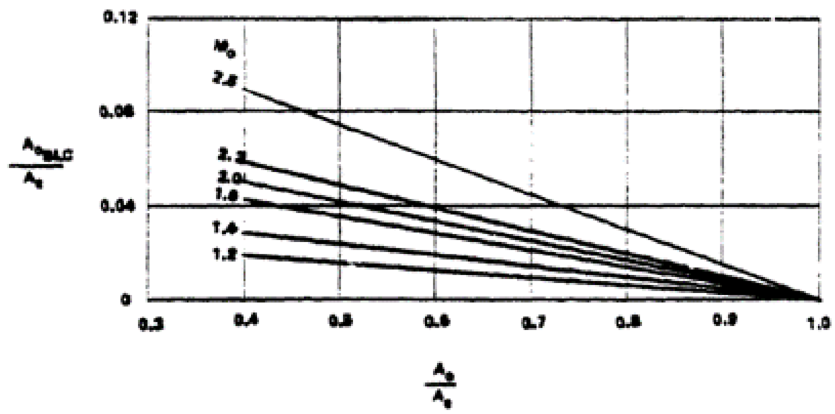

Figure 22. Relation of Bleed Mass Flow Ratio to Engine Mass Flow Ratio and Mach Number

The relationship between mass flow ratio through the bleed ducts and Mach number also known as the bleed schedule is presented in Figure 23. This figure shows that the amount of air flowing through the bleed ducts increases linearly as the Mach number goes from transonic to low supersonic speed. After that range of Mach numbers, the mass flow ratio of the bleed ducts stays mostly constant as the Mach number continues to increase. This likely indicates that there is a limit to the amount of air that can flow through the bleed ducts of the inlet and once reached it can no longer increase even as the aircraft's speed increases.

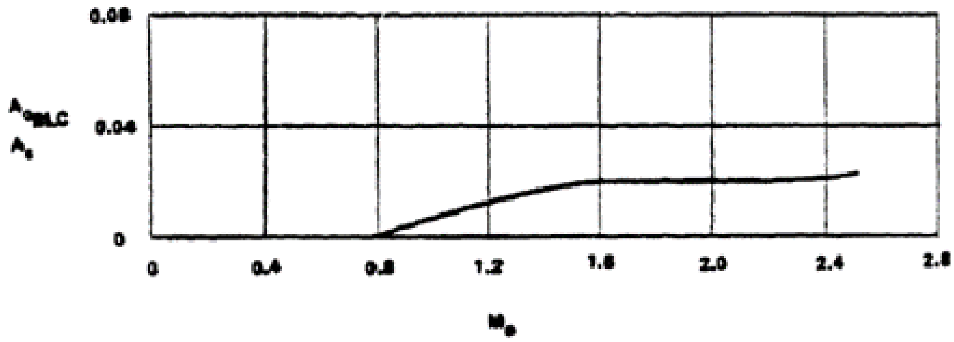

Figure 23. Relation of Bleed Mass Flow Ratio to Mach Number

The relationship between the coefficient of bypass drag and the mass flow ratio through the bypass doors is presented in Figure 24. This figure shows that bypass drag increases as mass flow ratio increases for each Mach number which should be expected as more flow means the bypass doors are more open and have more effect on the engine's geometry. It also shows that bypass drag decreases as the Mach number increases which indicates that bypass doors are most effective when the aircraft is travelling at high speeds.

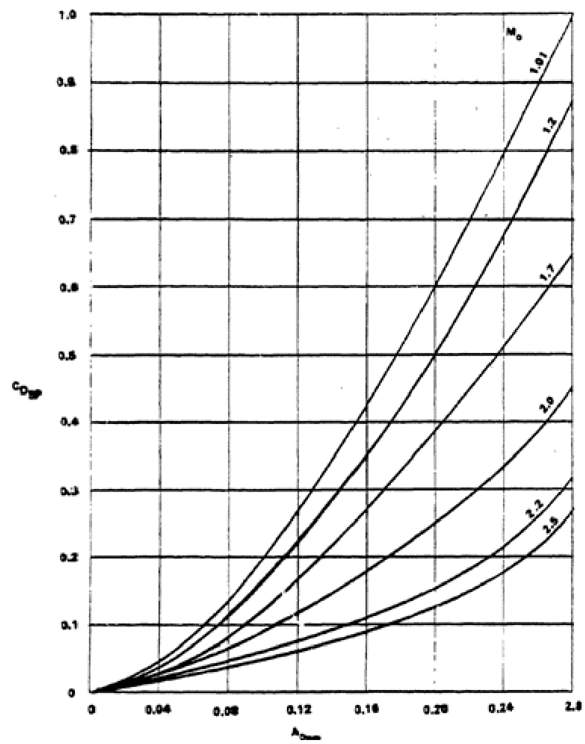

Figure 24. Relation of Bypass Drag Coefficient to Bypass Mass Flow Ratio and Mach Number

The tool loops through the entire flight envelope, examining a full-factorial matrix of all possible flight conditions (Mach and Altitude) and power settings (core from idle to maximum with the afterburner off, as well as core from idle to maximum with the afterburner on). This allows for an understanding of how well the engine will operate at each of these flight conditions now that it is limited by the necessary functions of an inlet. It is important to know when an engine is unable to function efficiently (or unable to function at all) as it helps to determine how to improve the engine system or inlet or if the engine can be used under normal flight operations.

The only inputs needed for the tool are the five column data sets of the three afterburner settings, the shape of the inlet, and size of the inlet. Every inlet that is accessible through the PIPSI Volumes not only contain the data needed to set the limitations and losses of the engine but also the parameters that define the type, shape, and size of the inlet. A table of inlet designs available in PIPSI Volume 4 and their respective non-dimensional sizes and ratios is presented in Figure 25.

DERIVATIVE PARAMETERS	DEFINITION	CONFIGURATION NUMBERS 1	2	3	4	5	6	7	8	9
1 Inlet Aspect Ratio	W_C/H_C	N/A	N/A	N/A	N/A	N/A	N/A	2.0	1.0	1.0
2 Sideplate Cutback	A_{CB}/A_{SP}	N/A	N/A	N/A	N/A	N/A	N/A	.75	.20	.25
3 First Ramp Angle	Deg.	N/A	N/A	N/A	N/A	N/A	N/A	7.0	7.3	6.0
4 Design Mach Number	~	.80	1.60	.50	.80	1.50	1.80	1.80	2.0	2.5
5 Cowl Lip Bluntness	R_{lip}/A_C	.03	.02	.030	.022	.022	0.	.012	.012	.006
6 Takeoff Door Area	A_{TO}/A_C	0.0	0.0	N/A	.036	.18	.22	.235	.20	.11
7 External Cowl Angle	Deg.	4.5	2.5	12.	17.	5.0	5.0	13.0	17.5	17.0
8 Bleed Exit Nozzle Type	Conv. or C-D	N/A	N/A	N/A	N/A	N/A	N/A	Conv.	Conv.	Conv.
9 Bleed Exit Nozzle Angle	Deg.	N/A	N/A	N/A	N/A	N/A	N/A	30.0	15.0	20.0
10 Bleed Exit Flap Aspect Ratio	W_F/H_F	N/A	N/A	N/A	N/A	N/A	N/A	1.0	2.0	.80
11 Bleed Exit Flap Area	A_F/A_C	N/A	N/A	N/A	N/A	N/A	N/A	.10	.10	.50
12 Bypass Exit Nozzle Type	Conv. or C-D	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Conv.	C-D
13 Bypass Exit Nozzle Angle	Deg.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	15.0	20.
14 Bypass Exit Flap Aspect Ratio	W_F/H_F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.0	.67
15 Bypass Exit Flap Area	A_F/A_C	N/A	N/A	N/A	N/A	N/A	N/A	N/A	.20	.268
16 Subsonic Diffuser Area Ratio	A_2/A_1	1.40	1.40	1.25	1.25	1.305	1.305	1.373	1.50	1.09
17 Diffuser Total Wall Angle	Deg.	2.5	3.5	12.0	12.0	4.0	4.0	5.0	10.0	8.5
18 Subsonic Diffuser Loss Coefficient	ε	.12	.12	.015	.015	.12	.12	.12	.12	.16
19 Throat/Capture Area Ratio	A_T/A_C	N/A	N/A	.80	.80	.96	1.00	N/A	N/A	N/A
INLET TYPE		Chin	Chin	Pitot	Pitot	Pitot (N.S.)	Pitot (N.S.)	E.C. 2-D	E.C. 2-D	E.C. 2-D
FILE NAME		A7	F8	MSSUB	MFSUB	NS	NS2	LWF	ATS2	ASF

DERIVATIVE PARAMETERS	DEFINITION	10	11	12	13	14	15	16	17	18
1 Inlet Aspect Ratio	W_C/H_C	N/A	N/A	N/A	1.0	1.0	1.0	N/A	N/A	N/A
2 Sideplate Cutback	A_{CB}/A_{SP}	N/A	N/A	N/A	0.0	0.0	0.0	N/A	N/A	N/A
3 First Ramp Angle	Deg.	25.0	22.0	18.0	7.0	7.0	7.0	10.4	10.0	10.0
4 Design Mach Number	~	1.60	2.0	2.5	2.5	3.0	3.5	2.35	3.0	3.5
5 Cowl Lip Bluntness	R_{lip}/A_C	.02	.015	.015	0.	0.	0.	0.	0.	0.
6 Takeoff Door Area	A_{TO}/A_C	.462	.46	.25	.17	.50	.30	.30	.30	.30
7 External Cowl Angle	Deg.	10.	19.	12.	12.	12.	15.0	1.0	0.0	3.0
8 Bleed Exit Nozzle Type	Conv. or C-D	N/A	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
9 Bleed Exit Nozzle Angle	Deg.	N/A	20.0	15.	20.0	0.0	15.	15.	15.	10
10 Bleed Exit Flap Aspect Ratio	W_F/H_F	N/A	1.0	1.0	.80	N/A	1.0	1.0	1.0	1.0
11 Bleed Exit Flap Area	A_F/A_C	N/A	.10	.10	.20	N/A	.20	.20	.20	.20
12 Bypass Exit Nozzle Type	Conv. or C-D	N/A	Conv.	Conv.	C-D	C-D	C-D	C-D	C-D	C-D
13 Bypass Exit Nozzle Angle	Deg.	N/A	20.	15.	20.	15.	15.	15.	15.	10
14 Bypass Exit Flap Aspect Ratio	W_F/H_F	N/A	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0
15 Bypass Exit Flap Area	A_F/A_C	N/A	.20	.20	.20	.20	.20	.20	.20	.20
16 Subsonic Diffuser Area Ratio	A_2/A_1	1.44	1.83	2.0	1.40	2.8	4.7	1.57	2.1	4.97
17 Diffuser Total Wall Angle	Deg.	6.0	9.0	15.0	9.0	12.0	11.5	7.0	12.0	9.0
18 Subsonic Diffuser Loss Coefficient	ε	.08	.12	.14	.14	.12	.14	.08	.12	.12
19 Throat/Capture Area Ratio	A_T/A_C	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
INLET TYPE		E.C. AXI	E.C. AXI	E.C. AXI	M.C. 2-D	M.C. 2-D	M.C. 2-D	M.C. AXI	M.C. AXI	M.C. AXI
FILE NAME		VSTOL	NVSTO	TM183	F8	INT	M3520	AST	NASA3	BCAC35

Figure 25. PIPSI Table of Inlet Geometry Values

In order to compute inlet aerodynamic losses, 1) total-pressure recovery losses, 2) spill drag, 3) bleed drag, and 4) bypass drag, the tool needs to balance the mass airflow supply of the inlet against the mass airflow demand of the engine. The tool is able to do this by first calculating the ideal mass flow ratio through engine with the size of the inlet at each engine parameter then interpolating the mass flow ratio that would come from the bleed ducts and bypass doors at each Mach number. Adding these three mass flow ratio values together will calculate the true value of mass flow ratio through the inlet which helps with further performance calculations and shows how much air is flowing into the inlet for each engine parameter.

Before any more performance values are calculated, the tool uses the distortion and buzz limit at each Mach number to interpolate the highest and lowest value the MFR can be at each parameter value of Mach number, altitude, and PLA to determine if the engine can function with the MFR value calculated at each parameter.

The inlet, bleed, and bypass mass flow ratio values are then used to interpolate the values of coefficient of spill drag, coefficient of bleed drag, and coefficient of bypass drag, respectively, at each Mach number. The drag coefficient values are then used to calculate the spill, bleed, and bypass drag values that are subtracted from the raw five column thrust data in order to calculate the true thrust and TSFC performance values at each engine parameter. The equations used for finding the mass flow ratio of the engine, bleed ducts, bypass doors, and inlet are presented in Equations 1, 2, 3, 4, and 5.

$$\dot{m}_{ideal} = \rho * V_{\infty} * A_{inlet} \quad (1)$$

$$MFR_{engine} = \frac{\dot{m}_{engine}}{\dot{m}_{ideal}} \quad (2)$$

$$MFR_{bleed} = \frac{\dot{m}_{bleed}}{\dot{m}_{ideal}} \quad (3)$$

$$MFR_{bypass} = \frac{\dot{m}_{bypass}}{\dot{m}_{ideal}} \quad (4)$$

$$MFR_{inlet} = MFR_{engine} + MFR_{bleed} + MFR_{bypass} \quad (5)$$

During the process of finding the mass flow ratios and drag losses of each inlet and engine system, the tool also performs steps to find the most effective bypass door condition at each engine parameter. The VBA code used in the inlet matching tool to calculate which bypass door condition produces the best thrust performance at each parameter is presented in Figure 26. The code shows that the total MFR of the system, the spill, bleed, and bypass drag, and the true thrust and TSFC performance values are calculated in a loop of various bypass MFR values. The loop starts with a bypass MFR value of 0, indicating closed bypass doors, and after all values in the loop are calculated it starts from the beginning of the loop and the bypass MFR value is increased by 0.01. For cases where the Mach number is below 1.0, the loop stops at the bypass MFR value of 0.01. The reason for this setup is spill drag does not become an issue until supersonic speeds, so at subsonic speeds the bypass doors at most would need to be slightly opened to deal with insignificant amounts of spilled airflow. For cases where the Mach number is above 1.0, the loop continues to run and increase the bypass MFR value by 0.01 after each iteration until it reaches the maximum bypass MFR value of 0.5. This maximum bypass MFR value was chosen as it became apparent in tests that bypass drag was already a determent to thrust and TSFC performance by the time this bypass MFR value was reached. The code also shows that in the process of each loop iteration, the true thrust value that is calculated is compared to the current highest true thrust value that was calculated from the previous bypass MFR values. If a true thrust value calculated at a specific bypass MFR value was found to be larger than the current highest true thrust value, then the new true thrust value replaces the old value as the highest true thrust value and the TSFC, bypass drag, and inlet MFR calculated at that specific bypass MFR value become the current values for the specific flight condition. This method of comparing true thrust values for every loop allows for the program to determine when certain bypass door conditions lead to better thrust performance due to the decrease in spill drag or worse thrust performance due to the increase in bypass drag. Once the entire loop runs through all of bypass MFR values, the program establishes the performance values calculated with the bypass door condition that achieved the highest true thrust value as the effective values of the engine parameters they were calculated at.

```
best_bypass_MFR = 0
best_thrust = -999999
best_tsfc = 99.99

If mmach < 1 Then maxbypass = 0.01 Else maxbypass = 0.5
For bypass_mfr = 0 To maxbypass Step 0.01
mfr_inlet = Val(mfr + mfr_bleed + bypass_mfr)

' If MFR is outside of distortion limit, blank points.
DLIMIT = InterpDistortionLimit(mmach)

' If MFR is outside of buzz limit, blank points.
bLIMIT = InterpBuzzLimit(mmach)

If (mfr_inlet >= DLIMIT) Then GoTo 1000
If (mfr_inlet <= bLIMIT) Then GoTo 1000

' Calculate Spill Drag
CDspill = InterpSpillDrag(mmach, mfr_inlet)
spillDrag = CDspill * q * inletArea

' Calculate Bleed Drag
CDbleed = InterpBleedDrag(mmach, mfr_bleed)
bleedDrag = CDbleed * q * inletArea

' Calculate Bypass Drag
CDbypass = InterpBypassDrag(mmach, bypass_mfr)
bypassdrag = CDbypass * q * inletArea

' Actual Thrust Output
thrust_new = thrust - spillDrag - bleedDrag - bypassdrag
tsfc_new = (tsfc * thrust) / thrust_new


If thrust_new > best_thrust Then best_thrust = thrust_new: best_tsfc = tsfc_new: best_bypass_MFR = bypass_mfr:
    best_bypassDrag = bypassdrag: BEST_mFR_INLET = mfr_inlet
```

Figure 26. VBA Code that Determines the Most Effective Bypass Door Condition of each Engine Parameter

The tool performs these calculations and interpolations on the three different five column data sets simulated from NPSS in order to calculate the engine performance through the desired inlet when the set engine is using no afterburner, minimum afterburner, and maximum afterburner. After the true performance values for each afterburner setting are calculated, the tool compiles the specified parameter and performance values from each afterburner setting into one five column data set to create the final engine performance data used for the aircraft performance tests.

The inlet configuration that was chosen from the PIPSI Volumes to be continuously used for the inlet matching tool and aircraft performance tests was "Inlet Configuration #12 – Half-Round, Three-Shock, External Compression, Variable Cone Inlet." A visual representation of this specific inlet's design is presented in Figure 27. According to PIPSI, the inlet has a fixed 18° first cone angle and variable second cone angle, has a porous plate boundary layer bleed on the second cone in the region of the design terminal shock location, and has the boundary layer bleed flow routed aft and exit through low angle louvers or a door aft of the cow lip. The #12 inlet configuration was primarily chosen for its axisymmetric external compression design and design Mach number of around 2.5 as these are some the desired parameters of the engine design for testing.

Figure 27. Diagram of Inlet Configuration #12

Empirical Drag Estimation Technique (*EDET*)

EDET is a legacy Fortran code initially developed for usage by NASA to calculate aerodynamic data and was later modified to run through the command prompt of modern PCs.[13] The tool allows for the estimation of various drag coefficient values of an aircraft over a range of altitudes, Mach numbers, and angles of attack. EDET can calculate these drag coefficient values by inputting the geometry of the aircraft's wing, tails, and fuselage.

For both preliminary testing of the analysis tools and trade studies, the aerodynamic performance data that was calculated through EDET was that of the Concorde. A diagram of the Concorde is presented in Figure 28. Just about any aircraft with the ability to reach a top speed of Mach 2.0 could have their aerodynamic data tested with the generated propulsion data for each engine design but the Concorde is a good fit for initial testing and consistent usage in performance analysis. Since the main goal of the study is to try to develop viable engine designs to be used for supersonic airliners, using the aerodynamic data of one of the only supersonic airliners to be operated is an effective way to demonstrate how well the tested engines work with an actual airliner designed for supersonic flight. The Concorde also has its own recorded aircraft performance data that would allow for the performance values calculated from use of the designed propulsion system to be compared to the values from use of its original propulsion system. An image of the EDET input file for the Concorde is presented in Figure 29. An image of the EDET output file for the Concorde is presented in Figure 30.

