# Utilizing qualitative meta-analysis and meta-synthesis towards emergent trends in supersonic transport aircraft

by

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# Abstract

There is real potential for a revival of supersonic air travel, with multiple companies developing new aircraft designs that take advantage of new design concepts, philosophies, and approaches to making these aircraft practical and profitable. As this push to return supersonic aircraft to the skies presses forward, there are questions regarding how these aircraft will operate, where they will operate, and how they will integrate into the airspace above the United States. There is a need to explore the contributing factors that will influence how and to what extent these aircraft will enter into the National Airspace System (NAS) and to what extent.

This study employs a combination of a qualitative meta-analysis and a meta-synthesis to identify key themes in the literature surrounding critical influencing factors for the reintroduction of supersonic aircraft into the NAS. This study explores routine supersonic flight's regulatory, technical, societal, and economic components to identify themes and trends that provide insight into how and where the industry will evolve. These theories can be used to understand challenges and other factors hindering or aiding in reintroducing these aircraft into the NAS.

The theories developed from this study highlight important factors that may influence the future of supersonic air travel. They identify regulatory hurdles, technological innovations, societal impacts, environmental concerns, and economic issues. The findings from this study are intended to offer insight and guidance into significant factors affecting the future of supersonic air transportation, offering potential avenues for solutions to new and long-standing challenges alike.

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# Chapter 1 - Introduction and Background

As aviation technology advances, there is renewed interest in high-speed transport aircraft. This is evidenced by Venckunas (2023), in which the author lists no less than ten supersonic business jets in various stages of development, all competing for a portion of the commercial market. As our increasingly connected society desires fast and efficient forms of transportation, there is a new push to develop and market high-speed supersonic transport aircraft. A key indicator can be seen in recent moves by major air carriers to invest in new, high-speed aircraft. According to Boom Supersonic, American, United, and Japan Airlines have all taken pre-orders of their Overture supersonic aircraft, and the company is scaling to build up to 66 aircraft per year (Boom Supersonic, 2025). These pre-orders add up to 130 total aircraft sold before production begins (Boom Supersonic, 2025). Current technological developments, such as Boom Supersonic's recent technology demonstrator test flights (Wall, 2025), are creating new potential that had not existed previously. With this renewed interest in supersonic flight comes challenges, new and old. This thesis explores the critical issues, policy, and technological considerations for reintroducing high-speed transport aircraft into the National Airspace System (NAS).

With the retirement of the Concorde in 2003 (Tikkanen, 2024), there have been no supersonic transport aircraft in service within the commercial sector for at least 21 years. Aviation technology has advanced significantly in the intervening years, giving rise to new methods of aircraft design using digital engineering and modern materials (Venckunas, 2023). This creates opportunities to reignite the supersonic transport industry and return to the skies in aircraft capable of traveling faster than sound.

While supersonic air travel is not new, developing new supersonic aircraft at scale could significantly alter the landscape, facilitating a new look at how these aircraft fit into the NAS. This paper explores the issues, regulations, policy, and technological considerations associated with the re-emergence of supersonic air travel. The following subsections provide a brief history of supersonic air travel and a brief overview of the re-emergence of supersonic aircraft.

## A Brief History of Supersonic Transport Aircraft

The Bell X-1 made history on October 14, 1947, in the skies above the Mojave when General Charles "Chuck" Yarger broke the sound barrier for the first time (Smithsonian, n.d.). This historic event ushered in the age of supersonic flight. Breaking the sound barrier changed the fundamental understanding of high-speed flight, ushering in a new era of aircraft design, manufacturing, and lofty concepts of high-speed air travel.

The two most prominent supersonic transport aircraft were the Soviet Tupolev Tu-144 and the Anglo-French Concorde (Figure 1).

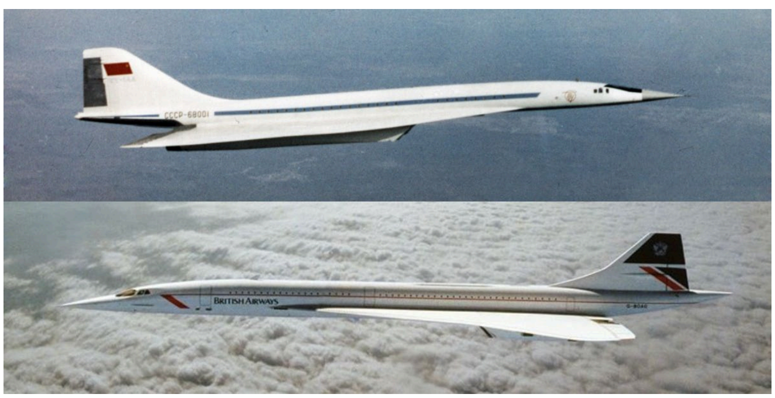

**Figure 1. Tupolev Tu-144 (Top) and Concorde (Bottom) (Leone, 2021)**

While the Soviet Tu-144 saw an incredibly limited service life of less than a year and was later relegated to use as a flying laboratory (Dryden, 2002), the Concorde was in service for 27 years and set numerous precedents for the operation of supersonic transport aircraft. What follows is a brief history of Concorde and an overview of some contributing factors that ultimately led to its retirement from service.

**Concorde – A Historical Footnote**

The era of turbine-powered passenger travel began in the late 1950s, with the Boeing 707 and the Douglas DC-8 offering some of the highest performance in passenger aircraft of the early jet era (Webb & Takahashi, 2022). While technologies found in supersonic aircraft were ultimately honed through military research and development programs and space exploration, entering into the commercial sector in the late 1960s (Pozzi, 2021), the development of Concorde began much sooner. The Concorde was developed before the Boeing 707 and the DC-8's entry into service (Webb & Takahashi, 2022). Technologies and design philosophies within the Concorde resulted from research and development conducted by the Royal Aircraft Establishment [Great Britain] in the mid-1950s (Webb & Takahashi, 2022). The Concorde resulted from the British Supersonic Transport Aircraft Committee – S.T.A.C., and a collaboration between Britain's British Aircraft Corporation (B.A.C.) and France's Aerospatiale (Webb & Takahashi, 2022). After a long development, the Concorde entered service in 1976.

Initially, 16 major air carriers placed orders for the Concorde, including Pan Am, United, American, and national flag carriers, such as Lufthansa and Air Canada (Webb & Takahashi, 2022). There was great interest in bringing supersonic aircraft to market, ensuring air carriers could capitalize on the benefits of faster aircraft along their respective routes. However, many of these orders eventually fell through, leaving Concorde with few buyers. Of the 16 air carriers to put in orders for the Concorde, all but two were canceled, leaving British Airways and Air France as the only air carriers to operate supersonic aircraft (Webb & Takahashi, 2022).

The loss of most of the Concorde's orders left it relegated to very few air carriers and contributed to its limited use. However, the fact that few air carriers operated the type was not the only reason for its limited success. The following section outlines the key contributing factors to the Concorde's failure. These same factors are still relevant to modern supersonic aircraft and inform current technical and regulatory challenges facing modern aircraft designers and air carriers.

### Hurdles to Supersonic Air Travel – A Brief Overview of the Concorde's Failures

While the Concorde was the most successful supersonic transport to see extended service, it ultimately failed to withstand the test of time. The marginal success, or failure, of the Concorde resulted from various factors relating to the aircraft's performance, regulations, restrictions, and how the aircraft operated. Webb & Takahashi (2022) provide an analysis of the challenges faced by the Concorde. Their findings provide insight into the current challenges faced by those seeking to revive supersonic air travel in the present day.

According to Webb & Takahashi (2022), the Concorde's success was ultimately hampered by four primary factors:

1. Limited Payload and Range,
2. Poor takeoff and landing performance,
3. Takeoff and landing noise, and
4. The sonic boom it created while at cruise.

These factors resulted from regulatory and operational constraints aimed at societal concerns, e.g., safety and environmental considerations. For example, Webb & Takahashi (2022) cite Concorde's poor payload and range, subpar takeoff and landing performance, general noise, and sonic boom as big drawbacks to its operation. Moreover, they highlight several regulations, such as Title 14 CFR §25.113 *Takeoff Distance and Takeoff Run,* that limited where the Concorde could operate due to requirements for long runways. Webb & Takahashi (2022) also cite regulations in Title 14 CFR Part 36 *Noise Standards: Aircraft Type and Airworthiness Certification* that further limited how and where the Concorde could operate. Future chapters will discuss these regulations and other limitations in greater detail.

Overall, Concorde's failures were primarily due to its incompatibility with a system designed around conventional, subsonic aircraft. Webb and Takahashi (2020) highlight the aircraft's limitations in the context of aircraft performance, noise, and infrastructure requirements. The limitations imposed on the aircraft for safety, society, and the environment ensured the airplane would complete its service, fulfilling a unique niche – transatlantic crossings between the United States, the UK, and France.

## A Revival of Supersonic Air Travel

The idea of supersonic air travel has seen a revival in recent years. While the Federal Aviation Administration (FAA) banned supersonic flight over land in 1973 (O'Neill, 2022, p.1), new designs and techniques to mitigate sonic booms offer the possibility of opening the skies to supersonic air travel once again. Research and development on technologies that enable supersonic air travel have continued despite the retirement of the Concorde.

There has been growing interest in reviving supersonic air travel over the past 20 years. Research programs such as the NASA High-Speed Civil Transport (HSCT) Program, Defense Advanced Research Projects Agency (DARPA) Quiet Supersonic Program (QSP), and the NASA N+2 Supersonic Program pioneered research into technologies to make supersonic air travel quieter and more affordable (Webb & Takahashi, 2022). Offshoots of this research have made their way into the civil sector, allowing private companies to build on these technologies to bring new aircraft to market. Boom Supersonic and Aerion are at the forefront of the revival of supersonic aircraft development (Webb & Takahashi, 2022). While Aeron has since declared bankruptcy (Reed, 2021), Boom has made significant progress in developing its technology demonstrator, the XB-1 (Figure 2), which achieved its first supersonic cruise on January 28, 2025 (Boom Supersonic, 2025).


**Figure 2. Boom XB-1 in Supersonic Cruise (Boom Supersonic, 2025)**

Similarly, a partnership between NASA and Lockheed Martin has developed a demonstrator aircraft, the X-59 (Figure 3), as part of the Quiet Supersonic Technology (QUESST) program (NASA, 2025). Like the XB-1, the X-59 is intended to demonstrate new technologies for further development of supersonic air travel, such as design techniques to minimize sonic booms to a dull “thump” (NASA, 2025). The X-59 has yet to make a supersonic cruise as of the drafting of this paper. While the ventures from Boom Supersonic and the QUESST program are not the only supersonic transport aircraft in development (Venckunas, 2023), their development programs are likely the most mature.

**Figure 3. NASA/Lockheed X-59 Demonstrator (NASA, 2025)**

However, the pursuit of supersonic air travel is not without its challenges. While aircraft manufacturers like Boom Supersonic have signed purchase agreements with companies like United Airlines to purchase new supersonic aircraft, other companies like Aerion Supersonic, which was partnered with highly experienced aircraft manufacturers like Lockheed Martin and GE Aviation, have collapsed (O'Neill, 2022, p. 1). These new, more efficient, low-boom designs could make supersonic transport aircraft viable for routes beyond oceanic transits (O'Neill, 2022, p. 2). However, challenges remain. With the collapse of Aerion, it is abundantly clear that while there is a demand for faster air travel, navigating the challenges of bringing such an aircraft to market is difficult. Understanding these challenges and how they contribute to the broader problem of integrating these aircraft into the NAS is essential to understanding the extent to which supersonic air transport will become a reality.

## Research Problem Statement

A revival of supersonic air travel at scale offers the potential for significant changes to how we view air transport. Supersonic air travel has the potential to bring new technology needs, considerations for aircraft routing and handling by ATC, procedures, and considerations for how to manage such things as aircraft noise and sonic booms (Underwood, 2017). This is in addition to questions regarding profitability (Klingenberg & Belke, 2024) and unique regulatory requirements for their operation (Webb & Takahashi, 2022), among others. This thesis identifies essential issues, regulations, policies, and technological considerations required to make routine supersonic air travel a reality. By identifying issues, regulations, and technological trends regarding supersonic air travel, this research will identify some of the most significant issues that may influence the integration of supersonic aircraft into the NAS. This answers the critical question: *What are the most significant trends and potential challenges to the supersonic transport aircraft revival?*

## Research Objectives

A revival of supersonic air travel will likely impact the aviation ecosystem. Questions still need to be answered regarding how well high-speed aircraft will integrate into the NAS at scale, and there are numerous other questions regarding how they will impact communities, the environment, air traffic, and other aspects of our society. Furthermore, economic, technical, and regulatory questions will decide whether supersonic air travel flourishes or fails.

This research seeks to identify the key issues and variables relating to the revival of supersonic air travel in the NAS. It will identify and classify issues within the following categories:

1. Regulatory considerations,

2. Technological considerations,
3. Societal considerations,
4. Environmental considerations, and
5. Economic considerations.

This research will identify the critical issues within these categories based on a thorough review of the literature and technical papers on supersonic air transport.

## Scope of Research

This research will identify critical issues relating to the growth and reintroduction of supersonic air travel into the NAS. It will identify core issues based on a review of technical papers and a classification of themes, core arguments, and data. This research will recommend areas of future research that may warrant additional focus and lend themselves to further exploration and technical solutions.

## Structure

Five chapters define core content and offer a structured approach to identifying issues associated with the revival of supersonic air travel in the NAS. They discuss the research problem, methodology, and other research components. This thesis is composed of the following chapters:

Chapter 1: Introduction

Chapter 2: Methodology

Chapter 3: Literature Review

Chapter 4: Analysis

Chapter 5: Discussion and Future Work

# Chapter 2 - Methodology

## Introduction

This study employs a qualitative approach to identify the key enablers and challenges to successfully integrating supersonic aircraft into the NAS. A qualitative approach was chosen due to the high variability in factors affecting supersonic aircraft's successful (or unsuccessful) integration into the NAS. While there are undoubtedly quantitative variables, such as those affecting economic considerations, the results of certain environmental studies, and hard data from various verification and validation efforts for aircraft and equipment, these things alone may not be the sole indicators of the future of supersonic air travel. This is especially true as integrating supersonic aircraft into the NAS is as much of a problem of public opinion, regulation, and policy as it is about technological progress and economic viability. Technical solutions enabling supersonic air travel must be weighed against the regulatory and policy issues determining how far and how fast supersonic aircraft will integrate. This is an issue of both practicality and rational assessment of the regulatory landscape when compared to the speed and direction of the industry and the concerns of the flying public. It is for these reasons that this study employs a qualitative methodology. While numerical models and quantitative metrics may determine the trajectory of certain facets of the supersonic transport sector, these things are not solely indicative of success or failure but rather components of a more extensive set of issues. Like the challenges of integrating unmanned aircraft systems (UAS) into the NAS, some factors are driven entirely by regulatory processes, policy, demand, and rational connections between these things and the technological components that enable routine flight. This study attempts to look at crucial variables in a manner that provides a snapshot of the current state of supersonic air travel and identifies areas that may influence its future development and growth.

The following sections in this chapter outline the foundational aspects of a meta-analytical approach to qualitative research. This study borrows from the guidance in *Meta-Synthesis of Qualitative Case Studies* by Hoon (2013) and *How to Conduct a Meta-Analysis in Eight Steps: A Practical Guide* by Hansen, Steinmetz, & Block (2022). Since this study adopts a meta-analytical methodology, it is warranted to discuss the fundamental aspects of the approach, its associated processes, and some of its limitations. The following sub-sections offer an overview of the approach, challenges, limitations, and coding and sorting processes used for the literature in this study.

## Overview: Qualitative Meta-analysis and Meta-Synthesis

A qualitative meta-analysis offers a procedural approach to gathering a meaningful literature sample within a given field. More importantly, it provides a broad overview of a research question in a particular field (Hansen, Steinmetz, & Block, 2022, p.1). Hoon (2013) further positions meta-synthesis [combining data from multiple studies to synthesize information or a theory] as "… an exploratory, inductive research design to synthesize primary qualitative case studies to make contributions beyond those achieved in the original studies" (p. 527). This places meta-analysis, and by extension, the associated synthesis processes, as a versatile approach that can inform quantitative and qualitative outcomes. This research emphasizes qualitative applications, providing an overview of current work in the field and offering an analysis of information that informs answers to the research question. As such, this study will utilize a coding system and correlate literature consistent with the steps discussed later in this section.

