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Commercial Aviation in Washington: *A Review of Forecasts, Policies, and Technologies*

The 2024 Washington State Legislature directed the Washington State Institute for Public Policy (WSIPP) to assess the forecasts cited in the Puget Sound Regional Council (PSRC) regional aviation baseline study ("baseline study").[1] In addition, WSIPP was tasked with conducting a review of strategies to reduce air travel demand and address its environmental impacts.

Section I of this report presents background on air travel in Washington State and reviews WSIPP's legislative assignment. In Section II, we present our analysis of the forecasts presented in the baseline study. In Section III, we discuss the results from a literature review conducted on strategies to reduce air travel demand. Then, in Section IV, we review technologies that aim to address the impact of air travel on climate change, including a discussion of the feasibility of implementing the interventions in Washington. Finally, Section V provides a summary of the report and a discussion of the key takeaways and limitations.

Summary

The Puget Sound area has seen significant growth in demand for air travel, putting pressure on current facilities. Forecasts from a recent study predict a substantial expected gap in service for the area. In addition, commercial aviation has a significant impact on the environment. In this report, the legislature directed WSIPP to examine the passenger activity and air cargo forecasts in the Puget Sound Regional Council's study, conduct a review of strategies aimed at reducing air travel demand, and investigate technologies addressing the environmental impacts of air travel.

In our assessment of the forecasts, we find evidence to suggest that both the passenger activity and the air cargo forecast overestimate the actual aviation activity in the Puget Sound area.

In our review of strategies to combat demand for air travel, we find the literature on strategies intended to reduce demand is sparse and often methodologically fraught. The policy changes that may lead to a reduction in demand typically do so by increasing the cost of air travel or limiting the supply. High-speed rail has also been shown to decrease demand in some countries as a substitute for air travel, though none of the papers study this in a U.S. context.

In the review of technologies to combat the environmental impact of air travel, we detail several technologies that have the potential to make air travel less impactful on the environment, including innovative airplane designs, electrification of key pieces in the commercial aviation system, and sustainable aviation fuels. We also discuss challenges to note when considering the feasibility of implementing these technologies in Washington State.

[1] Puget Sound Regional Council. (2021). Regional aviation baseline study: Final report.

I. Background

The 2024 Washington State Legislature assigned WSIPP a multicomponent study to examine commercial aviation in the state, outlined in Exhibit 1.

Policymakers have expressed concern about meeting future demand for aviation activity in the central Puget Sound region, specifically at the Seattle-Tacoma International Airport (SEA). With that in mind, the focus of this study is **commercial air travel**, or commercial aviation, which we define as passenger or air cargo operations that move paying customers or freight through a commercial service airport.

Commercial air travel excludes general aviation (e.g., private flight service, flight training) and military operations, as well as any air travel operating outside of a commercial service airport.

This background section provides an overview of aviation infrastructure terminology, a description of commercial air service in Washington State, and a brief discussion of commercial aviation issues that are relevant to WSIPP's legislative assignment.

Aviation Infrastructure

Commercial air service in the United States is a complex system made up of airports, airlines, aircraft manufacturers, and regulatory agencies.

Exhibit 1

Legislative Assignment

...for the Washington state institute for public policy to:

(1) *Conduct an independent **assessment of the passenger and air cargo forecasts cited in the Puget Sound regional council regional aviation baseline study**, including an evaluation of the underlying data, assumptions, methodologies, and calculation of the level of uncertainty around the forecast;*

(2) *Conduct a **comprehensive literature review to identify effective national and international strategies to reduce demand for air travel**, including diverting such demand to other modes and whether such diversion avoids net environmental impacts to overburdened communities and vulnerable populations;*

(3) *Conduct a **review of existing operational and technological enhancements to address environmental impacts from commercial aviation activities**, including, but not limited to, climate friendly routing of aircraft, innovations intended to address the climate change effects of noncarbon dioxide emissions from aviation activities, simulation models applied to congested airports, and online tools to track, analyze, and improve carbon footprints related to aviation activities. The review should identify the feasibility of enhancements to be deployed in the state of Washington; and*

(4) *Provide a report to the office of the governor and the transportation committees of the legislature by December 31, 2025.*

Engrossed Substitute House Bill 2134, Chapter 310, Laws of 2024

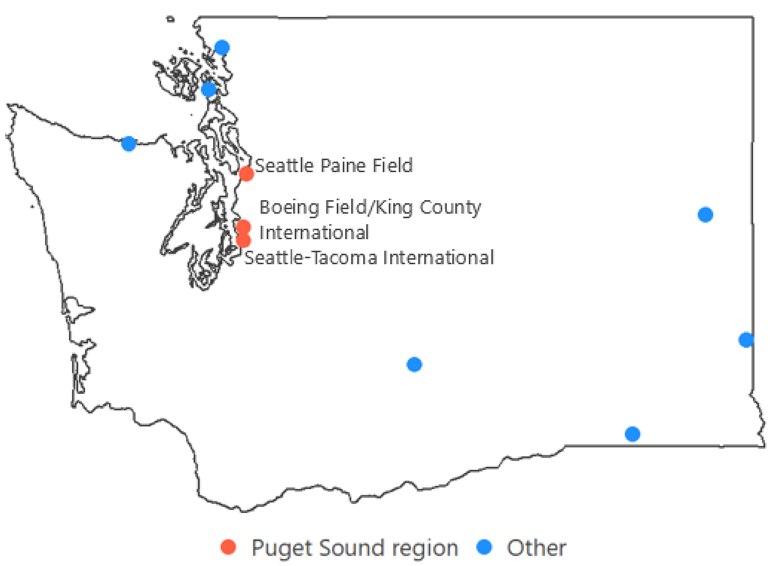
Airports provide the infrastructure necessary for commercial flights, including runways, gates, terminals, and ground support services and vehicles.[2] They are where air service starts and ends.[3] Generally, commercial service airports in the United States are publicly owned and operated. For example, SEA is operated by the Port of Seattle, a public entity. Airports host airline operations throughout the flow of passengers and goods (e.g., ticketing, gates). These operations are provided by the airlines, typically through agreements with the airport.[4] In Washington, the busiest and most prominent airport is SEA. However, there are nine other commercial service airports located throughout the state, as shown in Exhibit 2.

Airlines are private companies that provide air travel and cargo transit to customers. Airlines lease gates and slots at airports to provide these services. Many airlines service airports in Washington. At SEA, 36 airlines offer commercial service to passengers.[5] Some of these passenger airlines also offer air cargo service. For example, Alaska Airlines also offers Alaska Air Cargo, and both offer services through SEA airport.[6]

Airlines purchase or lease the aircraft used in their operations from **aircraft manufacturers**. Like airlines, aircraft manufacturers are private companies. The commercial aircraft market has two major players: Airbus, based in France, and Boeing, based in Washington State. Each firm manufactures about 40% of the commercial airplanes flying today.[7]

Exhibit 2

Commercial Airports in Washington



Notes:
The other commercial airports in Washington are Anacortes Airport, Bellingham International Airport, Pullman-Moscow Regional Airport, Spokane International Airport, Walla Walla Regional Airport, William R. Fairchild International Airport, and Yakima Air Terminal/McAllister Field.

[2] FAA. *Chapter 14: Airport operations.*
[3] Ibid.
[4] Sabel, J. (2004). Airline-airport facilities agreements: An overview. *Journal of Air Law & Commerce, 69*, 769.
[5] Seattle-Tacoma International Airport. *Air cargo carriers.*
[6] Alaska Airlines group fact sheet.
[7] International Air Transport Association (IATA). (2025). *The global commercial aircraft fleet.* International Air Transport Association.

Throughout this system, **regulatory agencies** set and enforce rules regarding safety, security, and environmental protection. Some of these agencies are international, such as the United Nations' International Civil Aviation Organization (ICAO), which coordinates air services and regulations between different countries.[8] Others are national, such as the Federal Aviation Administration (FAA), the U.S. Department of Transportation (USDOT), the Transportation Security Administration (TSA), and the Environmental Protection Agency (EPA). Many states and local governments also have their own agencies that regulate aviation within their jurisdictions.[9]

In Washington, the Washington State Department of Transportation (WSDOT) works with key partners, like airports and federal agencies, to support air transportation in Washington State. Other state and local agencies can also have an impact on the air transportation system. For example, aviation stakeholders have noted the Department of Ecology's enforcement of the State Environmental Policy Act (SEPA) has a particular impact on infrastructure projects.

Relevant Issues Associated with Commercial Aviation in Washington

Several challenges impact commercial air service in Washington. This section provides a brief overview of those most directly related to WSIPP's legislative assignment.

Capacity Constraints at SEA

Seattle-Tacoma International faces significant capacity challenges. In 2024, SEA served a record 52.6 million total passengers, including passengers boarding and departing aircraft.[10] As we will discuss in Section II of this report, the baseline study predicts even further growth in demand. Seattle-Tacoma International has limited room to expand its capacity to meet this projected demand, being surrounded by highways and neighborhoods.[11] Further, the size of aircraft served by the airport has increased over time, necessitating more space between aircraft and resulting in decreased capacity.[12]

In 2025, SEA identified 31 projects to expand this capacity. These include the construction of a second terminal and the expansion of existing taxiways and fuel facilities. All 31 such projects will be completed or underway by 2032.[13] However, taken together, these expansions are not projected to be sufficient to meet the projected regional aviation demand by 2050.[14]

[8] International Civil Aviation Organization. (2025). *About ICAO.*

[9] Library of Congress. (n.d.). *Airlines and commercial Aviation Research Guide: Regulatory Agencies & Industry Associations.*

[10] SEA airport statistics.

[11] Steinbrueck, P. (2020 February 13). *SEA Airport approaches capacity and faces difficult decisions.* Port of Seattle.

[12] Port of Seattle. (2017). *Technical memorandum No. 5 final: Facility requirements.*

[13] Port of Seattle. (2025). *Sustainable Airport Master Plan (SAMP).*

[14] Steinbrueck (2020).

Environmental Impacts of Air Travel

Commercial aviation has a variety of impacts on the environment—these are not unique to Washington State.

Aviation's impacts on climate change are frequently studied. Aircraft that run on fossil fuels release a number of different greenhouse gases (GHGs) with climate change-related impacts, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), water vapor, sulfur compounds, and hydrocarbons. Greenhouse gases are also emitted at airports by ground support equipment. Airports can also generate emissions through their electricity consumption. Accounting for all these sources of emissions, a recent study estimated that aviation is responsible for 3.5% of human-induced climate change globally.[15]

Aviation generates many different types of pollution beyond GHGs, including air pollution,[16] polluted runoff waters,[17] physical waste,[18] and impacts on local flora and fauna near airports.[19]

We further describe the environmental impacts of air travel in Section IV of this report.

Economic Impacts of Air Travel

Commercial air travel can bring economic benefits in the form of job creation, business and tax revenue, and the transportation of goods, to name a few.[20]

Discussion of the economic impacts associated with air travel is outside the scope assigned by the legislature and thus is largely absent from this report.

[15] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., . . . Wilcox, L.J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment, 244,* 117834.

[16] Riley, K., Cook, R., Carr, E., & Manning, B. (2021). A systematic review of the impact of commercial aircraft activity on air quality near airports. *City and Environment Interactions, 11,* 100066.

[17] Sulej, A. M., Polkowska, Ż., & Namieśnik, J. (2012). Pollutants in airport runoff waters. *Critical Reviews in Environmental Science and Technology, 42*(16), 1691-1734.

[18] Sebastian, R.M., & Louis, J. (2021). Understanding waste management at airports: A study on current practices and challenges based on literature review. *Renewable and Sustainable Energy Reviews, 147,* 111229.

[19] Радомська, М.М., Горобцов, І.В., Черняк, Л.М., & Тихенко, О.М. (2021). The analysis of airports' physical factors impacts on wildlife. *Scientific Bulletin of UNFU, 31*(3), 74-79.

[20] For more information about the economic impact of aviation, and to see a geographic representation of the economic benefits, see the WSDOT Aviation Economic Impact Study and explore the associated Airport Economic Modeling Tool.

II. Assessment of Forecasts

This section presents our assessment of the PSRC baseline study on aviation in the Puget Sound region.

The Puget Sound Regional Council completed the Regional Aviation Baseline Study in May 2021. In this baseline study, PSRC provided policymakers with a review of the aviation system in the Puget Sound region, a forecast for the passenger and air cargo markets, and an evaluation of different scenarios that could help meet varying levels of the anticipated service gap.

In our assignment, WSIPP was tasked with evaluating the forecasts within the baseline study.[21] For both the passenger and air cargo demand forecasts in the study, we outline the assumptions, data, methodology, and accuracy of the forecasts given the available data since the study's publication.

Passenger Activity Forecast

In the baseline study, commercial aviation is measured via enplanements. Enplanements are a measure of passenger boardings, where a single enplanement is one passenger boarding an aircraft.[22] In the central Puget Sound region, commercial aviation is primarily operated out of SEA and Paine Field Airport (Paine Field) in Everett.[23]

Baseline Forecast Summary

The baseline study forecasts commercial enplanements in the region to grow at an average annual growth rate between 2.4% and 2.8% from 2017 to 2050, reaching between 49.3 million and 55.6 million enplanements in 2050, as shown in Exhibit 3.[24] To construct this forecast, the baseline study used forecasts from other sources as inputs in conjunction with guidance from subject matter experts.[25]

Baseline Study Data

The year 2017 serves as the base year for forecasting, with information for SEA and Paine Field sourced from the FAA Terminal Area Forecast (TAF). The FAA uses a variety of sources of administrative data to construct the TAF, including operations data from air traffic control towers.[26] The annual growth projections were then applied to the actual count of enplanements from 2017 to project the total quantity of commercial aviation at SEA and Paine Field until 2050.

[21] We encourage those who are interested in learning more about the scenarios to read the baseline study and the associated Working Paper 3. Puget Sound Regional Council. (2021). *Regional aviation baseline study: Working paper 3 – Development and evaluation of scenarios*.

[22] Glossary for the 2021 Terminal Area Forecast.

[23] These are the two airports in the Puget Sound region that have scheduled commercial service with air carriers that have an FAA Part 121 operating certificate for regularly scheduled or air carrier service (Regional Aviation Baseline Study – Working Paper 1, Section 4.2).

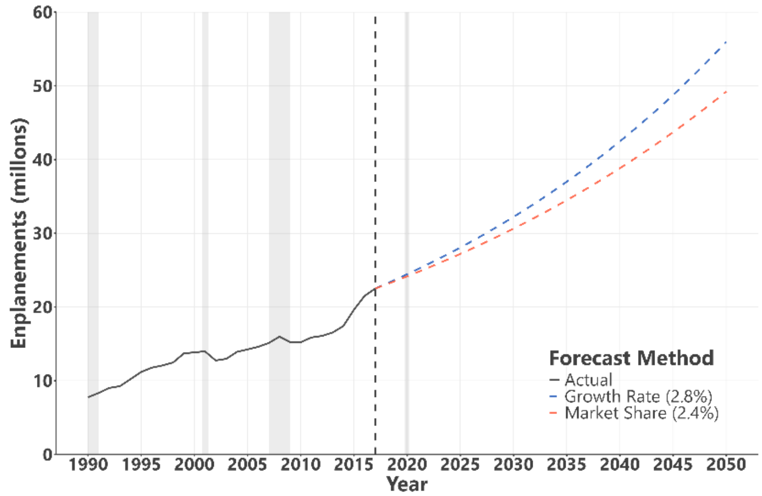
[24] PSRC baseline study, final report, section 3.2.1.

[25] Regional Aviation Baseline Study – Working Paper 1, Section 4.

[26] Forecast Process for 2024 Terminal Area Forecast (TAF). TAF is the official forecast of aviation activity for airports in the National Plan of Integrated Airport Systems (NPIAS).

Exhibit 3

Enplanements: Actuals & Forecast



Notes:
Figure created from data in the PSRC baseline study. The solid black line represents actual historical data, while the dashed lines are the forecasts developed by PSRC. The vertical dashed line marks the base year, 2017. The gray areas highlight periods of economic recession.
Sources:
Federal Aviation Administration Terminal Area Forecast and the baseline study.