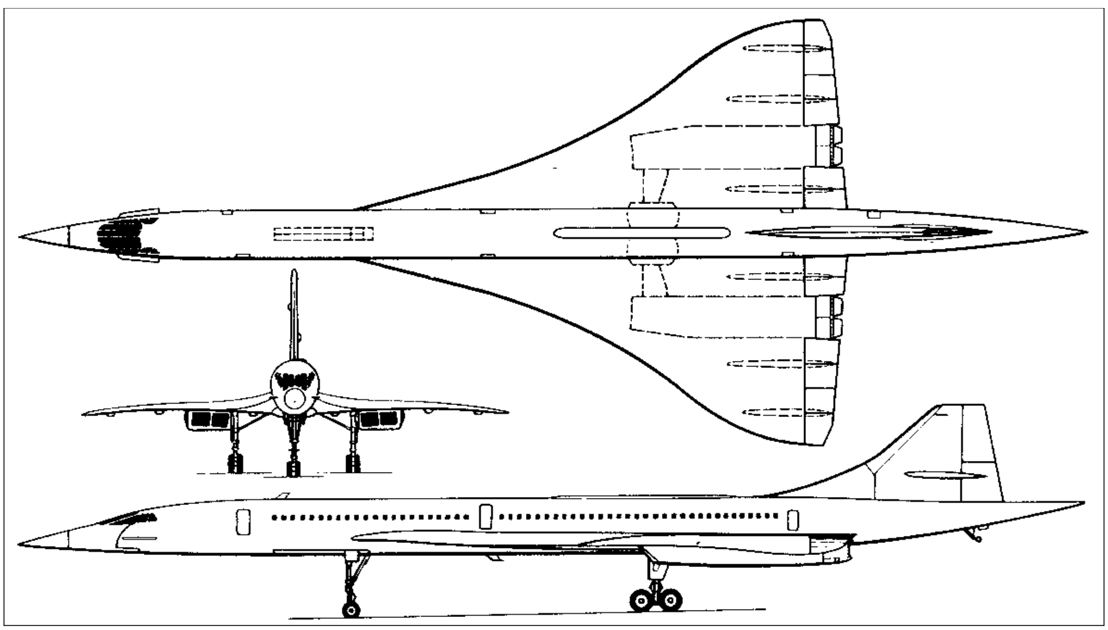

Figure 28. Diagram of Concorde

```
* EDET SAMPLE INPUT FILE - BaC/Aerospatiale CONCORDE (R Palma / T Takahashi)
*
*        1         2         3         4         5         6         7         8
*234567890123456789012345678901234567890123456789012345678901234567890123456789890
*
*SREF (FT^2) AR        TC       SW25      TR
    3856.      1.8      0.030      55.      0.09
*
* SWET_WING  %CAMBER  AITEK     TRU       TRL
    7500.      0.0      1.0      0.0      0.0
*
* SWET_FUSE  S_LEN    BODY_L/D  SBASE    CP_BASE
    4250.     203.7     20.1      1.       -9.9
*
* CRUDFACTOR
     0.25
*
* REFERENCE CONDITIONS
* REF_ALT    REF_MACH
   35000.      0.6
*
* EXTRA STUFF
* COMPONENT
*  S_WET       LEN       TC/FR   DELTA_CD0
V-TAIL
     745.      35.       0.03  0.000000
NACELLES/PYLONS
     200.      33.       10.0  0.000000
```

Figure 29. Concorde EDET Input File

```
* ****************************************************
*
* EDET RESULTS
*
* WING DESIGN CONDITIONS
* DES_MACH    DES_CL
 1.0661   0.1720
*
* POST-STALL LONGITIDUAL STABILITY ESTIMATE
* CRIT_AR          PITCH_BREAK
   1.4          UNSTABLE
*
* CD0 BUILD-UP
* MACH NUMBER     ALTITUDE        REFERENCE AREA      TECHNOLOGY LEVEL
   0.60           35000. FT      3856.00 SQ FT        CONVENTIONAL
*
* COMPONENT                  SWET      LENGTH    FINENESS     FORM       RN        CF          CDF
                             SQ FT       FT        RATIO     FACTOR   MILLIONS
WING                        7500.00     46.28     0.0300     1.039      66.6    0.00214     0.00432
FUSELAGE                    4250.00    203.70    20.1000     1.000     293.1    0.00174     0.00192
 V-TAIL                      745.00     35.00     0.0300     1.039      50.4    0.00223     0.00045
 NACELLES/PYLONS             200.00     33.00    10.0000     1.101      47.5    0.00224     0.00013
ADDITIONAL-CD0                                                                              0.00000
ADDITIONAL-CD0                                                                              0.00000
CRUD/MISC/BASE                                                                              0.00173
TOTAL                      12695.00                                                0.00260     0.00855
```

Figure 30. Concorde EDET Output File

Point Performance (*Skymaps*)

To determine the performance of the specified aircraft and engine together at varying altitudes and Mach numbers, a point performance tool referred to as Skymaps with algorithms documented by Takahashi was developed that utilizes the aerodynamic data of EDET and the five column propulsion data of the inlet matching tool.[14] The tool would interpolate the data from the aerodynamic and propulsion files and calculate a set of performance values with the inputs of maximum takeoff weight, number of engines, engine scale factor, and wing reference area. The values would be calculated and plotted as skymaps over a range of Mach numbers and altitudes in order to determine the optimal performance parameters as well as the speeds and altitudes when the aircraft and engine are unable to function. For preliminary testing and performance trade studies, the range for altitudes is set to 0 ft to 60,000 ft in increments of 1,000 ft and the range for Mach number is set to 0.0 to 2.0 in increments of 0.01 for all performance tests. A general Skymap plot of maximum thrust performance for an aircraft system is presented in Figure 31.

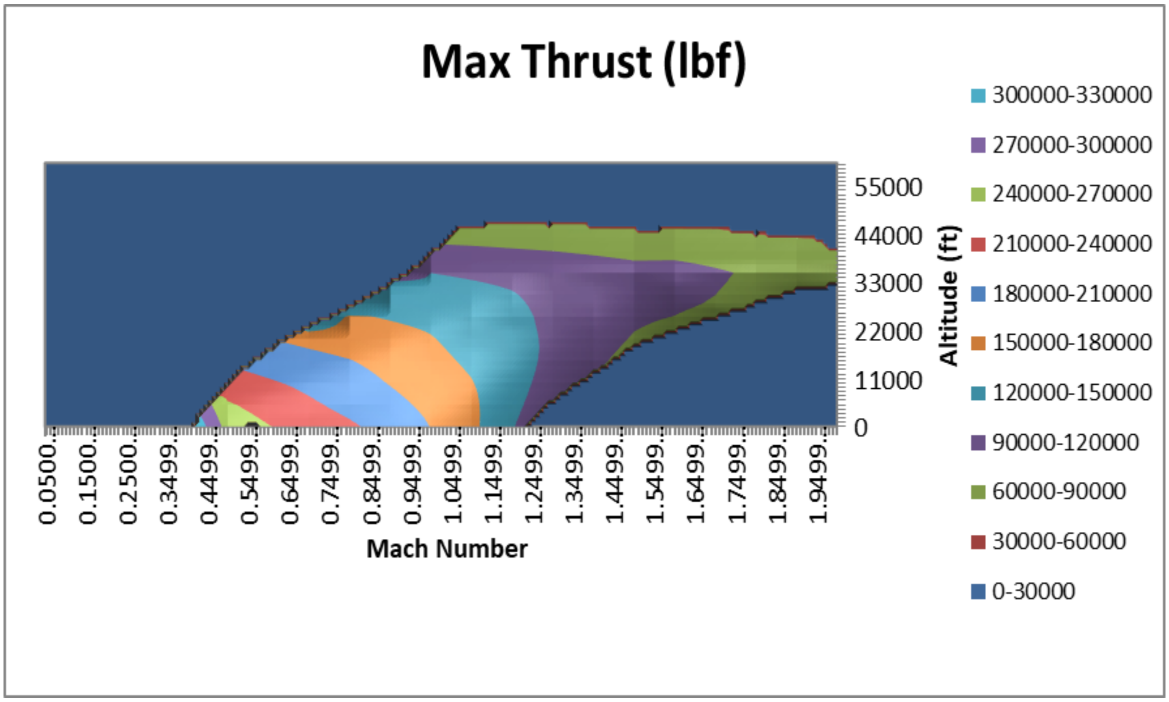

Figure 31. Skymap Plot of an Aircraft's Maximum Thrust

One of the most important performance values that is calculated through Skymaps is the specific range of the aircraft. Specific range is the efficiency of how much fuel is burned for every nautical mile travelled with higher values indicating less fuel burned. Knowing the altitude and Mach number when the SR value is the highest allows for one to determine how fast and where the aircraft should be during most of its flight in order to burn its fuel as efficiently as possible. SR also allows one to determine how much fuel is needed for a flight with the knowledge of how many nautical miles the aircraft needs to travel. Analysis of the SR skymaps for each chosen engine and aircraft combination is going to be the main focus on the Skymaps trade study when it comes to determining the effective performance of each engine.

TRADE STUDIES

With all the necessary analysis tools for the project set up, several trade studies were then performed in order to test both engine and aircraft performance of various engine designs. Before the trade studies were performed, preliminary testing was done with all the analysis tools in order to make sure they were functioning properly and get an idea of how the actual engine tests will proceed.

Three trade studies were performed that revolved around the principle of changing specific parameters of the engine designs to see how each parameter affects engine performance.

- The first trade study involved changing the bypass ratio while keeping all the other parameters constant.
- The second trade study involved changing the fan pressure ratio while keeping all the other parameters constant.
- The third trade study involved having several engines with set bypass ratios and changing the other parameters to achieve good TSFC efficiency.

The reason the trade studies were focused more on BPR and FPR instead of TIT and OPR is due to the fact that BPR and FPR are parameters of fan performance while TIT and OPR are parameters of core performance. One of the main goals of the project is to match external compression inlets with turbofan engines and the biggest factor when it comes to matching the systems is the inlet size. While the TIT and OPR do change the size of the engine somewhat in NPSS, BPR and FPR are the biggest factors when it comes to determining the size of the engine and therefore the size of the inlet. It was also desired more to see how changing fan parameters affect propulsion performance through inlet matching than changing core parameters.

The last trade study that was performed revolved around using the engines designed in the third trade study with the desired aircraft in Skymaps in order to determine the effective aircraft performance each engine provided.

For the trade studies, every engine would have its performance scaled up during the inlet matching process so that each one will have a maximum static thrust of 10,000 lbf at sea level. This decision was made as it allowed for better analysis of the engines in each trade study since each engine now essentially has the same static thrust performance. Scaling the engines up to 10,000 lbf at maximum static thrust also allows for easier appliance of engine scale factor when the desired engines are tested with the desired aircraft in Skymaps.

In order to demonstrate the difference in performance of the engine designs tested in each specific trade study, power hook plots were created that showed the thrust and TSFC of every PLA setting for each tested engine at specific flight conditions. It becomes apparent through initial inlet matching that certain PLA setting become inoperable at specific speeds and altitudes so certain limitations are set with thrust and TSFC values in order to clean up the power hook plots for analysis. For subsonic cases all TSFC values that are above 1.0 are removed, and for supersonic cases all TSFC values that are above 2.0 are removed. For both subsonic and supersonic cases, any thrust value that is below zero is removed.

For the last trade study, each engine was operated with the Concorde at various engine scale factors in order to find a thrust-to-weight ratio that allowed for an effective range of flight conditions. It was also observed for each engine how much performance and flight range were affected for the Concorde when the optimal ESF was increased or decreased. The performance values of each engine tests were then compared to recorded performance values of the Concorde that were achieved using its own engines.

General Inlet Matching Tests

The preliminary tests of the inlet matching tool revolved mostly around the analysis of how changing the radius of the inlet affected the performance of the test engine with no afterburner, minimum afterburner, and maximum afterburner. These tests were mostly performed to get an idea of what happens with engine performance when the inlet becomes too small or too large as well as determine the advantages and disadvantages of smaller and larger inlet sizes.

The tests showed that when an inlet becomes small enough, the inlet is not able to bring in enough air for the engine to function at maximum PLA of each afterburner setting at specific speeds and altitudes. The speeds and altitudes when the engine could not function depended on the afterburner setting but it would usually occur when the altitude was above 20,000 ft. For one test case using the preliminary test engine and an inlet radius of 0.85 ft, no afterburner could not run at maximum PLA between the Mach numbers of 0.7 and 1.2, minimum afterburner could not run at maximum PLA between the Mach numbers of 0.7 and 2.0, and maximum afterburner could not run at maximum PLA between the Mach numbers of 1.5 and 2.0. A sample of data from the five-column data of this test engine showing the inability to function at high PLA values is presented in Figure 32.

0.8	50000	0.01	20.39415	2.449905
0.8	50000	0.1	65.47239	1.220032
0.8	50000	0.2	137.4984	0.9509868
0.8	50000	0.4	233.207	0.8812809
0.8	50000	0.6	351.6797	0.8592898
0.8	50000	0.8	504.2725	0.8621188
0.8	50000	0.9	696.7285	0.8774491
0.8	50000	1	0	0
0.8	50000	1.01	1	3.177001
0.8	50000	1.1	234.8246	3.177001
0.8	50000	1.5	0	0
0.8	50000	2	1586.95	2.051959
0.8	52500	0.01	18.07132	2.449187
0.8	52500	0.1	58.06695	1.22054
0.8	52500	0.2	121.9104	0.9509672
0.8	52500	0.4	206.6136	0.882108
0.8	52500	0.6	312.065	0.8589385
0.8	52500	0.8	447.2321	0.8620192
0.8	52500	0.9	617.846	0.8775162
0.8	52500	1	0	0
0.8	52500	1.01	1	3.174833
0.8	52500	1.1	208.5017	3.174833
0.8	52500	1.5	0	0
0.8	52500	2	1407.237	2.051952
0.8	55000	0.01	16.09583	2.437746
0.8	55000	0.1	51.40886	1.221091
0.8	55000	0.2	108.0697	0.9510394
0.8	55000	0.4	183.2169	0.882165
0.8	55000	0.6	276.4942	0.8593505
0.8	55000	0.8	396.5516	0.8621104
0.8	55000	0.9	547.9448	0.8774484
0.8	55000	1	0	0
0.8	55000	1.01	1	3.176022
0.8	55000	1.1	184.9436	3.176022
0.8	55000	1.5	0	0
0.8	55000	2	1247.936	2.051922

Figure 32. Sample Data of Inoperable Flight Conditions due to Small Inlet Size

The tests also showed that when the inlet becomes large enough, the thrust produced by the engine at specific PLA values, speeds, and altitudes is not strong enough to overcome the combined spill, bleed, and bypass drag that is affecting the engine which leads to negative thrust and TSFC values and therefore inoperable. This would usually occur once speeds are supersonic, the PLA is lower than the maximum value, and the altitude is low. As the Mach number increases, the engines become less operable at lower PLA values and altitudes to the point where, as an example, an engine may not be able to operate at a Mach number 2.0 without operating at maximum PLA and an altitude above 40,000 ft. This is not unexpected or even a detriment to a supersonic engine design as engines of this power are not expected or supposed to operate at low PLA values and altitudes when the aircraft reaches supersonic speeds. As a worst-case scenario, it is possible for the engine to not be able to run at any PLA or altitude at supersonic speeds due to drag losses from the inlet, but this would only occur if the inlet is much too large for the engine. A sample of data from the five-column data of a test engine showing the inability to function at low PLA values and altitude and high speed is presented in Figure 33.

2	0	0.01	-12452.15	-0.2806908
2	0	0.1	-8840.547	-0.7238737
2	0	0.2	-7493.955	-1.001162
2	0	0.4	-7493.955	-1.001162
2	0	0.6	-7493.955	-1.001162
2	0	0.8	-7493.955	-1.001162
2	0	0.9	-7493.955	-1.001162
2	0	1	-7493.955	-1.001162
2	0	1.01	-7492.955	-2.718754
2	0	1.1	-7213.95	-2.718754
2	0	1.5	2930.317	10.1348
2	0	2	15264.79	3.989548
2	2500	0.01	-11384.73	-0.276049
2	2500	0.1	-8093.872	-0.7114455
2	2500	0.2	-6414.745	-1.115014
2	2500	0.4	-6414.745	-1.115014
2	2500	0.6	-6414.745	-1.115014
2	2500	0.8	-6414.745	-1.115014
2	2500	0.9	-6414.745	-1.115014
2	2500	1	-6414.745	-1.115014
2	2500	1.01	-6413.745	-5.086677
2	2500	1.1	-4088.111	-5.086677
2	2500	1.5	3340.307	8.365032
2	2500	2	14686.62	3.854869
2	5000	0.01	-10395.42	-0.2710279
2	5000	0.1	-7405.097	-0.6976745
2	5000	0.2	-5170.681	-1.317326
2	5000	0.4	-5170.681	-1.317326
2	5000	0.6	-5170.681	-1.317326
2	5000	0.8	-5170.681	-1.317326
2	5000	0.9	-5170.681	-1.317326
2	5000	1	-5170.681	-1.317326
2	5000	1.01	-5169.681	-5.349199
2	5000	1.1	-3581.742	-5.349199
2	5000	1.5	3823.281	6.873203
2	5000	2	14374	3.657973

Figure 33. Sample Data of Inoperable Flight Conditions due to Large Inlet Size

Though only smaller inlets will run into the problem of functionality at high PLA values due to low air flow, just about any inlet size will have the issue of negative thrust at low PLA values and altitudes when the speed is supersonic. When it came to increasing or decreasing the size of the inlet, it became very clear that the functionality of the engine is very sensitive to how large the inlet's opening is. A simple increase in the radius of the inlet by an inch could lead to a good chunk of lost thrust and TSFC efficiency due to drag losses. A simple decrease in the radius by an inch could lead to the engine not being able to function at maximum PLA at certain speeds and altitudes due to lack of air flow.

The information gained from the preliminary inlet matching tests helped to establish several conditions that would be applied to the actual trade studies that would occur with various engine designs. One of these conditions is that none of the engines for the trade studies will be tested with minimum or maximum afterburner and therefore be considered engines without afterburner capability. The reason for this is the afterburner for the preliminary engine test was found to be much too large compared to no afterburner use, with over a 200% increase of maximum thrust. Such a significant increase of thrust leads to difficult engine scaling with the Concorde aerodynamics in the point performance tool as well as horrible specific range and fuel consumption that would make usage of the engine unviable.