Hoon (2013) outlines eight steps for conducting a qualitative meta-synthesis as part of a broader analysis, framing them in a qualitative approach to case study analysis and constructing theories. Hansen, Steinmetz, and Block (2022) also outline an eight-step process for meta-analysis. However, Hoon (2013) provides a more generic approach with broader applicability and an emphasis on qualitative research. Given that this study adopts a qualitative approach to meta-analysis and synthesis, the steps outlined in Hoon (2013) are ideal for analyzing and synthesizing information from the literature. The following sections provide an overview of the steps outlined by Hoon (2013) and provide a stepwise approach to building a theory synthesized from qualitative case studies, with support from Hansen, Steinmetz, and Block (2022), where appropriate.

### Step 1 – Framing the Research Question

Like any research problem, a qualitative meta-analysis starts with a research question. Properly defining a research question is critical, as it offers a way to determine the scope of the analysis and the depth and breadth of literature to consult. Hansen, Steinmetz, and Block (2022) cite that the first major hurdle in selecting a research question is that the number of publications in a given field may skyrocket if the research question is too broad. This implies that researchers must be able to adequately refine their research question to control the scope of the work. While more published works may lend themselves to a thorough analysis, it may also lead to an unmanageable workload (Hansen, Steinmetz, & Block, 2022, p. 2). One potential approach recommended by Hansen, Steinmetz, and Block (2022) is to replicate an existing meta-analysis to either test its findings with newly developed methods or new data (p. 2). Similarly, Hoon (2013) identifies the need to define a well-specified research question (p. 530). The implication is that a well-developed research question is fundamental to determining the scope of a qualitative meta-analysis and constraining the literature and methodologies used to answer the question. More importantly, synthesizing knowledge from a qualitative meta-analysis must be guided by a sound research question grounded in theory and supported by literature.

### Step 2 – Locating Relevant Research

A qualitative meta-analysis is a systematic, reproducible literature review that follows the definition of the research question. Hoon (2013) highlights the necessity of identifying research relevant to the topic and incorporating targeted searches in databases using Boolean operators. This aligns with the approach defined by Hansen, Steinmetz, and Block (2022), who describe a literature search as often involving a keyword search or some regimented method of searching for literature in a reproducible manner. To simplify the process, Hansen, Steinmetz, and Block (2022) recommend consulting related meta-analyses or other topic-related literature reviews to understand the available literature. While these methods may provide a good cross-section of literature on the subject, obtaining various sources is crucial to ensure a thorough analysis. Hansen, Steinmetz, and Block (2022) also recommend consulting sources from multiple databases and unpublished literature from other sources. This process allows literature to inform the research question while covering various sources, creating a viable literature sample for further analysis.

### Step 3 – Inclusion/Exclusion Criteria

This step involves deciding which literature to include or exclude from the analysis. Decisions on which literature to include or exclude are typically based on a set of criteria from the researcher that allows the filtering of relevant and irrelevant content. Hoon (2013) emphasized the importance of establishing inclusion/exclusion criteria, as it significantly affects a study's validity. Hoon (2013) establishes example inclusion criteria based on quality, specific relationships to the research question/topic, and the nature of the study itself – i.e., case study.

The implication is that the researcher may set these criteria to ensure the inclusion of relevant literature to address the research question and exclude literature that is either irrelevant or out of scope.

### Step 4 – Extracting and Coding Data

Coding is organizing literature and information to allow for comparison and analysis. Hansen, Steinmetz, and Block (2022) state that a coding scheme for a meta-analysis is typically context-driven and emphasizes findings against the backdrop of relevant contextual information. To that end, a coding system allows researchers to extract information from relevant literature sources and sort information for a more detailed analysis.

### Step 5 – Analyzing on a Case-Specific Level

Analysis may begin following the initial selection and coding of the literature. This includes an analysis of relevant literature on a case-specific level. Hoon (2013) specifies that an analysis should address the research question and each case (p. 538). This includes ensuring that causal factors and variables within each study are accounted for (Hoon, 2013, p. 538). The case-specific analysis provides a deeper look at variables, correlations, and other relationships between relevant literature that inform a theory and address the research question.

### Step 6 – Synthesis on a Cross-Study Level

This step expands upon step five, increasing the scope of the analysis to look for commonalities, disconnects, and relevant information across various studies. Hoon (2013) describes this step as a point where a researcher compares and contrasts multiple studies to identify where they may agree and differ. This step allows a researcher to derive meaning from various studies to draw parallels that support the development of a theory and provide answers to the core research question.

### Step 7 – Building a Theory from a Meta-Synthesis

This step is the culmination of steps 1 – 6. It involves constructing a theory and/or supporting evidence that answers the research question. Hoon (2013) provides an example of a theory and justification of that theory from the literature and subsequent steps in the process. The theory and/or answer to the research question generated here is the culmination of the selection of literature, establishment of inclusion/exclusion criteria, extracting and coding data, analysis at the case level, and synthesis at the study level.

### Step 8 – Discussion

As with any study, there are bound to be primary considerations, limitations, and specific approaches to conducting the qualitative meta-analysis and subsequent synthesis. Hoon (2013) offers this step to address those considerations. The discussion provides an avenue to convey important information about the findings in a way that accounts for specific limitations, considerations, scope, or confounding factors.

## Application of Qualitative Meta-analysis and Meta-Synthesis

Given the research question and the qualitative nature of this research, the eight-step methodology described above is ideal. This approach offers an opportunity to explore the existing body of literature to identify current trends and patterns relating to supersonic transport aircraft's continued development and integration into the NAS. It represents a combination of the procedural aspects of a meta-analysis with a meta-synthesis component that offers the ability to develop emergent theories that mirror established qualitative approaches, such as grounded theory. The methodology adopted here represents a combination of qualitative meta-analysis and a meta-synthesis approach that is representative of the fundamental concepts present in grounded theory (Corbin, 2017; Timulak, 2014). Furthermore, this methodology borrows from the strengths of established qualitative research approaches, allowing data collection and supporting conclusions to be drawn to answer the research question. The following sub-sections outline inclusion/exclusion criteria and the general strategy for coding literature. Further discussion of literature, analysis, and discussion is covered in chapters 3 – 5.

## Inclusion/Exclusion Criteria

Identifying supersonic air travel's current and future trajectory in the United States requires analyzing contributing factors that enable its potential growth and integration into the NAS. An initial literature search identified five essential components of supersonic air travel that contribute to trends in its overall state and future trajectory. Figure 4 shows these components and how they relate to the growth of supersonic air travel.

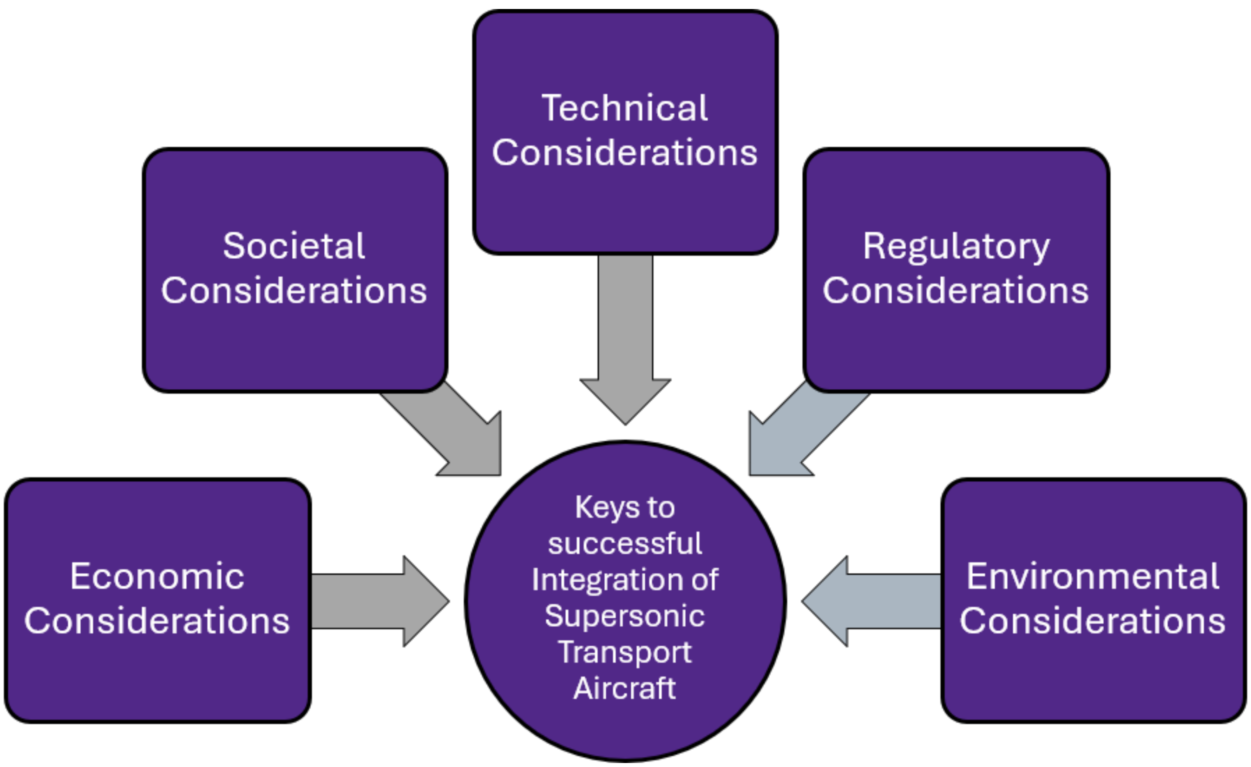


**Figure 4. Keys to Successful Integration of Supersonic Transport Aircraft**

The five key factors affecting the successful integration of supersonic transport aircraft into the NAS (Figure 4) were derived from an initial literature survey. Using Figure 4, the following considerations are critical to defining the success (or failure) of integrating supersonic transport aircraft into the NAS:

1. Regulatory considerations,
2. Technological considerations,
3. Societal considerations,
4. Environmental considerations, and
5. Economic considerations.

These five considerations capture high-level themes in the literature and point to elements that define the core subject areas of this research.

Table 1 identifies the types of works included in the literature review. These works consist primarily of scholarly articles but include non-peer-reviewed sources such as regulations, news articles, and industry white papers.

**Table 1. Types of Papers Included in Literature Review**

| Type of Publication | Rationale |
|---|---|
| Scholarly works – i.e., peer-reviewed article(s) | Peer-reviewed articles often capture the state-of-the-art in given topic areas and convey essential considerations for technical or practical issues based upon research. |
| Regulations and regulatory guidance from the FAA | Regulations/Regulatory guidance offers perspective directly from regulators, framing approaches of industry and academia when solving technical or regulatory challenges. |
| Historical articles and papers | Articles relating to the history of supersonic air travel. |
| News articles relating to current events | These articles often capture the most recent historical, technological, and economic considerations for developing and integrating supersonic aircraft into the NAS. |

| | |
|---|---|
| Industry white papers | Industry white papers often form the basis for use cases of technical and regulatory solutions. |

Similarly, Table 2 identifies criteria for the types of literature listed in Table 1 to be included in this literature review. Literature that did not meet the specified criteria was excluded from the analysis. However, literature that did not meet the specified criteria was used as supporting documentation – i.e., historical or background information that pertains to more recent research, technological advancement, or policy initiatives.

**Table 2. Criteria for Inclusion in Literature Review**

| Criteria for Inclusion | Rationale |
|---|---|
| Papers must relate to one of the five components (themes) identified above. | This requirement constrained the scope of this research to relevant topics. |
| Sources must capture some relevant aspect of supersonic transport technological development, history, airspace integration, or other pertinent factors that influence components in Figure 4. | This requirement ensures that the literature is relevant beyond simply addressing the key components identified in Figure 4. |

## General Approach to Coding and Sorting Literature

As mentioned above, coding is essential to a qualitative meta-analysis and synthesis. Coding ensures that only relevant literature is analyzed, and it provides a tool to compare different literature sources when analyzing data and synthesizing theories. The table below (Table 3) provides an example of the literature coding matrix used to sort literature for this study.

**Table 3. Example of Literature Coding Matrix**

| ARTICLE - SHORTHAND TITLE | APA 7 CITATION | ARTICLE TYPE | | | | | TOPIC(S) | | | | | INCLUDE? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCHOLARLY WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE | INDUSTRY WHITE PAPER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |
| | | - | - | - | - | - | - | - | - | - | - | - |

The matrix shown in Table 3 allows literature to be sorted consistently with the requirements specified in Figure 4 and Tables 1 and 2. The matrix provides a means to identify articles, provide citations, and sort them by how they meet established requirements for inclusion. Indications of whether an article will be included in the study are listed in the rightmost column. A copy of this matrix is found in Appendix.

## Limitations/De-Limitations of Qualitative Meta-analysis and Meta-Synthesis

As with any research methodology, various strengths and limitations are associated with this methodology. These strengths and weaknesses are rooted in the nature of the methodology itself, constraints of the study, and the tools used for analysis. This section discusses some of the strengths and limitations of this research methodology and their effect on the outcomes of this study.

### Strengths of Qualitative Meta-Analysis and Meta-Synthesis

The strengths of the qualitative meta-analysis and meta-synthesis approach are rooted in the nature of the methodology itself. It allows for the systematic collection of information and data extraction to address one or more research questions. These strengths are noted in both Hansen, Steinmetz, & Block (2022) and Hoon (2013), citing that a meta-analysis gathers and aggregates data from multiple sources and allows a researcher to identify patterns or trends in that data. Hoon (2013) further clarifies that a meta-synthesis enables a researcher to develop a theory surrounding aggregated data using observed patterns and/or statistical data gleaned from literature. Additionally, Hansen, Steinmetz, and Block (2022) highlight the ability to analyze data gathered from meta-analysis via statistical tools, increasing the objectivity of a study.

## Limitations of Qualitative Meta-Analysis/Meta-Synthesis

The methodologies associated with qualitative meta-analysis and meta-synthesis are not without their limitations. These limitations, like the strengths of these approaches, stem from the nature of the methodologies themselves. These limitations are also discussed within Hansen, Steinmetz, & Block (2022) and Hoon (2013). According to Hoon (2013), publication bias – i.e., published literature that reflects positive results being published instead of other forms of literature – may skew results. This increases the necessity to gather information from a variety of sources. Hansen, Steinmetz, and Block (2022) also cite the necessity of collecting data from various sources to reduce the likelihood of introducing biases. There are also challenges with a loss of context and subjectivity in the qualitative interpretation of data. This is highlighted by Hoon (2013) as partly a result of the qualitative nature of the interpretation data when synthesizing a theory via meta-synthesis. Finally, there is the limitation of time. From a rational perspective, a meta-analysis and meta-synthesis approach requires time. It takes significant time and resources to gather large quantities of literature, sort and code that literature, and interpret findings. Limitations on the time and resources available to conduct a study will create boundaries and limitations on its depth and scope.

# Chapter 3 - Literature Review

A literature review was the primary basis for this qualitative meta-analysis and subsequent meta-synthesis. This chapter captures an overview of the literature consulted to establish the current state and future trajectory of supersonic air travel in the United States. It compiles assessments of supersonic transport aircraft's current and future state through the lens of relevant literature that defines the basis for past, present, and future trends in supersonic air travel.

## NASA CONOPS – A Foundation

NASA's *Concept of Operations for Integrating Commercial Supersonic Transport Aircraft into the National Airspace System* (Underwood, 2017), henceforth referred to as the "NASA CONOPs," represents the culmination of a series of studies aimed at understanding the overall impact of supersonic air travel and its place within the NAS. The NASA CONOPs were developed to enable the integration of supersonic transport aircraft into the NAS, highlighting the benefits and challenges associated with integrating new and novel aircraft that, as of now, have seen little use over the continental United States.

According to Underwood (2017), the NASA CONOPs establish a pathway for understanding how to integrate supersonic transport aircraft into the NAS and identify the benefits and challenges. This document lays out the foundational approach to airspace integration through four sections:

1. Assumptions,
2. Study results,
3. Operational scenarios, and
4. Technology needs (Underwood, 2017).

This section explores the NASA CONOPs and discusses their potential ramifications on the future of supersonic transport aircraft. It discusses the general approach, studies, and influence the NASA CONOPs may have on future integration efforts and their impact on other sectors of supersonic passenger flight.