Baseline Study Methodology and Assumptions

The baseline study used two methods to forecast commercial aviation activity, one using annual aviation growth rates in the region (**growth rate method**) and one using the region's share of national aviation demand (**market share method**).[27] These methods resulted in two average annual growth rates, providing an upper and lower bound for aviation demand through 2050.

The **growth rate method** estimates that the number of passengers boarding planes in the Puget Sound region is estimated to grow each year by 2.8%. This rate comes from a combination of the average annual growth rates from the 2017-2038 forecasts of the Sustainable Airport Master Plan (SAMP) (2.8%) and the FAA TAF (2.7%).[28] This is depicted by the blue dashed line in Exhibit 3.

The **market share method** estimates that the number of passengers boarding planes in the Puget Sound region is estimated to grow each year by 2.4%. This method projected enplanements from 2018 to 2050 by multiplying the region's projected 2.93% share of the national market in 2037 by the forecasted U.S. national enplanements.[29]

[27] The baseline study also computed a regression-based forecast but ultimately did not prefer this forecast, arguing that this method did not adequately account for market-specific factors unique to the central Puget Sound region—such as heightened airline competition at SEA and the commencement of service at Paine Field.

[28] SAMP 2015 Forecasts of Aviation Activity and 2018 FAA Terminal Area Forecast.

[29] Regional Aviation Baseline Study – Working Paper 1, Figure 4-7.

In this method, the projected market share was taken from the TAF, and the projected count of U.S. enplanements was taken from the FAA Aerospace Forecast.[30] This is depicted by the orange dashed line in Exhibit 3. Notably, both forecasts assumed that any growth in aviation activities would not be constrained by the capacity of airports in the region.

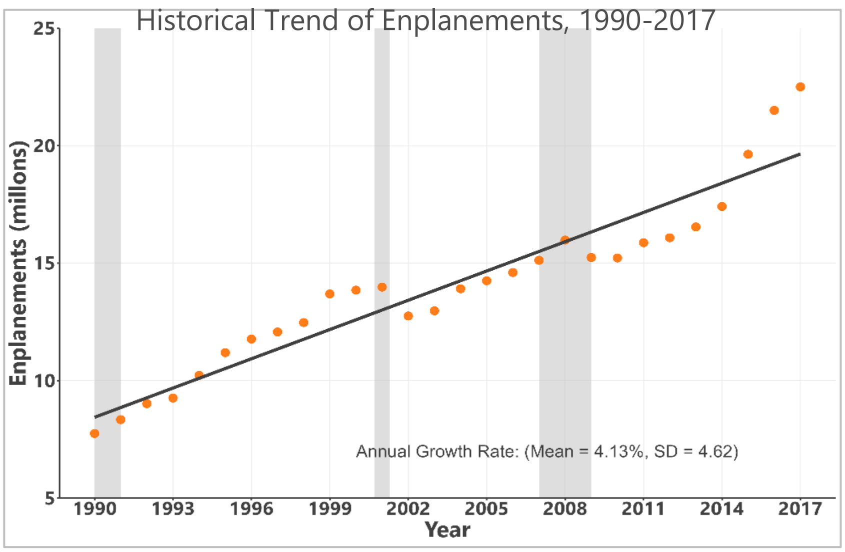
WSIPP's Forecast Assessment

We begin with a discussion of a few of the assumptions made in the baseline study. First, for each of these methods, the baseline study assumed that short-term disruptions and downturns in aviation or the economy would not significantly affect the long-term aviation activity projections for the region.[31] To evaluate this assumption, we analyzed historical data from 1990 to 2017 and presented the long-term trend in Exhibit 4.

As the exhibit shows, despite some fluctuations, actual enplanements generally follow the upward trend closely, supporting the assumption in the baseline study. The baseline study also assumes the general state of the Puget Sound region is not changing; for example, economic activity in the region will continue to grow.

In the market share method, the study assumes that the region's market share of U.S. enplanements would remain constant, at 2.93%. In actuality, the Puget Sound area's regional market share of U.S. enplanements has been growing steadily, as shown in Exhibit 5. If this upward trend were to continue, the assumption that PSRC made would not hold, and their forecast would likely underestimate the growth rate of passenger activity in the region.

Exhibit 4



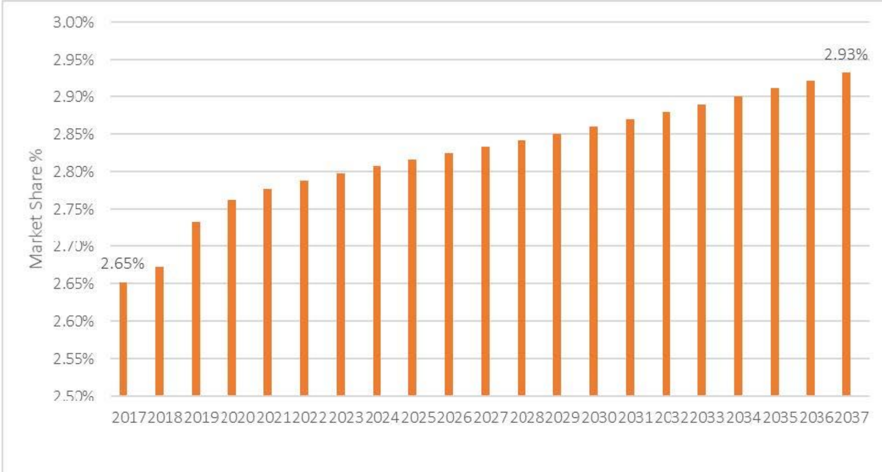
Notes:
The solid black line represents the fitted linear trend, while the dots represent the actual annual enplanements. The gray areas highlight recession periods.
Source:
Bureau of Transportation Statistics.

[30] Ibid Section 4.3.2.1.

[31] Ibid Section 4.3.

Exhibit 5

Projected U.S. Enplanement Market Share (Central Puget Sound Region)



Source:
Regional Aviation Baseline Study, Working Paper 1, Figure 4-7.

Actualized Comparison. An **actualized comparison** assesses differences between the forecasted estimates for passenger activity and the actual values for the same period. In this case, we compare the forecasts from 2018 to 2024 to actual values we can observe in enplanement data. As shown in Exhibit 6, air travel during this period was significantly impacted by the COVID-19 pandemic. Nonetheless, after a sharp decline in 2020, enplanements recovered to 2019 levels, though they have not fully recovered to the level that we would expect in the absence of the COVID-19 pandemic. Meaning, if the trendline from prior to the pandemic had continued through the early 2020s, we would see a larger number of enplanements in the Puget Sound region than we are seeing in the actual data. By 2024, the baseline study forecasts were roughly 7% above actual enplanements.[32] This suggests that the enplanement forecasts in the baseline study are an overestimate, potentially due to the decline caused by COVID-19.

Backcasting Comparison. We conducted backcasting from 2016 to 2000 using the annual growth rates of 2.4% and 2.8%, as applied in the baseline study, respectively. **Backcasting** is an approach that uses a forecast's methodology and applies it retroactively. By doing this, estimated historical values are created and compared against historical data to assess a forecast's performance.[33] This method extends our comparison with actual data over a longer time period.

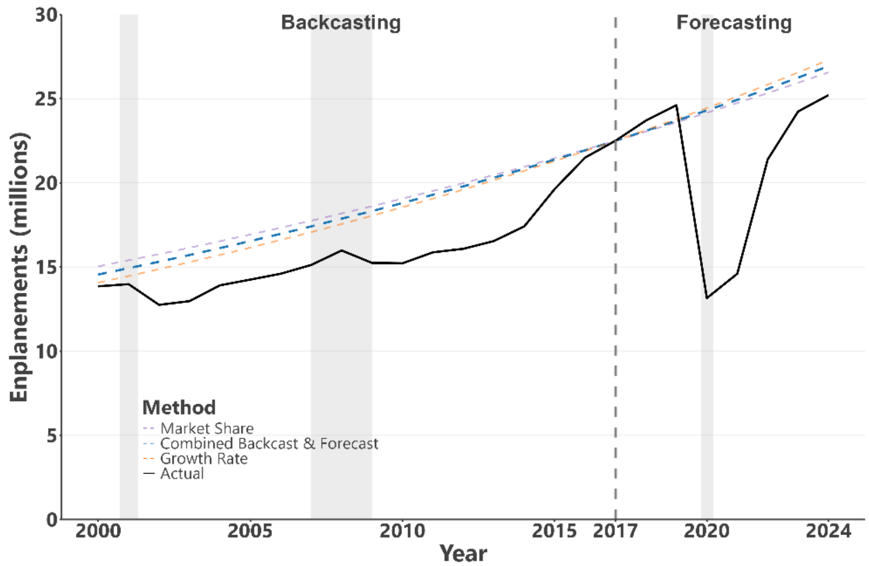
The results, presented in Exhibit 6, show that the actual enplanement values between 2000 and 2016 were below the two backcasted estimates.

[32] Here, we use the average of the growth rate method and the market share method forecasts.

[33] See Appendix II for backcasting details.

Exhibit 6

Enplanement Estimates: Backcast (2000-2016) and Forecast (2018-2024)



Notes:
The solid black line represents the actual data.
The vertical dashed line marks the year 2017, which serves as the base year.
The colored dashed lines indicate backcasts (2000-2016) and forecasts (2018-2024).
The gray areas highlight recession periods. See Appendix II for backcasting details.

On average, the combined backcast estimates exceeded the actual enplanements by 2.4 million annually, representing a 15.5% increase relative to the mean of the actual annual enplanements. Note that two economic recessions occurred during this period, which may have partially contributed to the difference. Moreover, there is variability in the differences over time, ranging from 0.4 million to 3.8 million. When using PSRC's forecast methodology retroactively, working backwards from the year 2016 to 2000, the backcast is an overestimate of the actual values.

Together, both comparative analyses suggest a similar result—forecasted enplanements were higher than actual enplanements. Despite disruptions from economic downturns, the overall trend returned to an upward trajectory. This suggests that the forecasts in the baseline study likely represent estimates on the high-end, assuming no significant or permanent changes occur in commercial aviation in the region.

Air Cargo Forecast

Air cargo (i.e., freight and mail) in the central Puget Sound region is primarily generated by activity at SEA and King County International Airport (KCIA).[34]

[34] As noted in the baseline study, air cargo generated at Paine Field is classified as general aviation and, therefore, was not included in the air cargo forecast.

Baseline Forecast Summary

As shown in Exhibit 7, in the baseline study's preferred forecast, the total weight of air cargo being transported on airplanes in the Puget Sound region is estimated to grow at a rate of 2.75% over the 33 years from 2017 to 2050. This would result in over 1.3 million metric tons of freight in 2050. Additionally, the baseline study highlighted uncertainty in these forecasts, with projected values for 2050 ranging from about 890,000 to nearly 2.4 million metric tons.[35]

Baseline Study Data

As in the passenger activity forecast, the baseline study used 2017 actual air cargo data as the base for forecasting.

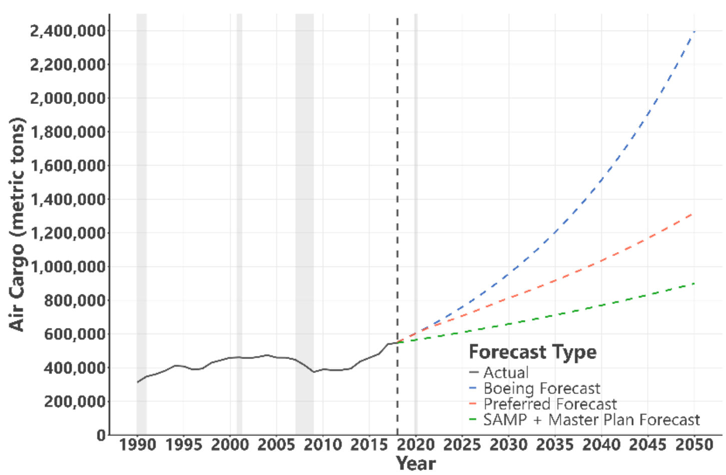
Other data sources used in the air cargo forecast were from well-known sources of administrative data in the aviation sector. Air cargo statistics for SEA were sourced from SEA airport statistics, which are published regularly by the Port of Seattle based on official data collected from SEA airport.[36] Since KCIA does not directly collect air cargo data from airlines, the base data for KCIA was obtained from the U.S. Bureau of Transportation Statistics T-100 Market and Segment (All-carriers) Report.[37]

Baseline Study Methodology and Assumptions

The Puget Sound Regional Council developed air cargo forecasts specific to each airport, SEA and KCIA. Each forecast was developed with input from two source forecasts: the Boeing World Air Cargo forecasts and the corresponding airport master plan forecasts.[38]

Exhibit 7

Air Cargo Forecast, 2018-2050



Notes:
Figure created from data in the PSRC baseline study. The solid black line represents historical data, while the dashed lines are the forecasts. The vertical dashed line marks the year 2017, which serves as the base year. The gray areas highlight the recession periods.
Sources:
SEA airport statistics, Bureau of Transportation statistics, and the baseline study.

[35] Appendix Exhibit A5 presents historical air cargo volumes and forecasts for SEA and KCIA.
[36] SEA airport statistics.
[37] Bureau of Transportation Statistics T-100 Market and Segment (All-carriers) Report.
[38] The master plan forecasts include the 2014 Sustainable Airport Master Plan for SEA, and the working paper produced in May 2016 as part of the KCIA Airport Master Plan Update for KICA.

To construct its preferred forecast, the PRSC applied different weighting combinations to the two forecasts over time.[39] The baseline study used subject matter expertise to guide the relative weighting of the Boeing and master plan forecasts.[40] In the short term, greater weight was given to the Boeing forecast. In the long term, the weighting shifted toward the master plan forecasts, which were more conservative in their estimates of aviation activity.

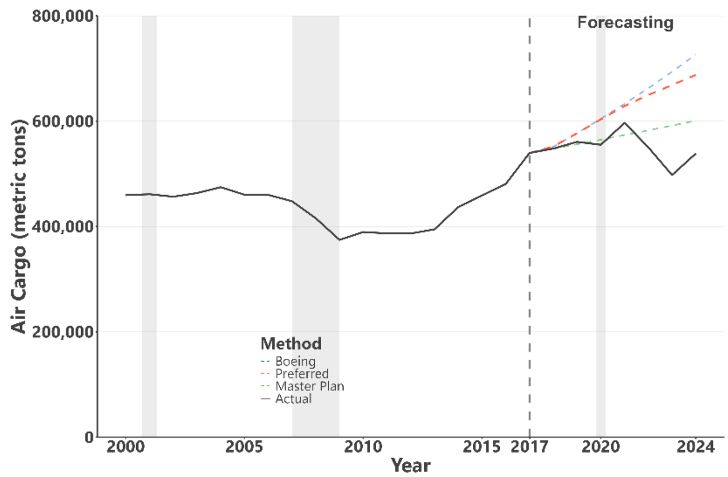
WSIPP's Forecast Assessment

To assess the baseline study's air cargo forecast, we compared the forecasted values to actualized values for the years available.

As shown in Exhibit 8, the COVID-19 pandemic significantly impacted the air cargo trend from 2018 to 2024, with an initial increase followed by a decline and a slow recovery. By 2024, the preferred forecast exceeded the actual air cargo volume by more than 27.7%, and even the conservative master plan forecast was higher than the actual value. This suggests that the air cargo forecasts presented in the baseline study could be overestimated going forward due to the impacts of COVID-19, unless a steeper recovery occurs in the future.

Exhibit 8

Air Cargo Forecast, 2018-2050



Notes:
Figure created from data in the PSRC baseline study. The solid black line represents historical data, while the dashed lines are the forecasts. The vertical dashed line marks the year 2017, which serves as the base year. The gray areas highlight the recession periods.
Sources:
SEA airport statistics, Bureau of Transportation statistics, and the baseline study.

[39] For details of two forecasts, refer to Appendix I.
[40] According to Chapter 6 of Regional Aviation Baseline Study – Working Paper 1, the considerations included significant market changes, such as the relocation of ABX Air and Atlas Air from KCIA to SEA, as well as the growing influence of e-commerce on the air cargo industry.