While the test engine was a low bypass ratio one that was only used to test the analysis tools, it showed how much more tinkering would be required with the NPSS files in order to generate efficient afterburner data for each desired engine. It was also desired to see if afterburners were even necessary for the tested engines to be viable for supersonic airliners since afterburners greatly increase fuel consumption with their increased thrust which is already affected by the sizing of the inlet as well.

Using just the dry propulsion data also allows for more engine tests to be performed as generating five column data with afterburners required running three different NPSS files for one engine design. One also needed to analyze how the inlet size affected the performance of the engine with no afterburner, minimum afterburner, and maximum afterburner, so testing an engine without afterburners allows one to focus solely on one set of propulsion data when sizing the inlet.

Another condition for the engine trade studies is that the inlet size for each engine is to be as small as possible without causing too many issues with air flow at high PLA values. The reason for this is that preliminary tests demonstrated that the engine is able to retain more of its raw thrust and TSFC data when the inlet size is smaller, so the best engine performance comes from the smallest possible inlet size. As noted previously, small inlet sizes run into the issue of not bringing in enough air for the engine to run at high PLA values at specific speeds and altitudes so certain leeway and limitations must be considered when sizing the inlets with the engines.

When performing the trade studies, it was decided that it was acceptable to use an inlet size with an engine that does not allow it to function at its maximum PLA at specific speeds and altitudes. When this would occur, the thrust and TSFC of the second highest PLA would be used as the values for maximum PLA at the specific parameters. This allows one to continue to decrease the size of the inlet to get more efficient thrust and TSFC values even when small air flow issues are present. This decision was made since it is not unreasonable or uncommon to operate an engine at its second highest PLA value when maximum PLA is not possible as the thrust and TSFC at the second highest PLA is still viable for aircraft functionality.

It should be noted that for just about every trade study, the issues of inoperability at maximum PLA would only happen at Mach 0.7 and possible between Mach 0.8 and Mach 1.2 as well, depending on the tested engine and inlet size, and at altitudes above

32,500 ft. It should also be noted that the trade study tests showed that as the engines increased in supersonic speed, the thrust and TSFC values at each parameter became rather constant no matter the PLA value. The decided limit to this procedure of inlet size decreasing is when both the maximum and second highest PLA values are inoperable at specific parameters due to lack of air flow.

Varying Bypass Ratio Tests

For this trade study, several engines will be tested with various bypass ratios while the fan pressure ratio, turbine inlet temperature, and overall pressure ratio are kept constant. The engine parameter and geometry values for each engine tested in this trade study are presented in Table 1. This is the only time an engine with a bypass ratio of one is tested and recorded instead of 1.0 with a bypass ratio of 6.0. This is due to the fact that an engine with these constant parameters and a bypass ratio of 6.0 is unable to run in NPSS which indicates such an engine design is not possible. An engine with a bypass ratio of 1.0 was used in order to have a sufficient number of tested engines for the trade study to demonstrate the trends caused by varying the bypass ratio.

Table 1. Design Parameters of Engines tested in Varying BPR Trade Study

Test Engine	BPR	FPR	TIT (°R)	OPR	Fan Diameter (in)	Inlet Diameter (in)
1	1.0	2.6	3000	55	27.036	26.64
2	2.0	2.6	3000	55	31.298	30.00
3	3.0	2.6	3000	55	34.482	32.16
4	4.0	2.6	3000	55	37.104	34.08
5	5.0	2.6	3000	55	39.498	35.76

A power hook plot of the varying BPR engines in takeoff roll at sea level and static thrust is presented in Figure 34. A power hook plot of the varying BPR engines in initial climb at 5000 ft and Mach 0.3 is presented in Figure 35. A power hook plot of the varying BPR engines in subsonic cruise at 40,000 ft and Mach 0.8 is presented in Figure 36. A power hook plot of the varying BPR engines in transonic acceleration at 45,000 ft and Mach 1.0 is presented in Figure 37. A power hook plot of the varying BPR engines in supersonic cruise at 50,000 ft and Mach 1.2 is presented in Figure 38. A power hook plot of the varying BPR engines in supersonic cruise at 50,000 ft and Mach 1.6 is presented in Figure 39. A power hook plot of the varying BPR engines in supersonic cruise at 50,000 ft and Mach 2.0 is presented in Figure 40.

All these plots demonstrate a consistent trend between an engine's BPR and the thrust and TSFC it achieves, both thrust and TSFC decrease as the BPR increases. This means that lower BPR engines achieve better thrust while higher BPR engines achieve better TSFC efficiency.

The plots also show that as the BPR of the engine increases, the less the decrease in thrust and TSFC becomes compared to the values of the previous BPR value. This indicates that the decrease in thrust and increase in TSFC efficiency is inversely proportional to the BPR increase of an engine with constant FPR, TIT, and OPR, and one would reach a point where an increase in BPR would do little or nothing to affect the engine's performance.

Figures 34 and 35 show that at low subsonic speeds and altitudes, the engine has its worst TSFC efficiency at its maximum PLA value.

Figure 36 shows that at high subsonic speeds and altitudes, the engine is unable to function at its lowest PLA settings and begins to have its most efficient TSFC values at its higher PLA settings.

Figures 37, 38, 39, and 40 show that at supersonic speeds and high altitudes, the most efficient TSFC value is achieved at the engine's maximum PLA value. Figures 37, 38, 39, and 40 also show that as the engine increases in supersonic speed at higher altitudes, more high PLA settings produce the same thrust and TSFC values and more low PLA settings become inoperable.

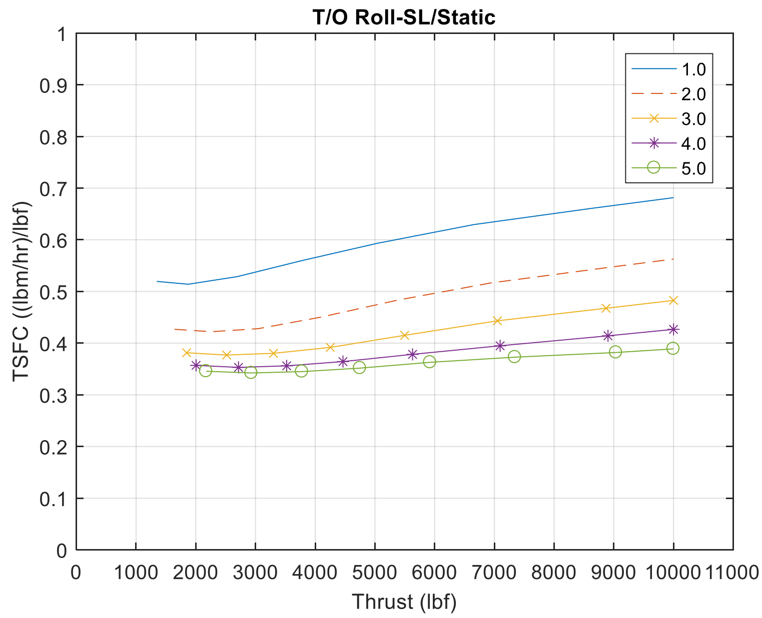

Figure 34. Power Hook Plot of Varying BPR Engines in Takeoff Roll

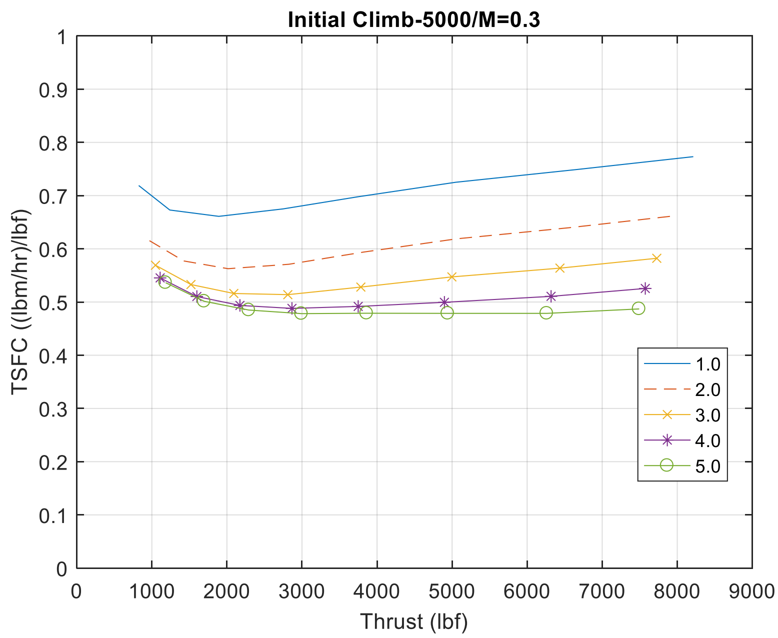

Figure 35. Power Hook Plot of Varying BPR Engines in Initial Climb

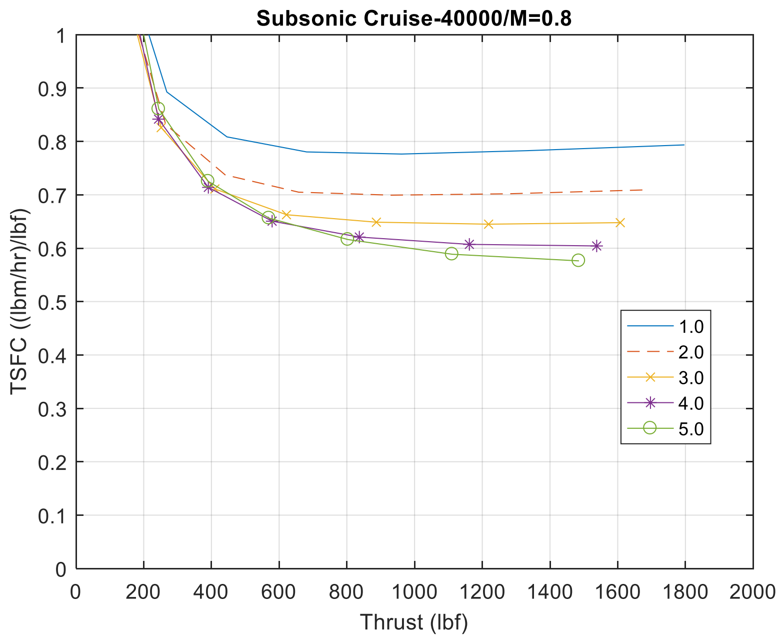

Figure 36. Power Hook Plot of Varying BPR Engines in Subsonic Cruise

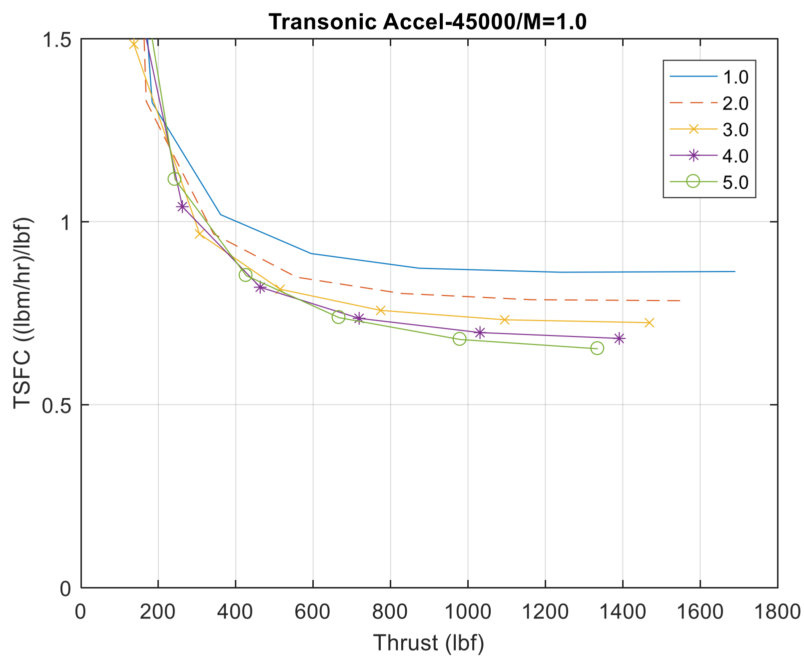

Figure 37. Power Hook Plot of Varying BPR Engines in Transonic Acceleration

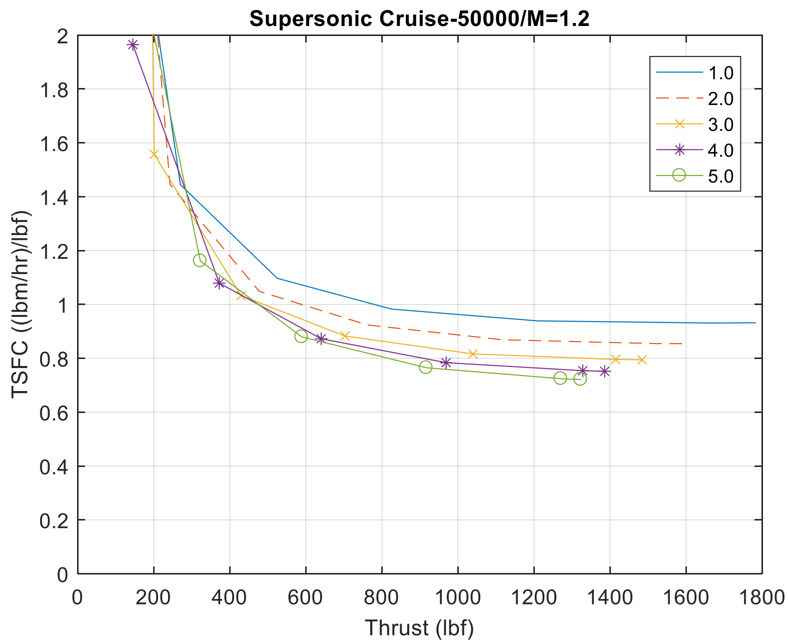

Figure 38. Power Hook Plot of Varying BPR Engines in Mach 1.2 Supersonic Cruise

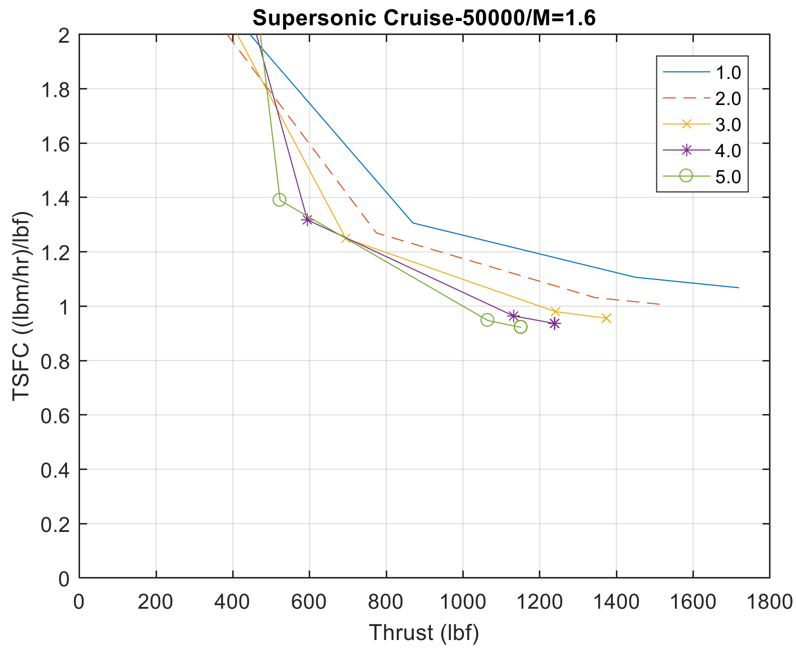

Figure 39. Power Hook Plot of Varying BPR Engines in Mach 1.6 Supersonic Cruise

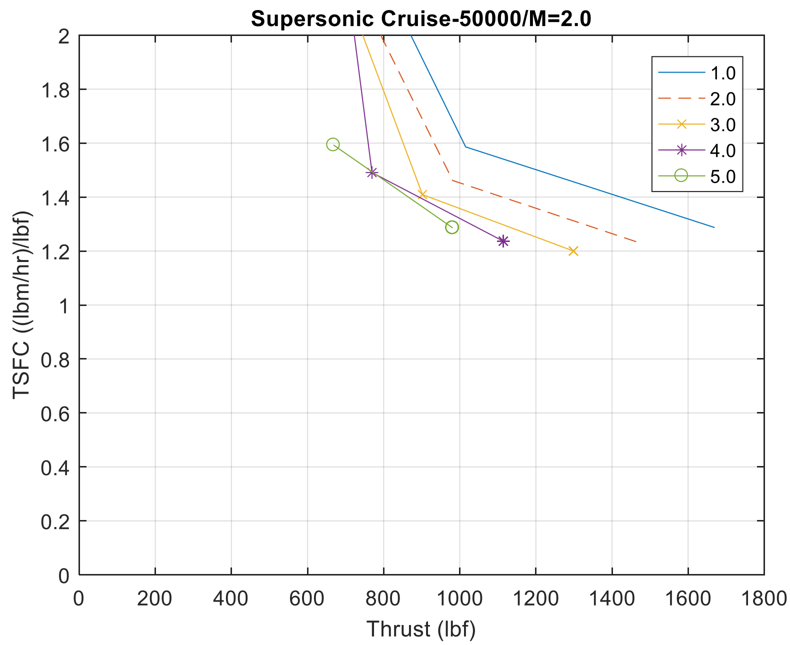

Figure 40. Power Hook Plot of Varying BPR Engines in Mach 2.0 Supersonic Cruise

Varying Fan Pressure Ratio Tests

For this trade study, several engines will be tested with various fan pressure ratios while the bypass ratio, turbine inlet temperature, and overall pressure ratio are kept constant. The engine parameter and geometry values for each engine tested in this trade study are presented in Table 2. The size difference between each of is FPR values is much smaller than the size difference of the BPR values from the previous trade study. This is due to the fact that compared to BPR, FPR is much more limited to its size and range when to comes to engine functionality.

Table 2. Design Parameters of Engines tested in Varying FPR Trade Study

Test Engine	BPR	FPR	TIT (°R)	OPR	Fan Diameter (in)	Inlet Diameter (in)
1	2.0	2.2	3000	55	31.774	30.96
2	2.0	2.6	3000	55	31.298	30.00
3	2.0	3.0	3000	55	30.958	29.76
4	2.0	3.4	3000	55	30.704	29.52
5	2.0	3.8	3000	55	30.514	29.52

A power hook plot of the varying FPR engines in takeoff roll at sea level and static thrust is presented in Figure 41. A power hook plot of the varying FPR engines in initial climb at 5000 ft and Mach 0.3 is presented in Figure 42. A power hook plot of the varying FPR engines in subsonic cruise at 40,000 ft and Mach 0.8 is presented in Figure 43. A power hook plot of the varying FPR engines in transonic acceleration at 45,000 ft and Mach 1.0 is presented in Figure 44. A power hook plot of the varying FPR engines in supersonic cruise at 50,000 ft and Mach 1.2 is presented in Figure 45. A power hook plot of the varying FPR engines in supersonic cruise at 50,000 ft and Mach 1.6 is presented in Figure 46. A power hook plot of the varying FPR engines in supersonic cruise at 50,000 ft and Mach 2.0 is presented in Figure 47.