## NASA CONOPs – Assumptions

The NASA CONOPs outline specific assumptions regarding supersonic transport aircraft design, equipage, and operational assumptions. These assumptions drove the studies that informed the NASA CONOPs and highlighted the fundamental differences between supersonic transport aircraft and their conventional subsonic counterparts. A brief discussion follows of these assumptions and how they impacted the development of NASA's CONOPs for supersonic transport aircraft.

### Design Assumptions

Basic supersonic aircraft design assumptions captured within the NASA CONOPs are rooted primarily in the requirement to mitigate sonic booms and general aircraft noise (Underwood, 2017, p. 4). These design assumptions and general considerations stem from experience with the Concorde and early research regarding sonic booms and shock wave propagation from aircraft that cruise at or above Mach 1 (Underwood, 2017, p. 4). The results of early studies, such as a joint research between the FAA and NASA in the early 1960s regarding sonic booms over populated areas, found that sonic booms could range from a nuisance to a genuine concern. These studies, carried out over St. Louis, Missouri, between July 1961 and January 1962, resulted in the Air Force being approved for restitution in 800 damage claims resulting from supersonic overflight of populated areas (Underwood, 2017, p. 5). These studies laid the groundwork for restrictions on supersonic flights over land and the eventual banning of supersonic flight over land in April of 1973 (Underwood, 2017).

The challenges associated with sonic booms led to studies on designing aircraft to minimize sonic booms. These designs initially compromised aerodynamics, but improvements in computational fluid dynamics and modern design methods have since produced far more viable designs (Underwood, 2017, p. 5). Figure 5 shows examples of early design explorations focused on shaping and minimizing sonic booms.

**Figure 5. (Left) Shaped Sonic Boom Demonstrator (NASA, 2009b); (Right) Quiet Spike (NASA, 2009a)**

More recent evolutions in design methodology and advanced computation methods have allowed supersonic aircraft designs to evolve into more efficient, numerically driven designs. One such example is NASA’s X-59 quiet supersonic demonstrator (Figure 6).

**Figure 6. Rendering of NASA's X-59 Quiet Supersonic Demonstrator (NASA, 2016)**

**Equipage Assumptions**

The NASA CONOPs also made some important assumptions for supersonic transport aircraft. These assumptions address unique requirements for vision systems, avionics, communication, and navigation technologies that are anticipated to be prominent in aircraft designs (Underwood, 2017, p. 8). Equipage assumptions reflect unique or novel operational requirements from unique aircraft design characteristics.

One of the more significant challenges associated with computationally driven aircraft designs intended to minimize sonic booms is the problem of pilot vision (Underwood, 2017, p. 8). As shown in Figure 6, an aircraft optimized for low-boom performance is not necessarily optimized for pilot visibility. The conventional workaround for this problem was the drooping nose, like the one used on the Concorde (Figure 7), which could lower for better pilot visibility during takeoff and landing and retract to optimize the airplane for supersonic cruise (Underwood, 2017, p. 8).

**Figure 7. Concorde with Drooping Nose (Fitzgerald, 1974)**

New supersonic transport airplane designs are anticipated to use external vision systems to enable pilot visibility without requiring complex mechanical systems to reconfigure the aircraft for takeoff and landing physically. A rendering of the NASA X-59 cockpit (Figure 8) shows how an external vision system may be fitted into the cockpit instead of conventional windows.

**Figure 8. NASA X-59 External Vision System (NASA, 2019)**

In addition to sophisticated vision systems, new supersonic transport aircraft are assumed to incorporate a complete flight management system (FMS), allowing the flight crew to fully control all aspects of the aircraft while in cruise (Underwood, 2017). The NASA CONOPs assumes the crew will have access to an aircraft communication addressing and reporting system (ACARS) and data link capabilities, enabling the crew to send and receive data while communicating verbally with ATC (Underwood, 2017, pp. 11-12).

**Operational Assumptions**

The final group of assumptions that the NASA CONOPs provides establishes assumptions for the operational environment. Environmental assumptions provide context on infrastructure, airport/city pairs, and baseline airspace assumptions that provide a starting point for assessing procedural and operational characteristics of supersonic aircraft.

A core operational assumption for supersonic aircraft is a NextGen environment (Underwood, 2017, p. 12). Underwood (2017) states that this will allow easier integration and promote integrated air traffic rather than requiring segregation. Underwood (2017) cites the network-enabled capabilities of NextGen as being crucial to supersonic aircraft integration, particularly position, navigation, and timing (PNT) services, the availability of trajectory information, arrival and departure information, and other layered services that promote fast and accurate information exchange. Furthermore, Underwood (2017) highlights that the procedures used for handling Concorde in the past may not be practical for modern supersonic aircraft, and NextGen technologies may be adapted to serve supersonic aircraft.

Operational assumptions for supersonic transport aircraft specified within the NASA CONOPs can be listed as follows:

1. Full NextGen implementation will be in place. This includes conventional communication mediums as well as ACARS, system-wide information management system (SWIM) feeds, and ADS-B (Underwood, 2017, p. 13).

2. Minimum flight distances between (paired) cities are 800 nautical miles. This distance was determined by analysis within the routing segment of an initial investigation by NASA Langley in 2014 (Underwood, 2017, pp. 16 – 17).
3. No significant changes to airspace are anticipated. Underwood (2017) noted that supersonic transport aircraft will operate in Class A airspace while remaining below 60,000 feet (FL600), utilizing designated sectors. This should ensure that no airspace re-structuring is required for supersonic transport aircraft. However, more research is required to verify assumptions regarding the use of conventional arrival/departure procedures and the use of standard terminal arrival routes (STARs) and standard instrument departures (SIDs) (Underwood, 2017, p. 13).

**NASA CONOPS – Foundational Study and Scenarios**

The assumptions listed in the previous section were components of a broader study to understand better how supersonic transport aircraft will integrate into the NAS. The study, Supersonic Transport Operations in the National Airspace System Experiment (STONE), consisted of a detailed operational simulation to quantify supersonic transport aircraft's impact and operational nuances (Underwood, 2017, p. 14). This study provided insight into how and to what extent supersonic transport aircraft would integrate into the NAS and how and why they may differ from more conventional aircraft. According to Underwood (2017), the study addressed three research questions:

1. What possible encounter characteristics (geometry, relative speed, and altitude) may be faced if CSTs flew with current-day traffic levels?
2. What are the relative impacts of various assumed climb and descent profiles on flight time for a CST?

3. What is the approximate time savings for a supersonic transport aircraft compared to a modern-day subsonic transport aircraft flying the same route? (p. 14)

The STONE experiment sought answers to these research questions using full factorial batch simulation, with each scenario being deterministic. The implication was that only one replication of each scenario was enough to render statistically significant findings (Underwood, 2017, p. 14).

**Operational Assumptions**

The simulation tool used for this study was called the Traffic Manager Executable (TMX) and was a joint effort between NASA and NLR (Underwood, 2017, p. 14). This simulation tool, hosted at NASA Langley, was chosen for its ability to simulate supersonic aircraft and its fast-time simulation capability (Underwood, 2017). To simplify simulation and development time, the research team used a generic supersonic fighter aircraft model to surrogate for a supersonic transport aircraft. While not representative of a transport aircraft, it was close enough to enable reasonable approximations for the experiment (Underwood, 2017, p. 14). Finally, the research team employed a conflict detection algorithm to simulate air traffic encounters. The primary assumption for this study component was a conflict volume with a five nautical mile radius and an altitude of ±1,000 feet from the aircraft's position (Underwood, 2017, p. 14). However, Underwood (2017) notes that the conflict algorithm was not tuned explicitly for some of the assumptions of this experiment, so the conflict resolutions may not necessarily have represented reactions that would be seen in real-world traffic conflicts (p.14).

**Scenario Description and Independent Variables**

The scenario for STONE was developed based on operational profiles for the Concorde, accounting for critical phases of flight and procedural nuances associated with each (Underwood, 2017). Figure 9 highlights the flight profile and associated phases with each segment of the flight.

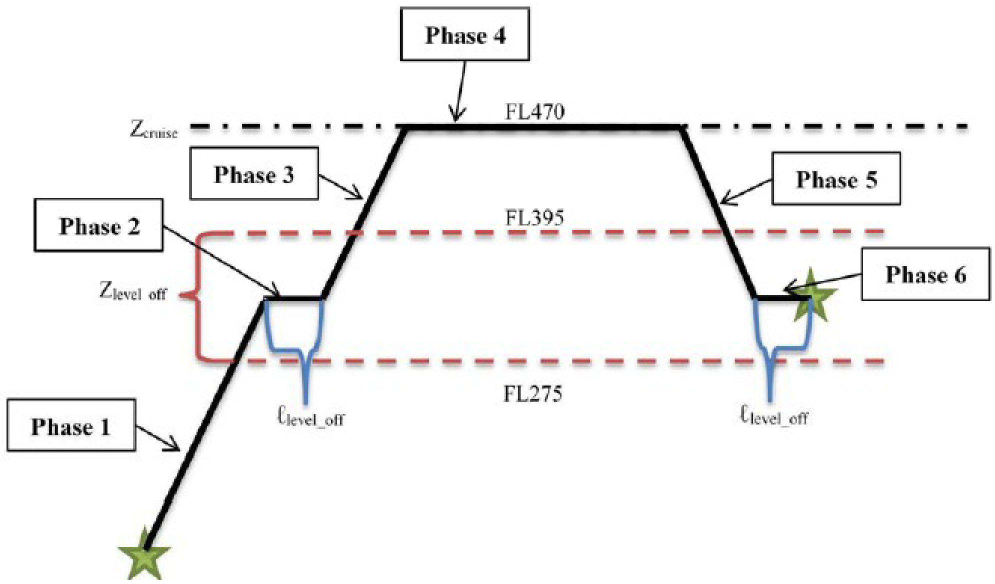


**Figure 9. STONE Flight Profile (Underwood, 2017)**

The NASA research team explored the following variables using this flight profile and simulated scenarios:

1. Aircraft route,
2. Departure time,
3. Length of intermediate subsonic level-off, and
4. Altitude of level-off (Underwood, 2017).

Additionally, the study used the following city pairs to evaluate the impact of routing, timing, and other variables. Table 4 highlights city pairs, with plus signs representing existing routes (Underwood, 2017).

**Table 4. STONE City Pairs (Underwood, 2017)**

| | | Arrivals | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | KSEA | KSFO | KLAX | KLAS | KPHX | KDEN | KDFW | KIAH | KORD | KATL | KMIA | KIAD | KJFK | KBOS |
| Departures | KSEA | | | | | + | + | + | + | + | + | + | + | + | + |
| | KSFO | | | | | | + | + | + | + | + | + | + | + | + |
| | KLAX | | | | | | + | + | + | + | + | + | + | + | + |
| | KLAS | | | | | | | + | + | + | + | + | + | + | + |
| | KPHX | | | | | | | + | + | + | + | + | + | + | + |
| | KDEN | | | | | | | | | + | + | + | + | + | + |
| | KDFW | + | + | + | | | | | | | | + | + | + | + |
| | KIAH | + | + | + | + | + | + | | | | | | + | + | + |
| | KORD | + | + | + | + | + | | | | | | + | | | |
| | KATL | + | + | + | + | + | + | | | | | | | | + |
| | KMIA | + | + | + | + | + | + | | | + | | | | + | + |
| | KIAD | + | + | + | + | + | + | | + | | | | | | |
| | KJFK | + | + | + | + | + | + | + | + | | | + | | | |
| | KBOS | + | + | + | + | + | + | + | + | | | + | | | |

## NASA CONOPS – STONE Study Summary and Results

The STONE study offered operational and procedural guidance regarding the future integration of supersonic aircraft into the NAS. According to Underwood (2017), the study highlighted the need for expedited climbs to cruise and limitations associated with aircraft encounters during climbs to cruise and descent (p. 31). The study also highlighted technology needs and potential challenges for controllers with descent, arrival, and approach segments of flight plans (Underwood, 2017, p. 31).

## NASA CONOPS – Conclusions and Notes

The NASA CONOPs outline a pathway for integrating supersonic transport aircraft into the NAS and define a starting point for future research and development to facilitate integration (Underwood, 2017). While the NASA CONOPs make some basic assumptions regarding aircraft design, equipage, infrastructure, and procedures, they incorporate data from research, e.g., STONE, to provide technological and procedural requirements for future supersonic transport aircraft integration (Underwood, 2017, p. 41). The result is a set of CONOPs that provide a foundation for integrating supersonic transport aircraft into the NAS while leaving room for future research to explore other issues, technological considerations, and procedural requirements that may arise. The following represents a summary of operational requirements identified within the NASA CONOPs and/or STONE (Underwood, 2017, pp. 32 – 38):

1. Preflight procedures will be similar to conventional subsonic aircraft with added emphasis on overpressure mitigation.
2. Supersonic transport aircraft are not anticipated to have specific taxi restrictions.
3. Supersonic transport aircraft will likely follow the same noise requirements as conventional, subsonic aircraft, with added automation to enable efficient speed and trajectory changes.
4. Supersonic transport aircraft may be required to maintain a subsonic cruise before commencing a supersonic cruise.
5. A clear corridor and uninterrupted climb are required for acceleration from subsonic to supersonic cruise.
6. Supersonic transport aircraft are anticipated to cruise at the most economical altitude and Mach number. Anticipated cruise altitudes are between FL450 and FL500. Traffic conflicts at these altitudes should be minimal.
7. Deceleration and descent should be uninterrupted, similar to ascent to supersonic cruise. Ideally, the aircraft will transition into an arrival procedure.
8. Arrival procedures should not require special handling by ATC and should not interrupt conventional subsonic traffic.

Additionally, the NASA CONOPs identified the following technology needs (Underwood, 2017, pp. 39 – 40):

1. Technologies are needed to manage corridors for ascent and acceleration, descent and deceleration, and cruise. These technologies include systems to manage traffic conflicts and automate trajectory planning.
2. Tools for mapping sonic booms and planning for overpressure mitigation.
3. Tools for optimizing routing and managing traffic conflicts.
4. Technologies for managing arrival and approach procedures that increase efficiency, routing, and spacing with other traffic.

The findings, conclusions, and recommendations from the NASA CONOPs provide a reasonable starting point and a solid foundation for defining the integration of supersonic transport aircraft into the NAS. More importantly, the NASA CONOPs offer a reasonable point of comparison for other literature when comparing assessments of technology, procedures, and other pathways to integrate new, high-speed aircraft into our airspace. The following sections highlight regulatory, technical, societal, and environmental considerations for operating supersonic transport aircraft. These considerations will be compared with the NASA CONOPs when appropriate.

## Regulatory Considerations

The regulatory framework is critical to how supersonic aircraft integrate into the NAS. Several regulations guide how, when, and to what extent supersonic aircraft may operate in the NAS. These regulations guide things like special flight authorizations, compliance with 14 CFR Part 36, noise limits, and other facets of aircraft operation. This section explores the existing regulations pertaining to supersonic aircraft.

### Applicability: Relation to Part 36 (14 CFR §91.801)

Title 14 CFR §91.801 outlines the applicability of operating rules outlined in 14 CFR Part 91 and associated noise limitations within 14 CFR Part 36. This requires that supersonic aircraft comply with basic operating rules and set noise requirements. 14 CFR §91.801(a)(3) states:

> Sections 91.803, 91.819, and 91.821 apply to U.S.-registered civil supersonic airplanes having standard airworthiness certificates and to foreign-registered civil supersonic airplanes that, if registered in the United States, would be required by this chapter to have U.S. standard airworthiness certificates in order to conduct the operations intended for the airplane. Those sections apply to operations under this part and under parts 121, 125, 129, and 135 of this chapter (Applicability: Relation to Part 36, 2013).

This paragraph outlines applicable regulations for civil supersonic aircraft that operate within the NAS. It also identifies applicability based upon specified operating certificates – i.e., 14 CFR §91.121, 125, 129, and 125. Additionally, 14 CFR §91.801(b) provides further definitions and distinctions between subsonic and supersonic aircraft per 14 CFR §36.

