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A Review of Boundary Layer Ingestion Modeling Approaches for use in Conceptual Design

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Abstract

The concept of boundary layer ingestion (BLI) has been proposed by NASA researchers and other groups for improving the performance of a number of future aircraft concepts. These future aircraft concepts include the STARC-ABL, D8 and N-3X among other examples. While BLI technology appears to be promising for improving the aircraft performance by reducing fuel burn, the benefits and challenges of using this technology are not well understood. As a result, there are a number of efforts ongoing within NASA which are attempting to model BLI and determine its overall benefit. Despite their common goal, there seems to be significant differences in the modeling approaches used in each effort, with limited communication and collaboration between these groups. The purpose of this report is to document NASA's in-house BLI modeling efforts and their associated methodologies. Furthermore, the report will identify strengths and weaknesses of each methodology, specifically in regards to each method's application in conceptual design.

Contents

Nomenclature

a	Speed of sound
D	Drag
f	Fraction of a quantity captured
F_n	Net force
K_{inlet}	Shear layer kinetic energy defect
$\dot{m}$	Mass flow rate
n_{eng}	Number of engines
$\hat{n}$	Unit normal vector
p	Static pressure
P	Power
P_K	Kinetic energy inflow rate or mechanical flow power
P_S	Shaft power
P_V	Volumetric power
Pr	Prandtl number
$PFEI$	Payload fuel energy intensity
PSC	Power saving coefficient
R	Aircraft range
S	Control volume surface
T	Thrust
V	Velocity
W	Weight
$\boldsymbol{V}$	Velocity vector
$\dot{\varepsilon}$	Energy outflow rate
ρ	Fluid density
$\bar{\bar{\tau}}$	Viscous stress tensor
Φ	Dissipation rate
γ	Ratio of specific heats
Subscripts	
air	Quantity of the air passing through the propulsion system
B	Quantity at the body surface
BLI	Quantity of a BLI configuration
E	Quantity at the engine surface
$exit$	Quantity at the propulsion system exit
$fuse$	Quantity of the fuselage
$fuel$	Quantity of fuel injected into the propulsion system
$inlet$	Quantity at the propulsion system inlet
$nonBLI$	Quantity of a non-BLI configuration
p	Quantity of the vehicle profile
O	Quantity at the outer control volume surface
$payload$	Quantity of the aircraft payload
S	Quantity at the solid body surface
t	Total condition
$wake$	Quantity of the wake
∞	Quantity at the freestream condition

1 Introduction

For the first 70 years of powered flight, the focus of most aeronautics research was to develop aircraft, and by extension their supporting subsystem technologies, that could travel higher, faster and farther. This research focus shifted in the 1970s, however, following several fuel crises to one centered on fuel economy as well as reductions in aircraft emissions and noise. [1] The focus on fuel efficiency has continued into the 21st century and is a prominent element of the NASA Aeronautics Research Mission Directorate's six strategic thrusts. [2]

Over the years, research efforts to improve aircraft fuel efficiency have often focused on technologies that are applicable to a single subsystem or discipline. These technologies include advanced engines to improve propulsive efficiency, winglets to reduce induced drag and composite materials to reduce the aircraft's weight. While improvements can continue to be made for each aircraft subsystem or discipline, there is increased interest in studying technologies that cut across disciplines as these technologies may provide a larger overall system benefit.

One such technology is boundary layer ingestion (BLI), which aims to better integrate the vehicle's propulsion system with the rest of vehicle. This integration places the engine or propulsor near the fuselage allowing it to ingest and energize the boundary layer air, thereby taking advantage of synergies between the aerodynamics and propulsion system performance. As a result of its potential benefits to the overall vehicle performance, the technology has been included on a number of relatively recent advanced concept aircraft. These proposed vehicle concepts include the STARC-ABL [3], D8 [4–6] and N-3X [7], among others.

To determine the conceptual design of these vehicles and quantify the potential benefits of BLI, NASA researchers have used a number of different modeling approaches. Each of these modeling approaches is unique in how the vehicle aerodynamics, propulsion system and interaction (or lack thereof) between those two disciplines are captured. The purpose of this report is to identify the various BLI modeling efforts ongoing within NASA (in the conceptual/preliminary design phase) and summarize the modeling approaches developed by researchers. Based on this review of modeling approaches, recommendations for best practices to be used in future conceptual design efforts for BLI concept vehicles will also be provided.

The remainder of this document is divided into three main sections. First, Section 2 will give a brief overview of BLI theory that will be helpful in understanding the modeling approaches. Following this overview, Section 3 will summarize the modeling approaches which are being used by different research groups at NASA. Finally, Section 4 will provide recommendations on the use of these modeling approaches for future conceptual design studies of BLI vehicles.

2 Boundary Layer Ingestion Overview and Theory

The concept of boundary layer ingestion seeks to design an aircraft to take advantage of synergistic effects between the vehicle's aerodynamics and propulsion system. This is done by passing the boundary layer generated by the vehicle surface through the propulsion system with the goal of improving the vehicle's overall fuel efficiency. [8] By ingesting the vehicle surface boundary layer into the engine, there are a number of changes produced in the aircraft aerodynamic and propulsion system performance. According to Hall [9], the five major changes produced by BLI, in rough order of importance, are:

1. An increase in the propulsive efficiency of the engine which is defined in Equation 1 below. Placing the engine(s) such that they ingest the boundary layer reduces the flow velocity entering the inlet which also reduces the velocity needed at the nozzle exit to produce the same thrust. [8]
2. A decrease in nacelle and pylon drag for some vehicle concepts. Closely integrating the propulsion system with the airframe is expected to reduce the total wetted area and its associated losses.
3. A decrease in wake mixing losses due to ingesting fuselage wake and filling in the wake with the propulsor exit flow. [10]
4. A reduction in propulsion system efficiency due to lower inlet total pressure recovery and lower fan efficiency due to inlet distortion.
5. Changes in airframe performance (drag) as a result of the interaction between the propulsion system and vehicle aerodynamics. For example, the presence of the propulsion system may provide suction that changes the flow characteristics around the fuselage.

$$\eta_p = \frac{TV_\infty}{[(\dot{m}_{air} + \dot{m}_{fuel})V_{exit}^2 - \dot{m}_{air}V_{inlet}^2]/2} \tag{1}$$

As can be seen by this list, the changes produced by employing BLI on an aircraft are significant and effect a large portion of the vehicle design. Capturing and quantifying all of these changes to the aircraft aerodynamics, propulsion system performance and overall vehicle design is a challenging task. This challenging design environment is why Rodriguez stated "the concept has not been successfully applied to a commercial aircraft design because of the high risk and limited design capabilities in this field." [11]

While there has not been a successful commercial aircraft design utilizing BLI, the potential benefits are substantial enough that numerous groups inside and outside of NASA are investigating designs using this technology. These groups have studied a variety of different BLI aircraft concepts including the D8 [9,12], STARC-ABL [3], N+3 BWB [10], SAX40 [8], N2A-EXTE BWB [13] and NOVA [14] vehicles. From these studies, predicted benefits of BLI technology have ranged anywhere from 4% to 18% benefit. This large spread in the predicted performance benefits of BLI as a technology is partly a function of the wide range of BLI vehicle concepts being studied. However, there are a number of other questions that must be considered when reviewing the analysis process and the predicted performance benefit:

1. What metric was used to quantify the benefit?
2. What is the technology level of the non-BLI baseline vehicle used in the comparison?
3. What was the mission flown by the vehicle?
4. What other assumptions were made during the analysis?

Clarifying the answers to these questions is important to understanding the potential benefits of specific BLI vehicle concepts as well as BLI as a broader technology for improving vehicle performance.

Before reviewing the modeling efforts that have looked at determining the potential benefits for the NASA studied concepts, the remainder of the section will briefly review several concepts that will be helpful in understanding the modeling efforts. The first two subsections examine two fundamental physical principles and how they are used to analyze aircraft. The first physical principle is the conservation of momentum which is used to examine the forces on an aircraft. The second principle is the conservation of energy which is used to examine the energy in the flow around a vehicle. Following these brief overviews, the last part of this section will discuss metrics used to quantify the benefit of BLI concepts.

2.1 Conservation of Momentum

The first fundamental principle for the analysis of aircraft concepts reviewed in this section is the conservation of momentum. This concept comes from Newton's Laws and is a common approach for analyzing aircraft performance. As a result, this approach will not be covered in extensive detail but will be briefly described with an emphasis on its use for BLI aircraft analysis.