Key Takeaways

In WSIPP's legislative assignment, we were directed to examine the passenger activity and air cargo forecasts in the PSRC baseline study, including an assessment of the assumptions, data, methodology, and accuracy of the forecasts. Generally, we find that the report used well-established data and methodology in the creation of its own forecast. In our review of the accuracy of the PSRC forecasts, we evaluated their performance against actual data for the years available and used a backcasting strategy to further evaluate the forecast performance where possible.

The COVID-19 pandemic occurred during the short time period for which we have actual data to compare the forecasted values against. This clearly disrupted the trend for both passenger and air cargo travel. This major disruption to a large portion of the available data adds uncertainty to our assessment of whether the forecasts are an accurate or inaccurate estimate of long-term demand. In addition, the subjective nature of the air cargo forecast did not allow us to use the backcasting strategy to evaluate the forecast for a longer time span.

In PSRC's passenger activity forecast, forecasted enplanements were higher than actual enplanements. Similarly, in the air cargo forecast, the forecasted metric tons of air cargo transported were higher than actual values. While some of this overestimation may be due to the COVID-19 pandemic, we find evidence to suggest that both the passenger activity and the air cargo forecast overestimate the actual aviation activity in the Puget Sound area.

III. Strategies to Reduce Air Travel

As directed by the legislature (Exhibit 1), we review the research literature on strategies and interventions to reduce air travel. We begin by describing the scope and methods of our literature review. Next, we summarize research on each intervention. We conclude with key takeaways and a discussion of the review's limitations.

Scope and Methods

We conducted a systematic literature review to identify studies evaluating the impact of policies or other interventions on the **quantity of air travel**. In the reviewed studies, several measures of air travel quantity were considered, including the number of passengers and the number of flights or seats provided by airlines.

Our team developed a set of search terms to capture relevant research and selected five publication databases for review. We established inclusion and exclusion criteria, which we applied through a two-stage screening process conducted by two researchers working independently. We filtered research based on relevancy to the legislative assignment, which directed us to examine national and international strategies.

We included strategies designed to reduce the quantity of air travel in the commercial aviation sector, whether through demand- or supply-side measures. These encompassed strategies aimed at lowering congestion, reducing emissions through behavior change, or both. We excluded evaluations in the civil and military aviation contexts.

Consistent with the legislature's emphasis on "effective" strategies, we focused on recent research (i.e., published within the last ten years) on interventions that were fully or partially implemented. We included both quasi-experimental and observational studies, provided they used multivariate techniques to control for potential confounders such as population, GDP, and other relevant factors.

Finally, we excluded studies that used less reliable measures for air travel, such as self-reported data or proxies (e.g., tourism activity).[41]

Additional details on our methodology are provided in Appendix III. Complete citations for works cited in the section can be found in Exhibit A5 in Appendix III.

Impacts on Vulnerable Populations

The legislative language also directed WSIPP to report on whether the identified strategies mitigate net environmental impacts on overburdened communities and vulnerable populations. Our review did not find any studies that assessed the avoidance of environmental impacts on such communities.

[41] Some relevant strategies—such as flight bans—were identified in our search but not represented in our final review because they lacked eligible outcome evaluations. A list of these interventions is provided in Exhibit A7 in Appendix III.

Interventions to Reduce Air Travel

We found 17 research articles that met our search criteria.[42] These studies spanned five interventions, including the following:

- High-speed rail
- Flight departure taxes
- Emissions trading programs
- Emissions taxes
- On-time performance policies

We organize our review by intervention category, starting with the largest category by number of studies reviewed (high-speed rail). At the conclusion of this section, we recap the key takeaways for each intervention in Exhibit 9.

Before presenting our findings, we emphasize that the available literature is limited in size and interpretation. Every study we reviewed looked at interventions outside of the United States context and had at least one methodological flaw.[43] As such, the evidence summarized for this review should be interpreted with caution.

High-Speed Rail

Of the 17 studies in our final review, 11 discuss the impacts of high-speed rail (HSR) on aviation demand. In theory, HSR could decrease demand for air travel by providing an alternative means of transportation between destinations (the substitution effect). Alternatively, HSR could make it easier for travelers to get to an airport, thereby facilitating access to air travel and increasing demand (the feeding effect). The larger of these two effects determines whether air travel demand increases or decreases following HSR entry into a transit market.[44]

Ten of the 11 studies on HSR look at the rollout of HSR in China, beginning in 2008 and continuing through the present day. Among these ten, eight find that the introduction of HSR had a net negative impact on demand for air travel, flights, or seats provided by air carriers. Seemingly, in these studies, the substitution effect outweighs the feeding effect of HSR. Among these eight analyses, estimates of the net impact of HSR entry on air travel passengers range from a decrease of 11% to 32%.[45]

However, two other studies from the same set of authors did not find this decrease in demand. The first, from 2020, demonstrates that HSR could increase demand for aviation, but did not make any conclusions about its overall impact on air travel in China.[46] The second, from 2022, finds that the introduction of HSR led to an increase in aviation demand by feeding potential passengers to airports, contradicting the findings of the other eight.[47]

[42] We report 19 sets of results, where two studies evaluated two different policies of interest.

[43] For example, only one study, Gu & Wan (2022), accounts for the impact of airfare prices as a factor affecting travel demand directly. Standard economic theory would hold that consumers of aviation services would consider airfare when making their purchasing decisions. The omission of airfare from consideration as a factor affecting air travel demand will lead to the estimates of the effects of the intervention being biased in an unknown direction.

[44] If airlines significantly lower their fares following HSR entry to remain competitive, demand for air travel may also increase in response.

[45] Ma et al. (2019) and Yuan et al. (2023).

[46] Gu & Wan (2020).

[47] Gu & Wan (2022).

Another study examines the impact of HSR services between major European cities, finding that HSR increases air passengers departing cities that have an HSR connection, such as Paris, Amsterdam, and Frankfurt.[48] High-speed rail only had a net negative impact on flyers between Paris and London; the authors theorize that the point-to-point nature of most travelers' itineraries on that route (i.e., without further connecting flights) makes HSR particularly competitive.

Additional Considerations. Many of these analyses also investigate how other factors influence the relationship between HSR and air travel demand. Most examine how HSR's impact varies by distance or time traveled on specific routes. Almost universally, they find more substitutions away from air travel toward HSR over short routes, or when travel time differences between HSR and air are smaller.[49] Over longer distances, however, the substitution effect of HSR diminished.[50]

The selected studies explored a few other differentiating factors. One investigated how HSR's effects vary by type of flyer, finding that business-class travelers were more likely to switch to HSR than economy-class travelers.[51] The authors also found that smaller, regional airlines are more negatively impacted than larger airlines in terms of passenger counts.

Similarly, another report found that cities that act as major hubs for airlines were less likely to see a falloff in air passengers following HSR entry than non-hub cities were.[52] These results demonstrate that HSR may have disparate impacts on different communities, businesses, and travelers.

Effects on Emissions. A handful of the studies also estimate HSR's impact on emissions of GHGs during the operations phase of HSR. Each of these analyses estimates emissions by multiplying aviation use by an emissions factor.[53] The result is that their estimates of changes in emissions resulting from HSR entry are mostly driven by estimated changes in the supply of and demand for air travel. One report estimated that HSR in China reduced emissions by 30 million tons in 2019 alone;[54] another estimated a reduction of only 8.48 million tons over five years.[55] In line with their conclusion that HSR had fed air travel demand, one research team estimated that HSR increased carbon dioxide emissions by over 2 million tons per year.[56] However, none of these analyses considered emissions generated by the construction of HSR.

It should be noted that none of these studies account for the fact that HSR entry in a specific city is almost certainly non-random. Rather, cities that act as travel hubs are likely the first to obtain HSR service to reduce the burden on other transit modes.

[48] Bernardo & Fageda (2020).
[49] One study, however, found no significant impact over routes of less than 600 kilometers. Li et al. (2024).
[50] Gu & Wan (2020).
[51] Ma et al. (2019).
[52] Chen (2017).
[53] The emissions factor is a measure of average GHG emissions. Different studies approached the construction of these emissions factors differently. Some incorporated route-specific emissions estimates or regional types of electricity generation. Others assumed general emissions factors for aviation and HSR and took the difference.
[54] Li et al. (2024).
[55] Wang (2019).
[56] Gu & Wan (2022).

This could mean that HSR was implemented where it would be most likely to have a large effect, and that a similarly sized effect might not occur in a different setting (i.e., a non-hub city). Additional limitations that are shared by these and the other studies in our review are discussed at the end of this section.

Flight Departure Taxes

Flight departure taxes (sometimes called aviation taxes) are excise duties levied on passengers departing from airports. These taxes are implemented for various reasons, including offsetting the environmental impacts of air travel or generating government revenue. They are levied on departures rather than arrivals and typically have lower duties charged on short-haul flights than long-haul flights.

We reviewed four studies that examine the impact of flight departure taxes on air travel. These studies focus on policies in Austria, Ireland, and Germany, though similar policies have been adopted (and at times repealed) in other European Union (EU) and non-EU countries.

The studies in our review generally find that flight departure taxes reduce passenger volumes or flights, though the magnitude and consistency of these effects vary across countries. The most consistent evidence comes from the German Aviation Tax (GAT), which was evaluated and found to reduce air travel in all four studies. Two studies report annual declines in passenger volumes ranging from 2% to 6%.[57]

Other research also finds reductions in passengers but finds the largest reduction in the year immediately following the tax's introduction, with effects dissipating in subsequent years.[58] One publication finds a reduction in the number of flights on routes departing Germany since the tax was implemented.[59]

Three of the four studies also assess the Austrian Air Transport Levy (ATL), either jointly or separately from the GAT, with mixed results. The two studies that jointly evaluate the GAT and ATL find significant reductions in passenger volumes.[60] However, when considered in isolation, the study finds no significant effect of the ATL on flights departing Austria.[61]

The same study additionally examines the Air Travel Tax (ATT) in Ireland, implemented in 2009 and abolished in 2014, finding no significant impact on flights departing Irish airports.[62]

Additional Considerations. Several of the studies also explore variation across airport types. Prior research indicates that declines in passenger volumes were concentrated at airports dominated by low-cost carriers (LCCs), with no significant effect at airports primarily served by full-service airlines, suggesting greater price sensitivity among LCC passengers.[63] Similar patterns have been observed between hub and non-hub airports: demand fell at non-hub airports but was negligible or slightly positive at hub airports.[64]

[57] Borbely (2019) and Oesingmann (2022).
[58] Falk & Hagsten (2019).
[59] Fageda & Teixidó (2022).
[60] Falk & Hagsten (2019) and Oesingmann (2022).
[61] Fageda & Teixidó (2022).
[62] Ibid.
[63] Falk & Hagsten (2019).
[64] Borbely (2019).

Collectively, these findings indicate that flight departure taxes primarily reduce demand among more price-sensitive travelers, such as lower-income passengers or leisure travelers, rather than business travelers.

Two studies also investigated whether departure taxes diverted demand to nearby airports across borders where such taxes did not apply. The evidence is mixed: one study finds no diversion,[65] while another identifies demand shifts to nearby foreign airports.[66]

Emissions Trading Programs

Emissions trading programs are regulatory "cap-and-trade" programs that limit GHG emissions by allocating or auctioning a fixed amount of emission permits and allowing companies to trade them. The theory is that, since placing a cap on emissions creates costs for companies, allowing the trading of permits ensures that emissions reductions occur at companies where they are least expensive. Firms may react through technological innovation to abate emissions or restrict their output.

We reviewed two studies on the EU's Emissions Trading System (ETS) specifically. The EU ETS was established in 2005, with emissions from aircraft carriers incorporated in 2012. These studies examine the system's impact on passenger volumes, flights, and emissions.

Evidence on the EU ETS's impact on air travel is mixed. One study finds no significant effect of the EU ETS on passenger numbers,[67] while another finds a reduction in flights relative to the comparison group.[68] In the latter report, the largest impacts were observed among low-cost carriers and on short-haul routes, particularly where HSR offered a competitive alternative.

Prior research also finds that the EU ETS slowed the growth of aviation emissions but did not necessarily reduce overall emissions.[69] The researchers argue that because emission reductions closely mirrored reductions in flights, the EU ETS primarily curbs emissions in the aviation sector by limiting output rather than by improving efficiency (e.g., through technological innovation).

The EU ETS is due to undergo a major change in the coming years that could cause the EU ETS to have a more drastic impact, curbing both aviation and emissions to a greater degree.[70]

Washington State implemented a similar but smaller-scale program under the Climate Commitment Act (CCA) called the Cap-and-Invest program. Like the EU ETS, Washington's Cap-and-Invest program currently gives no-cost allowances to specific industries until at least 2034. Among these are emissions-intensive, trade-exposed industries (EITEs), which include aerospace manufacturers and fuel producers.[71] Washington State Department of Ecology will publish a report on no-cost allowance allocation for EITEs for 2035-2050 in December 2025.[72]

[65] Falk & Hagsten (2019).
[66] Borbely (2019).
[67] Fageda & Teixidó (2022).
[68] Oesingmann (2022).
[69] Fageda & Teixidó (2022).
[70] European Commission. (n.d.). *Allocation to the aviation sector – EU Emissions Trading System (EU ETS)*. Climate Action. Retrieved December 9, 2025.
[71] RCW 70A.65.110.
Air carriers are not considered EITEs and must purchase emission permits under the CCA.
[72] Washington State Department of Ecology. (n.d.). *Emissions-intensive, trade-exposed industries (EITEs)*. Retrieved December 9, 2025.

Emissions Taxes

Emissions taxes, like emissions trading programs, seek to reduce emissions by forcing producers to either curb their emissions or pay a cost to the government. However, emissions taxes do not impose an overall emissions cap; instead, they increase the cost of activities that generate emissions.

We reviewed one study on Australia's Clean Energy Future (CEF) policy, which imposed a per-ton charge on carbon dioxide-equivalent emissions. Markham et al. (2018) find no association between the CEF and domestic aviation activity in Australia. The authors suggest that the tax level ($23 AUD per ton in 2012) may have been too low to influence aviation demand, particularly given the substantial fluctuation in oil prices during the study period.

On-Time Performance Policies

One study investigates the impacts of an on-time performance (OTP) policy by the Civil Aviation Administration of China in 2017. This policy was not intended to reduce air travel demand, but to increase on-time performance. Accordingly, the policy penalized airports with persistently poor OTP records by reducing allowable flight capacity and canceling services.

Fu et al. (2020) find that China's OTP policy reduced both departing and arriving flight frequencies, with the largest effects observed at hub airports and other busy airports relative to those with lower traffic.

The policy is unusual in that it departs from international industry practices of assigning airport slots to airlines. By contrast, China's OTP policy directly tied slot availability to performance, a divergence that, as the authors note, could create operational disruptions within the aviation sector.

Key Takeaways

Despite screening more than 3,000 research articles in our systematic review, we identified sparse literature on strategies to reduce the quantity of air travel. Only five categories of interventions had research literature that met our criteria for inclusion. All the identified interventions were implemented in countries outside of the United States context.

High-speed rail (HSR) was the most studied strategy for reducing air travel. Most of these studies found that HSR entry reduced air travel demand, particularly among flight routes where HSR was most competitive (i.e., short-haul routes). However, most of these studies did not control for airfare or the non-random rollout of HSR, omissions that may overstate the degree to which HSR entry decreases demand for air travel.

Flight departure taxes were the second most studied and mostly are associated with a decrease in passenger volumes—particularly at non-hub airports and routes serviced by low-cost carrier airlines. The reviewed policies were implemented at the national level, though one policy has since been removed.

In general, we found few studies evaluating emissions trading programs, emissions taxes, and on-time performance policies. We also identified studies on other in-scope interventions (e.g., flight bans), but we excluded them because they did not use research methods that met our inclusion criteria.

We summarize the key takeaways from each study by intervention category and outcome in Exhibit 9. The columns capture different measures of air travel used across studies: passengers, flights, seat capacity, and emissions. For each study, the table indicates how each intervention is expected to change each outcome.