### Part 125 Operators: Designation of Applicable Regulations (14 CFR §91.803)

Title 14 CFR §91.803 provides guidance for applicable regulations for airplanes that fall within the purview of 14 CFR §91 and are operated under rules established within 14 CFR §125. 14 CFR §91.803(c) applies to supersonic aircraft. It states:

> For each supersonic airplane operation to which requirements prescribed under this subpart did not apply before November 29, 1980, because the airplane was not operated in the United States under this part or part 121, 129, or 135 of this

> chapter, the requirements of §§ 91.819 and 91.821 of this subpart apply (Part 125 Operators, 2002).

This implies that 14 CFR §§91.819 and 91.821 apply to all supersonic aircraft operated in the U.S. under 14 CFR §121, 129, or 135 before November 29, 1980.

### Civil Aircraft Sonic Boom (14 CFR §91.817)

This regulation prohibits civil aircraft from exceeding Mach 1, creating sonic booms, unless in compliance with conditions within an authorization (Civil Aircraft Sonic Boom, 2021). It explicitly establishes regulations prohibiting civil aircraft from exceeding Mach one, except for aircraft that comply with the conditions established by an authorization per 14 CFR §91.818. This regulation also sets a limit on aircraft with a maximum Mach operating limit greater than one unless the sonic boom cannot reach the surface of the continental U.S. and the operator complies with any authorization under 14 CFR §91.818.

### Special Flight Authorization to Exceed Mach 1 (14 CFR §91.818)

Title 14 CFR §91.818 sets the conditions and requirements for a special flight authorization to exceed Mach 1. This regulation and its associated sub-parts offer a process for applying for a special flight authorization, requirements to operate outside of a test area, environmental findings, issuance of special flight authorizations, and the duration of special flight authorizations. It should be noted that 14 CFR §91.818 requires an application to the Administrator to conduct flights over Mach 1, and the requirements are a mixture of airworthiness and environmental requirements (Special Flight Authorization to Exceed Mach 1, 2021).

It is also important to note that this regulation has been updated to reflect the need to make compliance with existing regulations easier. Changes to this regulation were proposed in

2019 and codified in 2021. According to the Federal Register, the proposed rule is intended to update and modernize procedures for requesting special flight authorizations (Special Flight Authorizations, 2019). These changes will be discussed in more detail in the following sections.

### Civil Supersonic Airplanes That Do Not Comply with Part 36 (14 CFR §91.819)

Title 14 CFR §91.819 restricts the operation of civil supersonic aircraft that do not comply with the Stage 2 noise limitation specified in Title 14 CFR part 36 (Civil Supersonic Airplanes that do not comply, 1989). It sets requirements for applicability – civil supersonic airplanes operated after July 31, 1978, and it restricts airport use and flight of civil supersonic airplanes having undergone "acoustical changes" unless specific requirements within 14 CFR part 36 are met (Civil Supersonic Airplanes that do not Comply, 1989). Finally, this regulation restricts takeoff and landing times (Civil Supersonic Airplanes that do not Comply, 1989).

### Civil Supersonic Airplanes: Noise Limits (14 CFR §91.821)

Title 14 CFR §91.821 is quite simple. It sets straightforward restrictions for civil supersonic airplanes that are not the Concorde. This regulation states:

> Except for Concorde airplanes having flight time before January 1, 1980, no person may operate in the United States a civil supersonic airplane that does not comply with Stage 2 noise limits of part 36 in effect on October 13, 1977, using applicable trade-off provisions (Civil Supersonic Airplanes: Noise Limits, 2025).

The implication is that all aircraft other than the Concorde must comply with Stage 2 noise limits within 14 CFR part 36.

## Revisions to Existing Regulations

Some of the regulations listed above have been revised as recently as 2021 (Special Flight Authorizations for Supersonic Aircraft, 2019). As stated in the proposed rule within the

Federal Register, these revisions aimed to modify the existing regulations to make them easier to understand (Special Flight Authorizations for Supersonic Aircraft, 2019). The revisions contained within the proposed rule, which were integrated into existing regulations in 2021, still prohibit supersonic flight over land in the U.S. under most conditions (Special Flight Authorizations for Supersonic Aircraft, 2019). The result is that a de facto ban on supersonic flight over land in the U.S. remains in place.

### Regulations – Conclusions and Notes

The regulations listed above represent the current regulatory framework that defines how supersonic flight may be conducted in the U.S. Many of these regulations were drafted as a result of a perceived need to control sonic booms, which significantly restricts supersonic air travel, dictating routes, altitudes, etc. (Gardner, 1978). Existing regulations serve as a starting point for discussions surrounding the capability to develop, test, and bring new supersonic aircraft to market. This is particularly true as revisions to existing rules have taken place to reflect modern processes for approving authorizations and to account for technological innovations. However, they stop short of promoting supersonic flight over land in the U.S.

## Technical Considerations

Technical considerations for integrating supersonic transport aircraft into the NAS result from gaps in technological progress that must be addressed to enable smooth, safe, economic integration of supersonic transport aircraft into the NAS. These considerations stem from technologies that must be developed, improved, or conceived to enable routine commercial supersonic flight. These technologies may be found within the aircraft itself or may consist of specialized infrastructure, communications, or data-centric services that support the broader air traffic framework. This section explores the prominent technologies and technological gaps in the literature, framing them against a backdrop of a fully-realized supersonic transport network.

## Overpressure Mitigation and Noise

Unsurprisingly, one of the biggest technical challenges to integrating supersonic aircraft into the NAS is the mitigation of sonic booms. This is reflected by the regulatory restrictions on supersonic flights being firmly rooted in sonic boom and noise mitigation. This is further reinforced by the FAA's ban on supersonic flight over land due to the problems created by sonic booms (Civil Aircraft Sonic Boom, 2021); the challenges of overpressure and general noise must be addressed to enable routine flights over land. The literature indicates this is one of the larger issues facing routine supersonic travel.

The significance of sonic booms is highlighted within the NASA CONOPs, emphasizing the need to minimize sonic booms to enable supersonic flight over land (Underwood, 2017, p. 5). This is reflected in research and development regarding the mitigation and control of overpressure created when an aircraft breaks the sound barrier and is further reinforced in the literature, particularly by Goel and Jawahar (2022), who discuss the negative impacts of sonic shocks on people and structures.

Goel and Jawahar (2022) cite the primary effects on people as more of an annoyance, with sonic booms eliciting a startling response and a fear of damage to inhabited structures (pp. 1 – 5). While the effects of sonic booms on humans are generally benign, evidence suggests that prolonged exposure may cause adverse effects (Goel & Jawahar, 2022, p. 5). Similarly, Goel and Jawahar (2022) indicate that sonic booms can harm structures, causing rattling and apparent damage to structures that may already be weakened by cycles of light damage due to weather and other environmental factors (p. 5).

A survey of relevant literature indicates that technological solutions to mitigating sonic booms stem primarily from controlling and shaping the signature of the overpressure into a signature that is less “sharp” and distributed in a manner that is not so abrupt, potentially allowing supersonic aircraft to operate more freely over land. Figure 10 highlights the difference between a sonic boom from a conventional F-5E and the shaped sonic boom of a modified F-5E with specialized design characteristics for shaping and reducing the effects of overpressure.

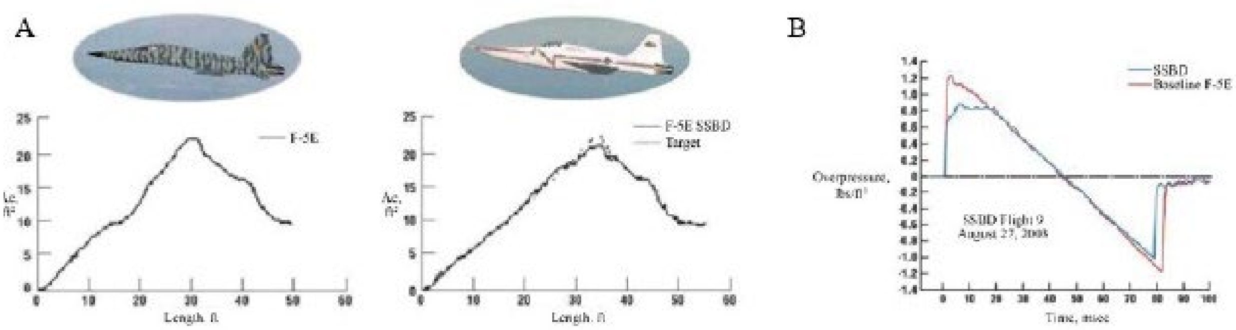


**Figure 10. Outcomes of Shaped Sonic Boom Demonstrator (Goel & Jawahar, 2022)**

The desire to mitigate sonic booms is reflected in other literature, including NASA sources on the X-59, which is hoped to pave the way for additional testing of quiet supersonic airplane designs (NASA, 2016) and further development from commercial test platforms into functional transport aircraft. Other studies, such as Berton et al. (2020) and *Supersonic Technology Concept Aeroplanes for Environmental Studies*, also emphasize noise mitigation in their concept design, reflecting a need to mitigate overpressure in cruise and general noise in terminal environments.

## Design for Optimization

Design optimization is another technical consideration that appeared throughout the literature consulted for this study. Supersonic aircraft are anticipated to use considerably more fuel than conventional subsonic aircraft. In some cases, it is anticipated that supersonic transport aircraft may use as much as five to seven times more fuel than conventional aircraft per kilometer (Schneider, 2021, p.31). The higher fuel consumption combined with the higher maintenance costs for supersonic fleets has been problematic in the past (Schneider, 2021, p.29), and it necessitates aircraft designs that are optimized for efficiency to ensure optimal performance and economic viability.

The literature search for this study revealed numerous papers on design studies for supersonic transport aircraft. However, not all of them could be considered part of the qualitative meta-analysis. However, two excellent examples of the need to design for optimization were identified in Hassan et al. (2020), *Design Tools for Conceptual Analysis of Future Commercial Supersonic Aircraft,* and Berton et al. (2020), *Supersonic Technology Concept Aeroplanes for Environmental Studies*.

Hassan et al. (2020) offer a more general approach emphasizing the design toolset and the calibration of key metrics for reliable outcomes. Hassan et al. (2020) provide an assessment of design considerations and trade studies for use in algorithmic generation of supersonic aircraft design constraints. This study addresses supersonic transport aircraft's technical, economic, and overall viability concerns using algorithm-based design tools to identify and optimize design constraints (Hassan et al., 2020). The study concluded that different combinations of constraints could affect takeoff weight, cruise conditions, and other technological improvements, with opportunities to conduct more trade studies for more design parameters (Hassan et al., 2020).

Berton et al. (2020) provide a focused assessment of design studies based on specific environmental considerations. In this study, the research team devises a notional 55-ton supersonic concept aircraft (Figure 11) to explore its environmental impact using design tools to optimize an aircraft design to account for fuel burn, noise, emissions, and other environmental considerations (Berton et al., 2020).

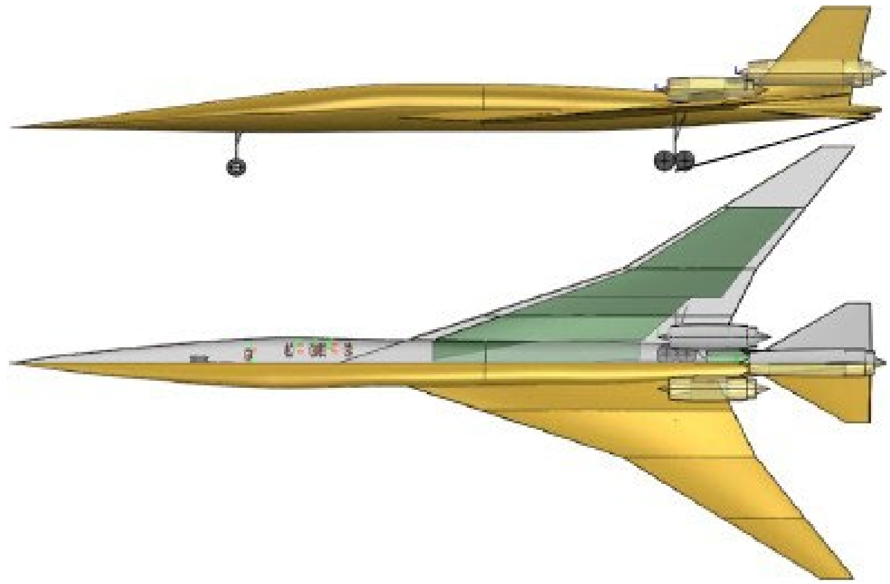

**Figure 11. 55-Ton Trijet Concept for Environmental Studies (Berton et al., 2020)**

The concept aircraft developed for this study considered airframe and propulsion, performance, noise, and procedural aspects – e.g., takeoff, landing, approach, etc. of the notional aircraft and their impact on the environment. The study ultimately developed a concept aircraft for use in NASA studies at the FAA and the International Civil Aviation Organization (ICAO) 's behest, investigated operations in terminal environments, noise requirements, and alternative engines, and assessed differences with a lighter, 45-ton configuration. Specific environmental outcomes of this study will be discussed in further detail in the Environmental Considerations Chapter of this study.

## Other Technologies

Other noteworthy technologies that will be needed to facilitate the integration of supersonic transport aircraft into the NAS are highlighted in the NASA CONOPS. Vision systems, datalinks, and systems to support critical phases of flight – e.g., climb/acceleration to Mach 1+ and descent/deceleration to subsonic speeds – are essential. For example, the NASA CONOPS (Underwood, 2017) indicates that a Flight Management System (FMS) with automation that will alleviate crew workload will be essential, as will data transmission systems that meet the latest standards (p. 11). While these technologies are not the only ones required to integrate supersonic transport aircraft into the NAS successfully, they represent a small cross-section of the most significant requirements.

The body of literature reviewed thus far indicates that technological hurdles represent some of the key barriers to making supersonic transport feasible, cost-effective, and practical. Technological innovation, particularly for mitigating sonic booms, is a common theme in literature. Similarly, the literature indicates that supersonic transport aircraft rely on sophisticated design philosophies emphasizing optimization, efficiency, and practical design characteristics to ensure effective integration into the NAS.

### Technical Considerations – Conclusions and Notes

As the literature implies, technical considerations for supersonic transport aircraft primarily focus on mitigating sonic booms and noise. Not surprisingly, these technical considerations seem well aligned with reducing some of the impact of existing regulatory hurdles to the operation of supersonic transport aircraft. Other technologies emphasized in the literature are intended to facilitate integrating these aircraft into the NAS. Technologies such as data links, flight management systems, and tools such as automation for aiding workload management are essential.

## Societal Considerations

Societal considerations for integrating supersonic transport aircraft can best be described as the greater ramifications of the operation of supersonic transport aircraft on both the flying and non-flying public. Societal considerations are a means to assess the impact of operating these aircraft based on a single fundamental question: "What impact does this mode of transportation have on society?" Societal considerations may be positive and negative, as they encompass some of the most basic impacts of supersonic transport aircraft on society, i.e., the effect on people beyond the aircraft and terminal. For this literature review, societal considerations are categorized as follows:

1. Noise, and
2. Integration and air traffic.

While economics and environmental considerations are societal considerations for supersonic aircraft in and of themselves, the author deemed them significant enough to stand alone in this paper. Thus, economic and environmental considerations stand alone as individual sections of the literature review. This is primarily due to the literature emphasizing their importance beyond basic noise, integration, and air traffic considerations.

The categories listed below are not intended to be in-depth summaries of every potential avenue for societal impact, but rather an overview of concepts identified in the literature. What is listed below reflects the most significant societal issues associated with supersonic air travel, as indicated in the literature, and is not comprehensive. The central recurring themes in the literature consulted for this study are as follows.

**Noise**

The noise associated with regular supersonic air travel is one of several contributing factors that have prevented supersonic air travel from becoming the norm. As mentioned in previous sections, noise associated with supersonic aircraft, including their sonic boom, is a considerable issue. Aircraft noise and the associated overpressure generated at cruise have an impact well beyond the immediate vicinity of the aircraft itself, and thus, are concerns as the supersonic aircraft industry attempts to find its footing again.