Applying the conservation of momentum allows for the forces to be computed on an aircraft. As a reference for this discussion, Figure 1 shows an example of a simple aircraft in flight. The aerodynamic and propulsive forces on this notional vehicle are present on the aircraft surface identified by the dashed line in the figure. To determine the net force (F_n) on this simple aircraft model, the pressure, shear stress and momentum forces must be integrated over the entire vehicle surface ($\mathcal{S}_B$) as described by Equation 2.

$$F_n = \oiint (p\hat{n} - \bar{\bar{\tau}} \cdot \hat{n} + \boldsymbol{V}\rho\boldsymbol{V} \cdot \hat{n}) \mathrm{d}\mathcal{S}_B \tag{2}$$

For an aircraft in steady, level flight, the net force in the vertical and streamwise directions on the vehicle must be zero. More simply, this means that the aerodynamic lift must equal the weight (in the vertical direction) and the aerodynamic drag must equal the thrust produced by the propulsion system (in the streamwise direction). Therefore, Equation 2 is often decomposed into more common components which can be defined by the individual surfaces over which the integration is

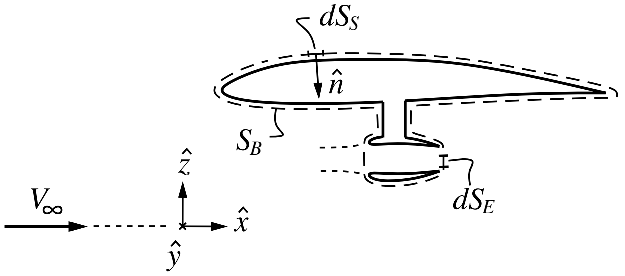

Figure 1. Simple aircraft with dashed lines indicating force integration surfaces (Adapted from [15]).

taken and in relation to the direction of freestream velocity ($\hat{x}$). For example, the drag of the vehicle can be defined as the integral of the pressure and shear stress forces over the solid surfaces of the vehicle in the streamwise direction as described by Equation 3. Similarly, the thrust produced by the propulsion system can be defined as the integral of the pressure and momentum forces over the engine inlet and nozzle exhaust surfaces, also in the streamwise direction, using Equation 4.

$$D = \left[\oiint (p\hat{n} - \bar{\bar{\tau}} \cdot \hat{n})\, \mathrm{d}\mathcal{S}_S \right] \cdot \hat{x} \tag{3}$$

$$T = \left[\oiint (p\hat{n} + \boldsymbol{V}\rho\boldsymbol{V} \cdot \hat{n})\, \mathrm{d}\mathcal{S}_E \right] \cdot \hat{x} \tag{4}$$

Equations 3 and 4 presented here are a logical decomposition of the forces on the overall vehicle. However, it should be noted that these definitions of drag and thrust are not the only possible definitions. For example, a researcher may choose to include some portions of the fuselage surface such as the engine nacelle as part of the thrust rather than as part of the drag. It should also be noted that in some cases, the surface over which the integrals are taken may be moved off the aircraft body to facilitate analysis. This is typically the case at the engine inlet where the surface will be moved upstream such that it lies in the freestream flow. The flexibility in the definition of drag and thrust can be valuable as it allows for selecting an appropriate definition for a particular aircraft configuration. However, it presents a challenge as the definitions of each term must be agreed upon by researchers working on the aerodynamics and propulsion system analyses.

Decomposing the net force into specific surfaces for drag and thrust allows for a relatively easy analysis of most conventional aircraft configurations. As stated by Ochs, "normal propulsion bookkeeping accounting for ram drag, inlet pressure recovery, cycle efficiency, and thrust production can adequately describe the propulsion system performance. Aircraft performance is well described with the typical parameters of weight, airframe drag, nacelle drag, and interference drag associated with the propulsion system installation." [13] Therefore, with this decomposition relatively simple empirical models can be used to quantify the thrust and drag of a conventional aircraft.

However, for BLI aircraft the use of the conservation of momentum through these drag and thrust definitions becomes more difficult. One issue is that "this decomposition is often ambiguous for aircraft whose propulsion system is closely integrated with the airframe." [9, 15] For these aircraft concepts, it is often more difficult to define which portions of the vehicle contribute to drag and which portions are measured as thrust. Furthermore, because of the tight integration of the propulsion system and airframe the traditional tools described by Ochs are not capable of properly capturing the coupled performance changes. For example, often the propulsion system model is not setup to handle non-uniform inflow that is present in the boundary layer. Similarly for the vehicle aerodynamics, the traditional empirical tools for prediction do not properly predict the changes to the boundary layer imparted by the suction of the propulsion system inlet.

As a result of these two issues, it is often difficult to apply the traditional design and analysis tools when analyzing BLI concepts. The overall analysis approach is still valid however and can be used as long as proper rigor is applied in creating the model and analyzing the results. The definitions proposed above can help facilitate this thrust-drag accounting but need to be agreed upon by all parties involved in the analysis. Also, the limitations of the traditional empirical tools need to be understood and will likely necessitate the use of higher-order, more physics-based models.

2.2 Conservation of Energy

The second fundamental principle that is used to analyze aircraft is the conservation of energy. This principle is less commonly used in studies of conventional aircraft as the conservation of momentum approach is more intuitive. However, for BLI aircraft examining the flow around the vehicle in terms of the conservation of energy can simplify the analysis. Because applying the conservation of energy is less common, this topic will be examined in more depth in this section.

The approach of using the conservation of energy to analyze aircraft performance is commonly attributed to Mark Drela [15] of MIT and some of his students. [9, 10] The formulation presented here is based on the power balance method proposed by Drela [15] with some minor changes as noted. Figure 2 from Drela shows the control volume and surfaces around a notional vehicle that will be helpful for this discussion.

The conservation of energy or power balance method starts by defining the kinetic energy of a flow in divergence form as shown in Equation 5.

$$\nabla \cdot (\rho \boldsymbol{V} \frac{1}{2} \boldsymbol{V} \cdot \boldsymbol{V}) = -\nabla p \cdot \boldsymbol{V} + (\nabla \cdot \bar{\bar{\tau}}) \cdot \boldsymbol{V} \tag{5}$$

Next, the right hand side of this equation is expanded by applying several general vector identities which gives Equation 6.

$$\nabla \cdot (\rho \boldsymbol{V} \frac{1}{2} \boldsymbol{V} \cdot \boldsymbol{V}) = -\nabla \cdot (p \boldsymbol{V}) + p \nabla \cdot \boldsymbol{V} + \nabla \cdot (\bar{\bar{\tau}} \cdot \boldsymbol{V}) - (\bar{\bar{\tau}} \cdot \nabla) \cdot \boldsymbol{V} \tag{6}$$

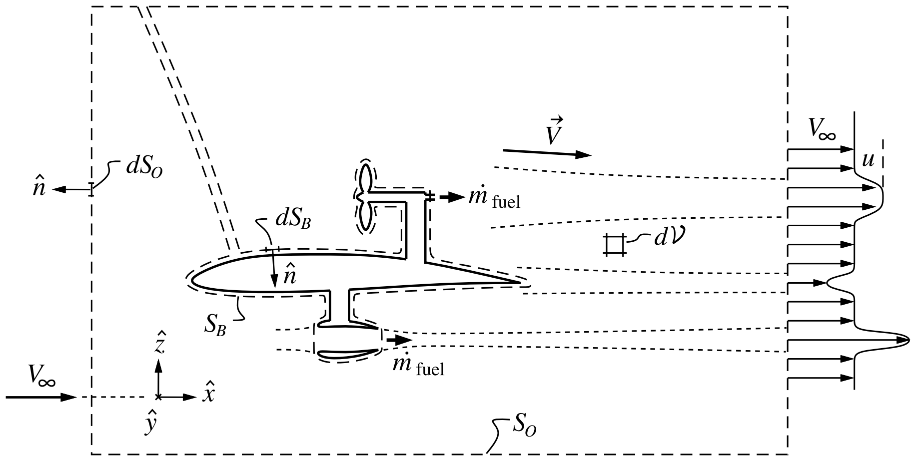

Figure 2. Control volume and surface definitions for the power balance method (Adapted from [15]).

Equation 6 specifies the kinetic energy at any point in the flow. In order to determine the total power in an aerodynamic flow, this equation is then integrated over the entire control volume ($\mathcal{V}$) as shown in Equation 7.

$$\iiint \nabla \cdot (\rho \boldsymbol{V} \frac{1}{2} \boldsymbol{V} \cdot \boldsymbol{V}) \mathrm{d}\mathcal{V} = \iiint -\nabla \cdot (p\boldsymbol{V}) + p\nabla \cdot \boldsymbol{V} + \nabla \cdot (\bar{\bar{\tau}} \cdot \boldsymbol{V}) - (\bar{\bar{\tau}} \cdot \nabla) \cdot \boldsymbol{V} \mathrm{d}\mathcal{V} \quad (7)$$

This equation is fairly complex and is unwieldy to use and understand in its full complete form. Therefore, Drela proposes grouping the terms into 5 macro-terms based on their physical meaning. The resulting conservation of energy or power balance with these 5 macro-terms is Equation 8.

$$P_S + P_V + P_K = \dot{\varepsilon} + \Phi \quad (8)$$

The definitions for each of the macro-terms are given below. Two things should be noted when looking at these definitions. For several of the macro-terms, Gauss's Theorem has been applied to convert the volume integral to a surface integral. In Drela's formulation, this surface is either on the body of the vehicle ($\mathcal{S}_B$) or on the outside edge of the control volume ($\mathcal{S}_O$). Second, it should be noted that the definitions below differ slightly from those presented by Drela [15] as the substitutions $p \to p - p_\infty$ and $V^2 \to V^2 - V_\infty^2$ have not been made.