Exhibit 9

Key Takeaways from Reviewed Papers

Study	Passengers	Flights	Seat capacity	Emissions
High-speed rail				
Chen (2017)	Decrease	Decrease	Decrease	
Yang et al. (2018)	Decrease			
Ma et al. (2019)	Decrease			
Wang et al. (2019)	Decrease			Decrease
Bernardo & Fageda (2020)	Decrease			
Gu & Wan (2020)			Mixed	
Strauss et al. (2021)	Decrease			Decrease
Yu et al. (2021)	Decrease			Decrease
Gu & Wan (2022)	Increase			Increase
Yuan et al. (2023)	Decrease	Decrease		
Li et al. (2024)			Decrease	Decrease
Flight departure taxes				
Borbely (2019)	Decrease			
Falk & Hagsten (2019)	Decrease			
Fageda & Teixidó (2022)		Mixed		
Oesingmann (2022)	Decrease			
Emissions trading programs				
Fageda & Teixidó (2022)		Decrease		Decrease
Oesingmann (2022)	No effect			
Emissions taxes				
Markham et al. (2018)	No effect*			
On-time performance policies				
Fu et al. (2020)		Decrease		

Notes:
Mixed reflects results that varied by geography or model specifications, and **No effect** indicates no statistically detectable impact. An asterisk **(*)** denotes that a study measured passengers in revenue passenger kilometers (RPKs). Complete citations for the papers in this section can be found in Exhibit A5 in Appendix III.

IV. Technologies to Reduce Environmental Impact

In this section, we survey new and developing interventions that are intended to reduce the environmental impact of commercial aviation.

While this review is not intended to estimate the effect of implementing any specific intervention, we provide descriptions and general information about the effect on environmental outcomes of each intervention as provided in the reviewed research. We also supplement this with a discussion of the feasibility of implementing these technologies where possible. This discussion is informed by insights from the reviewed literature, information on what other airports and airlines have implemented, and interviews with Washington stakeholders in commercial aviation.

Environmental Impacts of Air Travel

Commercial aviation has a variety of impacts on the environment. While there is uncertainty regarding the total environmental impact from aviation, especially with respect to non-CO_2 emissions, there is a general scientific consensus that emissions from aviation activities are contributing to climate change.[73]

Aviation generates many different types of pollution, including GHGs. Air pollution near airports is commonly cited as a health risk to nearby populations, contributing to respiratory problems and premature deaths.[74] Runoff waters from airports carry spilled fuel, deicing agents, and other chemicals that can infiltrate local water supplies and aquifers.[75] Airports also generate significant amounts of physical waste, including concessions, in-flight service items, defunct aviation equipment, and construction debris.[76]

The energy-intensive aircraft manufacturing process also generates emissions. Aircraft are usually made of materials like aluminum, titanium, and steel alloys, as well as various plastics, rubbers, and fabrics.[77] Greenhouse gas emissions and other pollutants are generated throughout the process of preparing these materials for assembly, including during extraction, purification, alloying or smelting, and fabrication.[78]

[73] For example, nitrous oxides can have photochemical reactions with other atmospheric chemicals to either warm the atmosphere or cool the atmosphere. Fahey et al. (2016). *White paper on climate change aviation impacts on climate: State of the science.* International Civil Aviation Organization.

[74] Riley, K., Cook, R., Carr, E., & Manning, B. (2021). A systematic review of the impact of commercial aircraft activity on air quality near airports. *City and Environment Interactions, 11,* 100066.

[75] Sulej, A. M., Polkowska, Ż., & Namieśnik, J. (2012). Pollutants in airport runoff waters. *Critical Reviews in Environmental Science and Technology, 42*(16), 1691-1734.

[76] Sebastian, R.M., & Louis, J. (2021). Understanding waste management at airports: A study on current practices and challenges based on literature review. *Renewable and Sustainable Energy Reviews, 147,* 111229.

[77] Dolganova, I., Bach, V., Rödl, A., Kaltschmitt, M., & Finkbeiner, M. (2022). Assessment of critical resource use in aircraft manufacturing. *Circular Economy and Sustainability, 2*(3), 1193-1212.

[78] Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., . . . Masanet, E. (2016). Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *Journal of Cleaner Production, 135,* 1559-1570.

Scope and Methods

Literature Review

Similarly to the preceding section, we systematically reviewed the research literature on interventions to reduce the environmental impact of aviation. Given the scope of the larger assignment, this literature review was focused on technologies and operational strategies that can be applied to air travel through commercial service airports.[79]

We developed search terms to identify relevant peer-reviewed journal articles and grey literature evaluating the impact of technologies or operational procedures on the environmental impact of commercial aviation.[80] We searched three databases and developed inclusion and exclusion criteria, which were applied through a two-stage screening process. From this process, we identified 36 studies and extracted relevant information from each.[81]

Additional details on our literature review methodology are provided in Appendix IV. Complete citations for works cited in the section can be found in Exhibit A10 in Appendix IV.

Feasibility Discussion

As directed by our legislative assignment, in our review of technological and operational enhancements, we also identify the feasibility of deploying those enhancements in Washington, where possible.

While this feasibility analysis does not constitute a formal feasibility study, it does provide an informed discussion of present challenges and opportunities for various enhancements. In addition to using information gathered from the papers in our literature review, this discussion is informed through two pathways—interviews with key stakeholders and subject matter experts within commercial aviation in Washington and a review of existing enhancements in peer airports and airlines in the US. In our interviews, we targeted a set of industry professionals in Washington State, such as regulators, airport personnel, manufacturers, and air cargo carriers.

Detailed information regarding our interview protocol can be found in Appendix V.

Interventions to Mitigate the Environmental Impact of Commercial Air Travel

We found 36 articles that met our search criteria. These studies spanned five intervention categories:

- Innovative aircraft design
- Electric and hybrid aircraft
- Airport design and electrification
- Ground operation optimization
- Sustainable aviation fuels
- Other alternative fuels

Each intervention category encompasses multiple specific technologies, as outlined in Exhibit 10.

[79] Commercial service airports are defined as publicly owned airports with at least 2,500 annual enplanements and scheduled air carrier service. Federal Aviation Administration. (December 7, 2022). *Airport Categories.*

[80] Grey literature refers to reports, studies, or other research papers produced outside of the traditional academic journals. For example, this could include work directly published by a university-affiliated research group, a government document, or a research paper from a non-governmental organization.

[81] Many of the studies discussed multiple interventions so there is not a one-to-one match of the interventions discussed and the studies reviewed.

Exhibit 10

Overview of the Reviewed Technologies and Operational Enhancements

Reviewed technologies and operational enhancements		
Aircraft design and routing	*Airports and ground operations*	*Alternative jet fuels*
Innovative aircraft design	*Airport design and electrification*	*Sustainable aviation fuels*
-Blended wing body	-On-site power generation	-Hydroprocessed esters and fatty acids
-Strut-braced wing	-Heating, ventilation, and air-conditioning	
-Boundary layer ingestion		-Alcohol-to-jet
-Double-bubble fuselage		-Fischer-Tropsch
-Counter-rotating open rotor	*Ground operation optimization*	-Power-to-liquid
	-Using towing vehicles to taxi planes	-Direct sugars to hydrocarbons
Electric and hybrid aircraft		-Pyrolysis
-Fully electric aircraft	-Single-engine taxiing	
-Hybrid aircraft	-Optimized departure and approach procedures	
Routing optimization	-Electrification of ground service equipment	*Non-drop-in alternative fuels*
-Changing the altitude		-Hydrogen
-Changing the flight path		-Ammonia
-Climate-restricted airspaces		-Ethanol
-Intermediate stop operations		-Methanol
-Continuous descent operations		-Liquefied natural gas

Note:
We present the reviewed technologies and operational enhancements in the order in which we discuss them in the report.

We organize our review by intervention category. First, we discuss technologies related to aircraft, then we discuss technologies and operational enhancements at airports, and then we discuss fuel-related technologies.

At the conclusion of this section, we recap the key takeaways for each intervention in Exhibit 13.

Innovative Aircraft Design

The fuel efficiency of new commercial jet aircraft has improved substantially in the last several decades.[82] Increased fuel efficiency leads to a decrease in fuel consumption and associated emissions.

One study found fuel savings of 14-25% when upgrading from a previous generation of aircraft (i.e., Boeing 767) to the newest generation (i.e., Boeing 787).[83] However, these newer aircraft do not typically immediately replace older planes that are currently in operation because of their expense. Rather, airlines gradually incorporate them into their fleets as older planes are retired.

Some new designs drastically overhaul the traditional design of commercial aircraft to improve aerodynamics and fuel efficiency. One example is the development of a new generation of planes with a **blended wing body** structure.

[82] Zaporozhets et al. (2020).

[83] Ibid.

This design minimizes drag and increases aerodynamic efficiency—and therefore, the fuel efficiency—of the aircraft.[84] Another design, the **strut-braced wing**, uses under-wing supports to increase the wingspan of an aircraft, allowing for larger, more fuel-efficient engines.

The four studies in our review that analyzed these conceptual designs found that switching from a conventional aircraft, like a Boeing 737-800, to one with a blended wing body or a strut-braced wing would result in fuel savings of 30-50%,[85] which would result in a proportional reduction of CO_2 emissions during flight.

Other new designs involve changes to the interior structure of aircraft. **Boundary layer ingestion**, for instance, involves moving the engine to the rear of the aircraft. This lets air flowing over the aircraft body become part of the mix of air going into the engine, allowing the entire fuselage to produce thrust.[86]

Another example is the **double-bubble fuselage**, which is a fuselage that consists of side-by-side tubes. This flatter fuselage creates additional lift, resulting in a reduction in fuel burn. The double-bubble fuselage design includes boundary layer ingestion, allowing for the same airflow and resulting thrust enhancement.

Three studies reviewed the boundary layer ingestion and double-bubble fuselage designs.[87]

These studies find reduced fuel burn and proportional CO_2 emissions reductions when implementing these aircraft design enhancements. For the boundary layer ingestion concept, the projected CO_2 reductions are as high as 40%. For the double-bubble fuselage concept, projected CO_2 reductions are as high as 56%. Both concepts are estimated to be introduced into service around 2035.

Alternatively, there are technologies in development that change the propulsion technology of aircraft. One of those enhancements is the **counter-rotating open rotor** engine. An open rotor system is a hybrid between a propeller and a conventional turbofan engine; it consists of two counter-rotating fans.[88] Three studies reviewed the open rotor conceptual design and projected CO_2 emissions savings due to the reduction in fuel burn during flight.[89] Compared to a conventional turbofan engine, projected CO_2 savings with an open rotor concept are between 30% and 40%.

Feasibility in Washington. These aircraft designs are still in the development phase and have not been rolled out at scale to the commercial aircraft market. Challenges still exist to ensure these new designs meet safety and performance requirements.

In addition, if future aircraft are larger or require different space allocations at airport gates, there would need to be increased investment and time to make necessary infrastructure changes at airports (i.e., widening the space between airport gates).

[84] Stauch & Müller (2022).
[85] Abrantes et al. (2024); Malina et al. (2022); Oguntona (2020); and Stauch & Müller (2022).
[86] Abrantes et al. (2024).
[87] Abrantes et al. (2024); Malina et al. (2022); and Oguntona (2019).
[88] Ibid.
[89] Ibid.

Electric and Hybrid Aircraft

There has also been progress towards commercially viable electric and hybrid-electric aircraft. A **fully electric aircraft** is operated by an all-electric propulsion system using electricity stored in batteries. All-electric propulsion systems produce zero emissions from operation and are much quieter.

An alternative closer to commercial viability, **hybrid aircraft**, are aircraft equipped with a hybrid propulsion system that features both a conventional internal combustion engine and an electric propulsion system. This hybrid system could allow for the aircraft to switch into fully electric mode during targeted times, for example, while taxiing on the ground or when passing through a climate-sensitive area. Prior research estimated a 2.8% CO_2 savings potential in a lifecycle analysis when implementing electric taxiing.[90] Another publication estimates at least a 15% reduction in overall environmental impact when switching into fully electric mode for ten minutes while passing through a highly climate-sensitive region.[91]

Feasibility in Washington. For fully electric aircraft to be a commercially viable option for the broader marketplace, battery technology will need to advance to allow for the propulsion power of a large jet without adding too much weight to the aircraft.[92] Additionally, charging infrastructure would need to be built at airports for either fully electric or hybrid aircraft to be integrated into the commercial aviation space.[93]

Routing Optimization

Optimizing flight routes is another strategy to mitigate the negative effects on the environment. We reviewed 12 studies that evaluated various types of optimal routing procedures. The most common types of routing procedures reviewed involved **changing the altitude** at which the plane is flown or **changing the flight path**.

Studies that explored changing the altitude for the flight found varying environmental impacts. One study evaluated a policy to fly uniformly higher or lower than a conventional altitude.[94] They found a slight decrease in fuel consumption and subsequent CO_2 emissions when flown higher, and the inverse when flown lower. However, looking at climate impact more holistically, another team found that flying at lower altitudes had a reduction in total climate impact, including a reduction in contrails, radiative forcing, and long-term average temperature change.[95]

Other research adds nuance to these disparate findings, finding that a policy of flying at lower altitudes does increase fuel consumption and subsequent CO_2 and NO_x emissions.[96] However, they also find that the location of these emissions matters. When these emissions are released at lower altitudes, they lead to less ozone formation and reduce the ultimate climate impact.

[90] Schäfer et al. (2016).
[91] Niklaß et al. (2023). This investigation considered a flight from Finland to the Canary Islands in Spain.
[92] Stauch & Müller (2022).
[93] Ibid.
[94] Matthes et al. (2021).
[95] Grewe & Linke (2017).
[96] Rao et al. (2022).

Studies that explored changing the flight path examined a variety of flight path alternatives. Two studies find similar environmental impacts for a few ways of rerouting flights.[97] They find that optimizing based on weather, wind, emissions, or distance has the potential to reduce the climate impact by about 25%. Another set of authors explores the idea of in-flight trajectory optimization.[98] They estimate modest fuel savings by allowing flight paths to be optimized hourly based on weather forecasts.

Another alternative routing procedure uses **climate-restricted airspaces**. This intervention would involve closing airspace that is particularly climate-sensitive, requiring flight paths to be rerouted to avoid those areas. The two studies we reviewed that evaluate this style of intervention find reductions in climate impact despite the increased fuel usage.[99]

Another routing optimization strategy in the research literature is **intermediate stop operations**, which are landings executed mid-service for the sole purpose of refueling the aircraft.[100] The reviewed analyses find that this method, if stopover locations are chosen using a climate-optimal framework rather than a fuel-optimal framework, can result in sizable reductions of climate impact despite the increase in CO_2 and other emissions due to the increase in takeoff and landing procedures.[101] Some of the climate impact mitigation is due to the lower altitude of flight when there is an intermediate stop.[102]

Finally, one study evaluated the use of **continuous descent operations**, or keeping the thrust at near-idle while the aircraft descends from cruise level to its destination airport.[103] The study finds that fuel savings result from this procedure.

Feasibility in Washington. These studies reviewed operational enhancements that, while technically feasible, would require coordination with larger entities as they would impact the global airspace. The exception to this is the continuous descent operations reviewed in one publication, which an air cargo carrier has implemented.[104]

Airport Design and Electrification

On-site power generation at airports has been explored as a way to reduce emissions generated by airports. The introduction of photovoltaic power at Brisbane International Airport in Queensland, Australia, for instance, led to an 18% reduction in the use of the local power grid, reducing CO_2 emissions by 8,000 metric tons per year.[105] A similar installation at Melbourne Airport is predicted to reduce CO_2 emissions by 920,000 metric tons over 15 years. One study discusses hybrid renewable energy systems, in which airports are connected to the broader energy grid but additionally generate renewable energy on-site.[106] This allows airports to both import and export power to the grid, aided by battery storage, leading to a 35%-38% reduction in emissions.[107]

[97] Zengerling et al. (2023) and Grewe & Linke (2017).
[98] Rosenow et al. (2021).
[99] Niklaß et al. (2017) and Niklaß et al. (2019).
[100] Grewe & Linke (2017).
[101] Zengerling et al. (2023).
[102] Zengerling et al. (2022).
[103] Baxter (2021a).
[104] Ibid.
[105] Baxter (2021b).
[106] Alruwaili (2022).
[107] Ibid. Specifically discusses a system using photovoltaic solar and hydrogen fuel cell power generation aided by hydrogen and lithium ferro phosphate battery storage.