## Sonic Booms

Sonic Booms represent the most obvious hurdle to routine supersonic air travel. As mentioned in this paper, sonic booms are a significant issue for supersonic aircraft, so much so that there are regulatory requirements to mitigate them (see: 14 CFR 91.817). They may also have an adverse effect to on people with prolonged exposure, as stated by Goel & Jawahar, (2022) in which the authors reference a, "… mid- 1980s study in Nevada by United States Air Force found no evidence that intermittent exposure to sonic booms lead to adverse health conditions although prolonged exposure could have health effects or make existing conditions worse" (p. 5). Additionally, Goel & Jawahar (2022) identified that while there was seldom physical damage to structures from exposure to sonic booms, people regularly feared damage to their homes and property (p. 5). Thus, the issue of sonic booms is still a significant concern.

Literature indicates that emphasis is placed on new supersonic aircraft designs that prioritize sonic boom mitigation. This was highlighted in Underwood (2017) and Goel & Jawahar (2022). It is also reflected in the increased reliance on optimized aircraft design described in Berton et al. (2020). However, Leylekian et al. (2022) do not anticipate that the next generation of low-boom aircraft will have perfected sonic boom mitigations and anticipate the continued restriction of supersonic flight over land until the technology is perfected. This contrast highlights that the next generation of supersonic air transport aircraft will likely rely on optimized designs for sonic boom mitigation. However, they may also initially struggle to meet minimum noise requirements. This struggle is reflected in an Air and Space Law article by Robert Payne (Payne, 2024). Payne laments the regulatory hurdles posing significant challenges to even the most advanced technical solutions to sonic booms. While there will undoubtedly be technological solutions for mitigating sonic booms, there will likely be some initial challenges in bringing them to market.

### Noise in Terminal Environments

Aside from the noise associated with sonic booms, there are issues with noise in terminal environments, which can potentially affect all who live near airports that service supersonic aircraft. Underwood (2017) referenced past issues with the Concorde at Dulles, citing that it accounted for less than one percent of all takeoffs and landings during its service at Dulles and yet generated the vast majority of noise complaints (p. 7). The challenge of noise in and around airports is still a significant issue. Leylekian et al. (2022) indicate that parallel efforts are needed to address aircraft noise, including new standards for supersonic aircraft and technology development (p. 132). The suggestion is that takeoff and landing noise should be addressed even before the challenge of sonic booms (Leylekian et al., 2022).

## Integration and Air Traffic

Ensuring a seamless integration of supersonic transport aircraft with the existing air traffic system is a key component of reintroducing supersonic transport aircraft into the NAS. This integration must account for the unique aspects of supersonic aircraft, with other considerations, such as maintaining separation from other aircraft, noise abatement and mitigation, flight phase management – e.g., climb, cruise, etc., and terminal operations.

Air traffic procedures for supersonic transport aircraft will likely differ somewhat from those of conventional transport aircraft due to their unique nature and performance characteristics. Underwood (2017) highlights the likelihood that supersonic aircraft will require a climb and acceleration and a descent and deceleration phase, which ideally would remain uninterrupted. This would require ATC to understand each supersonic aircraft's climb/descent and acceleration/deceleration requirements. This was true with the Concorde, which required ATC to understand the aircraft's need to climb, accelerate, descend, and decelerate along a corridor (Underwood, 2017, p. 35). This highlights the need for future supersonic transports to be under ATC direction and have ample room for acceleration and deceleration. Similarly, special requirements may be needed in the terminal environment. This is not only the case for potential noise abatement, but it may also be required to conduct approach and departure procedures (Underwood, 2017).

An additional consideration for supersonic transport aircraft is the notion of route optimization. This is reflected in Janić (2020) and Wen et al. (2024), where the authors emphasize the importance of optimizing routing. The need for route optimization is due to various factors, including navigating around weather, optimizing fuel, and mitigating the effects of sonic booms (Wen et al., 2024). Janić (2020) cites similar reasons but expands to include the impact of novel fuels, such as liquid hydrogen ($LH_2$), the need for economic efficiency, and greenhouse gas emissions. Wen et al. (2024) concluded that routing tools may aid in understanding the operational constraints of supersonic transport aircraft and assist in analyzing various mission profiles. Similarly, Janić (2020) identified areas where supersonic and subsonic aircraft may differ. For example, Janić (2020) identified noise as a key factor as supersonic transport aircraft are reintroduced into the skies. Janić (2020) also found that supersonic aircraft could have approximately 2.9 times higher productivity thanks to their much higher cruising speed and shorter turnaround, using the same routes as subsonic aircraft.

In addition to air traffic considerations, supersonic transport aircraft may require unique or novel infrastructure. DeRoo & Takahashi (2024) performed a study in which they evaluated some of the most significant factors affecting the economic viability of supersonic transport aircraft. As part of this study, they found that supersonic aircraft may require different terminal infrastructure, longer runways, and unique provisions for maintenance (DeRoo & Takahashi, 2024).

### Societal Considerations – Conclusions and Notes

Challenges associated with integrating supersonic air traffic into the NAS extend beyond the requirements for route optimization, ATC knowledge of performance, and the need for supersonic aircraft to use acceleration and deceleration corridors. However, these unique challenges are some of the more significant issues identified in the literature. These challenges are in addition to potential changes in infrastructure to accommodate novel aircraft. Further exploration of approach/departure procedures and the impact of subsonic performance of supersonic aircraft in terminal environments is warranted.

## Environmental Considerations

Alongside the technical challenges associated with supersonic transport aircraft, environmental considerations will likely influence the growth and sustainment of supersonic air travel in the United States. As previously mentioned, there are serious concerns regarding aircraft noise from sonic booms and general noise in and around airports. These are captured in existing regulatory requirements for environmental impacts and noise mitigation (Special Flight Authorization to Exceed Mach 1, 2021). While these constitute significant environmental impacts, they may be seen as separate from more direct environmental concerns stemming from aircraft emissions that may deleteriously affect Earth’s climate. This section discusses environmental considerations for the future of supersonic air travel in the United States, addressing some of the significant concerns, technical challenges, and proposed solutions to the problem.

A study by Weit et al. (2021) explored methods for estimating supersonic aircraft emissions using publicly available data. This study used routing data for existing commercial aircraft, aircraft type data, information on passenger loads, market forecast data, and a scenario-based approach to arrive at its findings. The study estimated supersonic aircraft operations using the above data categories, historical data comparisons, and assumptions regarding technology, market demand, and growth. The study concluded that higher demand may significantly impact the environment between 2035 and 2050, stating $CO_2$ emissions could increase anywhere from 3 – 5 % above the assumed baseline of 2018 (Weit et al., 2021). However, Weit et al. (2021) acknowledge early on that there is uncertainty regarding increased fuel burn per passenger on $CO_2$ levels when considering aviation on a global scale. They also acknowledge uncertainties with regulatory constraints prohibiting supersonic flight over land, which may affect outcomes (Weit et al., 2021).

Matthes et al. (2022) encountered similar limitations to Weit et al. (2021) in their study exploring supersonic aircraft emissions. The study highlights that emissions from supersonic aircraft have been a concern since the development of supersonic aircraft began, and stem from the release of nitrogen oxides ($NO_X$) that may impact the stratosphere and ozone layer (Matthes et al., 2022)[1]. Regulatory efforts have been made by the International Civil Aviation Organization (ICAO), and numerous studies have been carried out to explore the phenomenon over the past 50 years (Matthes et al., 2022). Matthes et al. (2022) also state that while there is a large body of scientific knowledge surrounding the potential impacts of supersonic transport aircraft on the environment, there are few, if any, consolidated works that adequately assess the potential impact of a variety of combined factors (Matthes et al., 2022, p. 2). The study by

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[1] This study addresses non-$CO_2$ sources of environmental impact.

Matthes et al. (2022) concluded that there is value to be gained through additional study, citing the need for accounting for uncertainty in modeling and estimates while acknowledging that routing, engine technology, and supersonic flights over land will be contributing factors. While different in scope and scale from Weit et al. (2021), these findings highlight some limitations and assumptions that make understanding the environmental impact challenging.

Similar to the above, a study by Mane et al. (2024) evaluated fleet-level impacts of commercial supersonic aircraft using the Fleet-Level Environmental Evaluation Tool (FLEET) to analyze the impact of supersonic aircraft emissions within the U.S. air routes and beyond. The study used a series of assumptions and modeling techniques. This study incorporated a complex modeling technique that assessed variables similar to those previously mentioned in the studies: routing, fuel burn, and technological advancement. The study concluded that the supersonic service is linked to the profitability of operations, citing that increased efficiency of supersonic transport aircraft is necessary to reduce emissions (Mane et al., 2024). This conclusion was reached by analyzing the operations of a notional 55-passenger supersonic transport aircraft and comparing it to alternative concepts, assessing routing, demand, and other factors. Mane et al. (2024) highlighted that sustainable aviation fuels (SAF) may offset increased emissions for supersonic aircraft. However, there are tradeoffs regarding cost, availability, and demand, which decrease with increased costs of SAF.

## Environmental Considerations – Conclusions and Notes

The studies reviewed on the environmental impact of supersonic transport aircraft point to a need for further study to ascertain the real impacts of supersonic aircraft on the environment. The studies listed above point to a potential for increased environmental impact that is not fully understood and highly dependent on cost, regulatory constraints on supersonic flights over land, technology/efficiency, and other factors that will affect the scope and scale of supersonic aircraft integration into commercial fleets. Additional information may be needed to assess and model these aircraft's environmental impacts accurately.

## Economic Considerations

The economics of supersonic transport aircraft represent a shift from conventional subsonic air carrier operations. This is particularly true considering the economic factors driving their operation, routing, and notional operating costs as they relate to the unique nature of supersonic aircraft. This section explores some of the key economic considerations for supersonic transport aircraft based on exploring existing literature. It identifies economic components and aspects of demand that play a role in the resurgence of supersonic air travel.

The reasoning for exploring the economic considerations for the resurgence of supersonic transport aircraft is primarily due to the historical pitfalls that have influenced past attempts at commercial supersonic travel. These include route limitations, which play a significant role in determining operational costs. Wen et al. (2020) point to the historically limited route choices available to supersonic aircraft when beginning their exploration of baseline market forecasting for supersonic transport aircraft, highlighting that past limitations do not necessarily represent future growth. However, Leylekian et al. (2022) state that it is not likely that supersonic flights over land will be allowed until low-boom technology is perfected, thus limiting routes for supersonic aircraft. This aligns with the current regulatory restrictions and authorization processes outlined within 14 CFR §91.818. To add to the complexity of the problem, Klingenberg & Belke (2024) highlight challenges with routing, stemming from time savings and advantages when differentiating between eastbound and westbound flights. Klingengerg & Belke (2024) account for the value of time saved for business travel, using the models for short-haul business travel to justify their assumptions. Klingenberg & Belke (2024) found that a westbound supersonic flight can potentially save up to four hours, half a business day. This justifies higher fares. The same was not true with eastbound flights. The implication is that optimizing supersonic aircraft routes, fare structures, and other aspects of aircraft operations is a matter of establishing a balance between east and westbound flights with complementary subsonic service (Klingenberg & Bekle, 2024). Klingenberg & Belke (2024) even go so far as to set supersonic air travel as its own class, apart from business class travel, justifying the premium fares and the value of time saved (p. 6).

Aircraft fuel also plays a role in determining the economic viability of supersonic aircraft. Like other literature on this topic, Mane et al. (2024) highlight the importance of routes and demand based on ticket pricing in exploring the fleet-level impacts of supersonic aircraft. However, Mane et al. (2024) emphasize the importance of fuel and its influence on costs. The authors identify economic differences between conventional jet fuel and sustainable aviation fuel (SAF). Mane et al. (2024) identify the initial increased costs of SAF and their potential to reduce passenger demand, citing generally higher costs. Klingenberg & Belke (2024) also cite higher seat costs due to fuel, citing past studies that estimate fuel consumption 100% more per available seat mile than conventional aircraft.

DeRoo & Takahashi (2024) identify the same primary economic concerns in their study on the viability of supersonic transport aircraft. While the authors reinforce the importance of routing and fuel efficiency, DeRoo & Takahashi (2024) also distinguish that design optimization for sonic boom mitigation is at odds with maximizing passengers per seat mile requirements. This compromise creates a tradeoff in which efficiency accounts for not just fuel burn, but also passenger volume as well. DeRoo & Takahashi (2024) conclude that, at least initially, supersonic transport aircraft may be beyond the reach of the average traveler. Like the Concorde before them, the new generation of supersonic transport aircraft may be the luxury of the wealthy (DeRoo & Takahashi, 2024, p. 19). This is reinforced by the findings of Klingenberg & Belke (2024), when the authors emphasize the role of supersonic air travel as supporting business-class travel and beyond, catering to travelers who can accept the higher fares being justified by the time savings offered by supersonic air travel.

### Economic Considerations – Conclusions and Notes

The economics of supersonic transport aircraft appear to differ significantly from those of conventional aircraft. The literature indicates that various factors, including routes, fuel, and overall aircraft design, determine a supersonic aircraft's economic viability. The literature indicates that optimizing supersonic aircraft for profitability represents a series of tradeoffs that may impact other areas. For example, aircraft optimized to mitigate sonic boom may have decreased passenger volumes as a result of the physical shape of the airplane. Similarly, the choice of fuel may directly impact ticket prices and cause fluctuations in demand. Unlike conventional subsonic aircraft, supersonic transports are far more limited in their routing, due to sonic booms, may not be optimized to maximize passenger volume, and may consume significantly more fuel per mile. These are some of the more noteworthy economic challenges facing the reintroduction of supersonic transport aircraft into the NAS.

# Chapter 4 - Analysis

Data analysis for this study consisted of analyzing information from the literature review conducted as part of Chapter 3. The analysis, or in this case, qualitative meta-analysis and meta-synthesis, analyzes findings from literature, identifies patterns in published works, and synthesizes theories that capture the current themes regarding the integration of supersonic transport aircraft into the NAS. This chapter encompasses the following steps according to Hoon (2013):

Step 4: Extracting and Coding Data,

Step 5: Analyzing on a Case-Specific Level

Step 6: Synthesis on a Cross-Study Level

Step 7: Building a Theory from Meta-Synthesis

It is important to note that Steps 1 – 3 in the process described above were completed as components of Chapters 1 – 3 of this study. Chapter 5 will address Step 8: Discussion. Steps 5 and 6 will be covered in a section dedicated to analyzing the data.

As discussed in Chapter 1, this qualitative meta-analysis and subsequent meta-synthesis aimed to answer the following research question: *What are the most significant trends and potential challenges to the supersonic transport aircraft revival?* The following sections within this chapter explore the answers to this question based upon findings from the literature and a qualitative assessment of themes in the published works.

## Extracting and Coding Data

Extracting and coding data for this research consisted of coding and categorizing information within the literature consulted as part of the literature review. The coding matrix for this research is located within Appendix A. The coding matrix allowed the literature to be sorted, categorized, and analyzed for relevance to this work. This matrix was foundational in identifying where the literature came from, the topics it covered, and how it fit into the larger construct of the qualitative meta-analysis.

The following classifications were made for articles consulted for this work. These classifications were derived based on the type of work consulted. Article types and their definitions are listed below and reflected in Appendix A's coding matrix. All classifications of article types were based on the author’s rational assessment of the published work and how it addressed the research question.

1. **Scholarly/Technical Work** – An article published in an academic journal or a technical publication.
2. **Regulations/Policy Guidance** – Published regulations, proposed rule(s), policy, or commentary on regulations, rules, or policy.
3. **Historical Article** – An article conveying historical knowledge or accounts of factual past events.
4. **News Article/Press Release** – An article released for public awareness, often from a news publication or a release from a private entity.
5. **Industry White Paper** – The paper relays facts or information intended to inform the industry outside academic channels.
6. **Other** – Information that does not fall into the categories (types) above but may be relevant.

These categorizations allowed the author to identify types of literature and aided in the initial sorting process for works collected for the qualitative meta-analysis. Table 5 highlights the number of each type of literature collected and analyzed for this research. It is important to note that Table 5 represents the total number of articles reviewed. It does not reflect the total number of articles used after the literature was sorted and reviewed for relevance.

**Table 5. Article Types and Counts (Total)**

| ARTICLE TYPE | COUNT |
|---|---|
| Scholarly/Technical Work | 40 |
| Regulations/Policy Guidance | 9 |
| Historical Article | 2 |
| News Article/Press Release | 9 |
| Industry White Paper | 1 |
| Other | 8 |

Similar to article types, the author coded topics to align with the keys to successful integration of supersonic transport aircraft, as indicated in Figure 4. These topics and their definitions are listed below and reflected in Appendix A's coding matrix.