The three terms on the left side of Equation 8 are sources of energy that applied to the flow. The first macro-term in Equation 8 is the net propulsor shaft power given by Equation 9. This term is used to capture the energy change due to pressure and shear stress on moving portions of the vehicle surface. For example, the control volume surface could be drawn on the blades of a propeller which are moving inside the volume. On portions of the body control volume surface that are not moving, this term will be zero. [10]

$$P_S = \oiint [-p\boldsymbol{V} + \bar{\bar{\tau}} \cdot \boldsymbol{V}] \cdot \hat{n} \, \mathrm{d}\mathcal{S}_B \tag{9}$$

The second macro-term is the net pressure-volume power present in the flow and is defined in Equation 10. This term is only present when heat is added within the control volume. [10] As an example, the control volume could be drawn such that it includes the propulsion systems combustor.

$$P_V = \iiint p \nabla \cdot \boldsymbol{V} \, \mathrm{d}\mathcal{V} \tag{10}$$

The last energy source macro-term on the left side of the equation is the net kinetic energy flow rate into the control volume. The term is defined by Equation 11. This term accounts for flow leaving and entering the control volume as would be the case when the propulsor is modeled outside the control volume.

$$P_K = \oiint -[p\boldsymbol{V} + \frac{1}{2}\boldsymbol{V}\rho\boldsymbol{V} \cdot \boldsymbol{V}] \cdot \hat{n} \, \mathrm{d}\mathcal{S}_B \tag{11}$$

The right hand side of Equation 8 contains two macro-terms that represent the energy leaving the control volume or dissipated inside the volume. The first term is the kinetic energy leaving the control volume and is defined by Equation 12. This equation is further decomposed by Drela to isolate terms for the change in potential energy, streamwise wake kinetic energy, transverse wake kinetic energy, the wake pressure-defect work rate and wave pressure-work and kinetic energy outflow rate. Readers are referred to Drela's paper [15] for a complete description of these specific terms.

$$\dot{\varepsilon} = \oiint [\frac{1}{2}\boldsymbol{V}\rho\boldsymbol{V} \cdot \boldsymbol{V} + p\boldsymbol{V}] \cdot \hat{n} \, \mathrm{d}\mathcal{S}_O \tag{12}$$

The last term in the power balance equation is the viscous dissipation rate inside the control volume. This dissipation rate is defined in Equation 13 and captures the conversion of kinetic energy to heat inside the control volume. Again, Drela further decomposes this dissipation macro-term to smaller sources such as the trailing vortex, propulsor jet, propulsor blading, shock waves, shear layers and wakes. Readers are referred to Drela's paper [15] for a complete description of these specific terms.

$$\Phi = \iiint (\bar{\bar{\tau}} \cdot \nabla) \cdot \boldsymbol{V} \mathrm{d}\mathcal{V} \tag{13}$$

While the equations presented are more complex than the conservation of momentum equations in the previous section, it is suggested that use of this power balance formulation simplifies the overall analysis of BLI concepts. First, using energy-based equations eliminates the need to compute thrust and drag. This is beneficial as the concept of thrust and drag equations for BLI aircraft is not clearly defined and computing their values are made more difficult by the coupled nature of the problem. In the energy-based approach, the analysis of the BLI aircraft uses a different set of terms that are more clearly defined by specific physical phenomena. One of the primary benefits of this approach stated by Hall, is that "dissipation, unlike forces on the airframe and propulsor, is insensitive to propulsor-airframe interference effects." [9] Therefore, if models can be defined that capture these more fundamental physics such as dissipation, the overall analysis process can be simplified.

2.3 Boundary Layer Ingestion Performance Metrics

Quantifying the benefit of BLI on the overall vehicle's performance characteristics can be a challenging endeavor. This challenge is partly due to the complex, multidisciplinary nature of the analysis required in order to assess the performance. Furthermore, the metrics used to quantify the performance of conventional aircraft are often inadequate for BLI concepts. As stated by Plas, "conventional parameters such as specific fuel consumption and propulsive efficiency are not the most useful metrics when boundary layer ingestion is involved." [8] For example, a BLI aircraft may have a higher specific fuel consumption than a conventional vehicle. But because the overall thrust required by a BLI aircraft is lower than a comparable conventional design, the overall fuel consumption of the vehicle may be lower.

As a result of issues like these, Plas [8] and many other researchers recommend using a different metric which was proposed by Smith. [16] This metrics is called the power saving coefficient (PSC) and is defined in Equation 14.

$$PSC = \frac{P_{nonBLI} - P_{BLI}}{P_{nonBLI}} \tag{14}$$

The PSC equation compares the power required by a BLI aircraft with that required by a non-BLI aircraft for the same net axial force to determine an overall benefit. "The use of PSC is relevant because, for constant fan efficiency, the power requirement is directly related to fuel burn. Any BLI design must have a positive PSC to be a worthwhile alternative to a (best) non-BLI configuration." [8] While there seems to be general agreement on the use of PSC as a valuable metric, there may be some slight differences in how it is computed. In this equation, the power values used for the non-BLI and BLI configurations can be drawn from several different definitions. One option is to define the power in the PSC equation as the propulsive power produced by the engine given in Equation 15.

$$P = \frac{\dot{m}_{air} + \dot{m}_{fuel}}{2} V_{exit}^2 - \frac{\dot{m}_{air}}{2} V_{inlet}^2 \tag{15}$$

Alternatively, the power in this equation could be taken directly from the shaft used to drive the propulsor fans. These definitions are both equally valid and primarily only differ in terms of inclusion of the fan efficiency in the power definition. As a result, either definition can be used when analyzing a BLI concept but the precise definition should be noted when documenting the results.

In addition to PSC, two other metrics are commonly cited when quantifying the benefit of a BLI aircraft in comparison to a conventional design. The first metric is simply the overall mission or block fuel required for a given mission. This metric is very similar to the PSC and measuring the overall benefit observed by the entire aircraft. An alternative to the simple mission or block fuel proposed by Sato [10] is the Payload Fuel Energy Intensity (PFEI) which is defined in Equation 16.

$$PFEI = \frac{W_{fuel} h_{fuel}}{W_{payload} R} \tag{16}$$

In this equation, W_f is the fuel weight, h_f is the fuel heating value, W_p is the payload weight and R is the aircraft range.

Lastly, the propulsive efficiency (Equation 1) is sometimes used to quantify the BLI benefit. While the improvement in propulsive efficiency is a major impact of BLI, using this as the predominant metric for assessing BLI is not advised. As noted previously, BLI improves not only the propulsion system performance but also significant aspects of the vehicles aerodynamics. Therefore, using propulsive efficiency to quantify the system level benefit omits these other sources of performance improvement or degradation.

3 Boundary Layer Ingestion Modeling Approaches

As mentioned in Section 1, a number of advanced concept vehicles have proposed using BLI to improve the overall aircraft efficiency. To determine the design and estimate the performance characteristics of these vehicles, a number of modeling approaches have been implemented by NASA researchers. These modeling approaches can be organized by classifying them based on two key characteristics.

The first characteristic is the degree of coupling between the vehicle aerodynamic and propulsion system models. This characteristic is extremely important as BLI technology seeks to exploit the interaction between those two disciplines to achieve an overall system benefit. As stated by Rodriguez, "Even these modern design methods ultimately fail because they treat aerodynamics and propulsion as separate disciplinary problems and do not truly address the tight coupling between these systems on this aircraft configuration." [11] From all the efforts reviewed in this work, three types of coupling were identified that can help describe the modeling approach taken in a given study. The three types of coupling are described below:

- **Uncoupled:** In uncoupled approaches, the aerodynamics and propulsion system models are typically evaluated in isolation. The models may pass a limited amount of information between them typically in a one-way exchange (e.g. aerodynamics model runs and provides boundary layer information to propulsion model, but the propulsion model output is not fed back into the aerodynamics model). As a result, the boundary conditions between the models are not converged through an iterative process.

- **Weakly Coupled:** Weakly coupled approaches allow for more interaction between the aerodynamics and propulsion system models. In this level of coupling, information is passed in a two-way exchange between both analyses. While information is exchanged between the analyses, weakly coupled approaches do not extensively iterate to reach convergence between the model boundary conditions. Typically several manual iterations will be performed with the process stopped at a predefined number of model executions.