Other interventions reduce energy use at airport facilities. Research reviewing three **heating, ventilation, and air-conditioning** (HVAC) related interventions in Chinese airports.[108] They find that improving the airtightness of airports (to limit infiltration of outside air) and using radiant floor heating in terminals can reduce HVAC energy consumption by 84% on average. Another research team reviewed a series of operational initiatives to reduce the environmental impact of aviation, including improved insulation of exterior walls, optimization of windows, and use of LED lights.[109] Together, these initiatives lower CO_2 emissions by 24% at Malpensa airport in Ferno, Italy.

Feasibility in Washington. Many airports, including SEA, are already implementing technologies to mitigate their environmental impact. These are explored further in the review of airports and airlines later in this section.

A challenge in this endeavor that was noted in our stakeholder interviews is the current battery technology. Currently, batteries are too heavy and underpowered to be used as reliable alternative energy sources at scale. As battery technology improves and other environmentally friendly alternative energy sources continue to become less cost-prohibitive, the transition away from fossil fuel energy sources is expected to increase.

Ground Operation Optimization

We reviewed three studies related to optimizing ground operations to reduce the environmental impacts of aviation.

Taxiing alternatives to traditional double-engine taxiing are explored in all three. Researchers investigate the impact of **using towing vehicles to taxi planes**, finding a 95% and 54% decrease in CO_2 emissions, respectively.[110] Another team explores **single-engine taxiing**, finding that the practice leads to a lifecycle CO_2 emissions reduction of 2%.[111] They also find that improved congestion management among taxiing aircraft can reduce lifecycle CO_2 emissions by 0.8% compared to the status quo.

The same publication also analyzes the lifecycle CO_2 impacts of **optimized departure and approach procedures** for aircraft, finding reductions of 1.6% for each. Finally, one study investigates how the **electrification of ground service equipment** can impact CO_2 emissions, finding an 84% reduction.[112]

Feasibility in Washington. In our review of peer airports and airlines, we found that some airports, including SEA, and airlines have implemented various ground operational enhancements. Specifically, the electrification of ground service equipment has been implemented at airports, and single-engine taxiing has been implemented by some airlines. In our interviews with stakeholders, it was noted that ground service electrification would likely continue to be scaled with the further development of environmentally friendly alternative fuel sources and battery technology.

[108] Liu et al. (2021).
[109] Zengerling et al. (2023).
[110] Soltani et al. (2020) and Zengerling et al. (2023).
[111] Schäfer et al. (2016).
[112] Zengerling et al. (2023).

Alternative Jet Fuels

Alternative jet fuels (AJFs) encompass a broad range of options for reducing aviation's carbon footprint. While jet fuel has conventionally been refined from petroleum (i.e., crude oil), AJFs often aim to be a more environmentally friendly alternative, utilizing more renewable resources and production processes. In this report, we focus on alternative fuels intended to mitigate the environmental impact of aviation and distinguish between drop-in AJFs, which are compatible with existing aircraft infrastructure, and non-drop-in AJFs, which are not compatible with current aircraft infrastructure.

Sustainable aviation fuel (SAF) generally refers to drop-in renewable or waste-derived hydrocarbon jet fuel. While chemically similar to conventional jet fuel, SAF is distinguished by significantly reduced life-cycle emissions, typically by at least 50%.[113] Some definitions of SAF impose additional sustainability criteria that restrict sourcing feedstocks from recently converted lands or those storing high levels of carbon.[114]

Sustainable aviation fuel can be produced through numerous conversion technologies, each of which relies on different types of feedstocks and chemical processing. Our literature review gathered evidence on six different SAF conversion technologies, which we describe in Exhibit 11.

The studies in our review consistently find that SAFs reduce life cycle emissions compared to conventional jet fuel, but the extent of those reductions varies by conversion technology, feedstock, land-use considerations, and place of origin. The most common conversion technology is hydroprocessed esters and fatty acids (HEFA), which produces more than 90% of the existing and near-term global SAF supply.[115] We summarize evidence from our review of the environmental impact of SAFs by conversion technology and feedstock in Exhibit 12.

Many SAF production processes use waste material like used cooking oil, municipal solid waste, and residues from agriculture, forestry, and other industries. Whether SAF uses waste or not affects its life-cycle environmental impacts. For example, one report shows that SAF produced using forestry feedstocks *increases* environmental burdens, like land use and mineral depletion, compared to conventional jet fuel.[116] On the contrary, burden-free forestry residues (i.e., waste) create similar emissions savings but do not create additional environmental impacts beyond those of the primary user of the material (the forester). These findings highlight the importance of feedstock sourcing assumptions when analyzing the environmental impact.

Though different feedstocks have different emission-reducing potential, the literature emphasizes that diversification of feedstocks and conversion technologies will be important to meet global supply for SAF.

[113] Because SAF production pathways and feedstocks vary widely in their resource and emissions profiles, assessing SAF's environmental performance requires a consistent life-cycle framework.

[114] U.S. Department of Energy, U.S. Department of Transportation, & U.S. Department of Agriculture. (2022, September). *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel.* In collaboration with the U.S. Environmental Protection Agency. Washington, DC.

[115] International Air Transport Association. & Worley Consulting. (2025, September). *Global feedstock assessment for SAF production: Outlook to 2050.*

[116] Lai et al. (2022).

Exhibit 11

Overview of the Reviewed Sustainable Aviation Fuel Conversion Technologies

SAF production pathway	Description	Feedstock examples
Hydroprocessed esters and fatty acids (HEFA)	Converts fats, oils, and greases into hydrocarbon fuels through hydrotreating.	• Fats, oils, and greases
Alcohol-to-jet (AtJ)	Ferments biomass into alcohols (e.g., ethanol or isobutanol), which are then upgraded through chemical processes into hydrocarbon fuels.	• Starch and sugar crops • Lignocellulosic (woody) biomass
Fischer–Tropsch (FT) synthesis *uses syngas produced via*	Converts synthesis gas (syngas)—a mixture of carbon monoxide and hydrogen—into liquid hydrocarbons. FT can upgrade syngas produced from other pathways, like PtL or pyrolysis, into SAF (see below).	• Renewable natural gas • Woody biomass • Residues (forestry, agricultural, industrial) • Municipal solid waste
→*Power-to-liquid (PtL)*	Uses renewable electricity to produce hydrogen via electrolysis, which is combined with captured carbon dioxide to create syngas. The syngas is then converted to SAF via FT synthesis.	• Renewable electricity + captured CO_2 (point-source or direct air capture)
→*Pyrolysis*	Thermally converts biomass into bio-crude oil, which is upgraded into SAF through hydrotreating or gasification, followed by FT synthesis.	• Woody biomass
Direct sugars to hydrocarbons (DSHC)	Converts simple sugars into hydrocarbons using engineered biological processes.	• Starch and sugar crops • Woody biomass (after pretreatment)

Notes:
We present conversion technologies in the order of how many papers we reviewed under each technology. We reviewed six studies on HEFA, four on AtJ, three on FT synthesis, and one paper on PtL, pyrolysis, and DSHC. The example feedstocks are those identified by our literature review and may not represent the full range of feedstocks that can be used per conversion pathway.

Exhibit 12

Life Cycle Emissions Reductions by SAF Production Pathway

Feedstock	CO_2e reductions	GHG reductions	GWP reductions	Studies
Hydroprocessed esters and fatty acids (HEFA)				
Camelina	46%			Bosch et al. (2017)
Carinata	58-65%			Alam et al. (2021)
Jatropha	37%	16-42%		Bosch et al. (2017); Alherbawi et al. (2021)
Pennycress			45-61%	Mousavi-Avval & Shah (2021)
Soybean		27%		Vardon et al. (2022)
Tallow		75%		Vardon et al. (2022)
Used cooking oil	69-87%	84%		Bosch et al. (2017); Vardon et al. (2022); Bell et al. (2025)
Alcohol-to-jet (AtJ)				
Agricultural residues*		67%		Vardon et al. (2022)
Corn	37%			Bosch et al. (2017)
Corn stover	60%	92%		Bosch et al. (2017); Male et al. (2021)
Forestry residues		62-98%		Male et al. (2021); Vardon et al. (2022); Akter et al. (2024)
Miscanthus		112%**		Vardon et al. (2022)
Steelmaking residues		67%		Male et al. (2021)
Sugar cane	70%	63-65%		Bosch et al. (2017); Vardon et al. (2022)
Switchgrass		88%		Male et al. (2021)
Fischer-Tropsch (FT)				
Agricultural residues		91%		Vardon et al. (2022)
Black liquor			68-69%	Lai et al. (2022)
Energy crops*	85-90%			Bosch et al. (2017)
Forestry residues	95%	91%	66-68%	Bosch et al. (2017); Lai et al. (2022); Vardon et al. (2022)
Miscanthus		125%**		Vardon et al. (2022)
Municipal solid waste		94%		Vardon et al. (2022)
Poplar (short rotation)		92%		Vardon et al. (2022)
Power-to-liquid (PtL)				
Electricity			63-64%	Lai et al. (2022)
Direct sugars to hydrocarbons (DSHC)				
Sugar cane	18%			Bosch et al. (2017)
Pyrolysis				
Forestry residues*	54-75%			Bosch et al. (2017)

Notes:
CO_2e stands for CO_2 equivalent emissions, **GHG** stands for greenhouse gas, and **GWP** stands for global warming potential, often estimated for 100 years. An asterisk **(*)** denotes unspecified feedstock *categories* that may include other feedstocks listed in the table (e.g., corn stover is a type of agricultural residue, and miscanthus is a type of energy crop). Double asterisks **(**)** denote reduction potential greater than 100% due to offsets from carbon sequestration.

We reviewed two studies on **non-drop-in alternative fuels**. In contrast to SAFs, which can be used within today's aviation systems, these fuels face significant technological and economic barriers before they are commercially viable. However, once developed, they have the potential to reduce aviation's environmental impacts greatly.

One alternative fuel technology is hydrogen combustion, which would require major redesigns of aircraft to incorporate large tanks capable of storing liquid hydrogen at extremely low temperatures. Research shows that the life cycle environmental costs of hydrogen combustion are 71%-95% lower than conventional jet fuel, depending on how hydrogen is produced (e.g., via solar or geothermal energy).[117] However, other research shows that hydrogen combustion aircraft would use *more* energy than conventional aircraft during flight due to the substantial weight of the tanks.[118] They note that this may improve as hydrogen technology progresses and tanks become lighter and more efficient.

Researchers also evaluated several other non-drop-in alternative fuels.[119] They found life-cycle reductions in the environmental impact of:

- Ammonia: 14%-43% depending on the electricity source (e.g., solar vs. geothermal)
- Ethanol: 19%
- Methanol: 24%
- Liquefied Natural Gas: 43%

Feasibility in Washington.
As required under RCW 28B.30.646, Washington State University (WSU) convenes the AJF Work Group—formerly the *Sustainable Aviation Biofuels Work Group*—in collaboration with legislative members and representatives from relevant sectors.[120] The group is tasked with collecting information and making recommendations to accelerate the production and adoption of AJF in Washington.

In its most recent report (December 2024), the AJF Work Group highlights key state and federal policies that have accelerated SAF production.[121] Sustainable aviation fuels are widely regarded as the most promising near-term option for decarbonizing commercial aviation, particularly for medium- and long-haul flights where electrification and hydrogen remain technically or economically infeasible in the short run.[122]

The report also summarized planned SAF production projects in the region. Despite strong policy support and upcoming regional production capacity, the report notes that full-scale SAF adoption remains challenging.

[117] Bicer & Dincer (2017).
[118] Mourouzidis et al. (2024).
[119] Bicer & Dincer (2017).
[120] RCW 28B.30.646.
[121] Washington State University. (2024, December). *Sustainable Aviation Fuel Updates and Recommendations: Opportunities for Washington.*
[122] U.S. Department of Energy, U.S. Department of Transportation, & U.S. Department of Agriculture. (2022, September). *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel.* In collaboration with the U.S. Environmental Protection Agency. Washington, DC; Experts predict that hydrogen combustion is unlikely to be commercially viable before 2040. The Boeing Company. (2025, April). *Hydrogen and sustainable aviation – Fact sheet.* Retrieved October 31, 2025.

Sustainable aviation fuel is currently significantly more expensive than conventional jet fuel, largely due to feedstock and distribution limitations. Per regulatory specifications, SAFs must be blended with conventional jet fuels prior to airport delivery, requiring significant capital upgrades for additional storage tanks and piping.[123] Moreover, ASTM certification restricts blending ratios for most SAF pathways to no more than 50%, with some limited to 10%, constraining the amount of SAF that can be used in commercial operations. While Boeing and Airbus have committed to deliver 100% SAF-capable planes by 2030, their planes are not presently certified to run on 100% SAF.[124]

In our interviews with industry professionals, similar themes about current challenges with SAF emerged, particularly regarding:

- price competitiveness;
- supply constraints;
- transportation, blending, and storage logistics;
- permitting capital improvement projects; and
- regulatory limits on blending ratios.

In response to these obstacles, the AJF Work Group recommended expanding state-level tax incentives, providing grants under the CCA, and streamlining permitting processes to support SAF producers. The group will continue to issue biennial reports through 2028 and is currently examining emerging topics such as book-and-claim systems and capital improvement plans for SAF blending and storage. The last two AJF Work Group reports will be published in 2026 and 2028.

Initiatives Implemented by Airports and Air Carriers

In this section, we build on the review and feasibility discussion by reviewing environmentally focused initiatives that have been implemented or are being implemented by airports and airlines in the United States. In this review, we position SEA in the context of its peer airports.[125] With this, environmentally focused initiatives that are pre-existing in the United States and, therefore, have been feasible to implement in similar scenarios are specifically identified and discussed.

[123] ASTM International—formerly the American Society for Testing and Materials—develops the technical specifications that approved SAF production pathways must meet, including the allowable blending limits for each type of SAF.
[124] The Boeing Company. (2025, February). *Sustainable aviation fuel (SAF) fact sheet.* Retrieved November 6, 2025.; Airbus. (n.d.). *Our commitment to sustainable aviation fuel (SAF).* Retrieved November 6, 2025.
[125] We use the peer airports identified by the PSRC report, Regional Aviation Baseline Study – Working Paper 2, Section 2.2.2.