The figures show an interesting trend of thrust and TSFC as FPR increases for the engine that is somewhat different from the trend observed from increasing the BPR.

Instead of having a consistent decrease in TSFC for each PLA setting that was seen with the previous trade study, TSFC seems to increase at low PLA settings, converge at medium PLA settings, then decrease at high PLA settings as FPR increases. This trend for TSFC is especially noticeable in Figures 41, 42, 43, and 44 which at subsonic and low supersonic speeds; these four figures also show that at these speeds, thrust increases slightly at maximum PLA as FPR increases.

Figures 45, 46, and 47 show that this initial trend for both TSFC and thrust beings to lessen as speed increases to point where at Mach 1.6, thrust decreases and TSFC increases for most of the functional PLA settings as FPR increases.

The three figures also show that larger FPRs lose more of their thrust and TSFC capabilities as speed increases to the point were at Mach 2.0, the engine with an FPR of 3.8 can only operate at one thrust and TSFC value no matter the functional PLA setting it is in. This indicates that while larger FPRs give somewhat better engine performance at lower speeds, once they go above Mach 1.0 they start to lose their efficiency to the point where they are barely operable at high speeds. When compared to smaller FPRs they are able to retain great functionality throughout all the different flight conditions and are able to have better thrust and TSFC efficient at higher speeds.

It should be noted that initial engine testing for this trade study showed that engines with FPR values of 4.0 and above produced horrible thrust and TSFC values at supersonic speeds that made the engines functionally impossible for desired usage. Similar to the trends seen in the varying BPR trade study, the figures also show that the increase to thrust and decrease to TSFC is inversely proportional to the change in the

FPR value. This means that just like changing the BPR, one will reach a point where changing the FPR of the engine to increase thrust and TSFC efficiency will yield little to no difference in engine performance.

It should also be noted that all the figures show that the change in thrust and TSFC is rather minimal as FPR increases or decreases. This indicates that while FPR does have an impact on engine performance, its effect very small, unless larger FPR values are used, when compared to how BPR affects engine performance.

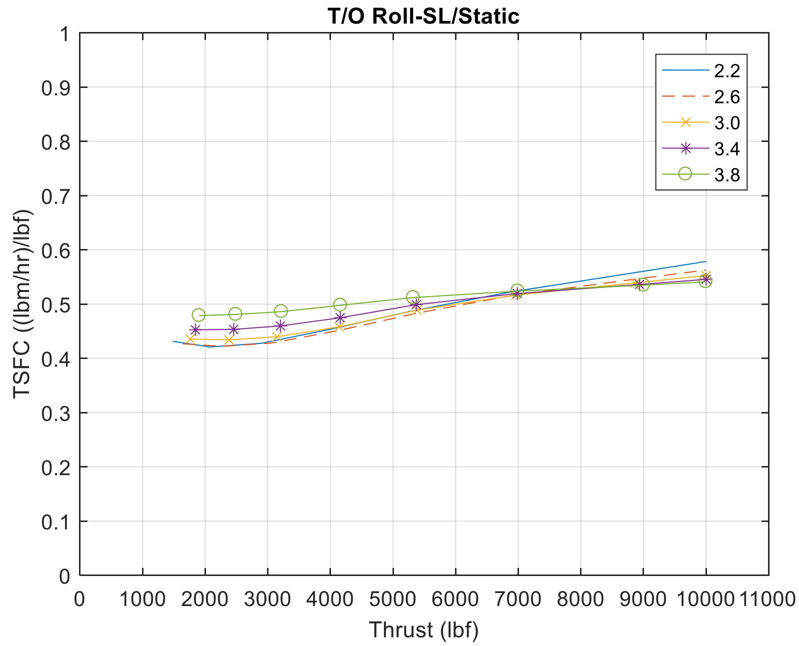

Figure 41. Power Hook Plot of Varying FPR Engines in Takeoff Roll

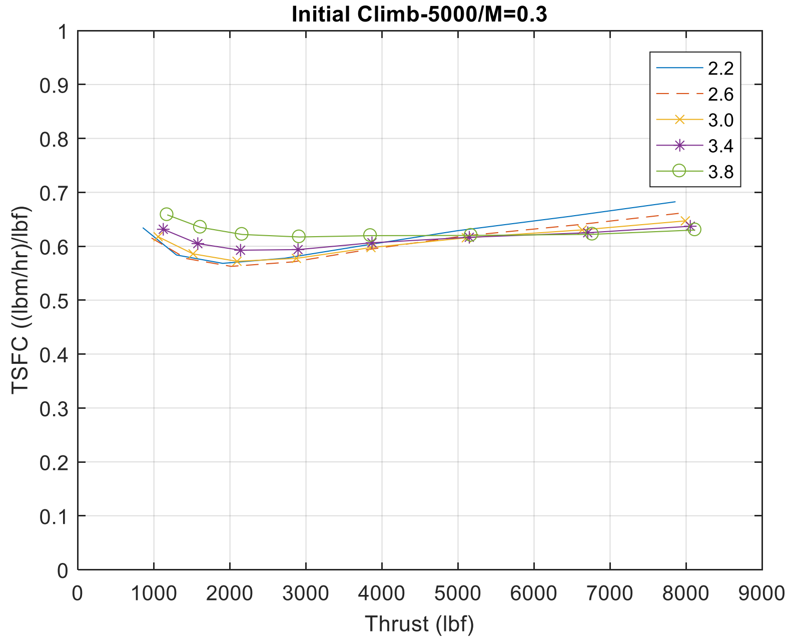

Figure 42. Power Hook Plot of Varying FPR Engines in Initial Climb

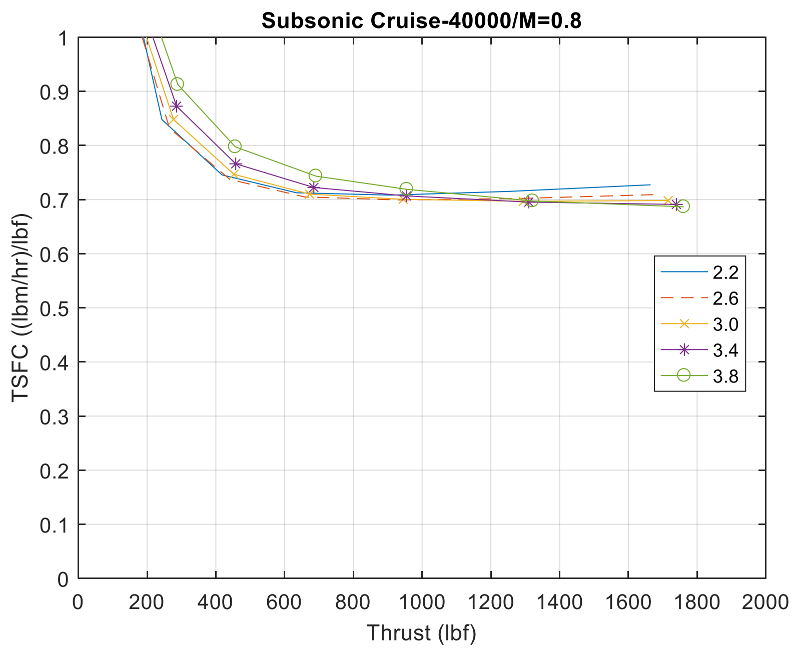

Figure 43. Power Hook Plot of Varying FPR Engines in Subsonic Cruise

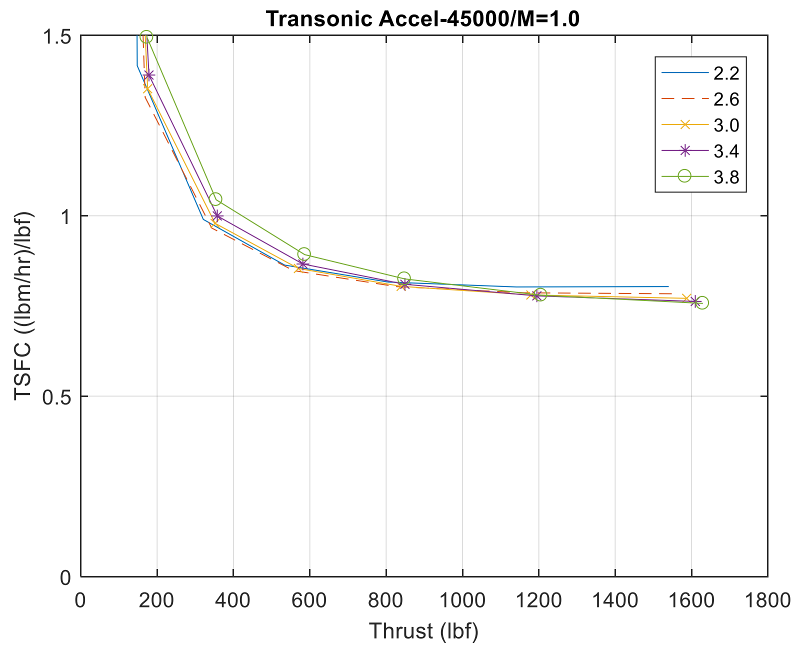

Figure 44. Power Hook Plot of Varying FPR Engines in Transonic Acceleration

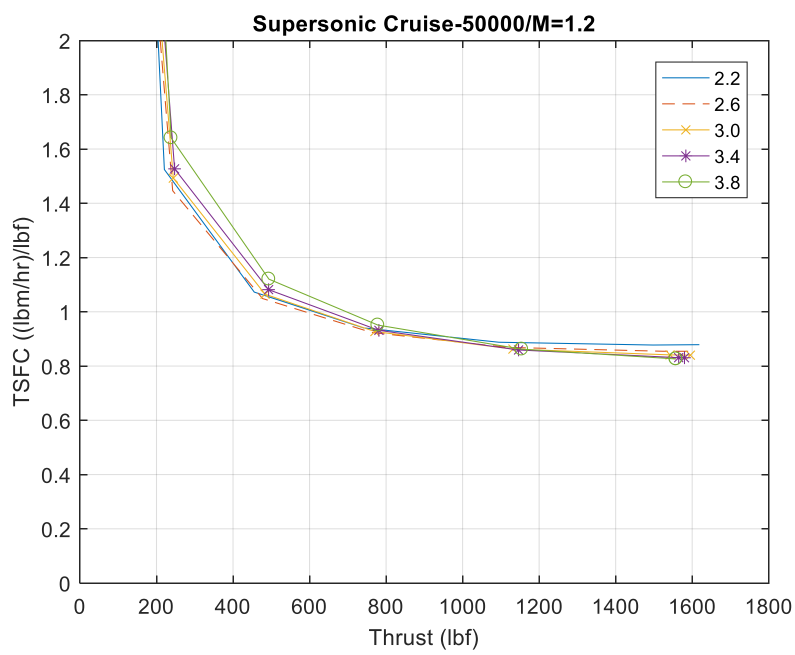

Figure 45. Power Hook Plot of Varying FPR Engines in Mach 1.2 Supersonic Cruise

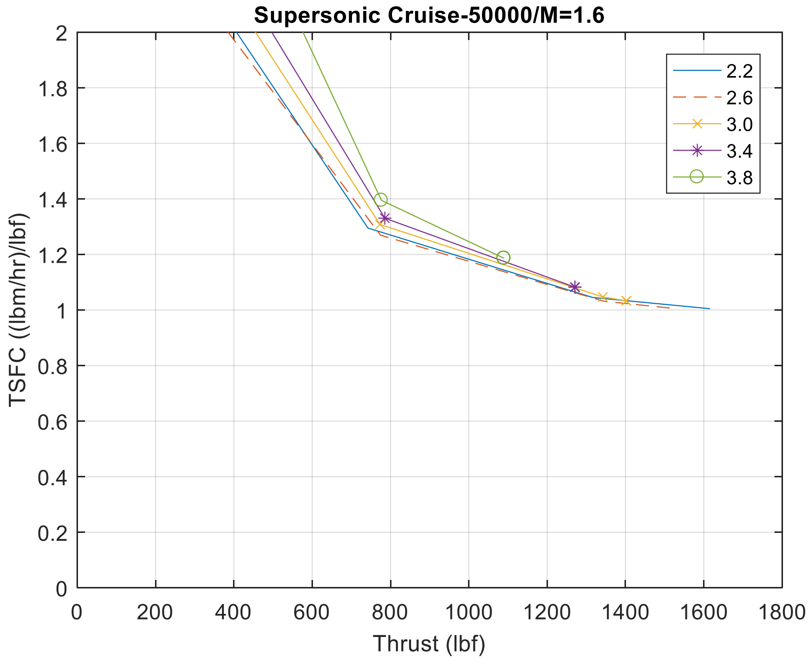

Figure 46. Power Hook Plot of Varying FPR Engines in Mach 1.6 Supersonic Cruise

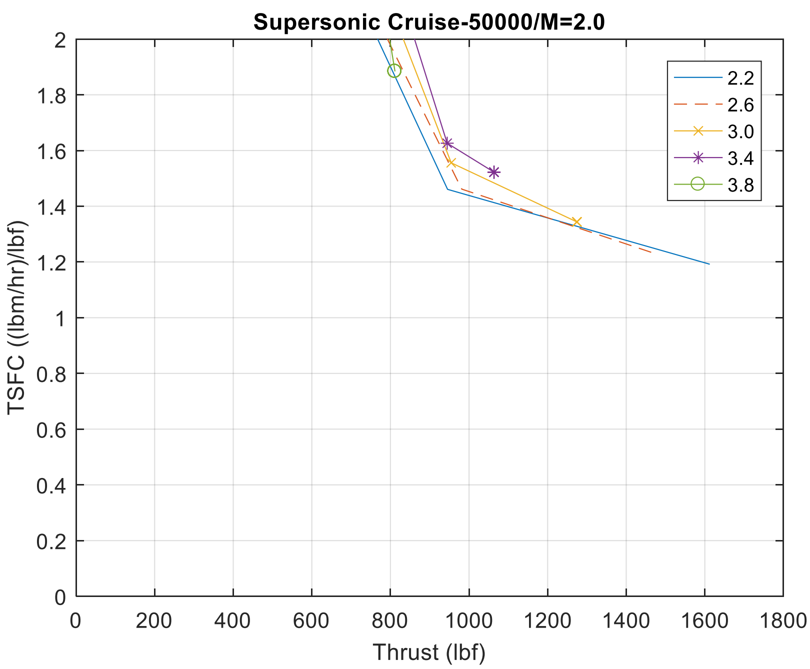

Figure 47. Power Hook Plot of Varying FPR Engines in Mach 2.0 Supersonic Cruise

TSFC Efficient Engines at Set Bypass Ratios

For this trade study, each engine was given a set bypass ratio and then the fan pressure ratio, turbine inlet temperature, and overall pressure ratio were changed in any way to produce efficient TSFC performance. This is the most important trade study out of the three different engine trade studies as the engines that are produced here are going to be the ones used in the final trade study that tests aircraft performance. It should be noted for most of the parameter changing tests that were performed, thrust efficiency usually decreased as TSFC efficiency increased. While both thrust and TSFC are the main focus for deciding effective and viable engine performance after inlet matching, it was decided that TSFC was the most important value to keep efficient when changing the engine parameters to test the engine in NPSS. The reason for this is that thrust can easily be scaled up during point performance testing in order to achieve the necessary aircraft performance, while TSFC remains relatively constant through the Skymaps process so it is important to make the TSFC of each engine as efficient as possible. The engine parameter and geometry values for each engine tested in this trade study are presented in Table 3.

Table 3. Design Parameters of Engines tested in TSFC Efficiency Trade Study

Test Engine	BPR	FPR	TIT (°R)	OPR	Fan Diameter (in)	Inlet Diameter (in)
1	2.0	2.6	3000	55	31.298	30.00
2	3.0	2.8	2700	60	37.538	34.20
3	4.0	2.6	3000	72	37.728	34.32
4	5.0	2.3	3000	73	40.644	36.84
5	6.0	2.0	2900	73	44.866	40.44

It is important to note that these are likely not the best engine parameters for achieving maximum TSFC efficiency for each set BPR value. This is due to the fact that all four engine parameters clearly affect each other's contribution to engine performance as they are changed and tested. This was seen from the NPSS tests performed for each BPR engine, each parameter was manually changed and tested one at a time until the best TSFC efficiency was found and then the next parameter would be changed and tested. This process did work in creating efficient and viable engines for each BPR value, but it became clear after going back to a previous parameter that it can still be changed and generate even better TSFC with how the other parameters are set currently. This indicates that manual testing of one parameter at a time is not enough to create a specific BPR engine with its best achievable TSFC values, every parameter would need to be changed and tested over a range of values at the same time in order to find the best engine design. While the project currently may not be able to get the best achievable engine design for each BPR value, that does not invalidate the viable engine performance that was achieved for each BPR engine through the manual NPSS testing.

The lowest BPR value was chosen to be 2.0 as commercial airports have regulations on the amount of noise that comes from jet engines, and 2.0 is generally the smallest BPR value a high bypass turbofan engine can have to pass these regulations. The highest BPR value was chosen to be 6.0 as NPSS tests with BPR values of 7.0 were found to rarely ever generate proper data, and even when they did the performance values occurred above the stoichiometric ratio of the turbine process. This means that the engine with a BPR of 7.0 is achieving performance values beyond the limitations of the engine's turbine and is therefore not a realistic engine design.

A power hook plot of the various engine designs in takeoff roll at sea level and static thrust is presented in Figure 48. A power hook plot of the various engine designs in initial climb at 5000 ft and Mach 0.3 is presented in Figure 49. A power hook plot of the various engine designs in subsonic cruise at 40,000 ft and Mach 0.8 is presented in Figure 50. A power hook plot of the various engine designs in transonic acceleration at 45,000 ft and Mach 1.0 is presented in Figure 51. A power hook plot of the various engine designs in supersonic cruise at 50,000 ft and Mach 1.2 is presented in Figure 52. A power hook plot of the various engine designs in supersonic cruise at 50,000 ft and Mach 1.6 is presented in Figure 53. A power hook plot of the various engine designs in supersonic cruise at 50,000 ft and Mach 2.0 is presented in Figure 54.

All these plot demonstrate a similar trend with thrust and TSFC that was seen in the varying BPR trade study, where both thrust and TSFC decrease as the BPR increases.

The plots also show the same trend of less decrease to thrust and TSFC compared to the values of the previous BPR value as BPR increases. This indicates that BPR is the most prominent factor for affecting engine performance when it comes to the design parameters of the turbofan engine.