1. **Economic** – Article identified economic drivers, demand, and critical economic factors affecting supersonic aircraft development, operation, and integration.
2. **Societal** – Identifies societal impacts of supersonic transport.
3. **Technological** – Provides insight into technological development or advancements required to integrate supersonic transport aircraft successfully.
4. **Regulatory** – Regulations, policy guidance, or articles referencing regulations or policy affecting the integration of supersonic transport aircraft.
5. **Environmental** – Addresses environmental impacts of supersonic aircraft; overlaps with societal impact to a degree.

6. **Other** – Work does not fit into other categories but may be relevant – i.e., may contain useful images, or other work cited in this study.

It is important to note that not all the identified literature fell into a single category. Some literature consulted for this study covered multiple topics and was coded as such. This allowed literature that spanned multiple topics to be used when addressing different aspects of the research question. Classification of all topics was based on the author's rational assessment of the content of each published work. Table 6 highlights the topics covered by the literature reviewed for this study. Table 6 represents the total number of topics prior to sorting and review for relevance.

**Table 6. Article Topics (Total)**

| Topics | COUNT |
|---|---|
| Economics | 14 |
| Societal Impact | 4 |
| Technological | 16 |
| Regulatory | 12 |
| Environmental | 11 |
| Other | 22 |

## Final Breakdown of Data

The literature reviewed for this study covered a range of article types and topics, as shown in the Tables 5 and 6. Overall, 68 sources were reviewed for this study, 43 of which were included in the literature review following further sorting and deeper review. Articles were chosen for inclusion based on criteria established in Chapter 2, relevance to the research question, and ability to address the categories established in Chapter 2, Figure 4. Table 7 shows the final breakdown of literature used for this study.

**Table 7. Final Breakdown of Literature**

| ARTICLE TYPE | COUNT | TOPIC | COUNT |
|---|---|---|---|
| Scholarly/Technical Work | 19 | Economics | 9 |
| Regulations/Policy Guidance | 9 | Societal Impact | 4 |
| Historical Article | 1 | Technological | 8 |
| News Article/Press Release | 9 | Regulatory | 10 |
| Industry White Paper | 0[2] | Environmental | 5 |
| Other | 7 | Other | 16 |

The data in Table 7 represents the final breakdown of all literature sources consulted for this study. As previously stated, the literature was sorted and assessed via inclusion and exclusion criteria established in Chapter 2. It should also be noted that practical limitations, such as the unavailability of software tools for processing data, time constraints, and practical limitations governing the quantity of literature included in a meta-analysis, such as those described in Hoon (2013), also played a role in limiting data collection in this study.

## Overview of Data Composition

As shown in Table 7, the literature consulted for this study spans a variety of types and topic areas. These topics addressed the contributing factors to integrating supersonic transport aircraft into the NAS. Figure 12 visually represents the breakdown of article types following

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[2] The limited number of industry white papers consulted for this study were ultimately excluded from this study for failing to meet inclusion criteria.

sorting. The data shown in Figure 12 represents the final breakdown of articles used for this qualitative meta-analysis that informed the theories derived via meta-synthesis.

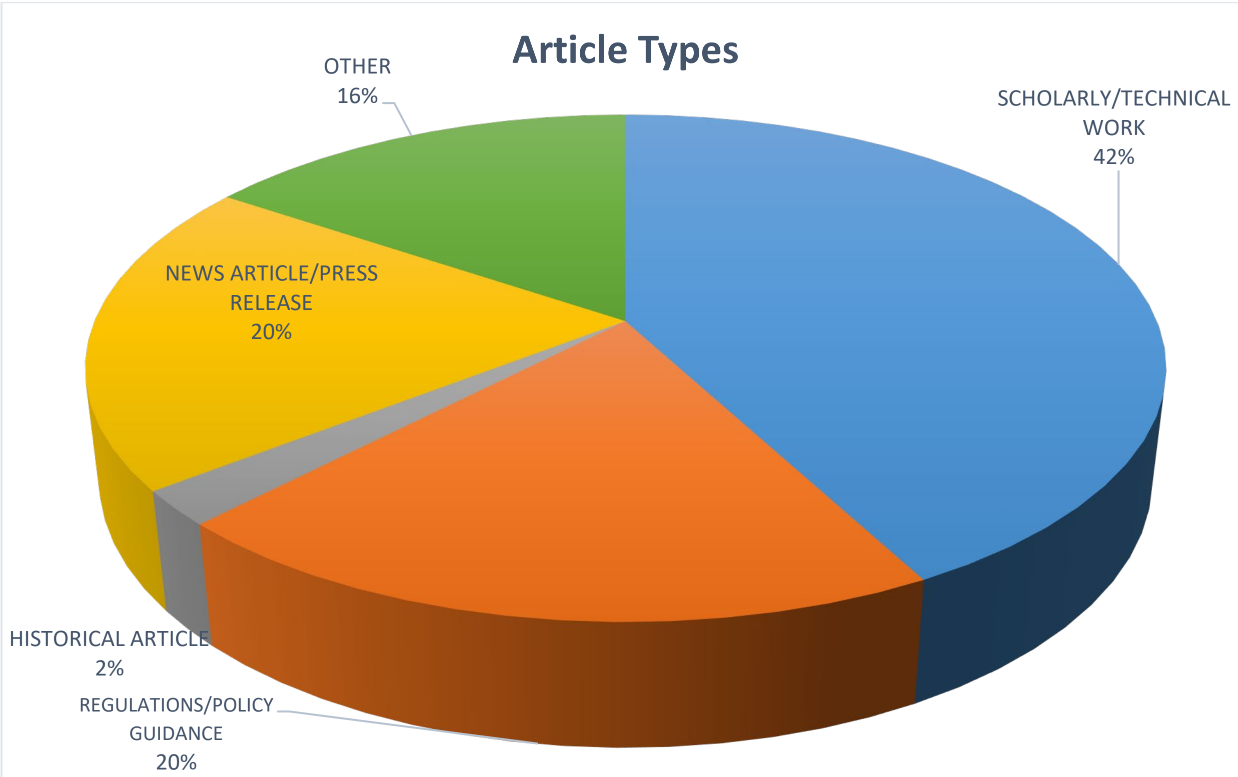


**Figure 12. Overall Breakdown of Article Types**

The breakdown shown in Figure 12 represents the variety in articles consulted for this research. As mentioned previously in this chapter, the different types of articles consulted represented varying sources of information intended to provide multiple contextual points of reference. The data in Figure 12 represents the intent to gather information from varying types of articles without limiting data collection to strictly academic and formally published sources. This is per recommendations from Hansen, Steinmetz, and Block (2022), in which the authors indicate the importance of gathering information from various sources to mitigate bias and add validity to findings.

Similar to the breakdown of article types shown in Figure 12, Figure 13 highlights a breakdown of topics that each article addressed. These topics are aligned with key factors contributing to the integration of supersonic transport aircraft identified in Chapter 2, Figure 4.

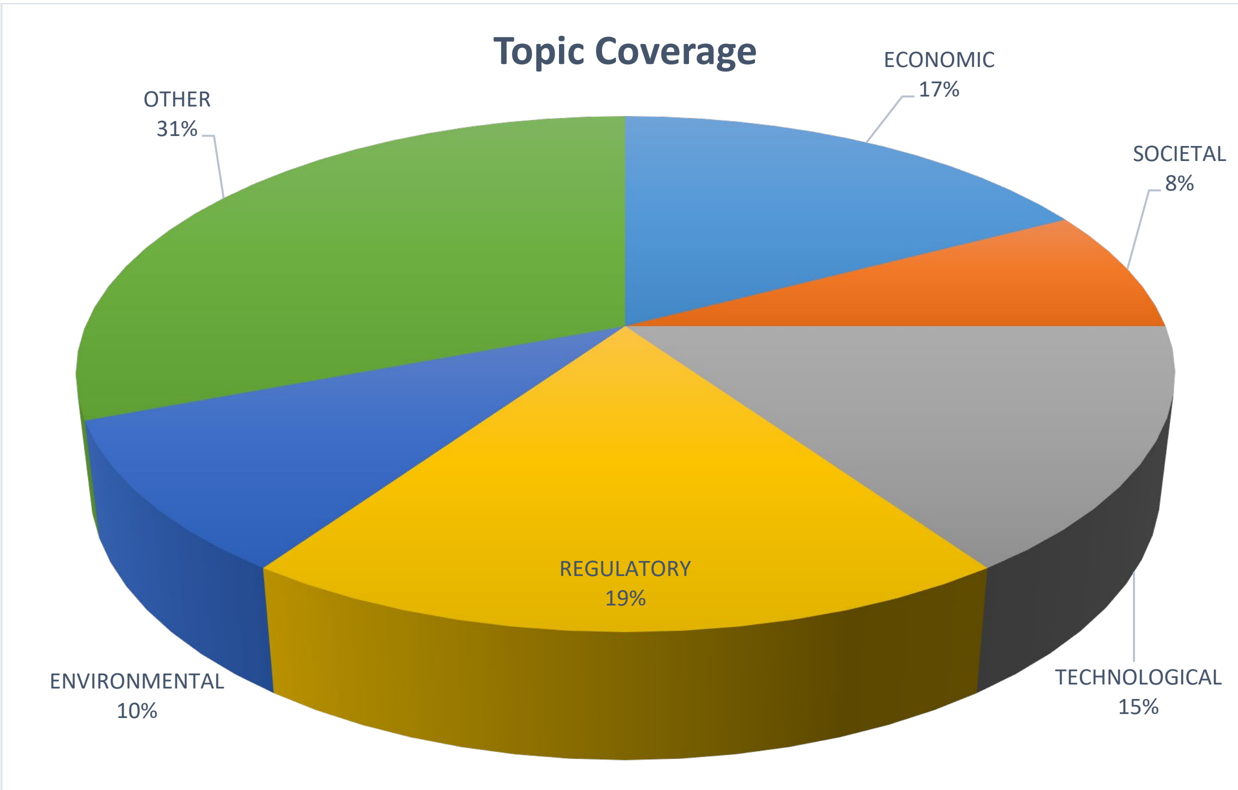


**Figure 13. Overall Topic Coverage**

As shown in Figure 13, topic coverage for this study spanned all areas addressed in Chapter 2, Figure 4. The distribution of topics was similar across all categories, with "Other being mostly composed of supporting material for other topic areas. It was also found that "Societal" topics largely overlapped with "Environmental" topics, addressing mostly sonic boom mitigation, general noise issues, and issues associated with traffic management and airspace integration.

### Summary of Data

Data collected for this qualitative meta-analysis and meta-synthesis were derived from various sources and topic areas identified as relevant to the key topics identified in Chapter 2, referencing applicable practices for data collection specified in Hansen, Steinmetz, and Block (2022). The author took care to prevent data collection from a single academic database or source, varied article types, and ensured that the literature consulted was relevant to the research question and specified data categories. The following sections discuss how the data collected through the literature informs theories on integrating supersonic transport aircraft into the NAS.

## Data Analysis – Summary of Findings

A series of patterns was observed in the literature as part of the larger qualitative meta-analysis. These patterns were derived from common topics, themes, and other patterns present within the literature. These patterns offer a potential avenue for understanding the evolution of supersonic air travel in the United States. The following sections summarize findings and identify patterns within the literature observed for each key topic area identified for successfully integrating supersonic transport aircraft into the NAS.

### Operational Considerations – Key Takeaways from the NASA CONOPs

The NASA CONOPs provide a detailed operational construct that may point the way to the future of supersonic air travel. The document outlines essential considerations for technological innovation, operational norms, environmental issues, and other critical questions of “how, why, and to what extent” supersonic aircraft may integrate. While this document was not the sole focus of this study, it provided critical insight that helped ground data from other sources. Overall, this document was a reasonable source for comparing issues raised in other documents and grounding assumptions in credible research.

## Regulatory Considerations

The regulations reviewed for this study frame the operational construct for supersonic transport aircraft in the NAS in the present day. They set the tone for how and to what extent these aircraft operate concerning baseline safety considerations, sonic booms, noise limitations, and other regulatory requirements for operation. As indicated by Payne (2024), these regulations represent rather onerous restrictions that may sometimes be obsolete. Payne (2024) highlights that the current regulations, as written, may stifle innovation and fail to reward trailblazers who truly innovate. This may pose challenges for those who wish to develop and operate the next generation of supersonic transport aircraft.

Regulations are anticipated to affect the integration of supersonic transport aircraft in other ways. According to Leylekian et al. (2022), regulations may still present challenges to integrating supersonic transport aircraft into the NAS due to the need to perfect low-boom technologies. This represents a potential slowdown in the advancement of supersonic flight, as operations over land may not be immediately viable due to low-boom technologies being largely unproven (Leylekian et al., 2022). However, a recent Executive Order[3] issued at the time this study concluded, may remove some hurdles to supersonic flight by relieving some restrictions on creating sonic booms over land. Whether this order is sufficient to propel the industry forward remains to be seen.

## Technical Considerations

Technical considerations for integrating supersonic transport aircraft into the NAS include enabling technological innovations and other advancements required to promote

[3] https://www.whitehouse.gov/presidential-actions/2025/06/leading-the-world-in-supersonic-flight/

supersonic flight. Underwood (2017) highlighted many ongoing technological advancements within the NASA CONOPs. These advancements consisted of sonic boom mitigation technologies and design techniques, synthetic vision systems to account for novel aircraft designs, and technologies intended to facilitate integration, such as data links and autonomous cockpit systems (Underwood, 2017). Other sources, such as Goel & Jawahar (2022), emphasized the need for sonic boom mitigations, which are heavily reflected in design philosophies for aircraft such as the NASA X-59 (NASA, 2025).

The need for technical innovation and advancement to promote the integration of supersonic transport aircraft in the NAS can best be described as focusing on technologies that mitigate the most considerable challenges facing supersonic flight. The literature indicates a significant focus on sonic boom mitigation and the need to operate within the existing regulatory environment. This is highlighted by the assumptions present within the NASA CONOPs (Underwood, 2017) and the emphasis on perfecting low-boom technologies, as expressed by Leylekian et al. (2022). This requirement was an ongoing theme throughout the literature and likely points to a core requirement for the next generation of supersonic aircraft.

## Societal Considerations

Perhaps unsurprisingly, societal considerations for integrating supersonic transport aircraft into the NAS were also well-aligned with environmental considerations. However, this study drew a distinction between larger environmental factors and direct societal impacts that have more immediate effects. This allowed the study to distinguish between far-reaching environmental impacts and things more immediately affecting the flying and non-flying public. Societal considerations also include the implications of integrating supersonic transport aircraft with more conventional subsonic air traffic and the effects of sonic booms and localized noise.

Themes within the literature indicated that the larger societal considerations stemmed from the need to mitigate sonic booms, noise in and around airports, and the unique requirements for routing and ATC handling. This is reflected in existing regulations, such as 14 CFR §91.817 (Civil Aircraft Sonic Boom, 2021), which imposes restrictions on supersonic flight. Further considerations for aircraft noise in and near terminal environments were expressed by Leylekian et al. (2022), in which the authors express the need for new standards to address supersonic aircraft noise. Additional literature from Underwood (2017) states that supersonic transport aircraft may require special ATC routing and handling, particularly when establishing acceleration and deceleration corridors. The practical implications are that sonic booms and aircraft noise are significant factors, particularly when considering flight routes and populated areas near airports. Underwood (2017) also implies the need for requirements to manage supersonic aircraft in flight and terminal environments. The implication is that these requirements may need to account for aircraft performance requirements and unique limitations – e.g., the need to accelerate and decelerate uninterrupted.

## Environmental Considerations

Environmental considerations uncovered through this research fell into two primary categories – noise pollution and emissions. These two categories encompass the most significant environmental impacts mentioned within the body of literature. While these two categories do not necessarily represent all environmental considerations for supersonic aircraft, they were the most prevalent.

Similar to the noise considerations with societal implications, there are regulations that govern noise certification requirements for supersonic aircraft. These requirements are reflected within 14 CFR §91.818, which requires supersonic aircraft to meet requirements for noise standards and environmental impact findings (Special Flight Authorization to Exceed Mach 1, 2021). 14 CFR §91.818 also requires considering where the sonic boom meets the surface, which has implications for those who may live along supersonic flight routes (Special Flight Authorization to Exceed Mach 1, 2021).