Exhibit 13

Key Takeaways from Reviewed Papers

Intervention	GHG emissions	Climate impact	Noise impact	Studies
Innovative aircraft design				
Blended wing body	Decrease			Abrantes et al. (2024); Malina et al. (2022); Oguntona (2020); Stauch & Muller (2022)
Strut-braced wing	Decrease			Abrantes et al. (2024); Malina et al. (2022)
Boundary layer ingestion	Decrease			Abrantes et al. (2024); Malina et al. (2022)
Double-bubble fuselage	Decrease			Abrantes et al. (2024); Malina et al. (2022); Oguntona (2020)
Counter-rotating open rotor	Decrease		Increase	Abrantes et al. (2024); Malina et al. (2022); Oguntona (2020)
Electric and hybrid aircraft				
Fully electric aircraft	Decrease		Decrease	Malina et al. (2022); Oguntona (2020); Stauch & Muller (2022)
Hybrid aircraft	Decrease			Malina et al. (2022); Schäfer et al. (2016); Stauch & Muller (2022)
Routing optimization				
Flying higher	Decrease			Grewe & Linke (2017); Matthes et al. (2021); Rao et al. (2022)
Flying lower	Increase	Decrease		Grewe & Linke (2017); Matthes et al. (2021); Rao et al. (2022)
Climate-optimized routing		Decrease		Niklaß et al. (2017); Niklaß et al. (2019); Zengerling et al. (2023)
Weather-adapted routing		Decrease		Grewe & Linke (2020)
Free routing		Decrease		Zengerling et al. (2023)
Wind-optimized routing	Increase	Decrease		Zengerling et al. (2023)
In-flight trajectory optimization	Decrease			Rosenow et al. (2021)
Climate-restricted airspaces	Increase	Decrease		Grewe & Linke (2020); NiklaB et al. (2017); Niklaß et al. (2019)
Intermediate stop operations	Decrease	Mixed		Grewe & Linke (2020); Grewe et al. (2017); Zengerling et al. (2023); Zengerling et al. (2022)
Continuous descent operations	Decrease			Baxter (2021a)
Airport design and electrification				
On-site power generation	Decrease			Alruwaili (2022); Baxter (2021b)
Heating, venting, and cooling interventions		Decrease		Liu et al (2021)
Occupant-based model predictive control		Decrease		Ma et al. (2024)

Exhibit 13 (Continued)

Key Takeaways from Reviewed Papers

Intervention	GHG emissions	Climate impact	Noise impact	Studies
Ground operations optimization				
Using towing vehicles for airplane taxiing	Decrease	Decrease		Soltani et al. (2020); Zengerling et al. (2023)
Single-engine taxiing	Decrease			Schäfer et al. (2016)
Optimized departure and approach procedures	Decrease			Schäfer et al. (2016)
Electrification of ground service equipment	Decrease	Decrease		Zengerling et al. (2023)
Alternative jet fuels				
Sustainable aviation fuels	Decrease	Decrease		Akter et al. (2024); Alam et al. (2021); Alherbawi et al. (2021); Bell et al. (2025); Bosch et al. (2017); Male et al. (2021); Mousavi-Avval & Shah (2021); Vardon et al. (2022)
Hydrogen	Decrease	Decrease		Bicer & Dincer (2017), Mourouzidis et al (2024)
Ammonia		Mixed		Bicer & Dincer (2017)
Other alternative fuels (ethanol, methanol, and liquified natural gas)		Decrease		Bicer & Dincer (2017)

Notes:

Mixed reflects results that varied by geography or model specifications, and **No effect** indicates no statistically detectable impact. An asterisk **(*)** denotes that a study measured passengers in revenue passenger kilometers (RPKs). Complete citations for the papers in this section can be found in Exhibit A10 in Appendix III.

We cannot always assess the extent to which these strategies have been implemented. Some organizations provided measures of the degree of implementation, such as gallons of SAF purchased or the percentage of a ground support equipment (GSE) fleet that had been electrified, but others did not.

Additionally, some strategies may have been implemented by organizations, but not documented, and hence are not discussed in our review. For more details about how we conducted our review, see Appendix V.

Initiatives by Peer Airports

We reviewed materials published by peer airports to document what technologies and practices are currently being implemented to address the environmental impacts of airports. Exhibit 14 reports the full names, abbreviations, and locations of each. Like SEA, these airports are large hubs for air travel.

The results of our review are presented in Exhibit 15, which indicates which types of initiatives are in place in each airport. For comparison, SEA is also included.[126]

In the following subsections, we briefly describe common initiatives.

Reducing Emissions. The most common strategies to reduce emissions at the reviewed airports focus on ground-side vehicles. These include ground support vehicles (e.g., deicers, refuelers, tugs, and tractors) and passenger transit vehicles (e.g., buses, vans, and light rail). All but two of the reviewed airports are in the process of converting their ground fleets to hybrid, alternative fuel (such as biodiesel), or fully electric vehicles. Boston Logan International also requires special filters for heavy machinery to remove particulate matter from exhaust. Chicago O'Hare International employs a herd of grazing goats to help maintain vegetation, replacing traditional gas-burning equipment.

Exhibit 14

Peer Airports Considered

Airport	Location	Abbreviation
Boston Logan International	Boston, MA	BOS
Chicago O'Hare International	Chicago, IL	ORD
Dallas-Fort Worth International	Dallas/Fort Worth, TX	DFW
George Bush Intercontinental	Houston, TX	IAH
Los Angeles International	Los Angeles, CA	LAX
Miami International	Miami, FL	MIA
Phoenix Sky Harbor International	Phoenix, AZ	PHX
San Francisco International	San Francisco, CA	SFO
Washington Dulles International	Dulles, VA	IAD

Note:
The word "Airport" is removed from the end of each airport's official name for ease of exposition.

[126] The specific airport documents referenced for this section are presented in Exhibit A14 in Appendix IV; any additional citations in this section are given in footnotes.

Exhibit 15

Peer Airports with Selected Environmental Initiatives

Strategy	SEA	BOS	DFW	IAH	IAD	LAX	MIA	ORD	PHX	SFO
Reducing emissions										
GSE fleet/transit electrification	x	x			x	x			x	x
GSE fleet hybridization/alternative fuel	x	x	x			x		x	x	
Gate electrification	x	x			x	x				
Purchasing electricity from renewables			x			x		x	x	x
SAFs	x									x
Energy efficiency										
On-site power generation	x	x	x			x	x		x	x
Central utility plant/efficient chillers			x		x	x			x	x
Efficient building design codes	x	x	x			x		x	x	x
Efficient lighting/equipment	x	x					x	x	x	
Water conservation										
Wetlands replacement/restoration	x				x					
Runoff management/treatment	x	x			x					
High-efficiency fixtures	x					x	x		x	
Water retention			x		x	x				
Waste minimization										
Construction material recycling			x		x	x				
Diversion from landfills	x								x	x
Replacing single-use materials	x		x							
Noise reduction										
Insulation installation	x	x				x				

Notes:
This table only reports initiatives that were implemented at multiple peer airports.
GSE stands for ground support equipment.
SAF stands for sustainable aviation fuel. Sources for the initiatives in the table can be found in Exhibit A12 in Appendix V.

Other initiatives focus on reducing emissions through gate electrification or the use of sustainable aviation fuels. Gate electrification consists of providing parked planes with electricity (and often preconditioned air), which allows planes to fully turn off their engines and reduce emissions. San Francisco International and SEA also support the research, development, and gradual inclusion of SAF into the fuel stock.

Finally, five of the nine peer airports described their efforts to purchase electricity that is largely or entirely produced from renewable, low-carbon sources such as solar or wind power.[127] Chicago O'Hare International is additionally planting vegetation on its buildings' roofs to capture carbon and provide cooling.

[127] This count only includes peer airports that explicitly mentioned purchasing renewable electricity in their sustainability documentation. Since most airports purchase electricity from their surrounding energy grid, it is possible that other airports also purchase renewable electricity if that grid is largely renewable.

Energy Efficiency. Other strategies focus on improving energy efficiency. Most of the reviewed airports have implemented sustainable design practices for new buildings. In particular, airports' sustainability documents noted buildings that had received a Leadership in Energy and Environmental Design (LEED) accreditation, a rating program developed by the U.S. Green Building Council. Buildings are awarded different levels of certification for adherence to design benchmarks spanning energy efficiency, water use, waste management, and indoor environmental quality.[128]

Seven of the nine peer airports engage in some degree of onsite solar power generation to supplement electricity purchased from nearby sources. This not only cuts airports' energy expenses but also offsets emissions from a power grid that may be more emissions-intensive than solar power. Another common improvement to buildings is to replace older lighting fixtures with efficient LED alternatives.

Five of the peer airports have central utility plants, which provide heating and cooling to airport structures. The centralization of utilities and maintenance reduces energy and space use at the airport by combining functions in a single location and allowing for equipment size optimization. Two airports also noted recent upgrades to more energy-efficient chillers to supply cold air to terminals. Washington Dulles International runs the chillers at a secondary airport, Reagan International, overnight to supply the much busier Washington Dulles Airport during the day.

Noise Reduction. Two of the peer airports, Boston Logan International and Los Angeles International, have programs to insulate nearby buildings and homes with noise-reducing retrofitting. Los Angeles International's program has provided noise remediation to roughly 20,000 homes, while Boston Logan has provided insulating materials to 36 schools and nearly 12,000 homes, and implements special flight paths for arriving and departing flights, runway restrictions, and ground run-up procedures to reduce noise pollution.

Waste Minimization. All the peer airports maintain some form of recycling program for waste generated by passengers, but a few have broader initiatives. Dallas-Fort Worth International, Los Angeles International, and Washington Dulles International recycle materials left over from the construction or demolition of buildings into new projects. Phoenix Sky Harbor International and San Francisco have waste diversion initiatives to shift end-use materials away from landfills through composting, donations to local food rescue programs, and environmental packaging. Chicago O'Hare likewise encourages the replacement of single-use containers by vendors.

Water Conservation. Airports require a lot of water, both to serve travelers and maintain equipment. Additionally, chemical runoff from aircraft maintenance and construction can contaminate local water supplies. As such, water conservation and treatment efforts can be impactful environmental remediations for airports.[129]

[128] U.S. Green Building Council. (2025). *LEED Rating System*.

[129] International Civil Aviation Organization. (n.d.). *Water Management at Airports*.

Water conservation efforts were less common at airports compared to other environmental initiatives. The most common were the installation of high-efficiency, low-flow fixtures and water retention and reclamation projects.

Dallas-Fort Worth International saves over 160 million gallons of water per year through its reclamation program. A new runway at Washington Dulles uses surface vegetation and underground sand and rocks to filter rain runoff and reclaim it for use in the terminals. Given their arid locations, Phoenix Sky Harbor and Los Angeles International have also implemented drought-tolerant landscaping to reduce water consumption.

Boston Logan and Washington Dulles International have initiatives to minimize runoff from aviation-related liquids like fuel and deicer, including monitoring. Washington Dulles, like SEA, also engages in wetland and other habitat restoration.

Initiatives by Airlines

We now discuss environmental initiatives that have been implemented by major U.S. airlines. For our review, we looked at sustainability documentation and programming by the U.S.' top five regular and low-cost carriers, as measured by total passengers (enplanements) within the United States between July 2024 and June 2025. For regular carriers, these include Alaska, American, Delta, Hawaiian, and United Airlines.[130] For low-cost carriers, we consider Allegiant, Frontier, JetBlue, Southwest, and Spirit Airlines. We also include the top five air freight carriers by weight of transported goods: Air Transport Services Group (ATSG), Atlas Air, Federal Express (FedEx), Kalitta Air, and United Parcel Service (UPS).[131]

The initiatives by each carrier are summarized in Exhibit 16. As above, we briefly discuss each type of initiative in the following subsections. We list the sources we used in Exhibit A12 in Appendix V.

Aircraft Upgrades. All 15 of the airlines considered were engaged in fleet renewal, replacing older planes with newer, more fuel-efficient (and often quieter) aircraft. By burning less fuel, these aircraft reduce both direct emissions from flying and indirect emissions that come from manufacturing and transporting aviation fuel.[132] Airlines also noted that consuming less fuel reduces their operating expenses.[133]

A few airlines also described retrofitting existing aircraft with more efficient engines to reduce fuel consumption and emissions. Other carriers described innovative forms of retrofitting, such as adding winglets to reduce drag or replacing existing seating with lightweight alternatives.

[130] Alaskan and Hawaiian Airlines merged in 2024. However, the two airlines publish different sustainability documents. We treat them as separate for this section of the report.
[131] Data from: U.S. Department of Transportation. (2025). *TranStats: Air Carriers: T-100 Domestic Market (U.S. Carriers).*
[132] It is important to note that global fuel consumption overall has been increasing with the growth of the industry since the 1970s. However, fuel used per passenger has been decreasing both due to more efficient aircraft design and engine technology, as well as manufacturers increasing the size of aircraft to accommodate more passengers.
[133] Fleet renewal towards more efficient aircraft can cause smaller, regional airports to be edged out from service. Newer, more fuel-efficient aircraft tend to be larger than existing models, and smaller airports often do not have large enough runways and facilities to accommodate them.

Exhibit 16

Passenger and Freight Carriers with Selected Environmental Initiatives

Strategy	Regular carriers					Low-cost carriers					Cargo carriers				
	Alaska	American	Delta	Hawaiian	United	Allegiant	Frontier	JetBlue	Southwest	Spirit	ATSG	Atlas	FedEx	Kalitta	UPS
Aircraft upgrades															
Engine upgrades				x		x	x			x					
Fleet renewal with efficient aircraft	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Non-engine retrofitting			x		x	x	x								
Operational initiatives															
Efficient routing/precision navigating	x	x	x	x		x		x	x		x	x	x	x	x
Gate electrification/ground power unit	x		x	x	x									x	x
GSE electrification		x	x		x	x		x	x			x			x
Incorporation of SAFS		x	x		x	x		x	x		x	x	x	x	x
Investment in research and development	x	x	x					x							x
Single-engine taxiing	x	x		x	x				x	x	x			x	
Weight optimization	x		x	x	x						x				
Noise reduction															
Fleet Renewal with quieter aircraft					x					x		x			
Noise-reducing retrofitting							x			x					
Routing/preferred runways					x							x			
Waste minimization															
Digitization/discontinuing in-flight magazine					x		x								
Refurbishing aircraft with recycled parts						x					x			x	
Replacing single-use service items	x				x				x	x					
Service item recycling/conversion from plastic	x		x	x	x	x		x	x	x	x	x		x	

Notes:

GSE stands for ground support vehicle. **ATSG** stands for Air Transport Services Group, and **UPS** stands for United Parcel Service. Sources for the initiatives in the table can be found in Exhibit A12 in Appendix V.

Operational Initiatives. Carriers may also seek to improve fuel efficiency and reduce emissions by changing the way their current fleet operates. Among the airlines we reviewed, all but three were incorporating more efficient navigation and routing procedures to improve efficiency. This often takes the form of routing aircraft in response to real-time wind and other weather conditions. Airlines also mentioned using monitoring and modeling to optimize takeoff and landing procedures and to investigate unusual fuel burn events. A handful also mentioned weight optimization strategies to avoid overloading or unbalanced payloads as ways to reduce fuel consumption.[134]

All but four of the airlines we reviewed discussed their use of SAFs. Most airlines reported that fuel burn is their greatest source of emissions and expressed that while operational initiatives and more efficient aircraft are critical to reducing emissions, they expected the largest reduction in emissions to result from the development of SAFs. Some carriers have already implemented some use of SAFs in their operations, but not to a significant extent overall. Citing that current SAF supply and technology are not sufficient for widespread implementation, five airlines reported partnering with and investing in SAF producers or researchers to expedite the technology to feasibility.

Like airports, many air carriers are pursuing gate electrification and replacing GSE with electric or hybrid alternatives to reduce emissions. The majority also had a policy of only using one engine to taxi aircraft around airports, reducing fuel burn.

Noise Reduction. Relatively few airlines explicitly described measures they had taken to reduce noise pollution. Three described the purchase of newer, quieter aircraft as a strategy to reduce noise. Frontier and Spirit described retrofitting of their existing planes with newer engines to reduce noise.[135] United and Atlas Air also described the use of preferred runways and noise-sensitive routing when flying louder aircraft to avoid impacts on residential areas.

Waste Minimization. The most common initiatives to reduce landfill waste among the reviewed airlines involve modifying service items to be more sustainable by converting them from plastic to recyclable, compostable, or reusable materials. For example, United replaced single-use cups with reusable cups and mugs and replaced plastic wine bottles with ones made from aluminum. Delta replaced plastic water cups with paper and removed excess packaging on earbuds. Alaska eliminated all plastic service items, including bottles, cups, and straws. Atlas Air took similar steps in its ground operations. ATSG has a wide-ranging recycling program for its ground operations, recycling everything from paper and batteries to jet fuel and oil.

[134] Federal Aviation Administration. (n.d.). *Weight and balance.*

[135] As mentioned earlier, all carriers engaging in fleet renewal or engine upgrades may be reducing their noise footprint even if it is not a stated goal. We only classified carriers under this category if they explicitly mentioned noise reduction as a reason for fleet renewal or engine upgrades.

Airplane parts themselves may also be reused. Allegiant, ATSG, and Kallita refurbish their aircraft with used parts, retreading used tires, or using parts from decommissioned aircraft. These actions reduce demand for new parts, reducing emissions and waste.