- **Strongly Coupled:** Strongly coupled approaches employ a high level of interaction between the aerodynamics and propulsion system models. These approaches again provide a two-way exchange of flow information between the codes. However, in this level the analysis codes are executed in an iterative, usually automated process until convergence is achieved.

The second characteristic that defines the modeling approaches taken for BLI concepts is the type of models used to represent the aerodynamics and propulsion system. This characteristic is important as it defines the physical representation in the analysis tool, assumptions made in those tools, and the computational complexity of the analysis. The efforts reviewed in this work identified a number of different model types that were used for both the aerodynamics and propulsion disciplines. For the vehicle aerodynamics, the following types of modeling tools were used in the reviewed research efforts:

- Modified aircraft drag polar
- Power balance analysis
- Vortex lattice codes with boundary layer corrections
- Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) codes

For the propulsion system, the following types of modeling tools were used in the reviewed research efforts:

- 1D thermodynamic cycle analysis
- Source terms (actuator zone or body forces) in RANS CFD
- Turbomachinery CFD

The lists above obviously do not encompass all the options for modeling the vehicle aerodynamics and propulsion systems. These lists should therefore not be viewed as the only options available, but simply as the methods that are currently being used in the reviewed efforts.

Modeling a BLI concept requires selecting an approach/tool to model both the vehicle aerodynamics and propulsion system. In the reviewed research efforts, the aerodynamics and propulsion tools in the above lists were selected in various combinations to develop the overall BLI modeling capability. For example, several efforts coupled a CFD analysis of the aerodynamics with a 1D thermodynamic model of the propulsion system.

The selection of the vehicle aerodynamics and propulsion system modeling tools is an important part of the modeling process and is determined by a number of factors. These factors include physics captured by the tool, assumptions made, computational cost, availability and ease of integration with other analyses. While the selection of the modeling tools is important for BLI, the approach for coupling the tools together is seen as the factor that ultimately determines the quality of the analysis. Therefore, the rest of this section will describe the reviewed research efforts by sorting them according to their coupling approach.

3.1 Uncoupled Approaches

The first analysis efforts reviewed fall into the uncoupled category. In these efforts, limited information is passed between the analyses, typically in a feed-forward fashion. Furthermore, these efforts showed no iteration between the aerodynamic and propulsion system analyses resulting in unconverged solutions. The sections below summarize the research efforts (identified by lead researcher's name) which were identified as using an uncoupled approach.

3.1.1 Felder and Welstead

The first uncoupled modeling approach reviewed in this paper was developed by Jim Felder of NASA GRC and Jason Welstead of NASA LaRC. This modeling approach was used to develop and analyze the STARC-ABL concept in support of the AATT project [3] and was previously used in evaluation of the N-3X concept. [17] Their modeling approach is still being actively refined as issues and limitations of the approach are identified.

Description For the vehicle aerodynamics, the STARC-ABL was modeled by traditional lower-order drag approximation tools with modifications made to capture the presence of the aft propulsor. Specifically, the drag was modified to include the BLI nacelle losses and the tailcone wetted area covered by the propulsor was removed. While these changes to the model attempted to capture the effects of adding the BLI propulsor, Welstead acknowledged that these modifications are not ideal as they fail to capture changes to reference lengths, Reynold's numbers and other factors present in the low-order analysis. To model the propulsion system of the STARC-ABL, Felder and Welstead used the Numerical Propulsion System Simulation (NPSS) code. [18] To capture the effect of ingesting the boundary layer on the aft fan, several different approaches were used to modify the engine design and operating conditions. These modifications have included:

- Reducing the inflow velocity and adjusting the static pressure at the engine inlet based on the boundary layer profile from a clean aircraft fuselage
- Expanding the inlet flow total pressure to ambient conditions to get an effective inlet velocity
- Applying a power savings coefficient to a freestream propulsor based on the results of Gray (described later)

These vehicle aerodynamics and propulsion system models were developed and executed in isolation with the results integrated into a Flight Optimization System (FLOPS) model [19] to determine the overall system level benefit. As a result, this integration did not exchange detailed information between these analyses making this analysis an uncoupled approach.

Application The BLI modeling approach developed by Felder and Welstead has been applied in the development and analysis of the STARC-ABL concept aircraft. [3] Their paper in 2016 initially propose this concept vehicle and the initial analysis of its performance estimated 7% and 12% reductions in fuel burn for the economic and design missions of the vehicle, respectively. This estimate was based on the first engine modeling approach listed above that only included the reduction in the inflow velocity. Later revisions to the propulsion system modeling with the other approaches resulted in a reduction of the engine performance leading to a decrease in the overall vehicle fuel burn benefit. The actual fuel burn benefits predicted by these additional engine modeling approaches are still being determined, but the results will likely not show as significant of a benefit as the initial study results. Furthermore, each of the engine modeling alternatives is producing a different estimate of the overall vehicle performance benefit indicating that there is significant uncertainty regarding which approach most accurately captures the effects of BLI. As a result, there is ongoing discussion about the proper approach that should be used to model the propulsion system and the overall BLI benefit that can be expected for the STARC-ABL vehicle.

3.1.2 Turnbull et al.

The next uncoupled BLI modeling approach reviewed is that developed by Andy Turnbull (under contract to LaRC) and his colleagues at NASA. Their work supported the Fixed Wing (FW) project (the predecessor to AATT) in an effort to assess the D8 aircraft concept. [4–6] This modeling approach is no longer in active development and is unlikely to be revived as it was not viewed as a long-term solution. Furthermore, access to some of the software has lapsed as the licenses have not been renewed by NASA.

Description For the BLI modeling approach developed by Turnbull et al., the vehicle aerodynamics were modeled using the Aerodynamic Prediction EXpress (APEX) code. [20] This code is primarily a vortex-lattice analysis with additional features to capture relevant effects on the drag polar. These features include methods to predict transonic 2D airfoil performance, high-lift devices and boundary layer buildup. In addition to predicting the vehicle aerodynamics, the APEX tool was used to determine the inflow conditions for the propulsion system. The propulsion system was modeled using NPSS. The effect of ingesting the boundary layer air by the propulsion system was captured by incorporating the flow conditions determined by APEX. Specifically, APEX calculated and supplied the average flow Mach number, total pressure, total temperature and overall engine mass flow over a range of operating conditions (freestream Mach number and altitude). These values were used to modify the NPSS inlet flow values and a table of engine performance characteristics were generated. This engine performance deck was then supplied to FLOPS to predict the overall vehicle performance. Overall, this analysis process was formulated and executed in a feed-forward analysis approach that did not tightly couple the aerodynamics and propulsion system models making this an uncoupled approach.

Application The BLI modeling approach developed by Turnbull et al. was used as part of the independent assessment of the D8 concept originally proposed by MIT in support of a NASA Research Announcement (NRA). [21] The objective of this assessment was to evaluate the D8 concept and verify their performance predictions. Applying this BLI modeling approach (in conjunction with more realistic assumptions in modeling other parts of the aircraft) helped identify that the block fuel savings for the D8 were about half that predicted in the original NRA study. These results were however consistent with the predictions of MIT in their NRA Phase II updated analysis.

3.1.3 Marien et al.

Ty Marien of NASA LaRC and his colleagues developed an uncoupled BLI modeling approach to complete a system level assessment of the D8 vehicle concept. [22] This work was funded by the AATT Project and was intended to be an independent assessment of the BLI fuel consumption benefits for this concept which was originally proposed by MIT. This assessment of the NASA D8 model (ND8) was completed and the method developed has the potential to be applied to other BLI vehicle concepts.

Description In order to complete their analysis, Marien et al. developed an uncoupled approach for modeling BLI configurations which was implemented in ModelCenter. [23] Within this approach, the OpenVSP tool [24] was used to produce an aircraft geometry which was then input into FLOPS. FLOPS was used to model the vehicle aerodynamics as well as the mission performance. However, the calculations within FLOPS were modified to account for BLI using a method adapted from the power balance formulation of Drela summarized in Section 2.2. From the power balance formulation, Equation 17 was developed which relates the propulsion system size (the left hand side) to the airframe drag (right hand side).

$$\dot{m}(V_{exit} - V_{\infty}) = D_{nonBLI} - f_{BLI} D_{p,nonBLI} - F_x \tag{17}$$

On the right hands side, F_x is the net streamwise force, D_{nonBLI} is the total drag of the isolated airframe, $D_{p,nonBLI}$ is the profile drag of the isolated airframe and f_{BLI} is the fraction of the boundary layer ingested. With this equation, an estimate can be made of the required propulsion system thrust by computing the drag values for a non-BLI aircraft and specifying the fraction of this drag ingested in the BLI configuration. The effective drag reduction from BLI implied by this equation was modeled within FLOPS by reducing the fuselage wetted area thereby reducing the overall vehicle drag.