It should be noted that some of the figures do show that there are a few exceptions to this trend of decreasing thrust and TSFC with increasing BPR value. Figure 49 shows that the BPR 6.0 engine is able to achieve a better thrust value at maximum PLA than all the other engines while still maintaining the best TSFC efficiency. Figure 51 shows a similar exception with the BPR 5.0 and 6.0 engines achieving better thrust values than the other engines with still the better TSFC efficiency. Figures 52, 53, and 54 show that the BPR 3.0 engine gets worse thrust values compared to the BPR 4.0 engine as the speed increases while still having worse TSFC efficiency.

These three figures also show that the BPR 6.0 engine has a larger decrease to maximum thrust as the speed increases when compared to the decline of thrust of the previous engine. Figures 49, 50, and 51 show that the BPR 3.0 engine has basically the same maximum thrust value as the BPR 4.0 engine even though the BPR 4.0 engine still has better TSFC efficiency.

These exceptions indicate that changing the other three engine parameters alongside changing the BPR definitely makes a difference in engine performance, though the effect in performance seems to be more towards just thrust efficiency. These exceptions also help demonstrate the statement that was made previously where these engine parameters are likely not producing the most efficient performance values for each

BPR engine. While these exceptions exist, the trend of decreasing thrust and TSFC with increasing BPR is still pretty consistent in the figures; so this leads to the conclusion that the BPR 2.0 engine has the best thrust efficiency and the BPR 6.0 has the best TSFC efficiency.

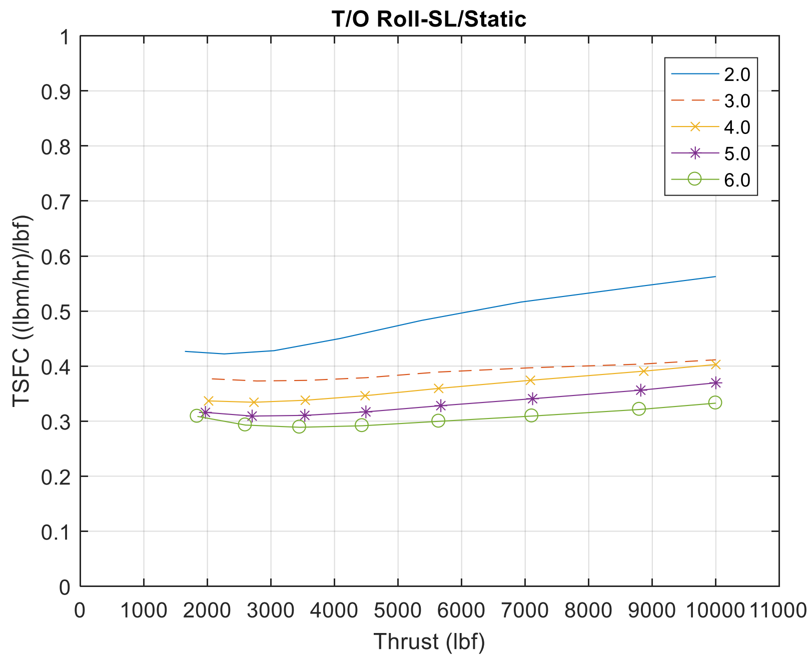

Figure 48. Power Hook Plot of TSFC Efficient BPR Engines in Takeoff Roll

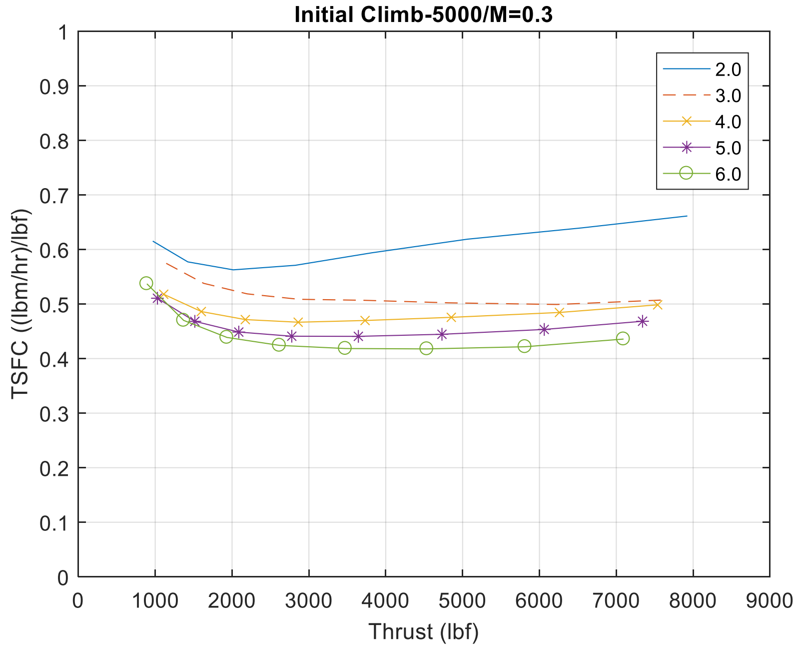

Figure 49. Power Hook Plot of TSFC Efficient BPR Engines in Initial Climb

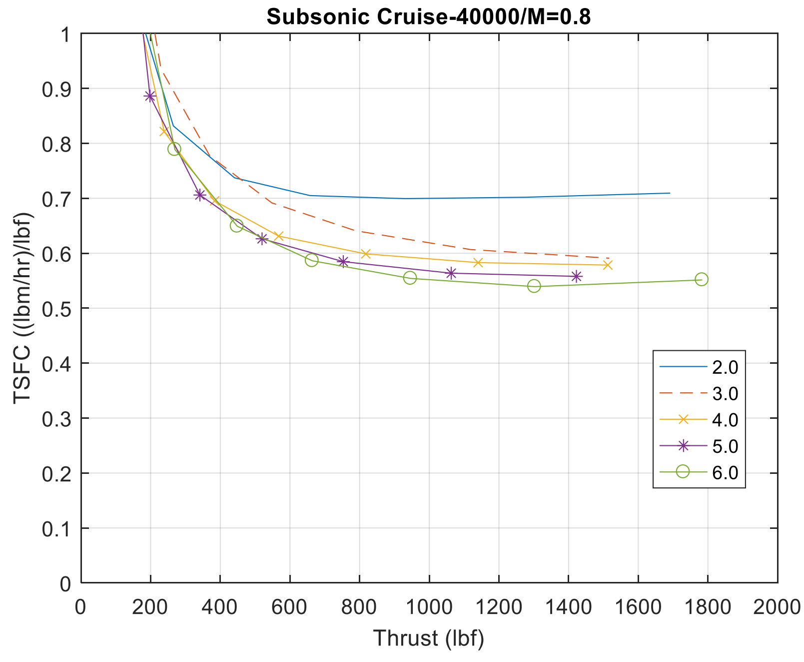

Figure 50. Power Hook Plot of TSFC Efficient BPR Engines in Subsonic Cruise

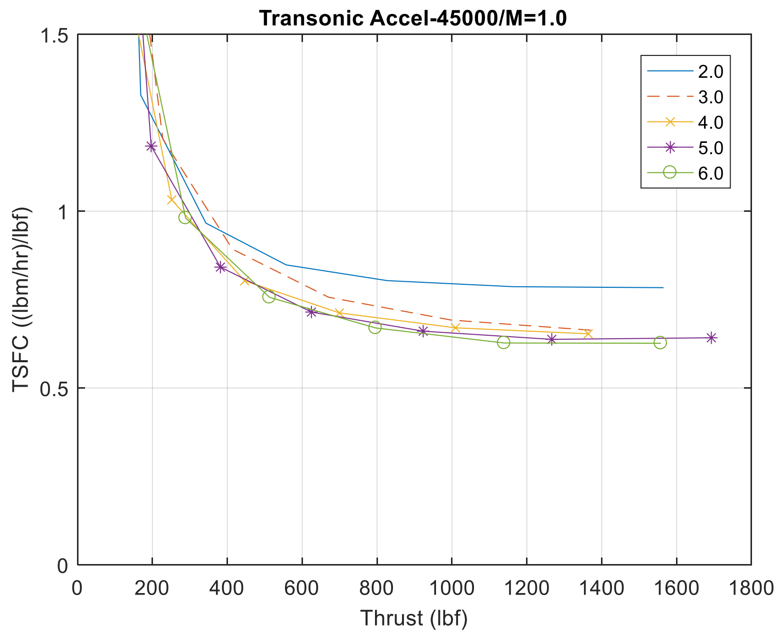

Figure 51. Power Hook Plot of TSFC Efficient BPR Engines in Transonic Acceleration

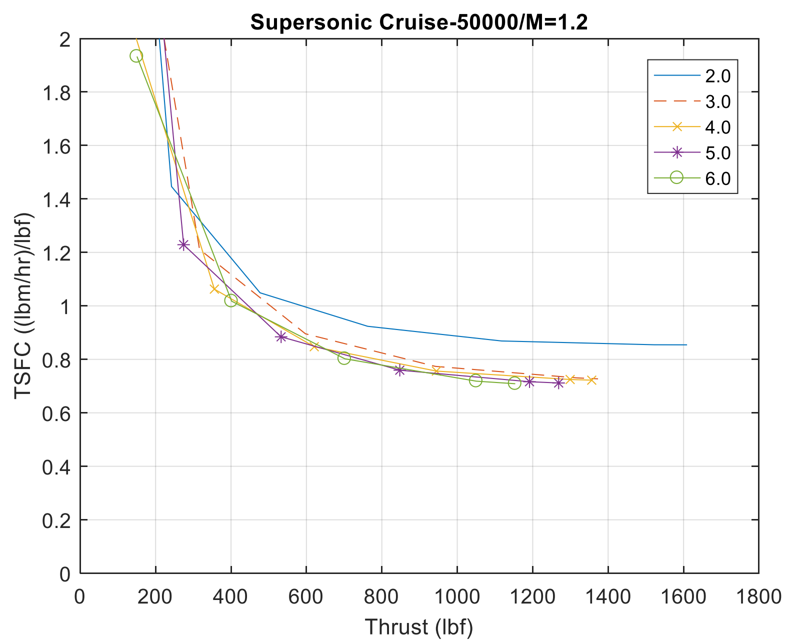

Figure 52. Power Hook Plot of TSFC Efficient BPR Engines in Mach 1.2 Supersonic Cruise

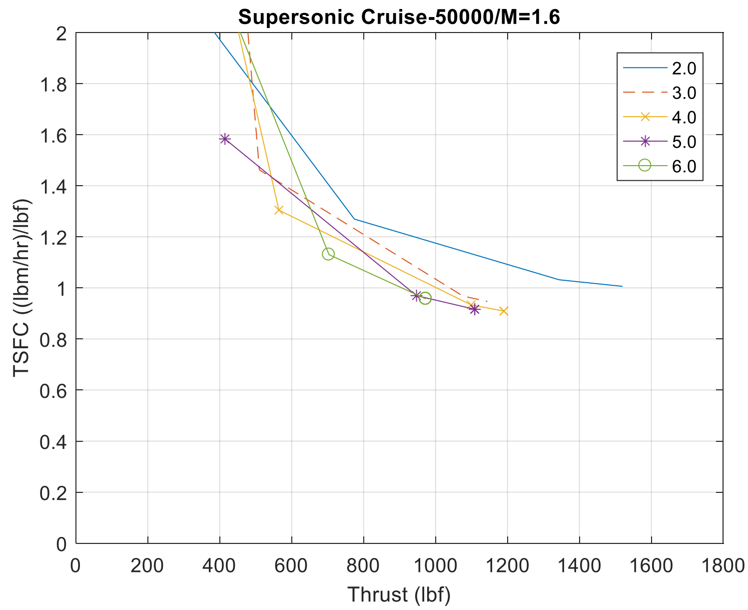

Figure 53. Power Hook Plot of TSFC Efficient BPR Engines in Mach 1.6 Supersonic Cruise

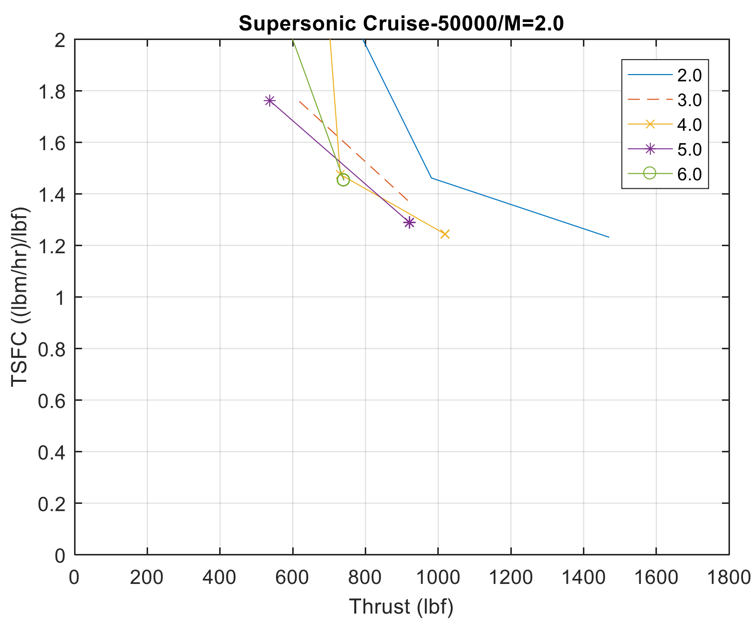

Figure 54. Power Hook Plot of TSFC Efficient BPR Engines in Mach 2.0 Supersonic Cruise

Skymaps Performance Tests

For the aircraft performance tests with Skymaps, the five column propulsion data of each BPR turbofan engine designed in the TSFC efficiency trade study was tested with the aerodynamic data of the Concorde. When it came to the other inputs of the point performance tool, the aircraft weight, number of engines, and wing reference area remained constant for each BPR engine test while the engine scale factor was changed depending on the desired thrust performance. The aircraft weight was set to 400,000 lbm, the number of engines was set to a value of 1, and the wing reference area was set to 3586 ft^2. The inputs for aircraft weight and wing reference area are based off the specifications of the Concorde as its maximum takeoff weight is around 400,000 lbm and its wing area is 3586 ft^2. While the Concorde uses four turbojet engines, it was decided that the number of engines for the tests would be set to 1 as this choice makes it easier for choosing the engine scale factor value for necessary thrust performance. With how the point performance tool is set up, it doesn't matter how many engines are used for the tests as long as the total amount of thrust generated by the engines after scaling them up reaches the desired performance.

As stated previously, the specific range that is obtained from each engine test is going to be to the main focus for determining the effective performance of the aircraft with each engine design. The specific range values and the flight conditions they are obtained at will be compared to the recorded SR value that the Concorde could achieve while in cruise. The Concorde was able to achieve a SR value of 0.02 nM/lbm at a cruise speed of Mach 2.02 and cruise altitude of 60,000 ft. Along with SR, the maximum thrust and thrust-to-weight ratio of each engine test will also be recorded and compared to the values of the Concorde in order to gauge engine effectiveness. The Concorde had a maximum thrust value of 152,200 lbf with all four of its turbojet engines running with afterburner and a thrust-to-weight ratio of 0.373.

For each BPR engine tested with the Concorde data in Skymaps, it was decided that after various tests are performed at different engine scale factor values, the results from three different ESF values would be used as the main focus for examining the aircraft performance of each engine. The reason for this decision is that it became very clear as initial tests were performed that there was no perfect ESF value for the engines; increasing ESF would lead to increased performance range but this meant more required thrust to do so and the performance at this new range was not guaranteed to be more efficient. With this realization, it became apparent that in order to truly demonstrate the effective performance of the Concorde using each engine, one needs to see how much the performance is affected by increasing or decreasing the ESF value. To choose the three ESF values that would used in analyzing every engine, tests were performed with each engine at various ESF values to find an ESF value that would give the engine a decent range of high supersonic flight conditions. Once this ESF value was determined for each engine, the two other ESF values used for each engine analysis would be that ESF value increased by a value of 5 and that ESF value decreased by a value of 5.

Initial testing made it clear that the maximum SR value will not always be at a flight condition of Mach 2.0 for the engine setups, so when this is the case the flight condition in high supersonic regime with the maximum SR value and the largest SR value at the fastest speed operable will both be recorded. Along with these two flight conditions, the largest SR value at a speed halfway between the speed of maximum SR and fastest speed will be recorded as well. The reason for these three values being recorded instead of just one is it allows for one to see how much SR performance decreases as the speed increases and gauge whether or not is viable to fly at higher speeds with less than optimal SR performance.

For the TSFC efficient BPR 2.0 engine, the initial tests demonstrated that the Concorde was able to achieve a decent range of high supersonic flight conditions with an ESF value of 35, so the analysis would be performed with the ESF values of 35, 40, and 30.

The Specific Range Skymap of the BPR 2.0 engine with an engine scale factor of 35 is presented in Figure 55. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0162 nM/lbm at a speed of Mach 2.0 and an altitude of 47,000 ft. The maximum thrust was found to be 350,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 0.875.

The Specific Range Skymap of the BPR 2.0 engine with an engine scale factor of 40 is presented in Figure 56. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0162 nM/lbm at a speed of Mach 2.0 and an altitude of 47,000 ft. The maximum thrust was found to be 400,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.0.

The Specific Range Skymap of the BPR 2.0 engine with an engine scale factor of 30 is presented in Figure 57. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0159 nM/lbm at a speed of Mach 1.92 and an altitude of 44,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0152 nM/lbm at an altitude of 43,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.92 and Mach 2.0, at Mach 1.96 the aircraft has a maximum SR of 0.0158 nM/lbm at an altitude of 44,000 ft. The maximum thrust was found to be 300,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 0.750.