Key Takeaways

In our literature review of technologies and operational enhancements, we reviewed innovative aircraft design technologies, electric and hybrid aircraft, airport design and electrification technologies, ground operation optimization enhancements, and alternative fuels.

We found that there are several interventions in development that can mitigate the environmental impact of commercial aviation, but there are barriers to widespread adoption. For many, like aircraft design technologies and electrification, the technology simply hasn't advanced enough. For example, the electrification of large, commercial aircraft will not be feasible until battery technology advances to the point where batteries can store more energy at much lighter weights. Other interventions, like more efficient airport designs, are well underway at airports like SEA.

In our review, the technology most readily available for widespread market adoption is SAF. There are multiple ways to produce SAF, both in terms of technical process and in raw materials. The production pathway and raw material for the specific SAF affect the fuel's climate impact. However, all the SAF production types in our review presented significant environmental benefits when compared to conventional jet fuel.

Washington State is already working towards bolstering the market for SAF, though barriers remain to widespread adoption. Namely, there are challenges in the supply chain and storage system for SAFs. We also heard from stakeholders that SAF is currently priced too high relative to conventional jet fuel to be competitive.

V. Conclusion and Key Takeaways

In this section, we provide a discussion of the key takeaways from each of our analyses.

Assessment of Forecasts

The Washington Legislature directed WSIPP to review the forecasts in PSRC's Regional Aviation Baseline Study. The Puget Sound region has seen an increasing demand for air travel, both passenger and air cargo. In our review of the PSRC forecasts, we evaluated their performance against actual data for the years available and used a backcasting strategy to further evaluate the forecast performance where possible.

The COVID-19 pandemic occurred during the short time period for which we have actual data to compare the forecasted values against. This clearly disrupted the trend for both passenger and air cargo travel. This major disruption to a large portion of the available data adds uncertainty to our assessment of whether the forecasts are an accurate or inaccurate estimate of long-term demand. In addition, the subjective nature of the air cargo forecast did not allow us to use the backcasting strategy to evaluate the forecast on a longer time span.

With these limitations in mind, the evidence available suggests that both the passenger activity and the air cargo forecast overestimate the actual aviation activity in the Puget Sound area.

Strategies to Reduce Air Travel

Our review of the research literature on strategies and interventions to reduce the quantity of air travel demanded by travelers and supplied by carriers resulted in 17 academic studies. These studies cover a range of topics, such as high-speed rail, flight departure and emissions taxes, emissions trading schemes, and even a policy aimed at improving on-time performance at congested airports.

High-speed rail (HSR) was the most studied strategy for reducing air travel. Most of these studies found that HSR entry reduced air travel demand, particularly among flight routes where HSR was most competitive (i.e., short-haul routes).

Flight departure taxes were the second most studied and mostly show a decrease in passenger volumes, particularly at non-hub airports and routes serviced by low-cost carrier airlines.

Between studies within each topic, there is some disagreement as to the magnitude, and in some cases the direction, of the impact of each intervention on the quantity of air travel. These differences demonstrate the sensitivity of results to the authors' assumptions, datasets, and methodologies. All but one of these studies suffer from methodological flaws that challenge the robustness of their findings. As such, the conclusions outlined in Section III should be interpreted with caution and may not apply to contexts outside of the region and timespan of each study.

Technologies to Reduce Environmental Impact

Our review of technologies and practices to reduce the environmental impact of aviation found a variety of interventions. Some efforts seek to redesign the traditional aircraft into a more fuel-efficient profile, blending wings with the body of the aircraft or adding bracing to allow for longer wingspans. Other modifications of planes seek to innovate away from the use of fossil fuels, favoring electric or hybrid-electric powered engines.

In this review, we also provide a discussion of the feasibility of deploying each type of intervention in Washington State's commercial aviation space. However, this discussion does not constitute a formal feasibility study. Thus, this report should not be interpreted to say that any identified intervention is specifically feasible to implement in Washington State or not.

Our review found that the most promising current route to decarbonize commercial aviation is through the use of sustainable aviation fuels. A lot is already being done at airports and airlines to transition to SAF, but more work is needed to develop the supply chains and storage capacities for SAF to be implemented on a larger scale.

Other potential enhancements are altering aircraft operations by taxiing with a single engine or optimizing takeoff and landing procedures. Modifying ground-side operations is also an option, including generating electricity on-site at airports, upgrading airport infrastructure, or electrifying ground support equipment. A variety of such technologies and operational practices have been implemented by both airports and airlines across the US.

Appendices

Commercial Aviation in Washington: *A Review of Forecasts, Policies, and Technologies*

Appendices

Appendix I. Details of Forecasts Cited in the Baseline Study

The passenger and air cargo forecasts constructed by the Puget Sound Regional Council (PSRC) in the Regional Aviation Baseline Study (baseline study) relied on external forecasts. PSRC, along with the consulting group WSP, used combinations of these input forecasts in constructing their preferred forecasts. This section details those input forecasts, including their data sources, assumptions, and methodologies, where available.

Passenger Aviation Activity Forecasts Cited in the Baseline Study

The Sustainable Airport Master Plan (SAMP) 2015 Forecasts of Aviation Activity[136]

Enplanements at Seattle-Tacoma International Airport (SEA) are projected to increase from 18.7 million in 2014 to 32.5 million by 2034, reflecting an average annual growth rate of 2.8%.

Data. Forecasts for enplaned passengers are based on airline-reported data from SEA.

Assumptions. Enplaned passenger forecasts were developed based on analyses of the economic drivers of airline traffic, historical trends, and key factors influencing future airline traffic. Long-term changes in airline traffic at SEA are generally assumed to reflect population and economic growth in the Seattle primary area, along with shifts in airline service. It was also assumed that the continued development of airline service at SEA would not be limited by aviation fuel availability, long-term fleet capacity, air traffic control, airport capacity, or restrictive government policies.

For FYs 2015-2034, the following assumptions were made:

- The U.S. economy was projected to grow at an average annual rate of 2.0% to 2.5% over the forecast period.
- The Seattle primary area economy, measured by employment and per capita income, was expected to grow at a rate comparable to the national average.
- Global economies were expected to experience sustained GDP growth, in line with historical trends and long-term projections.

[136] SAMP 2015 Forecasts of Aviation Activity.

- SEA would remain the primary commercial airport for the Seattle primary area, the main hub for Alaska Airlines, and a key west coast gateway for Delta Airlines.
- A stable international political environment and improved passenger and baggage screening procedures would sustain airline traveler confidence in aviation security while minimizing inconvenience.
- Airline service and passenger travel behavior would not be significantly disrupted by international hostilities, terrorist acts or threats, or global safety or health concerns.
- Aviation fuel prices would stabilize at historically high levels, though below the record prices seen in mid-2008.
- Competition among airlines serving SEA would maintain the availability of competitive airfares.

Methodology. The domestic origin and destination (O&D) passenger forecasts at SEA are based on an econometric model (i.e., regression model) that links passenger trends to economic and airline industry metrics. Specifically, the forecasts are based on per capita income projections for the Seattle primary area from the PSRC and SEA airfare projections derived from the Federal Aviation Administration's (FAA's) national forecasts.

The 2018 FAA Terminal Area Forecasts (TAF) Forecast[137]

Enplanements at SEA and Paine Field Airports are projected to grow at an average annual rate of 2.7% between 2017 and 2038.

Data. U.S. domestic and international enplanements, including both U.S. and foreign carriers, are sourced from the U.S. Department of Transportation's (USDOT) T-100 database.

Assumptions. The TAF assumes a demand-driven forecast for aviation services, based on local and national economic conditions and trends within the aviation industry. Airport forecasts are developed independently of the capacity constraints of the airport or air traffic control system. However, if an airport has historically operated under constrained conditions, the FAA forecast may reflect these limitations, as they are embedded in historical data. Statistically, the relationship between economic growth and aviation activity inherently accounts for such constraints.

Methodology. Domestic enplanements are forecast by modeling quarterly passenger flows using O&D market demand forecasts derived from the Airline Origin and Destination Survey 10% sample data.[138] The O&D passenger demand forecasts are based on regression analysis, with fares, regional demographics, and economic factors as independent variables. Then, the O&D forecasts are integrated with USDOT T-100 segment data to produce passenger forecasts by airport and segment pair.

International passenger enplanements are forecast quarterly using time series analysis and T-100 segment data.

[137] Forecast Process for 2018 TAF.
[138] Bureau of Transportation Statistics Origin and Destination Survey Data.

Air Cargo Forecasts Cited in the Baseline Study

The PSRC developed air cargo forecasts specific to each airport, SEA, and King County International Airport (KCIA). The airport-specific forecasts are shown in Exhibit A1. Each forecast was developed with input from two source forecasts: the Boeing World Air Cargo forecast and the corresponding airport's master plan forecast. [139]

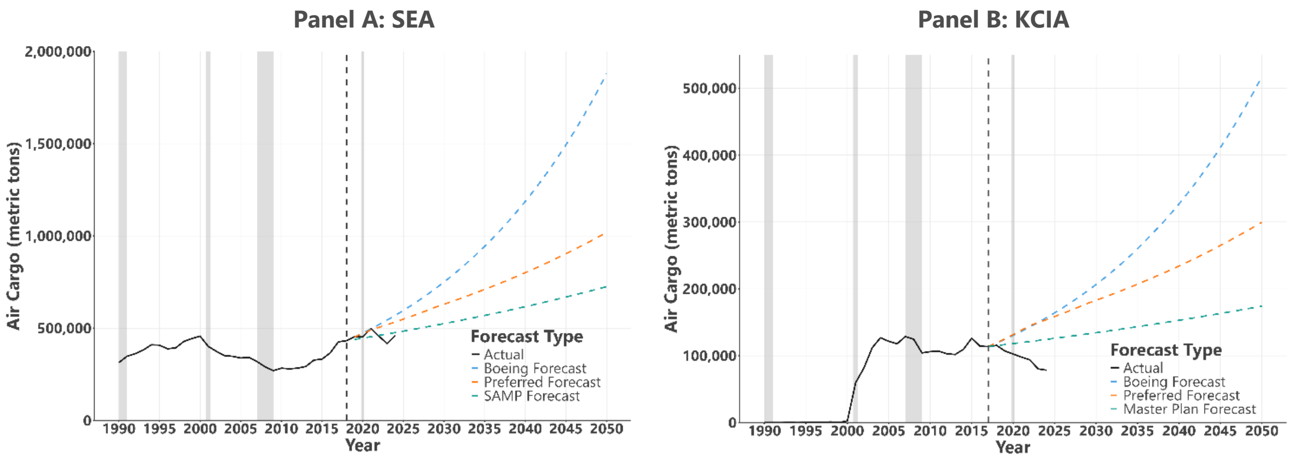
SAMP 2015 Forecasts of Aviation Activity[140]

Total air cargo at SEA is projected to grow from 319,490 metric tons in 2014 to 441,770 metric tons by 2034, reflecting an average annual growth rate of 1.6%.

Data. Forecasts for air cargo are based on airline-reported data from SEA.

Exhibit A1

Air Cargo Forecast by Airport, 2018-2050



Notes:
The solid black line represents the actual data, while the dashed lines are the forecasts.
The gray areas highlight the recession periods.
Sources:
SEA Airport Statistics, Bureau of Transportation Statistics, and the baseline study.

Assumptions. Domestic air cargo has stabilized since 2010, with an average annual increase of 1.7% between 2010 and 2014. It is assumed that this trend will continue and that domestic air cargo growth at SEA will align with the projected population growth in the Seattle primary area. The assumed growth rate for domestic air cargo at SEA is an average annual rate of 1.0% from 2014 to 2034.

Methodology. International air cargo forecasts at SEA are based on an econometric model that links cargo trends to economic and airline industry metrics. Typically, an air cargo regression model includes an income variable (e.g., total personal income, per capita income, or GDP in constant dollars) and a cost variable (e.g., oil and jet fuel prices, also in constant dollars). Unlike the passenger demand analysis, cost variables specific to SEA cargo activity are not available.

[139] The master plan forecasts include the 2014 Sustainable Airport Master Plan for Sea-Tac, and the working paper produced in May 2016 as part of the KCIA Airport Master Plan Update for KICA.
[140] SAMP 2015 Forecasts of Aviation Activity.

International air cargo forecasts at SEA are based on per capita income projections for the Seattle primary area, prepared by the PSRC. This is because the historical trend in international air cargo at SEA closely aligns with predicted values from a regression model incorporating per capita income in the Seattle primary area. Notably, models that include a cost variable were ineffective in explaining the historical trends in international air cargo at SEA.

International air cargo at SEA is projected to grow at an average annual rate of 2.8% from 2014 to 2034.

King County International Airport Master Plan Forecast[141]

Total air cargo at KCIA – Boeing Field (BFI) is projected to grow at an average annual rate of 1.3% between 2015 and 2035.

Data. The USDOT T-100 and FAA's Air Carrier Activity Information System are the basis for the airport's historical air cargo (freight and mail) activity.

Methodology. This forecast includes two scenarios for the air cargo forecast. The first scenario represents "low" growth, with a 1.3% compound annual growth rate (CAGR) based on a 10-year trend analysis of net changes in total enplaned and deplaned volumes (the volume of goods brought on and taken off an airplane), averaging an annual increase of 3.9 million pounds. This rate reflects the maturity of the air cargo market, the steady historical growth at BFI, and the FAA's projected slower growth in revenue ton miles, estimated between 0.5% and 1.0% CAGR. The second scenario represents "high" growth, with a 3.5% CAGR, projecting a more aggressive expansion supported by continued e-commerce growth. This could lead to the introduction or expansion of air cargo operations at BFI, such as the launch of Amazon Prime Air services.

Given the existing conditions driving air cargo activity at BFI—such as existing carriers, operational characteristics, and potential site development constraints—the low growth scenario is selected as the preferred forecast. Note that the selected low growth rate is conservative compared to Airbus's Global Market Forecast (2016-2035) and Boeing's World Air Cargo Forecast (2016-2035), which project U.S. air cargo to grow at CAGRs of 1.6% and 2.2%, respectively, over their 20-year horizons.

The Boeing World Air Cargo Forecast[142]

Boeing's air cargo forecast is not specific to individual airports but focuses on global geographic regions and worldwide trends. The upper bound (the "high" scenario) for world air cargo growth from 2018 to 2037 is 4.7% annually, corresponding to the average annual growth rate between East Asia and North America. This average annual growth rate was used for the air cargo forecasts of SEA and KCIA.

Assumptions. The Boeing air cargo forecast used by the PSRC assumes that air trade across the Pacific Ocean will grow at an average annual rate of 4.7% over the next 20 years. The flow from East Asia to North America is expected to grow at 4.6% per year, while the reverse flow is forecast to grow at a slightly higher rate of 4.8%. The forecast also assumes continued rapid economic growth in East Asia, particularly in China, where the middle class is expected to expand significantly. Over the next decade, more than 960 million people are projected to live in cities, with real personal disposable income increasing by 55%. These developments will drive China's shift from a manufacturing-based to a consumption- and service-driven economy.

[141] The 2017 KCIA Master Plan Forecast.
[142] The Boeing world air cargo forecast, 2018-2037.

Methodology. The forecasting process employs multiple approaches:

- Econometric modeling: This method is useful for medium- and long-term forecasts in regional markets.
- Judgmental evaluation: Judgmental modifications typically account for anticipated changes in non-econometric growth factors.
- Trend analysis: This approach is valuable for assessing general market changes driven by the combined effects of multiple factors, which can then be extrapolated into the future.

Appendix II. Details of Backcasting Strategy

In this section, we explain how we apply a backcasting approach, using the forecasts from the baseline study, to estimate enplanements retroactively from 2017 to 2000.

In time series analysis, backcasting refers to the process of estimating historical values by working backward in time.[143] Backcasting is often employed to evaluate or refine forecasting models by comparing the estimated values for earlier periods with actual historical data.

Why We Use Backcasting to Evaluate Forecasts in the Baseline Study

We have only seven data points from 2018 to 2024 available for comparing each forecast with historical data. Further complicating the analysis, the COVID-19 pandemic significantly disrupted aviation trends, causing sharp deviations from existing historical patterns. To enhance the credibility of insights derived from these comparisons, we applied backcasting to extend the forecasting models' predicting time period. This allows for a longer comparison period, helping to mitigate the influence of short-term noise.