In addition to applying this correction to the vehicle drag, the propulsion system was modeled in NPSS with modifications made to account for changes to the inflow total pressure and fan efficiency. The inlet total pressure was modified by using Equation 18 which was developed by Greitzer [5] and Equation 19. The first equation relates the inlet total pressure to the freestream pressure and kinetic energy defect in the flow at the inlet. The second equation estimates this kinetic energy defect by modifying the profile drag power of a non-BLI fuselage with terms for the fraction of fuselage boundary layer ingested and fraction of the fuselage drag which is associate with wake dissipation. Equation 19 was non-dimensionalized into a power coefficient in Equation 20 and this value was calculated at cruise then held constant across all flight conditions.

$$P_{t,inlet} = p_{t,\infty} \exp\left(-\frac{K_{inlet}\gamma\sqrt{Pr}}{\dot{m}_{inlet} a_{inlet}^2} \right) \tag{18}$$

$$K_{inlet} = f_{BLI_{fuse}} \left(1 - f_{wake_{fuse}}\right) V_{\infty} D_{p_{fuse},nonBLI} \tag{19}$$

$$C_{K_{inlet_e}} = \frac{f_{BLI_{fuse}} \left(1 - f_{wake_{fuse}}\right) C_{D_{fuse}}}{n_{eng}} \tag{20}$$

To capture the effect of distortion on fan efficiency, a sensitivity analysis was initially used to determine the performance over a range of different efficiency values. This approach was taken as the ongoing Boundary Layer Ingesting Inlet - Distortion Tolerant Fan (BLI2DTF) testing [25] was still in progress. Ultimately, a single efficiency was selected based on the experimental data obtained from the BLI2DTF test.

Application The BLI modeling approach developed by Marien et al. was used to assess the ND8 vehicle concept as well as non-BLI analytic variants of this design. In these analyses the following assumptions were made:

- $f_{BLI_{fuse}} = 0.4$ (40% of fueselage boundary layer ingested)
- $f_{wake_{fuse}} = 0.1$
- Fan efficiency penalty of 3.5%

The results of the analysis with these assumptions showed that the baseline ND8 configuration had lower block fuel burn than non BLI configurations. However, the amount of this improvement was highly dependent on the vehicle being compared in this analysis. The approach implemented by these researchers allowed for the BLI to be analytically turned off by changing the assumptions listed above. This created a non-physical aircraft that showed the isolated effect of BLI. The isolated benefit was shown to be around a 2.8% decrease in fuel burn, which was further increased to 4% when the non-BLI analytical vehicle was resized to meet mission requirements. Then the non-BLI ND8 vehicle design was changed to be physically valid with the configuration having underwing, podded engines. Comparing this configuration to the baseline ND8 showed a 5.6% lower fuel burn was possible.

3.1.4 Kenway and Kiris

Kenway and Kiris have developed a BLI modeling approach which they have applied in the analysis of the STARC-ABL and D8 concepts with their work supported by AATT. Given the continued interest in these concepts, their approach is actively being refined and improved for further study of BLI concepts. In particular, their analysis approach is being merged with that of Gray (described in Section 3.3) which will likely move their work into a strongly coupled approach.

Description The modeling approach developed by these researchers focused mostly on evaluating the aerodynamics of a BLI vehicle but included some effects from the propulsion system. The vehicle aerodynamics were modeled using the RANS CFD code ADflow which was developed at the University of Michigan. [26, 27] This code was selected due to its familiarity to the researcher and its use of adjoint derivatives to facilitate optimization studies. ADflow code was linked with OpenVSP [24] which is used to generate the geometry for the analysis. To model the propulsion system, an actuator zone model was implemented within the CFD code. This approach introduces a general pressure rise in the flow without the need for detailed turbomachinery design. However, this model could be improved if more detailed blade design and performance data were available. The benefits of this approach are that it guarantees mass flow continuity since the flow never leaves the control volume and simplifies the computation of the forces on the vehicle. While this approach currently does not strongly couple with a dedicated propulsion system model, efforts are currently underway to couple this analysis with PyCycle [28, 29] to capture the impact of BLI on the propulsion system.

Application The analysis approach developed by Kenway and Kiris has primarily been used to model the STARC-ABL concept. [30] However, this analysis approach was also developed and used by Kenway to study the D8 concept when he was a research engineer at the University of Michigan. In the study of the STARC-ABL, the focus was to examine the distortion present in the flow at the fan face. The researchers modeled two aircraft configurations. The first was a simple fuselage with the tailcone thruster and the second being the full aircraft including the wings. With these configurations, an optimization of the tailcone and nacelle shape was completed to minimize the distortion (as defined by the ARP 1420 distortion metric) on the aft fan face. This optimization considered the distortion at up to 5 different operation points that considered different Mach numbers, altitudes, angles-of-attack and propulsor thrust. The results showed that optimizing the aft section geometry could significantly reduce the fan face distortion on all configurations. However, the results also showed that the downwash created by the wings has a significant effect on this distortion in comparison to the analysis of a tailcone thruster on a clean fuselage. With the wings present, the optimal distortion on the fan face at cruise flight conditions is higher than the fuselage only case. Achieving this minimum distortion in the presence of the wings also requires selecting a different tailcone and nacelle geometry. These results further emphasize the complicated nature of the boundary layer which will enter a BLI propulsor and the need to include all elements of the vehicle when developing and analyzing a design.

3.1.5 Pandya et al.

Pandya of NASA Ames along with researchers at MIT developed a BLI modeling approach to analyze the MIT D8 Double Bubble concept aircraft. This analysis was supported by NASA's Fixed Wing Project and was paired with wind tunnel experiments evaluating the concept.

Description The BLI modeling approach developed by Pandya primarily focused on analyzing the external aerodynamics of the vehicle with higher order tools. Their approach used the Overflow code [31] to analyze the flow over the vehicle. To capture the effect of the BLI propulsors, actuator disks were included in the analysis to simulate the flow through the engines. This actuator disk applied a uniform static and total pressure rise to the flow passing through it (implying that the velocity did not change across the actuator disk). With this approach, they were able to compute the mechanical power (P_K defined in the power balance method) added by the propulsors to the flow.

Application Pandya et al. applied their BLI modeling approach to the analysis of the MIT D8 concept with results reported in two papers. In the first paper, the analysis focused on modeling the D8 in an unpowered (no propulsor) configuration. [32] This configuration was evaluated in support of wind tunnel experiments on that configuration occurring at the time and served as a means of tool validation. The results presented from this work showed that modeling the wind tunnel walls and mounting structure were important for accurately predicting lift but were less important for capturing the vehicle drag. Furthermore, the analysis was used to identify a turbulence model that predicted the lift and drag most closely to the measured wind tunnel data.

In the second study, three different D8 models were evaluated in support of ongoing wind tunnel experiments. [33] The first model was again an unpowered configuration similar to that reported in the first paper. The second model used the same fuselage but placed propulsors on engine pods attached to the tail fuselage (similar to an MD-80 configuration) making this a non-BLI configuration. The last model was of the integrated BLI D8 configuration that placed two propulsors inside the pi-tail at the aft end of the fuselage. Each of these cases were evaluated and results were compared at three axial stations. The results showed that the integrated BLI propulsors reduced the overall viscous dissipation in the flow by 6% compared to the non-BLI podded configuration. In terms of the required mechanical power, the analysis concluded that the BLI configuration required 9% less propulsive power than the podded design.

3.1.6 Lee et al.

Researchers Lee et al. of NASA GRC are developing a BLI modeling approach with the goal of designing a BLI propulsor. Their work is currently funded by the AATT project and is therefore focusing on the STARC-ABL concept. This modeling approach is in active development with future plans to improve the coupling between the aerodynamic and propulsion system modeling. Therefore, this analysis approach may need to be reclassified in the future as a weakly coupled or strongly coupled approach as improvements are implemented.

Description The multi-fidelity modeling approach being developed by these researchers applies CFD to the analysis of both the vehicle aerodynamics and the propulsion system. The use of CFD for modeling the propulsion system, specifically the turbomachinery, was selected to enable more detailed design of the propulsion system for BLI applications. As described in [34], their analysis process starts with a CFD analysis of the integrated propulsion and airframe system to generate the inflow conditions for the propulsion system. For this part of their analysis process, they are initially using the CFD tool Go-flow [35] with plans to eventually replace this code with FUN3D [36]. To generate the proper boundary layer conditions with Go-flow, the researchers have implemented a body force model to capture the propulsion system influence within the external aerodynamics CFD. The generated inlet boundary layer profile is then passed to two turbomachinery models for analysis of the engine.

The first model is a quasi-2D throughflow analysis which is used to determine some initial fan geometry design parameters such as camber line, work profiles and ultimately the blade geometry. This information along with the inlet flow profile from the external CFD are used to initiate the turbomachinery CFD. For the CFD analysis of the turbomachinery, several different analysis codes will be used throughout the design process: SWIFT [37], APNASA [38], and TURBO [39, 40]. SWIFT was selected for the initial implementation due to its simplicity and execution speed. APNASA and TURBO will be incorporated later into the process to increase the fidelity of the analysis and include unsteady effects. Regardless, each of these codes have an extensive history of use at NASA and are well validated against experimental data for a number of turbomachinery geometries. [41] From these turbomachinery CFD results, the fan performance is then predicted and the nozzle is also designed.