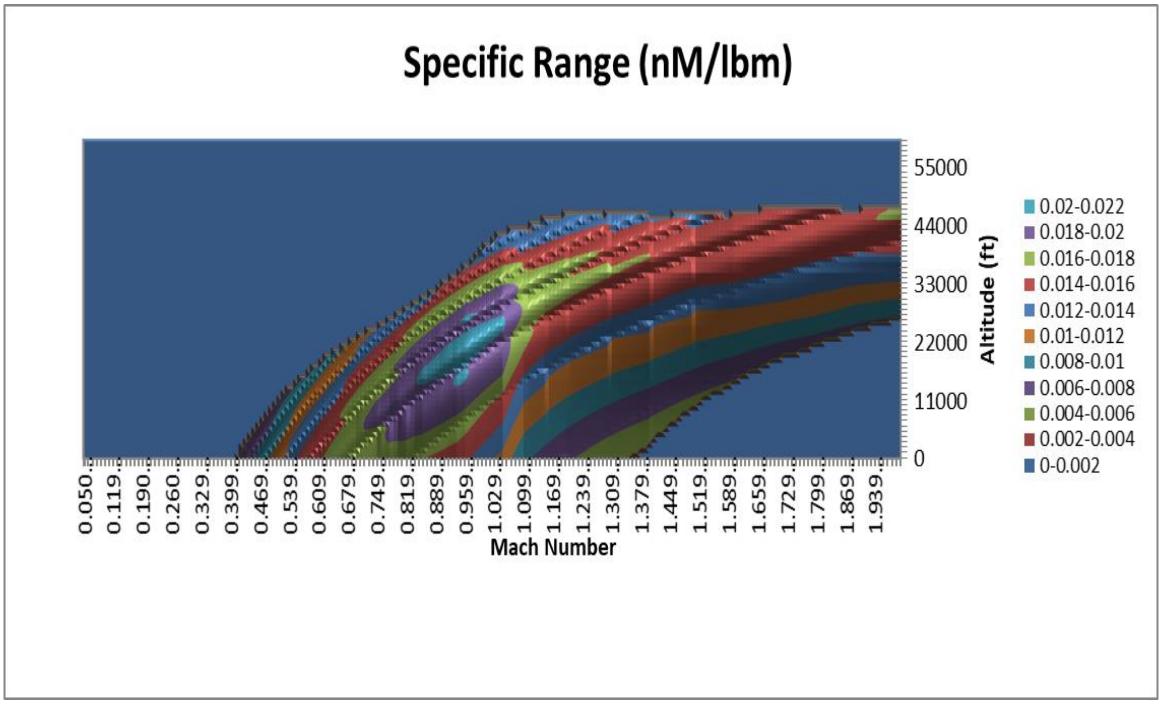

Figure 55. Specific Range Skymap of BPR 2.0 with ESF of 35

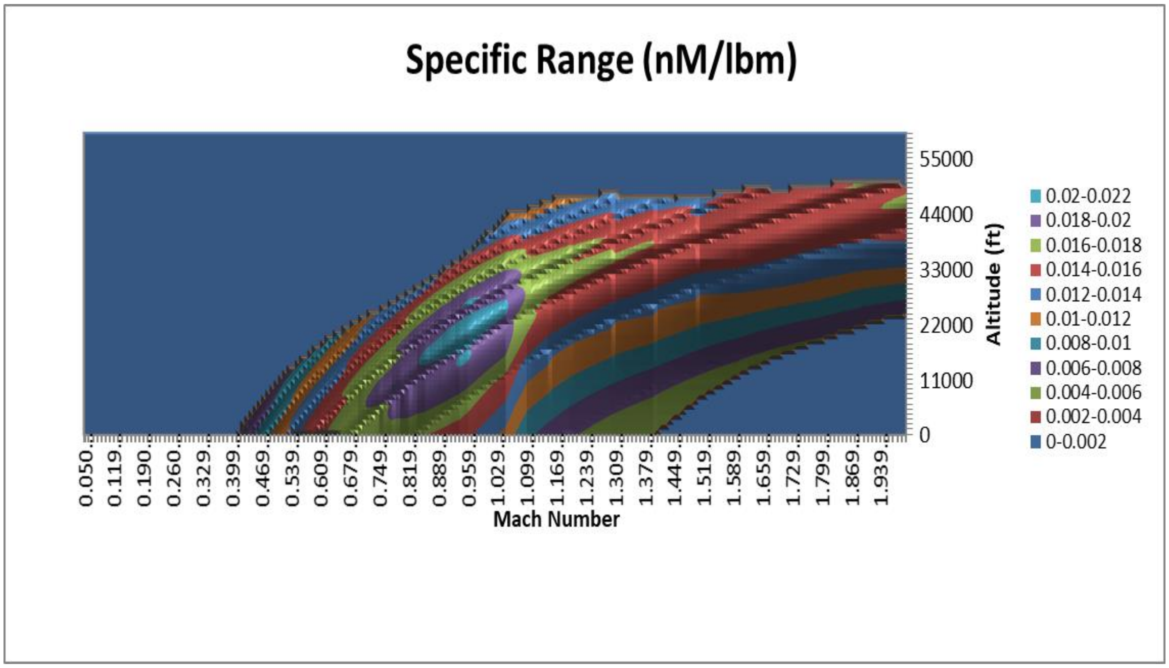

Figure 56. Specific Range Skymap of BPR 2.0 with ESF of 40

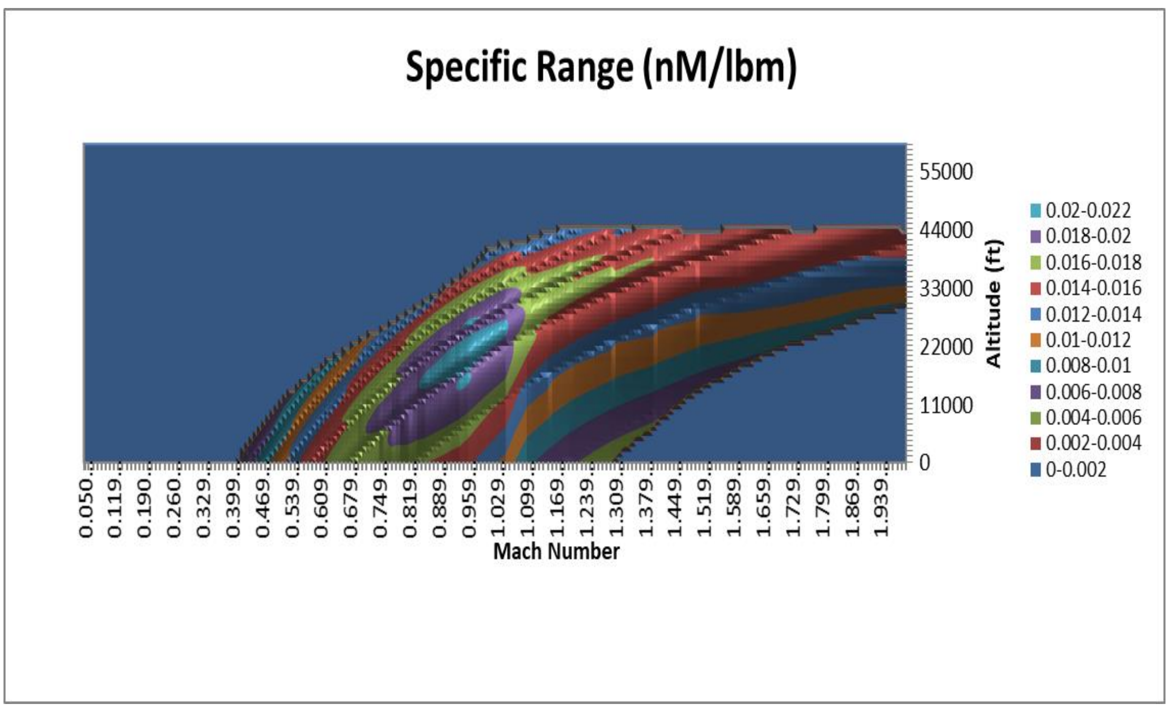

Figure 57. Specific Range Skymap of BPR 2.0 with ESF of 30

For the TSFC efficient BPR 3.0 engine, the initial tests demonstrated that the Concorde was able to achieve a decent range of high supersonic flight conditions with an ESF value of 45, so the analysis would be performed with the ESF values of 45, 50, and 40.

The Specific Range Skymap of the BPR 3.0 engine with an engine scale factor of 45 is presented in Figure 58. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0167 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0129 nM/lbm at an altitude of 40,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0151 nM/lbm at an altitude of 44,000 ft. The maximum thrust was found to be 450,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.125. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.47 to 0.69 and altitudes 0 ft to 3000 ft.

The Specific Range Skymap of the BPR 3.0 engine with an engine scale factor of 50 is presented in Figure 59. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0167 at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0145 nM/lbm at an altitude of 45,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum

SR of 0.0154 nM/lbm at an altitude of 47,000 ft. The maximum thrust was found to be 500,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.250. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.44 to 0.74 and altitudes 0 ft to 4000 ft.

The Specific Range Skymap of the BPR 3.0 engine with an engine scale factor of 40 is presented in Figure 60. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0167 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the aircraft can only achieve this speed at an altitude of 37,000 ft with an SR value of 0.0123 nM/lbm which makes using this engine setup at this speed rather unviable. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0153 nM/lbm at an altitude of 42,000 ft. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.51 to 0.65 and altitudes 0 ft to 1000 ft. The maximum thrust was found to be 400,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.0.

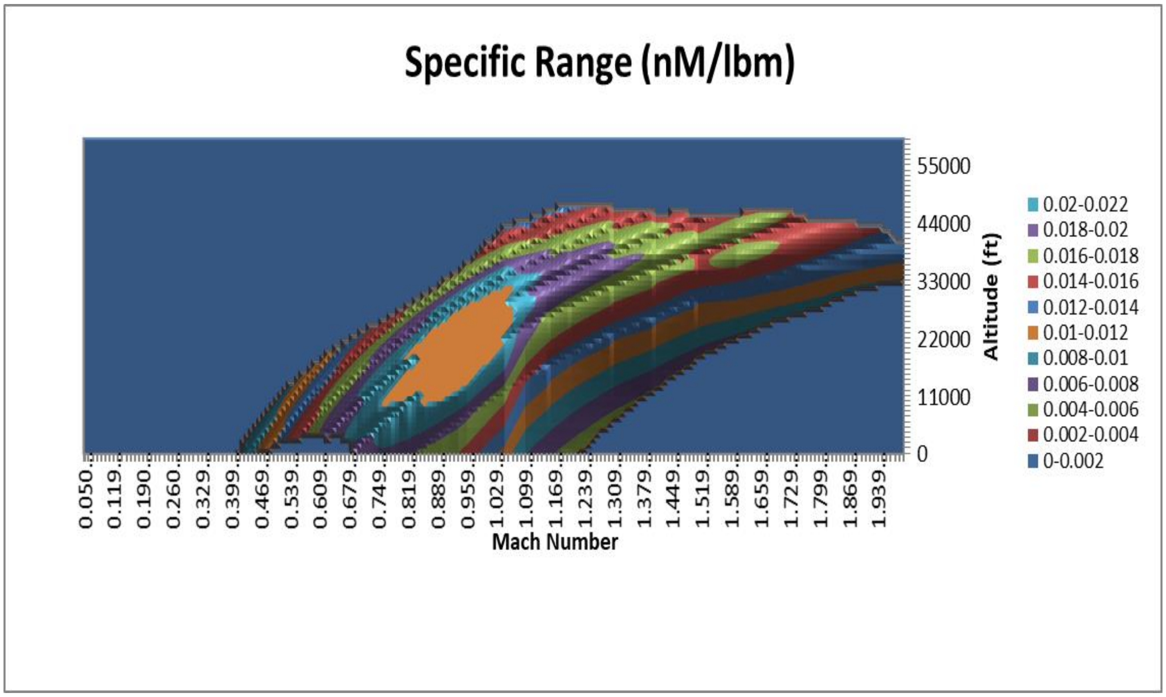

Figure 58. Specific Range Skymap of BPR 3.0 with ESF of 45

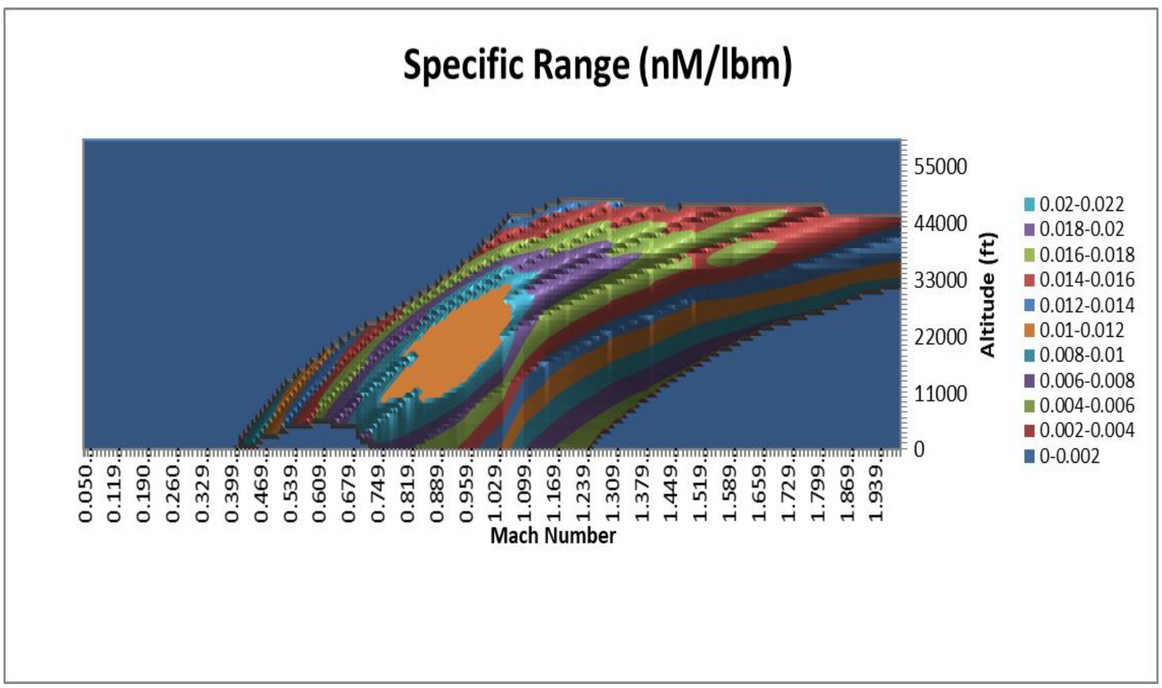

Figure 59. Specific Range Skymap of BPR 3.0 with ESF of 50

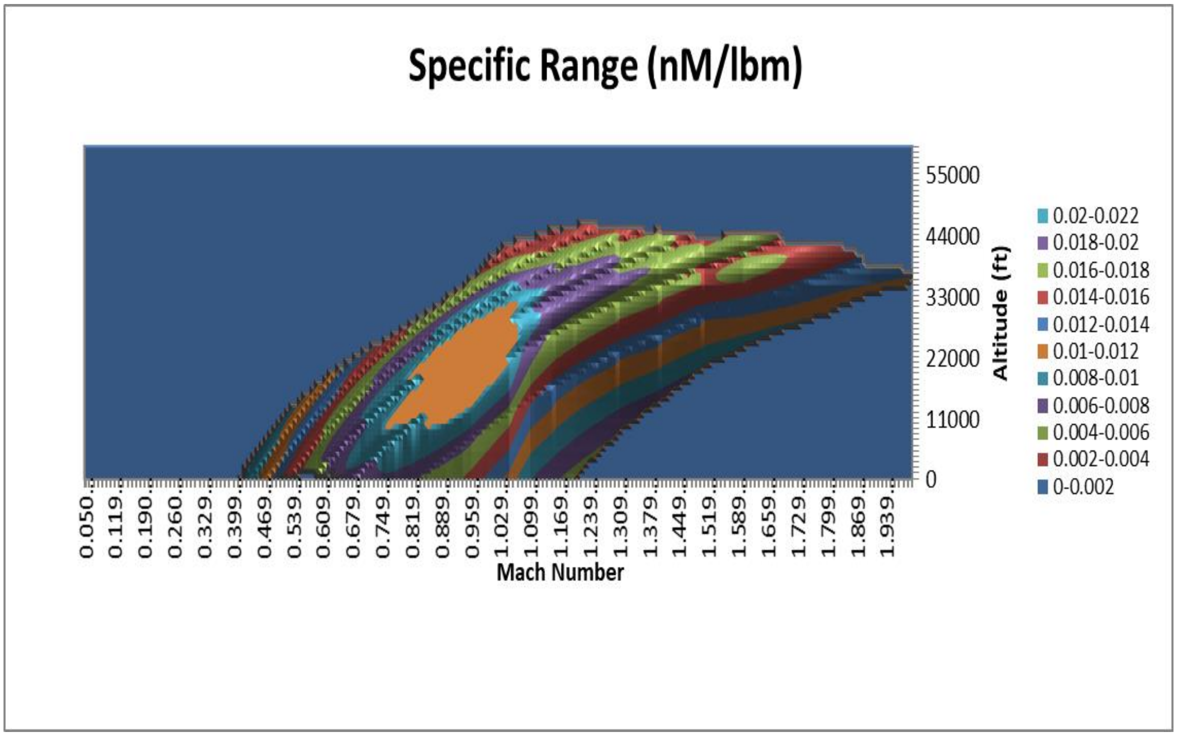

Figure 60. Specific Range Skymap of BPR 3.0 with ESF of 40

For the TSFC efficient BPR 4.0 engine, the initial tests demonstrated that the Concorde was able to achieve a decent range of high supersonic flight conditions with an ESF value of 45, so the analysis would be performed with the ESF values of 45, 50, and 40.

The Specific Range Skymap of the BPR 4.0 engine with an engine scale factor of 45 is presented in Figure 61. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0174 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0159 nM/lbm at an altitude of 45,000 ft which means it is less efficient to fly at this speed. Examining the performance

of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0163 nM/lbm at an altitude of 42,000 ft. The maximum thrust was found to be 450,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.125. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.47 to 0.71 and altitudes 0 ft to 3000 ft.

The Specific Range Skymap of the BPR 4.0 engine with an engine scale factor of 50 is presented in Figure 62. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0174 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0161 nM/lbm at an altitude of 46,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0164 nM/lbm at an altitude of 48,000 ft. The maximum thrust was found to be 500,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.250. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.46 to 0.76 and altitudes 0 ft to 5000 ft.

The Specific Range Skymap of the BPR 4.0 engine with an engine scale factor of 40 is presented in Figure 63. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0174 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0141 nM/lbm at an altitude of 40,000 ft which means it is less efficient to fly at this speed. Examining the performance

of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0163 nM/lbm at an altitude of 42,000 ft. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.51 to 0.65 and altitudes 0 ft to 1000 ft. The maximum thrust was found to be 400,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.0.