Alongside aircraft noise and sonic booms, emissions are a considerable concern. A study by Weit et al. (2021) highlights that supersonic air travel may increase $CO_2$ emissions above the established baseline. These findings were supported by additional findings by Matthes et al. (2022), who found that supersonic air travel may also increase Nitrous oxides in the stratosphere. Furthermore, Matthes et al. (2022) reference efforts by ICAO to explore broader impacts of emissions from supersonic aircraft. Exploring supersonic aircraft emissions is especially critical as the full environmental impact of supersonic transport aircraft is unknown, despite much research (Matthes et al., 2022). This implies that while supersonic air transport may affect the upper atmosphere, the extent to which it affects it is still unknown.

Overall, the literature indicates environmental concerns that will likely influence the development and integration of supersonic transport aircraft in the NAS. The two most significant issues include challenges with noise, which extend beyond basic societal impacts, and aircraft emissions. Despite existing research, as Matthes et al. (2022) indicated, there is still more to be learned about how emissions will impact the upper atmosphere. There are also implications for compliance with 14 CFR §91.818, which requires environmental impact findings for supersonic aircraft, including meeting noise requirements within existing regulations (Civil Supersonic Airplanes: Noise Limits, 2025). These considerations for noise, sonic booms, and emissions form the baseline environmental concerns established by the literature.

## Economic Considerations

The literature exploring the economics of supersonic air travel supports the notion that the broad adoption of supersonic transport will face numerous complexities that could hinder its growth, at least in the short term. These complexities are rooted in some historical challenges associated with supersonic air travel, such as route limitations due to sonic booms and noise, and the aircraft's overall operating expense. This section summarizes the findings from the literature regarding the economic aspects of supersonic air travel. It consolidates findings to build a realistic picture of the economic considerations that may influence how supersonic air transport evolves and integrates into the NAS.

The literature emphasized the importance of routes and their impact on the profitability of supersonic air travel. For example, Wen et al. (2020) indicate that historically, route choices have been limited for supersonic aircraft. This was true for the Concorde, which was highly limited in the routes and frequency with which it could fly them (Wen et al., 2020, p. 2). Similarly, the issue of policy, specifically policy regarding the current ban on overland supersonic air travel, will play a large part in determining the future of supersonic air travel (Wen et al., 2020). As Wen et al. (2020) indicate, there is much uncertainty regarding the direction of policy and regulation surrounding supersonic air travel and noise standards, which could significantly influence the direction of supersonic air travel in the U.S. Additionally, Leylekian et al. (2022) express a lack of optimism surrounding supersonic flights over land. This is due to the need to prove low-boom technology. This potentially limits the viability of supersonic air transport by limiting where these aircraft can operate. Additionally, Klingenberg & Belke (2024) found that westbound routes were the most likely profitable, offering more time savings in a given business day to justify the higher fares associated with supersonic air travel. Klingenberg & Belke (2024) stated that while supersonic air travel can be profitable, it must be built on a network that offers a combination of westbound supersonic flights complemented by eastbound subsonic routes. This is all predicated on the notion that those using such supersonic flights value the time saved enough to justify the cost of flying (Klingenberg & Belke, 2024).

In addition to routing, the literature sheds light on other issues affecting the profitability and economic viability of supersonic air travel. DeRoo & Takahashi (2024) emphasize that the current design trend for minimizing sonic booms also results in a decreased ability to carry passengers. Designing for optimal supersonic cruise does not result in a shape that maximizes passenger-carrying volume (DeRoo & Takahashi, 2024, p. 4). Additionally, Mane et al. (2024) and Klingenberg & Belke (2024) indicate that supersonic flight raises concerns regarding fuel consumption, offering that supersonic air travel will cost significantly more per seat mile. Klingenberg et al. (2024) estimate up to 100% more fuel consumption per seat mile than conventional subsonic aircraft, and fuel type, availability, and price fluctuations will influence costs (Mane et al., 2024).

## Meta-Synthesis: Theory from Data in Literature

The preceding qualitative meta-analysis collected literature from various sources to establish a snapshot of the current state of supersonic air transport and identify trends in the literature. The goal of developing this snapshot, which uses current literature, historical context, regulatory constraints, economic considerations, technical considerations, and other critical factors that influence supersonic air travel, was to establish a theory regarding the likely trends influencing the direction the industry will develop. The qualitative meta-analysis collected information on the evolution and revitalization of supersonic air travel to predict how it may develop in the coming years. This approach allows for the rational construction of an emergent theory that is the product of grounded, informed research and bounded by contextual information – e.g., themes in multiple studies and literature. What follows is a final, simplified summary of the literature and a structured approach leading to theories on trends influencing how supersonic air travel may evolve and integrate into the NAS. The resulting theory seeks to answer the question: *What are the most significant trends and potential challenges to the supersonic transport aircraft revival?*

## Components of Emergent Theory – Themes in Literature

A critical aspect of constructing theories that answer the question regarding the potential challenges to the revival of supersonic air travel involves identifying themes in the literature consulted as part of the qualitative meta-analysis. These themes form the foundation of a theoretical path toward identifying significant challenges to supersonic air transport. The Themes identified resulted from patterns in literature; concepts found throughout multiple published works that occurred with frequency were considered significant enough to inform answers to the research question. The following represent themes in the literature that point to factors and trends that may influence the revival of supersonic air travel:

### Regulatory Themes

Themes present in the existing regulations and supporting literature are presented below. These themes result from a review of the most significant regulations governing how supersonic aircraft operate in the NAS. An initial review indicates the themes in the regulations appear to emphasize minimizing some of the more negative effects of supersonic air travel, such as noise and sonic booms:

- Existing regulations place restrictions on supersonic aircraft, particularly concerning noise and sonic booms.

- Regulations exist to promote safety and compatibility with society and the environment – e.g., restrictions on takeoff and landing times within 14 CFR §91.819 and requirements for environmental findings in 14 CFR §91.818.
- Existing regulations may limit the advancement of supersonic air travel (Payne, 2024).

**Technical Themes**

Themes present in the technical aspects of supersonic air travel were rooted in the need to meet practical and regulatory requirements to manage aircraft noise, optimize aircraft for supersonic flight regimes, and adapt to requirements to operate with other (subsonic) aircraft in the NAS. Themes in literature covering technical aspects of supersonic flight primarily addressed the need for technological development, optimization, and new approaches to ensure that new generations of supersonic aircraft do not meet the same pitfalls as legacy aircraft like the Concorde and Tu-144. Themes present in literature addressing technical needs for supersonic air travel are as follows:

- Sonic boom mitigation is a primary driver for new aircraft designs. This is shown in current testbed platforms such as the Boom XB-1 (Boom Supersonic, 2025) and NASA's X-59 (NASA, 2016). This is substantiated by guiding assumptions and findings within the NASA CONOPs (Underwood, 2017) and supporting literature, such as findings from Goel & Jahawar (2022) that emphasize the need to mitigate sonic booms. This is further reinforced by regulatory requirements to prevent sonic booms (Civil Aircraft Sonic Boom, 2021), which drives this focus on technical solutions for meeting regulatory requirements.

- Aircraft design optimization is essential to the next generation of supersonic transport aircraft. This is emphasized heavily by Hassan et al. (2020) and Berton et al. (2020), who convey the need to optimize aircraft designs for such factors as fuel burn, environmental considerations (emissions), and other critical factors influencing aircraft performance.
- Other technologies, such as a robust FMS and some level of cockpit automation, will ensure smooth integration and safe operation of supersonic aircraft. Underwood (2017) sheds light on the need for the ability of a flight crew to manage workload and share data with other users in the airspace.

**Societal Themes**

Themes stemming from societal impacts of supersonic air travel overlap with environmental considerations. They primarily focus on mitigating the far-reaching effects of sonic booms and noise in and around terminal areas. These considerations arise from the need for these aircraft to be fundamentally compatible with existing aviation infrastructure and not adversely affect people in and around the aircraft's flight path:

- Sonic booms and their effect on people in the surrounding environment are a significant concern. This is reflected by Goel & Jahawar (2022), who state that while sonic booms are unlikely to cause damage or serious harm, people still worry that they may.
- Noise in and around airports is a significant problem. This is reflected in Leylekian et al. (2022), in which the authors suggest that takeoff and landing noise should be addressed before sonic booms. This is reinforced by 14 CFR §91.819(b)(2), which specifies limits on takeoff and landing times for supersonic

aircraft due to noise (Civil Supersonic Airplanes that do not Comply, 1989). This is reflected in historical precedent, with Concorde making up most noise complaints at Dulles during its service (Underwood, 2017).

- Supersonic transport aircraft are expected to have unique requirements within the airspace. Underwood (2017) addresses requirements for acceleration/deceleration corridors and the need for ATC to understand the unique requirements of these aircraft. These unique needs may influence how ATC interfaces with supersonic aircraft, potentially affecting the handling of other air traffic.

**Environmental Themes**

Environmental themes deal primarily with issues of noise and emissions. The implication is that supersonic air travel will contend with challenges associated with sonic booms, potentially despite mitigating efforts, and emissions from their engines. What follows is a brief list of the most significant environmental themes found in the literature:

- Existing regulatory requirements require an environmental study for supersonic aircraft (Special Flight Authorization to Exceed Mach 1, 2021).
- Aircraft emissions are a concern. This is reflected in studies by Weit et al. (2021) and Matthes et al. (2022), which attempt to quantify the impact of $CO_2$ and nitrous oxides, respectively. Both studies convey challenges associated with the accuracy of models for predicting trends.
- Fuel selection, cost, and availability of different fuels, such as sustainable fuels, may be challenging (Mane et al., 2024).

## Economic Themes

Finally, economic themes highlighted some of the primary considerations for the success and profitability of supersonic air travel. These themes emphasized the need for routing, fuel/efficiency, and some primary considerations for successful integration and profitable supersonic operations. Key themes were:

- Routes are critical to supersonic flight and have been historically limited (Wen et al., 2020). This is problematic, as advanced low-boom technology may not immediately open up supersonic routes over land (Leylekian et al., 2022).
- Westbound routes may be far more advantageous than eastbound routes because they represent greater time savings to those who value time in a given business day – i.e., business travelers (Klingenberg & Belke, 2024). This represents a potential need to supplement supersonic routes with subsonic routes, facilitating route optimization and planning (Klingenberg & Belke, 2024).
- Fuel costs may be substantial, representing up to 100% more fuel burned per seat mile than conventional subsonic aircraft (Klingenberg & Belke, 2024). There are also complexities with the availability of SAF, which may also increase costs (Mane et al., 2024).
- Design trends to optimize supersonic aircraft for efficiency and mitigate sonic booms, reduce passenger volume, ultimately affecting the cost of travel. This is reflected by DeRoo & Takahashi (2024).
- Supersonic air travel may be cost-prohibitive for ordinary travelers. This is reflected by DeRoo & Takahashi (2024) and Klingenberg & Belke (2024). Both studies indicate that costs may be substantially higher, and Klingenberg & Belke

(2024) indicate that increased costs may potentially be justified by time savings. This implies that supersonic air travel may only be viable for those who can justify the increased costs by saving time in a given day.

## Emergent Theories – Answers to the Research Question

Using the data and themes in the literature, it is possible to develop theories and identify answers to the research question: *What are the most significant trends and potential challenges to the supersonic transport aircraft revival?* What follows are emergent theories resulting from the data, themes, and a rational assessment of information collected from the qualitative meta-analysis. It represents the result of this qualitative assessment of driving forces that will influence the future development and integration of supersonic transport aircraft in the NAS. These theories address regulatory, technical, societal, environmental, and economic considerations for supersonic air travel. What follows are theories synthesized by the author from the qualitative meta-analysis, fulfilling the meta-synthesis component of this study. These theories are justified by the trends previously discussed in this chapter and the literature review in Chapter 3.

### Theory – Regulatory Trends

Current regulations challenge the development and future integration of supersonic transport aircraft into the NAS because they restrict supersonic travel in most cases. However, these regulations promote technological development and engineering solutions to mitigate sonic booms and aircraft noise, increase efficiency, and promote solutions to comply with existing regulations or work around them. As development continues on the next generation of supersonic aircraft, new standards for noise, emissions, and measures of efficiency may be needed to promote regulatory compliance. It also follows that changes to existing regulations and updated policies may be required to address new technologies and technical solutions to common problems – e.g., noise, sonic booms, automation, low-boom designs, etc.

**Theory – Technical Trends**

Technical solutions and technological advancements for the next generation of supersonic aircraft are rooted in the desire to free these aircraft from regulatory and practical constraints that have historically held back supersonic air travel. Such advancements include low-boom technology for mitigating sonic booms, design optimization via computerized design philosophies, vision systems to increase situational awareness, and automated systems to reduce pilot workload and facilitate better communication with ATC and other airspace users.

Interestingly, existing restrictions on supersonic flight appear to catalyze many of the innovations we see in supersonic aircraft design. For example, low-boom technologies aim to allow flight over land with minimal impact on populations below. Novel design techniques emphasize optimization to account for fuel burn to meet emissions requirements while maintaining profitability, and other innovations aim to make integrating these aircraft more practical, emphasizing automation and reductions in pilot workload. Technological innovations aim to make supersonic aircraft compatible with the NAS while ensuring environmental and societal compatibility.

**Theory – Societal Trends**

A key component of the future of supersonic air travel appears to focus on making these new aircraft compatible with our society. To that end, there is a big focus on mitigating sonic booms, reducing airport noise, and managing environmental impact via emissions. Regulatory and technical trends are very much aligned with a larger societal benefit. However, there is still work to be done to quantify environmental impacts. This will likely be an ongoing challenge that will play a role in the future development of supersonic aircraft.

Beyond environmental concerns, there is the need to ensure supersonic aircraft integrate into the NAS alongside conventional air traffic. The requirement to integrate seamlessly ensures that these aircraft do not adversely affect other aircraft with which they share the air. Additional ATC procedures may be needed for acceleration/deceleration corridors. New standards may be needed to account for how these aircraft climb, descend, maneuver, and interact with our air traffic systems at scale.

**Theory – Environmental Trends**

Supersonic aircraft are anticipated to have environmental impacts beyond societal compatibility, and the nature of these impacts will be driven by societal need. The need to address sonic booms and noise in terminal environments is likely the most visible trend, but it is not the only one. There will likely be a need to set new noise standards for terminal environments and en route operations. These standards will likely support compliance with existing regulations and/or propose alternatives incorporating novel technological solutions.

Further studies will be carried out regarding emissions from supersonic aircraft. While there is a large body of knowledge regarding these emissions, existing models are incomplete. There will likely be a need to explore alternative, sustainable fuels, their cost, benefits, and availability. Addressing emissions may drive other technologies and improvements to increase fuel efficiency and reduce emissions further.

**Theory – Economic Trends**

The supersonic air travel economy will likely differ from conventional subsonic aircraft. Current regulations restrict supersonic flight over land, but are currently influencing technological innovations intended to serve as a means to address existing limitations, intending to open up profitable supersonic routes for routine operations. This drives economic considerations that emphasize routine, efficient operations.

Ultimately, the profitability of supersonic aircraft will be heavily influenced by operating costs, which will be significantly higher than those of conventional subsonic aircraft. This, in turn, may make justifying significantly higher fares difficult for average commercial travelers. Supersonic aircraft may fill a niche within a network that supports business travel, emphasizing the tradeoff of increased cost for time saved.

Aircraft and fuel efficiency will also be an economic concern, as supersonic transport aircraft are anticipated to have a much smaller passenger volume than their conventional subsonic counterparts. As such, supersonic aircraft will be significantly impacted by fuel costs and routing fluctuations compared to other aircraft, making their margins slimmer due to decreased ability to carry passengers compared to conventional subsonic aircraft. Overall, these aircraft can be profitable, but the demand will likely come from a narrower customer base, and the success or failure of these aircraft will be a matter of optimization of routing, time, fuel, and balancing increased operating costs with higher fares.

# Chapter 5 - Discussion and Future Work

This study represents a combination of meta-synthesis and qualitative meta-analysis to arrive at a series of theories that address some of the significant trends and challenges affecting the revival of supersonic air travel in the United States. It represents a qualitative, rational analysis of a cross-section of the current body of knowledge and trends impacting the future development and integration of the next generation of supersonic transport aircraft. This section discusses the study's results and the potential for future work.