To date, the propulsion system (turbomachinery) design and performance information determined in this process has been compared with that assumed in the body force model in the full propulsion-airframe CFD analysis. This comparison has not been extensively used to update the body forces in the full vehicle CFD making this process at the present time an uncoupled analysis. Future improvements to feed this information back to the vehicle CFD for several manual iterations would result in a weakly coupled approach, while iteration to convergence on the propulsion system inlet and exit flows would result in a strongly couple approach.

Application The BLI modeling approach developed by Lee et al. is currently being applied in the study of the STARC-ABL concept. The focus of this study is designing the tailcone thruster turbomachinery under the relatively axi-symmetric inlet distortion that it is expected to experience. A paper describing the initial conceptual aerodynamic design of the tailcone thruster will be presented at the ASME Turbo Expo conference in 2018. [34] The report first examines the flow over the tailcone with several different propulsor models in the CFD. Of these, the model containing the body force representation of the thruster is used to generate the inflow conditions for quasi-2D and 3D CFD models of the turbomachinery. These different models match up well in terms of total pressure and flow angle at both the fan inlet and fan exit. Using these turbomachinery models, several different fan designs are explored with a performance map ultimately produced for one of the conceptual designs. The tailcone thruster nozzle spike was also redesigned from a baseline geometry to minimize losses and improve performance.

3.2 Weakly Coupled Approaches

The second group of analysis efforts reviewed are those that are weakly coupled. Weakly coupled approaches pass information in a two-way fashion between the aerodynamic and propulsion system analyses. While relevant information is shared between these analyses, these efforts have a limited amount of iteration between the analyses resulting in solutions that are not fully converged. The section below summarizes the single research effort which was identified as using a weakly coupled approach.

3.2.1 Heath et al.

Chris Heath of NASA GRC in partnership with several other researchers developed and implemented a weakly coupled propulsion-aircraft integration approach for research efforts on supersonic aircraft. These research efforts were supported by the Commercial Supersonics Technology (CST) project and published in several AIAA conference papers. While these efforts were successful, this work is not in active development for CST as the researchers have transitioned to other efforts. Although this analysis approach was applied to study propulsion-airframe integration and not BLI, the approach does not explicitly preclude evaluation of BLI vehicle concepts. The analysis approach is therefore included in this review as an example of how a weakly coupled approach could be applied in the conceptual design of BLI concepts.

Description The analysis approach developed by Heath et al. used a collection of tools to capture the propulsion-airframe integration (PAI) effects of supersonic vehicles. For the analyses completed by these researchers, they first started by designing the supersonic inlet using the SUPIN code. [42] This inlet design was then integrated with the rest of the vehicle with the aerodynamics of this geometry analyzed in FUN3D. [36] Within this CFD analysis, the propulsion system was represented by outflow and inflow boundary conditions at the fan face and turbine exit. The pressure and temperature values at these boundary conditions were initially determined from a baseline cycle model created in NPSS. [18] These values were then perturbed (specifically the fan face static pressure) to vary the mass flow through the engine. This static pressure and mass flow variation was used to generate supersonic inlet performance maps (referred to as cane curves) which were then used to update the NPSS engine analysis. The feeding back of the revised inlet performance characteristics to the cycle model makes this a weakly coupled approach. Furthermore, the CFD analysis provided an examination of the fan face distortion produced by the inlet design. In addition to vehicle aerodynamics and propulsion system modeling, the analysis approach developed by these researchers also included the characterization of the sonic boom produced by the overall vehicle.

Application The PAI analysis method developed by Heath et al. was used to study the design and integration of the inlet and propulsion system on supersonic vehicles, with the results presented in two reports. In the first report, a trade study was completed to evaluate two different inlet designs for a low-boom SST. [43] One inlet was of a conventional axi-symmetric spike design while the other was of a streamline-traced external-compression (STEX) design. These designs were integrated onto a low-boom vehicle design and an optimization was executed with the objective of matching a target lift coefficient. This objective was achieved by varying the aircraft angle of attack and nozzle throat area with constraints ensuring thrust was equal to drag. The results showed that the integrated inlets had different performance characteristics than predicted by the isolated SUPIN analysis and the importance of designing the inlet in the installed configuration. Furthermore, the results showed tradeoffs between the two designs. The spike design gave better pressure recovery and sonic boom while the STEX design had lower wave drag and therefore better vehicle range. In terms of sonic boom, the study found that the STEX design produced a higher perceived loudness which was unexpected and provided further evidence of the importance of designing the inlet as part of an integrated system.

The second study by Heath et al. examined design of the aft section of a supersonic concept vehicle including a non-embedded spike inlet. The placement of the engine near the fuselage altered the inlet flow characteristics from freestream requiring the nacelle and tail geometry to be redesigned for optimal performance. First, a shape optimization was performed on the initial isolated spike inlet design developed by SUPIN to generate a design that operated better in an installed configuration. This redesign was completed in FUN3D and the final design was evaluated over a range of Mach numbers and auxiliary door positions to generate an inlet performance map. The resulting performance map was used to update the NPSS model of the propulsion system. Following these steps, a shape optimization of the tail was completed with the objective being to match a target near-field pressure signature below the aircraft. The results from this optimization showed changes that could be made to the tail and nacelle geometries to better match this target pressure signature. Overall, the optimization presented in this study produced an inlet pressure recovery 1.8% higher than the baseline design and the sonic boom was reduced by 2.9 decibels perceived loudness level (PLdB).

3.3 Strongly Coupled Approaches

The last set of analysis efforts reviewed in this report are those that are considered strongly coupled. In these efforts, the modeling environment is setup to ensure information is shared between the aerodynamics and propulsion system analyses with the final results being a fully converged solution. The sections below summarize the two research efforts which were identified as using a strongly coupled approach.

3.3.1 Gray

The first strongly coupled BLI modeling approach reviewed in this paper was developed by Justin Gray of NASA GRC. The development of his analysis approach was supported by the TTT and AATT projects with his approach applied to analyzing the STARC-ABL concept. His methodology and some of his results are described in a paper presented at the 2017 AIAA Aviation conference. [44] This methodology is still being actively developed and implemented with the results also being a key element of his upcoming Ph.D. dissertation (defense planned for 2018 at the University of Michigan).

Description To develop a strongly coupled analysis approach for modeling BLI, Gray selected two compatible tools and integrated them into a single analysis process. For modeling the vehicle aerodynamics, he selected the RANS CFD code ADflow. [26, 27] This code was selected for its ability to provide adjoint derivatives as well as an in-memory interface to Python. Both of these features improve the integration of ADflow with the overall analysis framework and enable the use of gradient based optimization algorithms. To model the propulsion system, a new cycle analysis tool being developed at GRC called PyCycle was selected. [28,29] PyCycle was selected for this study to leverage its unique analytic derivatives features to achieve multidisciplinary convergence and to facilitate optimization. Using these two analysis tools, a strongly coupled analysis process was developed by integrating the tools in the OpenMDAO framework. [45] This framework facilitates the passing of information between different analysis tools enables the entire modeling process to be controlled by a numerical solver or optimizer.

Application The BLI modeling approach developed by Gray has been applied to a simplified geometry that is representative of the STARC-ABL concept as described in his 2017 Aviation paper. In this analysis, an axi-symmetric fuselage and tailcone thruster were modeled with the wings and tail excluded from the analysis. Working from an initial geometry, the tailcone portion of the fuselage geometry along with the propulsor design (nacelle geometry, nozzle geometry and fan pressure ratio) were optimized using a gradient based algorithm. The objective of this optimization was to minimize the shaft power required to produce a given net force on the entire body.

The results from this analysis on a simplified STARC-ABL geometry show a number of valuable results. First, there is a clear PSC benefit to the BLI configuration in comparison to a podded configuration for the same net vehicle force. This benefit increases as transmission of power to the tailcone propulsor becomes more efficient with the trend indicating that a larger tailcone propulsor with more power is desired in these cases. A more detailed analysis of the results also showed that the benefit of BLI comes from changes to both the propulsion system performance and the vehicles aerodynamics. Of note, Gray's results highlight the differences in the boundary layer profile around the tailcone section of the aircraft that occur when the propulsor is added.

3.3.2 Ordaz

The second strongly coupled BLI modeling approach was developed by Irian Ordaz of NASA LaRC. Development of his analysis process was supported by the AATT project. His methodology is described in detail in a white paper [46] and is summarized below.