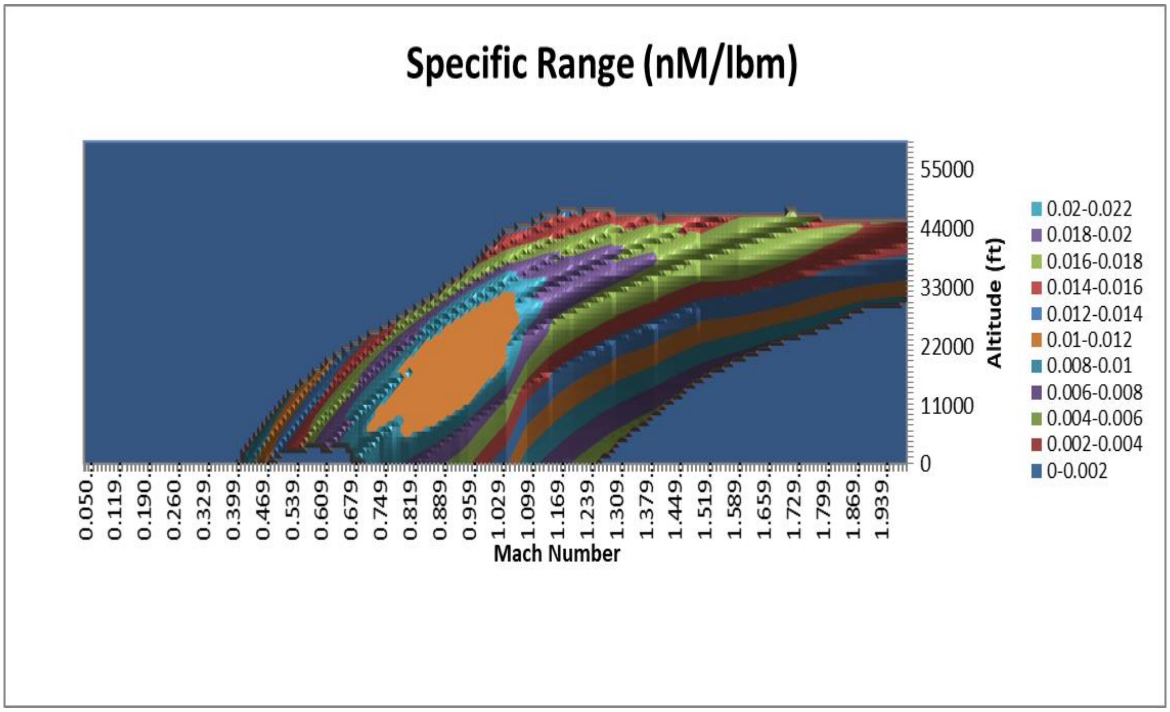

Figure 61. Specific Range Skymap of BPR 4.0 with ESF of 45

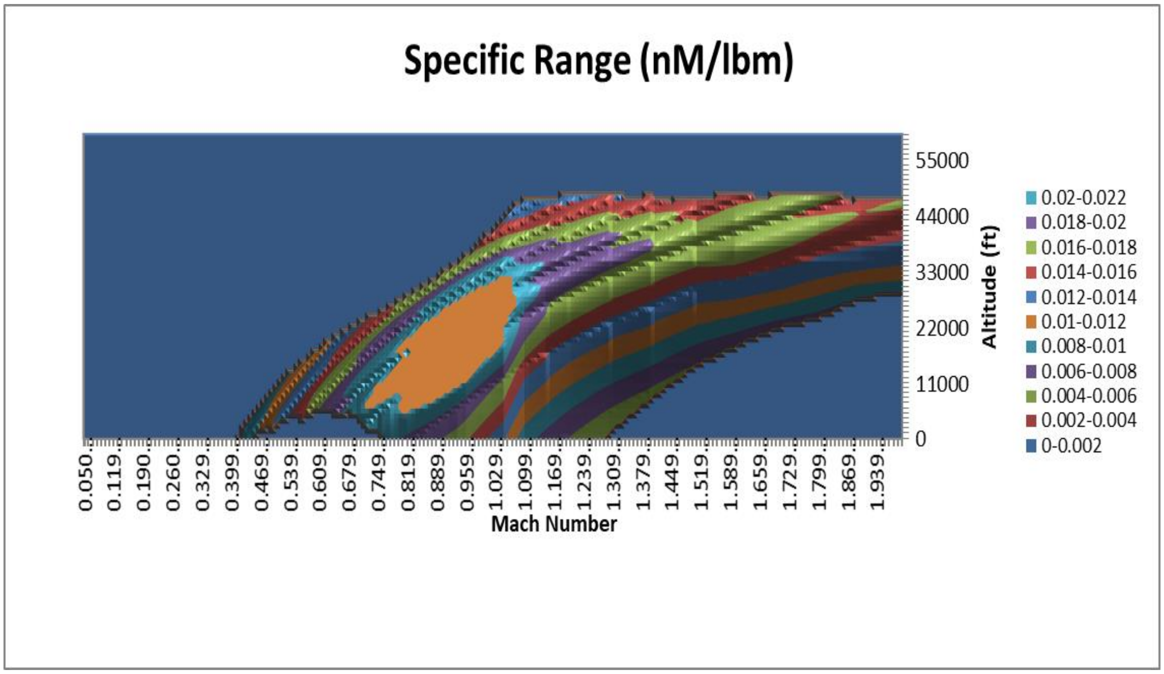

Figure 62. Specific Range Skymap of BPR 4.0 with ESF of 50

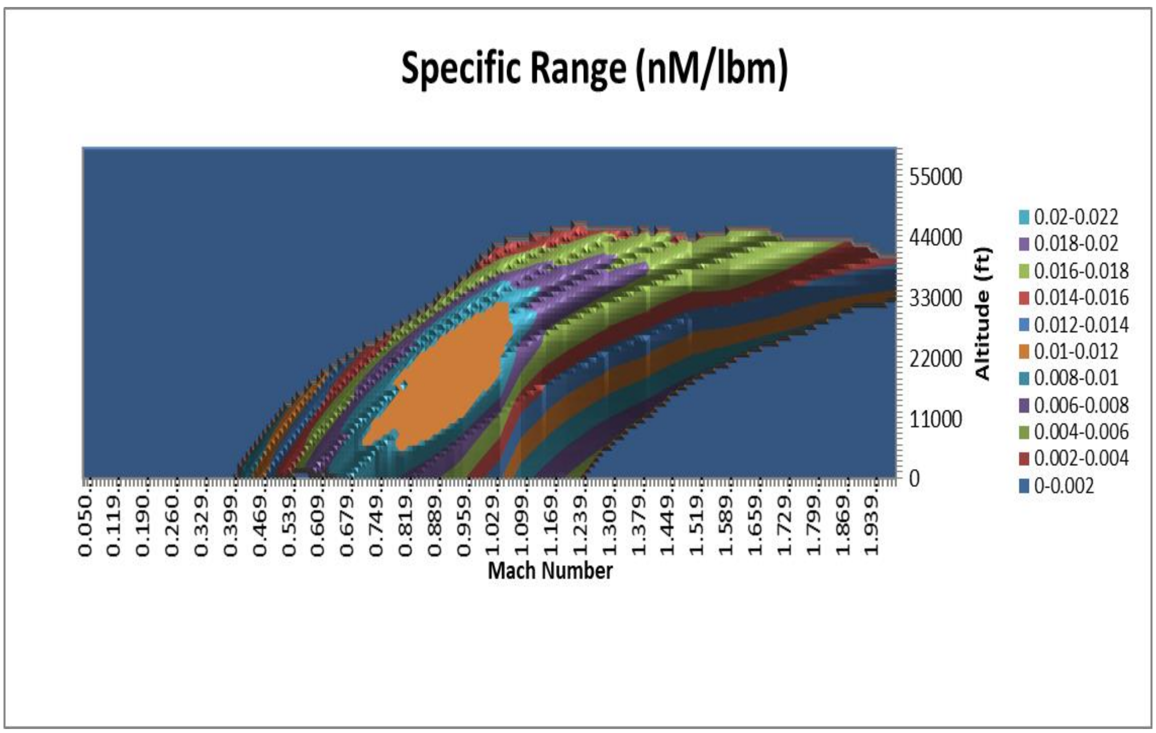

Figure 63. Specific Range Skymap of BPR 4.0 with ESF of 40

For the TSFC efficient BPR 5.0 engine, the initial tests demonstrated that the Concorde was able to achieve a decent range of high supersonic flight conditions with an ESF value of 50, so the analysis would be performed with the ESF values of 50, 55, and 45.

The Specific Range Skymap of the BPR 5.0 engine with an engine scale factor of 50 is presented in Figure 64. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0173 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0154 nM/lbm at an altitude of 45,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0158 nM/lbm at an altitude of 42,000 ft. The maximum thrust was found to be 500,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.250. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.49 to 0.65 and altitudes 0 ft to 2000 ft.

The Specific Range Skymap of the BPR 5.0 engine with an engine scale factor of 55 is presented in Figure 65. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0173 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0155 nM/lbm at an altitude of 46,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0160 nM/lbm at an altitude of 48,000 ft. The maximum thrust was found to be 550,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.375. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.46 to 0.67 and altitudes 0 ft to 3000 ft.

The Specific Range Skymap of the BPR 5.0 engine with an engine scale factor of 45 is presented in Figure 66. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0173 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0136 nM/lbm at an altitude of 40,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0158 nM/lbm at an altitude of 42,000 ft. It should be noted that while not really visible on the figure, the aircraft is unable to function at the flight conditions of Mach 0.55 to 0.57 at sea level. The maximum thrust was found to be 450,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.125.

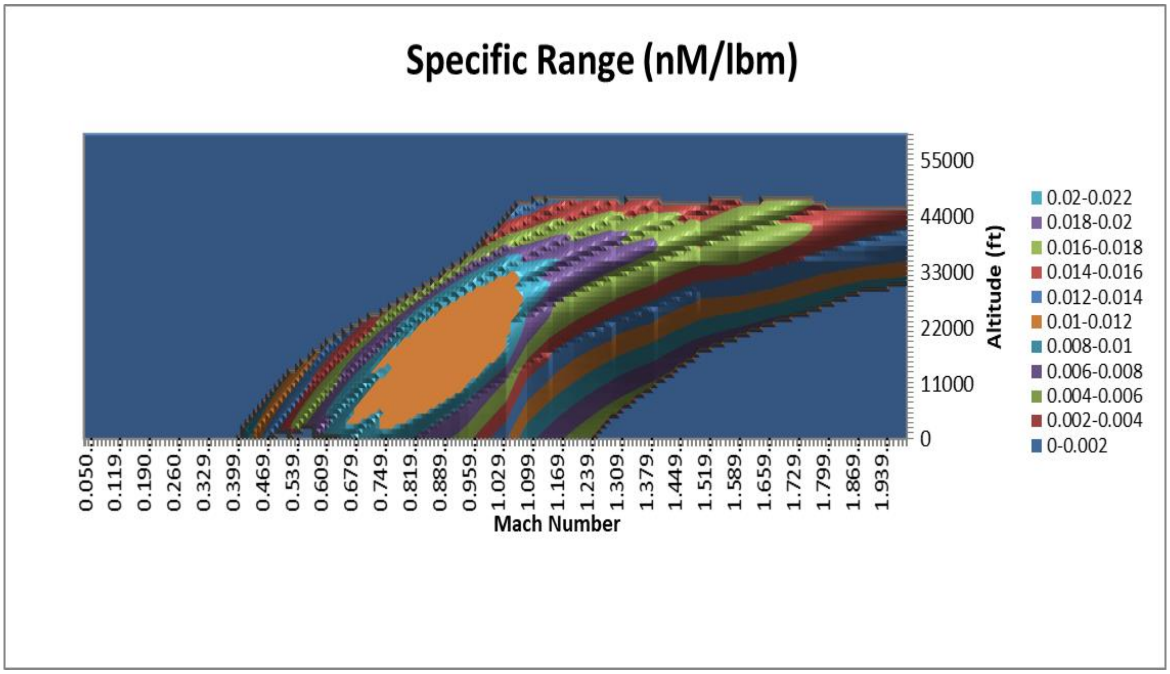

Figure 64. Specific Range Skymap of BPR 5.0 with ESF of 50

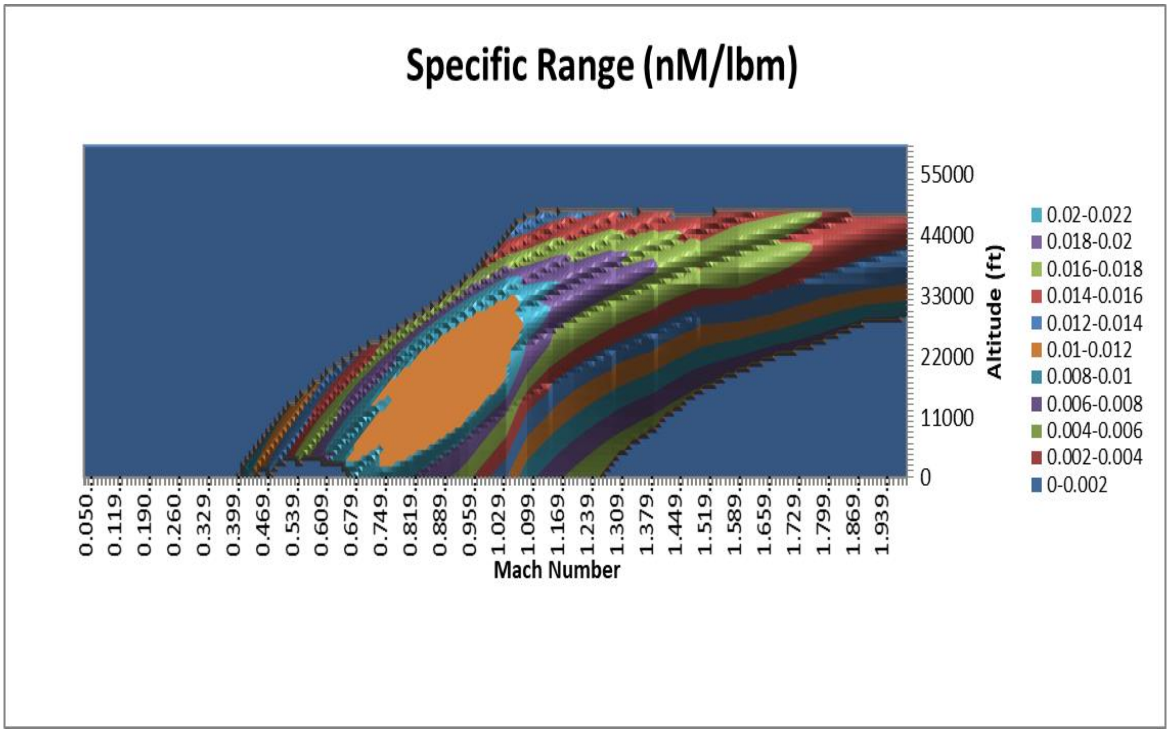

Figure 65. Specific Range Skymap of BPR 5.0 with ESF of 55

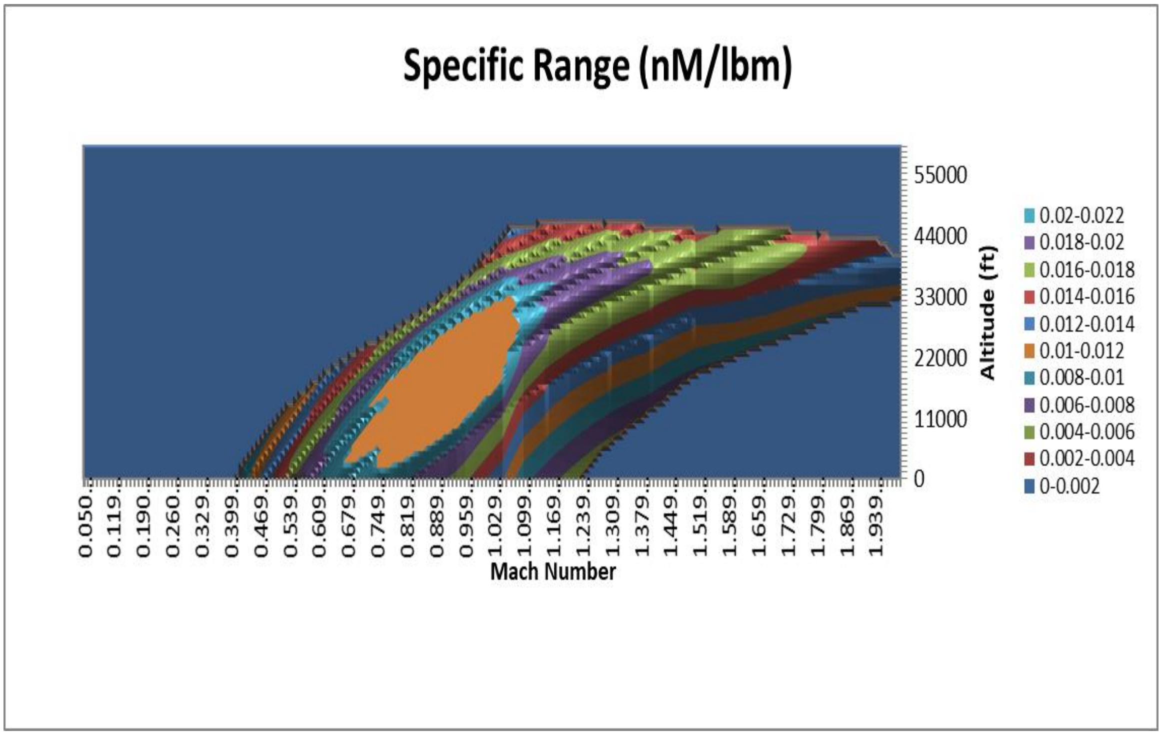

Figure 66. Specific Range Skymap of BPR 5.0 with ESF of 45

For the TSFC efficient BPR 6.0 engine, the initial tests demonstrated that the Concorde was able to achieve a decent range of high supersonic flight conditions with an ESF value of 55, so the analysis would be performed with the ESF values of 55, 60, and 50.

The Specific Range Skymap of the BPR 6.0 engine with an engine scale factor of 55 is presented in Figure 67. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0166 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0122 nM/lbm at an altitude of 40,000 ft which means it is less efficient to fly at this speed. Examining the performance

of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0144 nM/lbm at an altitude of 42,000 ft. The maximum thrust was found to be 550,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.375.

The Specific Range Skymap of the BPR 6.0 engine with an engine scale factor of 60 is presented in Figure 68. At supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0166 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the maximum SR the aircraft can achieve at this speed is 0.0134 nM/lbm at an altitude of 44,000 ft which means it is less efficient to fly at this speed. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8 the aircraft has a maximum SR of 0.0144 nM/lbm at an altitude of 42,000 ft. The maximum thrust was found to be 600,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.50. It should be noted that the figure shows that the aircraft is unable to function at the flight conditions of Mach 0.46 to 0.67 and altitudes 0 ft to 3000 ft.

The Specific Range Skymap of the BPR 6.0 engine with an engine scale factor of 50 is presented in Figure 69. At higher supersonic speeds, the Concorde with this engine setup was able to reach a maximum SR value of 0.0166 nM/lbm at a speed of Mach 1.6 and an altitude of 43,000 ft. While this engine setup can reach a speed of Mach 2.0, the aircraft can only achieve this speed at an altitude of 37,000 ft with an SR value of 0.0116 nM/lbm which makes using this engine setup at this speed rather unviable. Examining the performance of the aircraft between the speeds of Mach 1.6 and Mach 2.0, at Mach 1.8

the aircraft has a maximum SR of 0.0144 nM/lbm at an altitude of 42,000 ft. The maximum thrust was found to be 500,000 lbf at static thrust which equates to a maximum thrust-weight ratio of 1.250.