## Discussion of Results

The theories presented in Chapter 4 represent the culmination of the data collected in this study. They represent theories that resulted from a rational assessment of themes within the literature and are qualitative assessments of information gathered through qualitative meta-analysis. The results of this study provide a starting point for discussions regarding new standards, policies, and thinking regarding the integration of supersonic transport aircraft into the NAS.

## Regulatory Implications

This study, and the resulting theory derived in Chapter 4, highlight the relatively static nature of our nation's regulations regarding supersonic aircraft and their ability to operate within the NAS. Although some were amended as recently as 2021, the current regulations still generally prohibit supersonic flight over land in the United States (Special Flight Authorizations for Supersonic Aircraft, 2019). This is a double-edged sword. The general prohibition on supersonic flight over land in the U.S. creates potential roadblocks to developing and integrating supersonic transport aircraft into the NAS. However, it can also be shown that these regulations are spurring technological innovation and new ideas to develop aircraft and systems to either comply with these regulatory requirements or mitigate the challenges these regulations were intended to prevent – i.e., disrupting the non-flying public with sonic booms. This is evidenced in Underwood (2017), which reflects current technological developments and realistic assumptions regarding how supersonic transport aircraft will operate in the NAS. Despite the innovations that arose from the restrictive regulatory environment, there is an opportunity to observe how these new aircraft, systems, and operational constructs perform and ensure that regulations, policies, and standards reflect the industry's current state while promoting safety, societal well-being, innovation, and growth.

### Technical Implications

According to the literature and the theory derived as part of the meta-synthesis, the innovations we are seeing with the next generation of supersonic transport aircraft are aimed at addressing the physical and practical challenges associated with supersonic flight, such as sonic booms, noise, and other realities associated with supersonic aircraft. This is evidenced by current technology demonstrators, such as Boom Supersonic’s XB-1 (Boom Supersonic, 2025) and NASA’s X-59 (NASA, 2016), which offer a glimpse of new, innovative aircraft designs and technological innovations that may make future supersonic air travel more practical. Similarly, we can likely expect to see new design methodologies focused on optimization and efficiency, emissions, and other considerations (Berton et al., 2020). The likely result will be aircraft that capitalize on new concepts for aircraft design and emphasize mitigating challenges associated with supersonic flight – i.e., noise and sonic booms. This aligns with the NASA CONOPs (Underwood, 2017) and assumptions emphasizing low-boom technology and advanced systems that facilitate streamlined operations in the NAS.

### Societal Implications

Current trends in the development and integration of supersonic transport aircraft are focused on addressing some of the more significant issues with societal implications, such as sonic booms (Underwood, 2017), noise in and around airports (Leylekian et al., 2022), and unique ATC handling (Underwood, 2017). This is in addition to some of the additional infrastructure requirements mentioned by DeRoo & Takahashi (2024), in which the authors mention the need for additional infrastructure, which has the potential to affect surrounding communities.

These trends align well with the current regulatory requirements and technological innovations discussed in previous sections. They support the theory that the next generation of supersonic transport aircraft will be designed to be integrated into the NAS with regard for all in the airspace and surrounding communities. They further reinforce the need for future supersonic air travel to be compatible with other airspace users, communities near airports, and those along the aircraft's flight path.

**Environmental Implications**

The theory regarding environmental trends for supersonic aircraft has implications that are spread across regulatory, technical, societal, and economic sectors. This is evidenced by the combination of regulatory requirements (Special Flight Authorization to Exceed Mach 1, 2021), studies aimed at emissions such as Weit et al. (2021) and Matthes et al. (2022), design trends for optimization, such as those from Berton et al. (2020), mitigation of sonic booms (Underwood, 2017), and considerations for fuel consumption for profitability (Klingenberg & Belke, 2024). These studies support the need for a consolidated approach to environmental impact that is a function of regulations and policy, aircraft design, and economic viability.

**Economic Implications**

The theory on economic trends highlights the difficulties associated with integrating supersonic aircraft into the NAS in a manner that will be profitable. As evidenced by Wen et al. (2020), the availability of routes and regulatory limitations pose challenges to profitable operations. There are also challenges with operating costs, which will be significantly higher than those of conventional subsonic aircraft (Mane et al., 2024; Klingenberg & Belke, 2024).

Supersonic flight operations must account for significantly higher fuel burn and the need to justify significantly higher fares with time saved (Klingenberg & Belke, 2024). This places supersonic air travel in the position of operating at significantly increased costs when compared to conventional subsonic aircraft. This potentially limits its appeal to those who can justify paying significantly higher fares.

## Future Work

This study explored the essential components and trends associated with introducing routine supersonic flights in the NAS. It uncovered more significant trends associated with existing regulations, technological development, societal impacts, environmental considerations, and economic trends that will influence supersonic air travel. However, there is room for additional research to fully understand how supersonic air travel may continue to evolve in the U.S. The following is a list of recommendations for potential future work:

- Repeat this study with software-driven search algorithms – This study was conducted via a traditional (manual) literature search that informed the qualitative meta-analysis and resulting meta-synthesis. A software-defined search may yield more literature and increase efficiency when sorting through relevant literature. The additional use of artificial intelligence (AI) and/or large language models (LLMs) may also offer more pointed insight into themes associated with the continued development and integration of supersonic aircraft into the NAS.
- Address societal and environmental considerations specifically – While this research addressed these topics, there appeared to be additional room to explore the ramifications of aircraft emissions, sustainable fuels, and societal impacts of overland aircraft routes.

- Validate the findings of this study against a commercial supersonic aircraft operation – It would be beneficial to compare the trend identified in this study against the realities faced by an air carrier using supersonic aircraft.

Overall, this study provided insight into some of the driving forces behind the resurgence of supersonic air travel in the United States. Exploring and understanding the factors influencing the operational complexities associated with these novel aircraft can ensure that the next generation of high-speed commercial aircraft is developed with technological advancements that promote safety, regulatory compliance, societal benefit, environmental consciousness, and have economic viability in mind.

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Wen, J., Weit, C. J., Mayakonda, M., Anand, A., Zaidi, T., & Mavris, D. (2020). A Methodology for Supersonic Commercial Market Estimation and Environmental Impact Evaluation (Part II). *AIAA AVIATION 2020 FORUM*, *1 PartF*. https://doi.org/10.2514/6.2020-3261

Wolfe, F. (2020). *FAA Moves Forward on Standards for Supersonic Aircraft*. Avionics International. https://www.aviationtoday.com/2020/04/03/faa-moves-forward-on-standards-for-supersonic-aircraft/

# Appendix A - Literature Sorting Matrix

| *CITATION* | *ARTICLE TYPE* | | | | | | *TOPIC(S)* | | | | | | *INCLUDED?* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | |
| Anderson Jr., J. D. (1998). Research in Supersonic Flight and the Breaking of the Sound Barrier. In P. E. Mack (Ed.), FROM ENGINEERING SCIENCE TO BIG SCIENCE The NACA and NASA Collier Trophy Research Project Winners (pp. 59-90). National Aeronautics and Space Administration. https://www.nasa.gov/history/SP-4219/Chapter3.html | - | - | YES | - | - | - | - | - | - | - | - | YES | NO |
| Applicability: Relation to Part 36. (2013). Title 14 C.F.R. §91.801. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-I/section-91.801 | - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| Banke, J. (2023). NASA's Quesst: Reassessing a 50-Year Supersonic Speed Limit. https://www.nasa.gov/centers-and-facilities/armstrong/nasas-quesst-reassessing-a-50-year-supersonic-speed-limit/ | - | - | - | YES | - | - | - | - | YES | - | - | - | YES |
| Berton, J. J. (2023). Variable Noise Reduction Systems for a Notional Supersonic Business Jet. Journal of Aircraft, 60(3), 688–701. https://doi.org/10.2514/1.C037019 | YES | - | - | - | - | - | - | - | - | - | YES | - | NO |
| Berton, J. J., Huff, D. L., Seidel, J. A., & Geiselhart, K. A. (2020). Supersonic Technology Concept Aeroplanes for Environmental Studies. In AIAA (Ed.), AIAA SciTech Forum and Exposition. American Institute of Aeronautics and Astronautics. https://ntrs.nasa.gov/api/citations/20200000513/downloads/20200000513.pdf | YES | - | - | - | - | - | - | - | YES | - | YES | - | NO |
| Boom Supersonic. (2025). Boom Supersonic Achieves Supersonic Flight. https://boomsupersonic.com/press-release/boom-supersonic-achieves-supersonic-flight | - | - | - | YES | - | - | - | - | YES | - | - | - | YES |
| Boretti, A. (2024). Hydrogen hypersonic combined cycle propulsion: Advancements, challenges, and applications. International Journal of Hydrogen Energy, 55, 394-399. https://doi.org/10.1016/j.ijhydene.2023.11.234 | YES | - | - | - | - | - | - | - | YES | - | - | - | NO |
| Chernyshev, S. L., Pogosyan, M. A., & Sypalo, K. I. (2024). On ecologically-safe high-speed vehicles: Conceptual design study of the next generation supersonic transport. Acta Astronautica, 216, 437–445. https://doi.org/10.1016/j.actaastro.2023.11.040 | YES | - | - | - | - | - | - | - | YES | - | YES | - | NO |

| *CITATION* | *ARTICLE TYPE* | | | | | | *TOPIC(S)* | | | | | | *INCLUDED?* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | |
| Cheung, M. W. L., & Vijayakumar, R. (2016). A Guide to Conducting a Meta-Analysis. Neuropsychology Review, 26(2), 121–128. https://doi.org/10.1007/s11065-016-9319-z | YES | - | - | - | - | - | - | - | - | - | - | YES | YES |
| Christensen, C., Albert, S., Mullins, C., Ahadi, B., Smith, P., Buley, D., Lehmer, R., Smith, J., Leonard, C., Long-Davis, M. J., Hendricks, E., Linne, A., Martin, J., Robinson, J., Seidel, J., & Storch, A. (2021). Independent Market Study: Commercial Hypersonic Transportation. April. https://ntrs.nasa.gov/api/citations/20210015471/downloads/SAIC BryceTech Commercial Hypersonics Transportation 20210506.pdf | YES | - | - | - | - | - | YES | - | - | - | - | - | NO |
| Civil Aircraft Sonic Boom. (2021). Title 14 C.F.R. §91.817. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-I/section-91.817 | - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| Civil Supersonic Airplanes: Noise Limits. (2025). Title 14 C.F.R. §91.821. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-I/section-91.821 | - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| Civil Supersonic Airplanes that do not Comply with Part 36. (1989). 14 CFR §91.819. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-I/section-91.819 | - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| DeRoo, M., & Takahashi, T. T. (2024, January 8). A Study of the Economic Viability of Commercial Supersonic Flight. AIAA SCITECH 2024 Forum. https://doi.org/10.2514/6.2024-2214 | YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| Dryden Flight Research Center. (2002). The Tu-144L: A Supersonic Flying Laboratory. https://www.nasa.gov/wp-content/uploads/2021/09/120315main_fs-062-dfrc.pdf | - | - | - | - | - | YES | - | - | - | - | - | YES | YES |
| Dryden, H. L. (1954). Supersonic Travel within the Last Two Hundred Years. The Scientific Monthly, 78(5), 289–295. https://www.jstor.org/stable/21480 | YES | - | - | - | - | - | - | - | - | - | - | YES | NO |
| Fisher, L., Liu, S., Maurice, L. Q., & Shepherd, K. P. (2004). “Supersonic Aircraft: Balancing Fast, Affordable, and Green.” International Journal of Aeroacoustics, 3(3), 181–197. https://doi.org/10.1260/1475472042887461 | YES | - | - | - | - | - | YES | - | YES | - | YES | - | YES |
| Fitzgerald, S. (1974). Concorde Droop Nose. https://en.wikipedia.org/wiki/Droop_nose_(aeronautics)#/media/File:Concorde_landing_Farnborough_Fitzgerald.jpg | - | - | - | - | - | YES | - | - | - | - | - | YES | YES |

| *ARTICLE TYPE* | | | | | | *TOPIC(S)* | | | | | | *INCLUDED?* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| YES | - | - | - | - | - | - | - | - | - | - | YES | NO |
| YES | - | - | - | - | - | - | YES | YES | - | YES | - | YES |
| YES | - | - | - | - | - | - | - | - | - | - | YES | YES |
| YES | - | - | - | - | - | - | - | YES | - | - | - | NO |
| YES | - | - | - | - | - | - | - | - | - | - | YES | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | NO |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| YES | - | - | - | - | - | - | - | YES | - | - | - | NO |

| ARTICLE TYPE | | | | | | TOPIC(S) | | | | | | INCLUDED? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | |
| YES | - | - | - | - | - | - | - | YES | - | - | - | NO |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| - | - | YES | - | - | - | - | - | - | - | - | YES | YES |
| YES | - | - | - | - | - | - | YES | - | - | YES | - | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | NO |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| YES | - | - | - | - | - | - | - | - | - | YES | - | YES |
| - | - | - | YES | - | - | - | - | YES | - | - | - | YES |
| - | - | - | YES | - | - | - | - | - | - | - | YES | YES |
| - | - | - | - | - | YES | - | - | - | - | - | YES | YES |

| ARTICLE TYPE | | | | | | TOPIC(S) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | INCLUDED? |
| - | - | - | - | - | YES | - | - | - | - | - | YES | YES |
| - | - | - | YES | - | - | - | - | - | - | - | YES | YES |
| YES | - | - | - | - | - | - | - | YES | - | - | - | YES |
| - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| - | YES | - | - | - | - | - | YES | - | YES | - | - | YES |
| YES | - | - | - | - | - | - | - | - | - | - | YES | NO |
| - | - | - | - | - | YES | - | - | - | - | - | YES | YES |
| - | - | - | YES | - | - | YES | - | - | - | - | - | YES |
| - | - | - | - | - | YES | - | - | YES | - | - | - | NO |
| YES | - | - | - | - | - | - | - | - | YES | - | - | NO |

| ARTICLE TYPE | | | | | | TOPIC(S) | | | | | | INCLUDED? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCHOLARLY /TECHNICAL WORK | REGULATIONS/POLICY GUIDANCE | HISTORICAL ARTICLE | NEWS ARTICLE/PRESS RELEASE | INDUSTRY WHITE PAPER | OTHER | ECONOMIC | SOCIETAL | TECHNOLOGICAL | REGULATORY | ENVIRONMENTAL | OTHER | |
| YES | - | - | - | - | - | - | - | - | - | YES | - | NO |
| - | - | - | - | YES | - | - | - | - | - | YES | - | NO |
| YES | - | - | - | - | - | - | - | - | - | - | YES | NO |
| YES | - | - | - | - | - | - | - | YES | - | - | - | YES |
| - | - | - | - | - | YES | - | - | - | - | - | YES | YES |
| - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| - | YES | - | - | - | - | - | - | - | YES | - | - | YES |
| - | - | - | - | - | YES | - | - | - | - | - | YES | YES |
| YES | - | - | - | - | - | - | YES | - | - | - | YES | YES |
| - | - | - | YES | - | - | - | - | - | - | - | YES | YES |

| ***ARTICLE TYPE*** | | | | | | ***TOPIC(S)*** | | | | | | ***INCLUDED?*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SCHOLARLY /TECHNICAL WORK** | **REGULATIONS/POLICY GUIDANCE** | **HISTORICAL ARTICLE** | **NEWS ARTICLE/PRESS RELEASE** | **INDUSTRY WHITE PAPER** | **OTHER** | **ECONOMIC** | **SOCIETAL** | **TECHNOLOGICAL** | **REGULATORY** | **ENVIRONMENTAL** | **OTHER** | |
| YES | - | - | - | - | - | - | - | YES | - | YES | - | NO |
| - | - | - | YES | - | - | - | - | YES | - | - | - | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | NO |
| YES | - | - | - | - | - | - | - | - | YES | - | - | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | NO |
| YES | - | - | - | - | - | - | - | - | - | YES | - | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| YES | - | - | - | - | - | YES | - | - | - | - | - | YES |
| YES | - | - | - | - | - | - | - | - | YES | - | - | NO |
| YES | - | - | - | - | - | - | - | - | - | - | YES | NO |
| - | - | - | YES | - | - | - | - | - | - | - | YES | YES |