Description Ordaz's method for modeling BLI is a strongly coupled approach that integrates a number of complementary analysis tools within a larger analysis and design framework. The overall framework is developed in Phoenix Integration's ModelCenter tool [23] which facilitates the passing of information between analysis tools and setting up trade studies and optimizations. To model the propulsion system within this framework, Ordaz used engine models developed in NPSS. For the vehicle aerodynamics, the CFD tool FUN3D developed by NASA LaRC was selected. [36] An important feature available in this analysis framework is the ability to leverage FUN3D's adjoint-based mesh adaptation to reduce grid discretization errors. This capability was found to be valuable in producing accurate fan distortion calculations [47] and in determining the drag of an engine operating in freestream. [46] In addition to these primary analysis tools, the BLI modeling framework Ordaz created includes a number of supporting tools to facilitate the analysis process. These include OpenVSP for modeling the geometry and creating a surface mesh, AFRL3 for generating the volume mesh and various tools used for solution post-processing. These post-processing tools include force and moment calculations based on user-specified book keeping for the aerodynamics and propulsion system, as well as averaging of flow parameters at the aero-propulsion interfaces and calculation of fan face distortion. All of the analysis tools were selected as they are very well established and respected in the research community. ModelCenter integrates all these analysis codes into an automated process that can be executed with different options on a wide range of BLI concepts.

Application Ordaz has applied his analysis framework to several BLI vehicle concepts to demonstrate its capabilities. First, as part of the framework development process he applied it to the analysis of the MTA450 [47] which is a business jet loosely based on the Gulfstream G450 but with a tailcone thruster. In this application, a simplified fan model was used for the tailcone thruster to demonstrate the convergence of the model. The focus of this study was a design optimization of the tailcone and inlet geometry to minimize fan face distortion. The results from this optimization show that fan face distortion could be significantly reduced by properly shaping the tailcone and inlet geometry. The results also showed the importance of the mesh adaptation capabilities in reducing grid discretization errors.

Following the framework development, he has primarily used the analysis capability to quantify the performance of the STARC-ABL concept. [46] This work evaluated the full vehicle geometry (minus the underwing engines) and included the model of the tailcone thruster. The results from this analysis resolved discrepancies between the CFD and propulsion performance predictions through the identification of a missing pressure term in the original propulsion model. This missing pressure term had resulted in an over-prediction of the propulsor performance by under-predicting ram drag. These results from this analysis also highlighted the importance of coupling the aero-propulsive models to accurately predict the performance of the vehicle. [46]

3.4 Summary

Section 3 has presented an overview of the modeling approaches used by NASA researchers to evaluate BLI aircraft concepts. As part of this review, a classification scheme was developed to organize the modeling approaches implemented by these researchers. This classification scheme was based on the two key characteristics: the type of coupling between the vehicle aerodynamics and propulsion system models, and the type of model used to analyze each discipline (aerodynamics and propulsion). Of these characteristics, the type of coupling was used as the primary classifier as this dimension is considered critical for properly capturing the effects of BLI on aircraft performance. Using this classification framework, each individual research approach was described in terms of its analysis approach and how it was applied to the study aircraft dependent on BLI or PAI technologies. A summary of these research efforts and where they fit into the classification scheme are presented in Table 1.

Table 1. Summary of BLI Modeling Approaches

Aerodynamics Model	**Propulsion Model**	**Uncoupled**	**Weakly Coupled**	**Strongly Coupled**
Modified Drag Polar	1D Thermodynamic Cycle	Welstead & Felder		
Power Balance Method	1D Thermodynamic Cycle	Marien et al.		
Vortex Lattice	1D Thermodynamic Cycle	Turnbull et al.		
3D CFD	1D Thermodynamic Cycle		Heath et al.	Gray, Ordaz
3D CFD	Source Terms in Aerodynamics CFD	Kenway & Kiris, Pandya et al.		
3D CFD	Turbomachinery CFD	Lee et al.		

As can be seen in this table, most of the BLI modeling approaches implemented by NASA researchers to date fall within the uncoupled category. These uncoupled research efforts span the full range of the aerodynamics and propulsion system modeling types. Despite the wide range of aerodynamics and propulsion system model types implemented, a number of observations can be made about uncoupled approaches. The strengths of these approaches are:

- Models can be evaluated rapidly in isolation following a traditional division of modeling between research groups
- Models of the aerodynamics and propulsion system can be of any type (order)
- Modeling approach does not require use of an integration tool/framework to manage the execution and convergence of the analysis codes

While there are strengths to using uncoupled approaches, there are also some important weaknesses that must be noted. These weaknesses are:

- Information is only passed in one direction and therefore it does not ensure consistency at the interfaces between the aerodynamics and propulsion system model
- The analysis cannot capture complex, detailed interactions between the aerodynamics and propulsion system performance characteristics

- Particularly for the lower order analyses, uncoupled approaches complicate the accounting of thrust and drag forces on the vehicle
- Uncoupled approaches do not enable the optimization of the overall vehicle design to achieve the best performance

While most BLI modeling efforts reviewed fell into the uncoupled category, several research efforts were identified that implemented weakly and strongly coupled approaches. These efforts used a specific set of modeling tools (specifically 3D CFD for aerodynamics and 1D thermodynamic cycle analysis for propulsion), however these types of coupling are general and could be applied with other analysis techniques. Several researchers whose work is currently categorized as uncoupled indicated they are planning to continue developing their BLI modeling approaches, possibly moving them into the weakly or strongly coupled categories. Focusing on the strongly coupled approaches, the strengths are:

- They promote developing consistency between the aerodynamic and propulsion system models at the defined interface planes (boundary conditions)
- They generally simplify accounting for all the forces on the vehicle by clearly defining the modeling control volumes and computing all the forces in the aerodynamics tool
- They enable high level trade studies and optimization to be completed that change the design of the fuselage geometry and propulsion system

While there are significant strengths for strongly coupled approaches, there are also some important weaknesses that must be noted. These weaknesses are:

- They require running analyses to achieve multidisciplinary convergence at all operating conditions which could make it challenging and time consuming to include in systems analysis assessments
- They generally require using higher order tools (i.e. CFD) in order capture complex physical interactions
- Using higher order tools often requires a more detailed specification of the vehicle and propulsion system geometry

Weakly coupled approaches blend the strengths and weaknesses of the uncoupled and strongly coupled approaches and will therefore not be enumerated here.

4 Recommendations for Future BLI Conceptual Design Studies

The previous sections of this report have provided an overview of the BLI concept and modeling approaches that have been developed to analyze this technology. This review has shown that BLI aircraft concepts are an emerging area of research based on relatively strong theoretical principles. As a result, BLI technology is garnering a lot of attention from aeronautics research teams across many NASA centers.

The research efforts of these teams are being funded by a variety of projects, most notably the AATT project (formerly Fixed Wing). With these different sources of funding, the research efforts have been focused on addressing a number of different research objectives. Some analyses have focused on trying to determine the overall system level benefit of ingesting boundary layer air with the engines or propulsors. Other efforts have examined more specific elements of BLI such as determining the flow distortion entering the propulsors or determining the required design of the engine turbomachinery. This breadth of research objectives has resulted in research teams developing custom modeling approaches that utilize a wide variety of tools with different levels of coupling.

The objective of this section is to make recommendations regarding the first set of studies that are focused on estimating the system level benefits of various BLI concept aircraft. The studies with this objective that were reviewed in this paper produced a wide range of predictions regarding the potential benefit of BLI technology. One contributing factor to this variation are the differences in the vehicle concepts being studied. Concepts like the D8 and STARC-ABL place elements of the propulsion system in different locations around the aircraft and therefore may have significantly different benefits. Another contributing factor to the disparity in analysis results is undoubtedly due to differences in the modeling approaches implemented in each study. As a result of these modeling differences, there seems to be a lack of confidence that BLI technology will actually produce system level benefits as projected by theory.

Therefore, there is a need to further develop BLI modeling approaches that will enable accurate analysis of these vehicle concepts. These developments primarily need to enable researchers to quantify potential benefits of ingesting the boundary layer. Ideally, this quantification should not only predict the absolute benefit but should also identify the uncertainty present in this prediction. Quantifying this uncertainty can help in identifying elements of the design that present high levels of risk which require more research attention. This information can be used to inform and guide the direction of disciplinary or component level research efforts related to BLI technology. As these researchers gain a better understanding of BLI technology, this information can be used to update the system level models and reduce the overall system level prediction's uncertainty. Improved understanding of the physical principles also allows for model verification and the use of optimization to generate better BLI designs.

Given these system level modeling needs and applications, a set of recommendations are provided below to help improve the analysis of BLI concepts.

Recommendation 1: Strive to Use Strongly Coupled Approaches

The concept of BLI seeks to exploit complex interactions between the aircraft's aerodynamics and propulsion system to improve the overall system level performance. As a result, the problem is fundamentally multidisciplinary in nature and therefore requires modeling that tightly couples these analyses. As evidenced in Table 1, most of the BLI modeling approaches to date have treated the problem as an uncoupled analysis. However, these approaches have significant weaknesses that do not ensure they properly capture the coupled, multidisciplinary effects of BLI technology. Therefore, analyses completed with an uncoupled approach need to acknowledge these weaknesses and identify these sources of uncertainty on the performance characteristics computed.