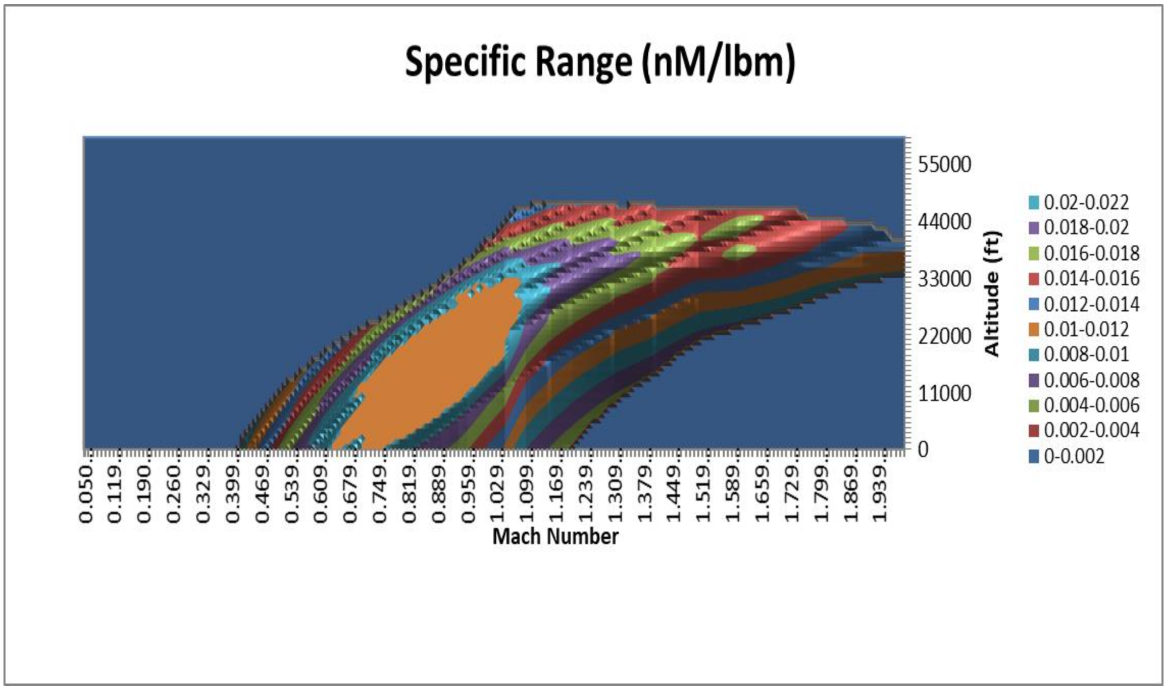

Figure 67. Specific Range Skymap of BPR 6.0 with ESF of 55

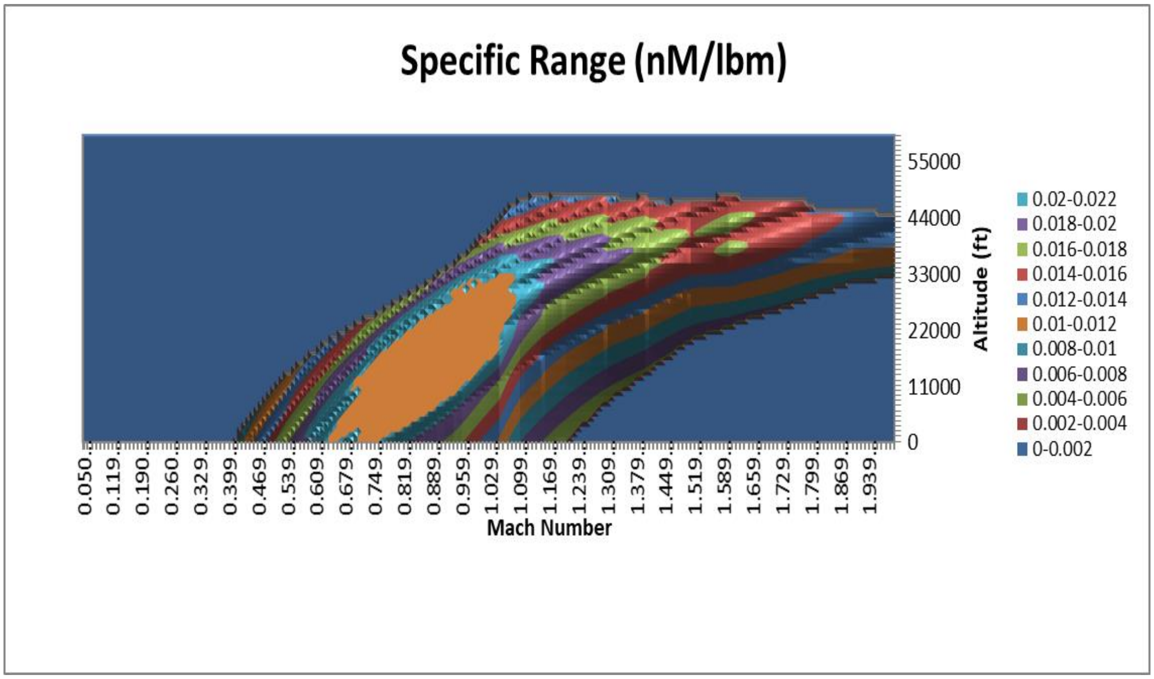

Figure 68. Specific Range Skymap of BPR 6.0 with ESF of 60

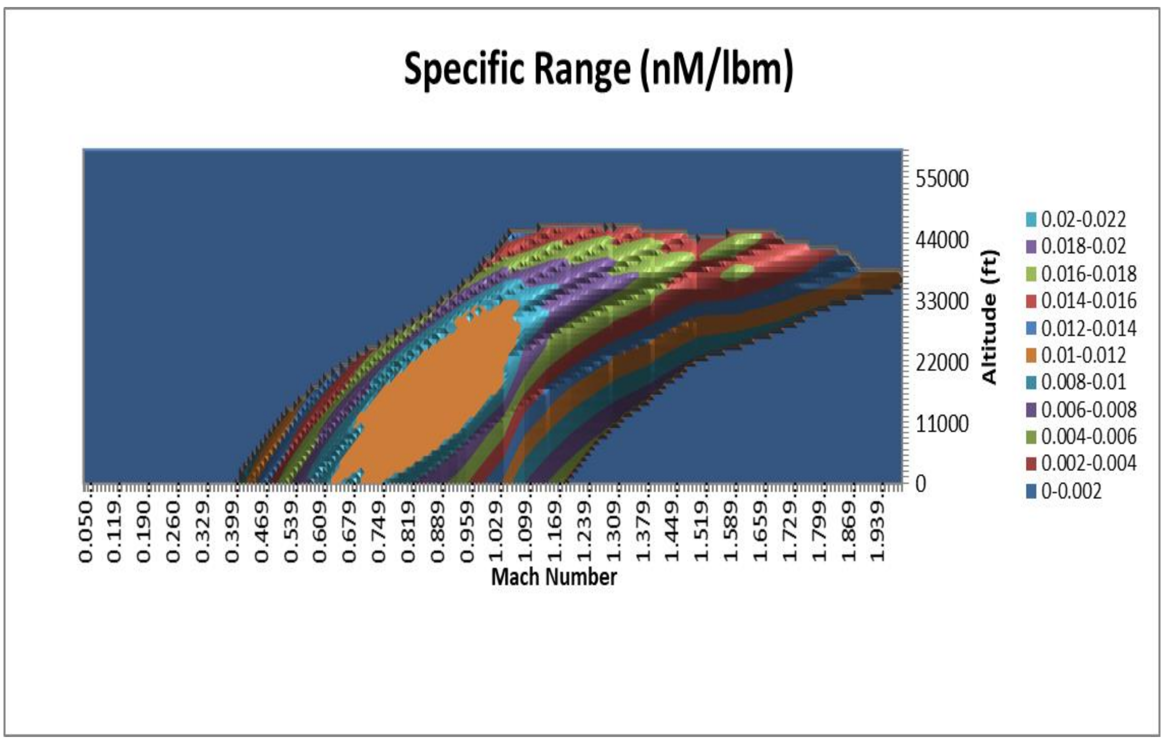

Figure 69. Specific Range Skymap of BPR 6.0 with ESF of 50

With the figures and data values presented for each BPR engine tested at three different ESF values, several different consistent results become apparent that define the effectiveness of these turbofan engines.

One common consistency with the different BPR engines is all the figures show that no matter the ESF value that is used, the Concorde with every tested engine setup is unable to operate above an altitude of 50,000 ft. The Concorde using its normal turbojet engines could reach an altitude ceiling of 60,000 ft which indicates a decline of altitude range performance for these turbofan engines.

Another consistency is besides the BPR 2.0 engine, all the engine setups achieve their maximum SR value at a speed of Mach 1.6 and an altitude of 43,000 ft. It is also apparent that none of the engine setups were able to achieve maximum SR values above 0.018 nM/lbm in the high supersonic regime. This indicates that none of the turbofan engines were able to match the SR performance of the Concorde's turbojet engines which could achieve an SR of 0.02 nM/lbm at a speed of Mach 2.02 and an altitude of 60,000 ft. The only one that comes close to that performance is the BPR 2.0 engine which has its maximum high-speed SR value at Mach 2.0, but that maximum SR value is only 0.0162 and that is not even the largest high-speed SR achieved from the various engine setups.

Another consistency that should be noted is for just about every tested ESF value with each BPR engine, the maximum SR value is almost always the same value at the same speed and altitude. This indicates that for the most part, increasing the ESF value does not yield better SR performance at the same flight conditions. It seems that increasing ESF only increases the amount of specific flight conditions that aircraft is able to fly at, but this increase to the aircraft's speed and altitude range seems to rarely lead to better SR performance at these new operable flight conditions. It is possible that larger ESF values than the ones used for each BPR engine might be needed to increase the flight range enough to find better high-speed SR performance, but the initial ESF values are already pretty substantial.

It is also important to note that just about every skymap figure shows that SR performance values of between 0.018 to 0.020 nM/lbm and even between 0.020 to 0.022 nM/lbm could be achieved at low supersonic regimes up to about Mach 1.4. This indicates that these turbofan engines would operate with much better fuel consumption performance if they flew at low supersonic speeds compared to flying at higher supersonic speeds above Mach 1.5. The reason these low supersonic regimes were not observed and recorded as thoroughly as the high supersonic regimes is it is desired to see how well each engine can perform at high supersonic speeds in order to compare them to the Concorde's Mach 2.0 capabilities.

From the recorded data it is apparent that as the BPR of the turbofan increases, the worse the SR performance becomes at similar high supersonic speeds. This indicates that even though the engines with larger BPR values have better TSFC efficiency, it is not enough to overcome the drag that occurs so it more important for the engine to have good thrust capabilities. It could possibly be argued that increasing ESF leads to worse SR performance since the BPR 3.0 and BPR 4.0 tests share the same ESF values and the BPR 4.0 engine had better SR performance at the same speeds as the BPR 3.0 engine. Though to it seems more likely that the BPR 3.0 engine is just not as thrust and/or TSFC efficient as the BPR 4.0 engine since the BPR 5.0 and BPR 6.0 test show a trend of decreasing SR performance with increase BPR even when ESF values are shared.

The data of each engine setup also shows that as the BPR value of each engine increases, the more thrust is needed for the Concorde to operate at a larger range of flight conditions. This increase to thrust gets to a point where the BPR 6.0 engine can only obtain a decent range of supersonic flight conditions when its maximum thrust is above 500,000 lbf which leads to a thrust-to-weight ratio greater than 1.250. When compared to the maximum thrust of 152,200 lbf and thrust-to-weight ratio of 0.373 for the Concorde with its turbojet engines, all the turbofan engines that were tested require much more thrust and therefore a larger thrust-to-weight ratio in order for the Concorde to fly at Mach 2.0 conditions. The closest one of the engines get to matching the thrust performance of the Concorde's turbojet engines is the BPR 2.0 engine with an ESF of 30 with a maximum thrust of 300,000 lbf and maximum thrust-to-weight ratio of 0.750, but this is still a 97% difference in thrust and this engine setup can only achieve a maximum SR of 0.0152 nM/lbm at Mach 2.0. With these results it is quite clear that while all these turbofan engines can allow for the Concorde to fly in the high supersonic regime, their performance with SR, thrust, speed, and altitude are neither better or even equal to that of the performance the Concorde could achieve with its own turbojet engines.

CONCLUSIONS

To conclude, the data obtained and analysis performed from this research project yielded very interesting results that granted partial achievement of the initial goal of creating high bypass turbofan engines that could effectively operate with supersonic airliners. The process of matching an external compression inlet with raw turbofan engine performance data proved to be successful. A range of high bypass turbofan engines from BPR 2.0 to 6.0 were able to be created that retained effective thrust and TSFC efficiency after inlet matching, which made them viable for supersonic flight usage. When it came to actually applying these high BPR turbofan engines with the Concorde aerodynamic data in the point performance tool, it turns out that the Concorde can operate with these engines but not as effectively as was hoped for. All of these engines required substantial amounts of thrust in order to operate at Mach 2.0 flight conditions and were still unable to achieve as good of aircraft performance as the Concorde with its turbojet engines operating at much less thrust. The engine setup with the best SR performance at Mach 2.0 was the BPR 2.0 engine with an ESF of 35 but was only able to achieve a maximum SR value of 0.0162 nM/lbm even with a maximum thrust of 350,000 lbf. Since there are many variables that come into play when it comes to testing propulsion and aircraft performance, one could speculate several different possibilities as to why these high bypass turbofan engines are unable to perform viably with the Concorde.

One such possibility is that these high bypass ratio turbofan engines may not be suitable for usage with large-scale commercial airliners. Initial testing of a few of these engines in Skymaps were performed with an aircraft weight of 300,000 lbm and there were definite differences in the SR performance of the Concorde when compared to those obtained with an aircraft weight of 400,000 lbm. Further analysis of various aircraft weights could demonstrate that these engines may be able to perform effectively with airliners of smaller sizes or even ones of normal commercial sizes but with much smaller passenger capacity. It is not uncommon for aircraft to exist that are large enough to hold over a hundred seats but are designed to only have around 30 to 40 seats to function as a large-scale business class only jet airliner.

Another possibility is that these high bypass turbofan engines may not be meant for cruising at speeds of Mach 2.0 with larger aircraft. The data from the Skymaps trade study showed that most of the time the engines had their best high supersonic SR performance when the speed was Mach 1.6. The data also showed that even better SR performance could be achieved when the speed was around and below Mach 1.4. This may indicate that while speeds of Mach 2.0 are possible for these engines, the loss in SR performance and need for greater thrust performance to achieve these flight conditions is too substantial to fly an airliner at such high speeds. It would not be unreasonable to create supersonic airliners that had a maximum speed between Mach 1.4 and 1.6, this is around twice the speed a normal commercial airliner could reach.

It is also possible that the inlet used in the inlet matching process may not have been the best possible one to use for high bypass turbofan engines that are desired to reach speeds of Mach 2.0. The PIPSI Volumes provided the inlet performance of 18 different inlet designs and while about half of them are meant for engines flying at speeds above Mach 3.0 or below Mach 1.0, there are about five other provided inlets that could possibly be used with engines that have a maximum speed of Mach 2.0. These other usable inlets are also external compression inlets that function off the same principles as initially discussed, with two of these inlets being axisymmetric external compression designs just like the one used in the inlet matching tool and the other three being twodimensional external compression designs. With more time, one could integrate the inlet performance of some or all five of these other external compression inlets into the inlet matching tool to find the inlet that allows for the best possible thrust and TSFC performance of the turbofan engines.

Another possibility is the turbofan engines that were used in the Skymaps trade study need more tinkering with their design parameters to yield better thrust and TSFC performance at each set BPR value. As stated previously the TSFC efficient engines that were developed in the third engine trade study are not as efficient as they could possibly be since every engine parameter affects the others when they are changed, and it would be incredibly time consuming to find the perfect BPR engine design with just manual adjusting. Not much analysis was performed on how changing the TIT or OPR parameters affected performance as inlet matching is affected mostly by changing the fan of the engine and not the core of the engine. Also, the Skymaps trade study seemed to show that engines with better thrust performance allowed for better SR performance and a wider range of flight conditions compared to engines with better TSFC performance. With more time, one could perform trade studies to see how much focus should be put on TIT and OPR adjustments for better thrust and TSFC performance as well as design the set BPR engines with thrust performance as priority instead of TSFC to compare the Skymap performance of the two groups of engines.

It is also possible that afterburners may be necessary for these turbofan engines to allow the aircraft to function at a wider range of flight conditions. As previously stated, it was decided that the engines used in trade study of this project would be ran without afterburner settings as the preliminary testing demonstrated that the afterburner generated too much thrust. It was also desired to see how well the engines would function without afterburners and gauge whether they are needed for optimal thrust performance. The Skymaps trade study shows that every tested engine required very large ESF values to scale the thrust to substantial amounts in order for the Concorde to function at Mach 2.0 flight conditions. This may indicate that afterburners may be needed for the engines in order to avoid the issue of scaling the engines to the point of a 1:1 thrust-to-weight ratio. It should be noted that afterburners do not generally help with SR or TSFC performance, their main contribution to the issues of these engines would be thrust performance and flight condition range.

The last notable possibility is that the Concorde may not be the best aircraft to use with these high bypass turbofan engines. While one of the only supersonic airliners to have a successful flight history, it is still an aircraft that was designed over 50 years ago and was in use for less than three decades. The turbojet engines the Concorde uses were also specifically built for the Concorde so its possible one cannot simply use a different supersonic engine with it, especially one of different properties like a turbofan engine. If one took the time to design a clean sheet supersonic airliner with modern day programming tools, one may find a design that could run effectively with high bypass turbofan engines.

Taking all of these speculations into consideration, it is easy to see that while the results of this project did not achieve everything that was hoped for, it is definitely not the end of the road. An important achievement of the project was proof that high bypass turbofan engines can be built with external compression inlets and have effective and viable supersonic performance. Knowing that the development of these engines is possible, the next big step in creating turbofan engines that are viable for supersonic airliners is to put the time and resources into understanding which properties of propulsion and aerodynamic performance limit the effectiveness of aircraft using these engines.

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APPENDIX A

NPSS INPUT AND OUTPUT FILES

[Consult Attached Files]

Text editor computer program such as Microsoft Notepad is required to view files.

APPENDIX B

EDET INPUT AND OUTPUT FILES

[Consult Attached Files]

Text editor computer program such as Microsoft Notepad is required to view files.

APPENDIX C

FIVE COLUMN PROPULSION DATA

[Consult Attached Files]

Text editor computer program such as Microsoft Notepad is required to view files.