Developing more strongly coupled analysis approaches will necessitate making several important changes to the analysis process. First, strongly coupled analyses require that the individual tools be integrated via a multidisciplinary framework such as ModelCenter or OpenMDAO. These tools automate the process of ensuring convergence at the boundaries between these disciplinary models By requiring convergence at these boundaries, the development of strongly coupled approaches forces researchers to clearly define the control volumes and boundary conditions between each discipline. This clear definition will also ensure that if a momentum-based approach is being used that all forces will be accounted for properly. Second, the use of strongly coupled approaches is likely to necessitate the use of higher-order analysis tools. These tools are required over traditional, lower-order, systems analysis methods as they are physics based and do not contain empirical assumptions developed based on traditional aircraft. Using higher-order analysis tools however presents the additional challenges for conceptual design of needing more detailed geometry information and increasing the computational overhead. Lower-order tools may still be used for rapid conceptual designs studies, but researchers must recognize the limitations of these tools and the increased uncertainty introduced into their results. Lastly, because this problem is truly multidisciplinary, a new collaborative research process is going to be required that integrates disciplinary research teams and their analysis codes into a single, tightly coupled process.

Recommendation 2: Validate Modeling Tools and Approaches

The analysis of BLI concepts requires using a set of multidisciplinary tools. As shown in Table 1, various combinations of aerodynamics and propulsion modeling tools have been used by each BLI research effort. Most of the modeling tools identified in both disciplines are well known and have been validated in specific applications. However, it is unlikely (or at least unclear) that many of these tools have been validated within the context of a highly integrated BLI system. Therefore, there is a need to validate all the modeling tools being used for these systems. Specifically, experimental data is needed for scaled BLI concepts or generic BLI test articles to serve as validation for higher-order, physics-based tools such as CFD. This data and the validated higher-order tools can then be used to develop empirical or semi-empirical correlations to improve the lower-order tools that commonly serve as the basis for systems analysis. Furthermore, these validation results can be used to verify the accuracy of both the momentum and energy based formulations described in Sections 2.1 and 2.2, respectively. While this is an area of ongoing need, there have been some efforts to validate BLI modeling tools and approaches. These validation efforts include the computational analyses completed as part of the BLI2DTF [25] test and a low speed test of the D8 concept. [12]

Recommendation 3: Appropriately Use the Momentum and Energy Based Formulations

Sections 2.1 and 2.2 describe two different theoretical principles that can be used to describe the benefits of BLI. These theoretical principles are the conservation of momentum and conservation of energy. As described in those sections, those approaches for describing and modeling BLI are fundamentally equivalent as both physical principles must be true.

While conservation of momentum and energy are theoretically equivalent modeling approaches, in the author's opinion there are appropriate situations for each of the methods to be applied. Of the two approaches, modeling aircraft performance with a conservation of momentum approach is more common in practice and is natural for most engineers. This approach appears to work well when the physics of problem are fully captured in the analyses (not overly reliant on empirical models), the analysis domains of each discipline are clearly defined, and the analysis process is strongly coupled. In these situations, the individual disciplines can be relied upon to accurately determine the forces present within their respective domains. Furthermore, the strong coupling ensures that the boundary conditions between these domains are converged. As an example, the strongly coupled approaches of Ordaz and Gray satisfy these requirements and allow for the forces to be computed by integrating pressure and viscous force on all vehicle surfaces.

Applying the conservation of energy, also referred to as a power balance approach, to the analysis of aircraft is less common and therefore less intuitive to most engineers. In the author's opinion, conservation of energy is likely best applied to the conceptual design of BLI vehicles in situations where the analysis tools do not capture the complex physical interactions and the analysis process is uncoupled or weakly coupled. Using the power balance approach isolates non-BLI-effected energy terms and directly specifies inputs defining the BLI physical interactions. For example, terms such as the dissipation in the flow (which are not affected by BLI) can be estimated from an isolated, non-BLI aircraft configuration. Meanwhile, other parameters which describe the interaction between the aerodynamics and propulsion system, such as the fraction of the boundary layer air ingested, are inputs in this type analysis. These parameters are often conceptually easier to understand in the context of conceptual design. However, given their dependence on the complex physics of the interacting system, the values of these parameters are often more difficult to precisely determine. But the intuitive nature of these parameters allows for appropriate design assumptions to be made during conceptual design to capture the aerodynamics and propulsion system interactions. The power balance method therefore seems well suited to situations where information about the detailed design geometry, boundary layer profiles and physical interactions is not readily available. As a result, using energy conservation appears to better enable the conceptual design of BLI concepts as shown by the work of Drela and Marien.

Recommendation 4: Evaluate BLI Concepts with Appropriate Metrics

As described in Section 2.3, there are number of metrics which are commonly used to describe the benefit of BLI on aircraft performance. These include traditional metrics like block fuel burn, TSFC and propulsive efficiency along with newer metrics like power saving coefficient (PSC) and payload fuel energy intensity (PFEI). Given this variety of metrics, it is important to select the appropriate option when evaluating BLI concepts.

It is the author's opinion that many of the traditional metrics such as TSFC and propulsive efficiency are inadequate merit functions for BLI systems. As noted in the Introduction, for BLI aircraft it is often difficult to distinguish what elements of the force on the vehicle are attributable to thrust or to drag. Therefore, computing TSFC (fuel flow divided by thrust) is highly dependent on this force accounting scheme making comparisons between BLI and non-BLI engine performance questionable. Propulsive efficiency is also less than ideal as it only captures changes to the engine performance and does not capture changes to drag of the vehicle induced by BLI.

Of the metrics presented in Section 2.3, the author's opinion is that evaluation of BLI system level benefits should be completed using the block fuel burn or PSC. These two metrics evaluate the overall vehicle performance and do not attempt to quantify the improvements in the isolated aircraft aerodynamics or propulsion system performance. The PSC metric is valuable in that it compares the performance of a BLI design to a non-BLI design at a single operating condition. This makes the PSC metric independent of the overall mission allowing it to be computed via analysis with a single multidisciplinary analysis at that flight condition. However, PSC has a limitation in that the metric requires knowing the power for a non-BLI design making it difficult to apply without developing two independent, yet comparable BLI and non-BLI models. Similarly, evaluating designs based on the changes to block fuel burn captures the effect of BLI on vehicle performance and considers changes to the propulsion system and vehicle weight. This metric therefore requires evaluating the design over the entire mission making it a more difficult (but probably more complete) metric value to compute.

Recommendation 5: Apply Optimization When Design Details are Unknown

The research efforts reviewed in this paper identified a wide range of BLI modeling approaches that are being used by NASA researchers. One aspect of these modeling approaches not extensively discussed was the use of optimization in generating results. The reviews of the various research efforts showed some approaches are focused on purely doing analysis of a fixed design, while others incorporate optimization schemes to modify these designs to generate a better solution. The ability to do analysis, particularly in a strongly coupled process, is an important capability that provides a solid foundation for assessing BLI concepts.

However, as mentioned in Recommendation 1 a move to strongly coupled approaches is likely going to require the use of higher-order tools. These tools generally need more detailed vehicle and propulsor geometries in order to complete their physics-based computations. This level of information is not commonly available during conceptual design, and if it is, the geometry is often based on simple representations developed for non-BLI applications. The lack of detailed design information (or design information based on non-BLI installations) can lead to poor performance metrics being predicted by these tools. In these cases, shape optimization should be applied to improve the geometric design characteristics that will lead to better overall vehicle performance. Ultimately, it is the performance of these optimized BLI concept vehicles that should be evaluated and compared to non-BLI concepts that have been optimized for the same mission.

Recommendation 6: Improve Communication Between BLI Researchers

Lastly, during the course of researching and writing this report it became clear that there is a great deal of excitement and interest revolving around modeling and analyzing BLI concepts. Despite this common interest among researchers, it was noted that most of these research teams are working largely in isolation from the other groups. As a result, there is little discussion and sharing results that could help the entire BLI research community produce better, more insightful results.

The final recommendation is therefore to develop and support a BLI modeling working group to bring the researchers in this community together. Such a forum would allow for research teams to share their knowledge of BLI physics and best practices for modeling these systems. Mary Jo Long-Davis of NASA GRC along with an organizing team is currently planning one such meeting for late May 2018. This event will be called the Propulsion-Airframe Integration Technical Interchange Meeting (PAI-TIM) and will allow researchers from NASA, other government agencies, industry and universities a PAI/BLI focused forum to share their work. Meetings such as this (and others in the future) will be critical to developing a community of researchers with the tools and techniques needed to produce accurate analyses of BLI concepts.

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