How We Determine the Backcasting Endpoint

We have historical enplanement data dating back to 1990. We selected 2000 as the endpoint for backcasting because it is relatively close to the midpoint of the available historical range. This choice helps balance having enough data points for comparison while avoiding the increased noise associated with projecting too far back. Nonetheless, the selection of 2000 is ultimately somewhat arbitrary.

Backcasting in the Evaluation of Passenger Activity Forecasts

Recall that the baseline study projected future enplanements from 2018 to 2050 by applying a constant annual growth rate to 2017 enplanement data. It used two compound annual growth rates: 2.8% from the growth rate method and 2.4% from the market share method. To implement backcasting for these two methods, we applied their respective constant compound annual growth rates to the 2017 enplanement data in reverse using the following formula, projecting backward from 2016 to 2000. This yielded two sets of estimated historical enplanement values.

$$Backcast\ enplanement_t = enplanement_{2017} * (1 + r)^{(t-2017)}$$

where $t \in [2000, 2016]$ is the year in the backcasting period, and r is the constant compound annual growth rate used in the method, and $enplanement_{2017}$ is the enplanement volume for the base year 2017.

[143] Some relevant references include: Robinson, J.B. (1982). Energy backcasting: A proposed method of policy analysis. *Energy policy*, *10*(4), 337-344; Breidt, F.J., Davis, R.A., & Dunsmuir, W. (1992). On backcasting in linear time series models. *Institute for Mathematics and Its Applications*, *45*, 25; and Contreras-Reyes, J.E., & Idrovo-Aguirre, B.J. (2020). Backcasting and forecasting time series using detrended cross-correlation analysis. *Physica A: Statistical Mechanics and its Applications*, *560*, 125109.

Appendix III.
Systematic Literature Review of Strategies to Reduce Air Travel Demand

In this section, we provide additional details on our systematic review of national and international strategies to reduce or divert demand for air travel. We begin by outlining our search procedures, including the databases queried, search terms used, and screening criteria applied. We then cite all studies deemed in scope for the review. Finally, we describe other strategies identified during the process that did not appear in the final review due to a lack of eligible, in-scope evaluations.

Systematic Literature Search

We conducted our search for relevant research across studies in five databases. Three of these, Business Source Complete, Environment Complete, and GreenFILE, are part of the larger EBSCOhost database. We also accessed literature via Google Scholar and Web of Science. We searched these databases in February of 2025; studies published in these databases thereafter were not considered.

We used consistent search terms across databases:

("air travel" OR aviation) AND (reduc* OR mitigat* OR diver* OR decreas*) AND (demand OR consum*)

Where possible, we filtered for research published in English on or after January 1, 2015. We applied additional topic filters in Web of Science to further remove irrelevant research. Finally, we used Publish or Perish to retrieve the first 200 results from Google Scholar.[144] Exhibit A3 presents an overview of our search settings and results by database.

Exhibit A2

Air Travel Demand Reduction Review—Search Settings and Results

Database	Date range	Other filters	Download date	Number of hits
Business Source Complete (EBSCOhost)	2015-Present	English	2/13/2025	974
Environment Complete (EBSCOhost)	2015-Present	English	2/13/2025	467
GreenFILE (EBSCOhost)	2015-Present	English	2/13/2025	142
Google Scholar	N/A	N/A	2/14/2025	200*
Web of Science (WoS)	2015-Present	English; WoS Topic Filters[#]	2/18/2025	1,684

Notes:
[#] Web of Science topics include: Engineering, Energy Fuels, Environmental Sciences Ecology, Transportation, Science Technology Other Topics, Business Economics, Operations Research Management Science, Social Sciences Other Topics, Telecommunications, Psychology, Public Environmental Occupational Health, Mathematics, Public Administration, Optics, Government Law, Education Educational Research, Sociology, Urban Studies, Mathematical Methods in Social Sciences, Behavioral Sciences, Anthropology, Communication, International Relations, Area Studies, Cultural Studies, Development Studies, History, Information Science Library Science, Linguistics, Social Issues. An asterisk **(*)** denotes that researchers retrieved the first 200 citations using the free software, Publish or Perish.

[144] Publish or Perish is a free software that retrieves academic citations.

Inclusion and Exclusion Criteria

We provide additional details on the inclusion and exclusion criteria we developed to identify relevant research in Exhibit A3. If a research article met one or more exclusion criterion, it was excluded from our final review.

Exhibit A3

Air Travel Demand Reduction Review—Inclusion and Exclusion Criteria

Dimension	Inclusion criteria	Exclusion criteria
Publication year	-2015 onward	-Pre-2015 -Articles published after our search in February 2025
Geography	-All countries	
Governing body	-National governments -State and provincial governments -Local governments and airport authorities -Other organizations (e.g., corporations, universities)	
Language	-Published or translated in English	
Context	-Commercial aviation (e.g., passengers, cargo, or both)	-Civil aviation -Military aviation
Study design	-Outcome evaluations, including quasi-experimental and observational designs, provided they used multivariate techniques to control for potential confounders	-Process and implementation evaluations -Models (ex-ante studies) -Reviews and meta-analyses -Willingness-to-pay or contingent valuation studies -Studies that evaluate determinants of air travel demand (e.g., income or GDP) -Opinion pieces
Intervention	-Fully or partially implemented policies or interventions	-Theoretical policies -Technological and operational enhancements in aviation -Economic shocks (e.g., the COVID-19 pandemic, recessions, government shutdowns)
Intent of intervention	-Strategies intended to decrease air travel -Strategies intended to divert air travel -Strategies intended to decrease airport congestion -Strategies intended to decrease emissions from air travel (provided they do so through behavioral change and not technological innovation)	-Interventions intended to increase air travel (e.g., airline deregulation or airport incentive programs)
Outcomes	-Enplanements -Flights -Seat capacity -Landed weight	-Proxy measures (e.g., tourism) -Self-reported air travel

Note:
We applied our inclusion and exclusion criteria to all articles returned by the systematic database search. Any article that met one or more exclusion criteria was removed from the review.

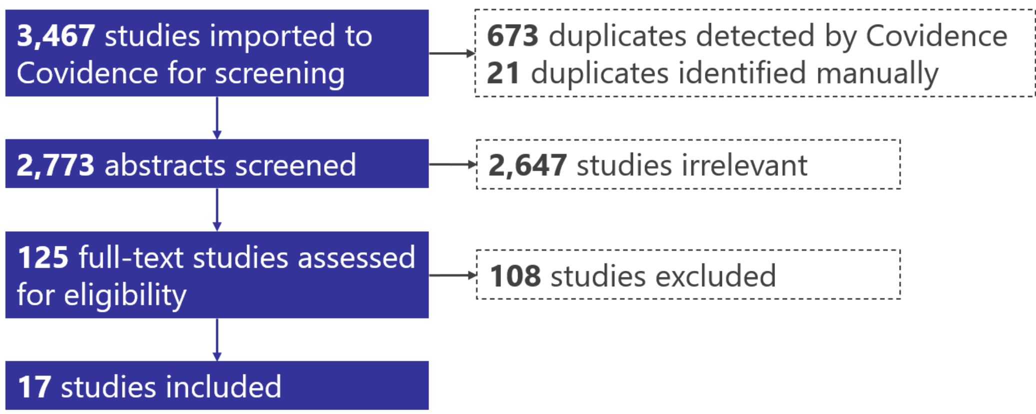
Reference Screening

We screened references in Covidence, a web-based platform for systematic reviews and data extraction, using a two-stage process with independent coders. Screening discrepancies were resolved jointly. In the first stage, we reviewed article abstracts to determine whether each study was plausibly an outcome evaluation measuring the quantity of air travel in the commercial aviation context.

In the second stage, we assessed full-text articles to further narrow the sample to evaluations measuring the impact of a policy or strategy on the quantity of air travel. This process yielded 17 in-scope articles for data extraction. We provide a diagram of our review and screening process in Exhibit A5.

Exhibit A4

Air Travel Demand Reduction Review—Screening Diagram



Data Extraction

We collected information on key dimensions, including intervention type, geography, governing body, assessed outcomes, and study quality considerations. Each study was independently coded by two reviewers, with discrepancies resolved jointly. We summarize the full list of in-scope articles used for data extraction in Exhibit A6.

Non-Represented Interventions

During our systematic review, we encountered several interventions aimed at reducing or diverting demand for air travel that did not appear in our final set of included studies. These interventions were excluded because they lacked eligible outcome evaluations that used in-scope research methods. Exhibit A6 summarizes these non-represented interventions.

Exhibit A5

Air Travel Demand Reduction Review—In Scope Studies by Intervention Category

Study	Location	Outcomes
High-speed rail		
Chen, Z. (2017). Impacts of high-speed rail on domestic air transportation in China. *Journal of Transport Geography*, 62, 184-196.	China	Passengers, flights, seat capacity
Yang, H., Burghouwt, G., Wang, J., Boonekamp, T., & Dijst, M. (2018). The implications of high-speed railways on air passenger flows in China. *Applied Geography*, 97, 1-9.	China	Passengers
Ma, W., Wang, Q., Yang, H., Zhang, A., & Zhang, Y. (2019). Effects of Beijing-Shanghai high-speed rail on air travel: Passenger types, airline groups and tacit collusion. *Research in Transportation Economics*, 74, 64-76.	China	Passengers, airfare
Wang, B., O'Sullivan, A., & Schäfer, A. W. (2019). Assessing the impact of high-speed rail on domestic aviation CO_2 emissions in China. *Transportation Research Record*, 2673(3), 176-188.	China	Passengers, diversion to HSR, seat capacity, emissions
Bernardo, V., & Fageda, X. (2020). Impacts of competition on connecting travelers: Evidence from the transatlantic aviation market. *Transport Policy*, 96, 141-151.	Europe	Passengers
Gu, H., & Wan, Y. (2020). Can entry of high-speed rail increase air traffic? Price competition, travel time difference and catchment expansion. *Transport Policy*, 97, 55-72.	China	Seat capacity
Strauss, J., Li, H., & Cui, J. (2021). High-speed rail's impact on airline demand and air carbon emissions in China. *Transport Policy*, 109, 85-97.	China	Passengers, emissions
Yu, K., Strauss, J., Liu, S., Li, H., & Kuang, X. (2021). Effects of railway speed on aviation demand and CO_2 emissions in China. T*ransportation Research Part D: Transport and Environment*, 94, 102772.	China	Passengers, emissions
Gu, H., & Wan, Y. (2022). Airline reactions to high-speed rail entry: Rail quality and market structure. *Transportation Research Part A: Policy and Practice*, 165, 511-532.	China	Passengers, emissions
Yuan, Z., Dong, C., & Ou, X. (2023). The substitution effect of high-speed rail on civil aviation in China. *Energy*, 263(Part C), Article 125913.	China	Passengers, flights
Li, J., Sun, X., Cong, W., Miyoshi, C., Lee Chui Y., & Wandelt, S. (2024). On the air-HSR mode substitution in China: From the carbon intensity reduction perspective. *Transportation Research Part A: Policy and Practice*, 180, Article 103977.	China	Seat capacity, emissions
Flight departure taxes		
Borbely, D. (2019). A case study on Germany's aviation tax using the synthetic control approach. *Transportation Research Part A: Policy and Practice*, 126, 377-395.	Europe	Passengers
Falk, M., & Hagsten, E. (2019). Short-run impact of the flight departure tax on air travel. *International Journal of Tourism Research*, 21(1), 37-44.	Europe	Passengers
Fageda, X., & Teixidó, J. J. (2022). Pricing carbon in the aviation sector: Evidence from the European emissions trading system. *Journal of Environmental Economics and Management*, 111, 102591.	Europe	Flights
Oesingmann, K. (2022). The effect of the European Emissions Trading System (EU ETS) on aviation demand: An empirical comparison with the impact of ticket taxes. *Energy Policy*, 160, 112657.	Europe	Passengers
Tradeable emissions permits		
Fageda & Teixidó (2022)	Europe	Flights, emissions
Oesingmann (2022)	Europe	Passengers
Emissions taxes		
Markham, F., Young, M., Reis, A., & Higham, J. (2018). Does carbon pricing reduce air travel? Evidence from the Australian 'Clean Energy Future' policy, July 2012 to June 2014. *Journal of Transport Geography*, 70, 206-214.	Australia	Revenue passenger kilometers (RPKs)
On-time performance policies		
Fu, X., Lei, Z., Liu, S., Wang, K., & Yan, J. (2020). On-time performance policy in the Chinese aviation market - An innovation or disruption? *Transport Policy*, 95, A14-A23.	China	Flights

Exhibit A6

Non-Represented Interventions

Intervention	Description	Example literature
Airport congestion pricing	Using higher airport charges as a congestion management tool, with tolls that can fluctuate based on demand or peak travel windows.	Wang, Y., Pels, E., Teunter, R. H., Sun, L., & Wu, J. (2023). Railway liberalization, airport congestion toll, and infrastructure pricing: Modelling and numerical analysis for European and Chinese markets. *Transportation Research Part A: Policy and Practice, 170,* 103616.
Airport relief valves	Operational choices by air carriers to divert routes to nearby airports in order to alleviate congestion and increase available airspace.	Rosenblatt, L. (2025, April 29). Why Alaska Air wants Portland to be its Sea-Tac 'relief valve'. *The Seattle Times.*
Aviation fuel taxes	Levies on air carriers' jet fuel consumption, typically reflected in higher fares for passengers.	Fukui, H., & Miyoshi, C. (2017). The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry. *Transportation Research Part D: Transport and Environment, 50,* 234-253.
CO_2 labeling	Point-of-sale flight emissions labels.	Carroll, J., Brazil, W., Howard, M., & Denny, E. (2022). Imperfect emissions information during flight choices and the role of CO_2 labelling. *Renewable and Sustainable Energy Reviews, 165,* 112508.
"Fly less" movements	Voluntary campaigns that encourage curbing personal air travel.	Katz-Rosene, R. M., & Pasek, A. (2023). Spiral-scaling climate action: lessons from and for the academic flying less movement. *Environmental Politics*, *33*(2), 259-280.
Frequent flier levies	Tiered levy structures that increase with the frequency or distance of personal air travel.	Fouquet, R., & O'Garra, T. (2022). In pursuit of progressive and effective climate policies: Comparing an air travel carbon tax and a frequent flyer levy. *Energy Policy, 171,* 113278.
Governmental campaigns	Public awareness campaigns that encourage curbing personal air travel.	Higham, J., Veisten, K., Landa Mata, I., Farstad, E., Hopkins, D., & Bian, Y. (2024). Healthy persuasion: A values-based messaging approach to leisure air travel decision-making. *Journal of Sustainable Tourism, 33*(11), 2459-2483.
Short-haul flight bans	Command-and-control policies that eliminate short-haul flights when lower-carbon travel alternatives (e.g., bus or rail) are available.	Maertens, S., & Grimme, W. (2024). The discontinuation of domestic flights in Austria: A case study on the impact on passenger routings, regional airports and the environment. *Regional Statistics, 14*(5), 898-921.
Workplace incentive programs	Workplace programs that grant employees extra paid leave when they choose surface travel (e.g., car, bus, rail) instead of flying for personal holidays.	Hoolohan, C. (2025). Shifting air travel demand: A case study on enabling experimentation in surface travel. *Journal of Sustainable Tourism, 33*(9), 1778-1795.

Appendix IV. Literature Review of Interventions to Reduce the Environmental Impacts of Aviation

In this appendix, we provide additional detail on our literature review of technological and operational enhancements aimed at reducing the environmental impacts of aviation. We document the defined search terms and screening criteria here. We also include full citations for all research included in this review.

Literature Search

We conducted our search for relevant research in Google Scholar and two EBSCO databases, Environment Complete and GreenFILE. We searched all databases in March of 2024. We used different search terms across databases and multiple search terms in Google Scholar. Refer to Exhibit A7 for more information on our search settings by database.

Exhibit A7

Environmental Literature Review—Search Settings and Results

Search terms	Database	Date range	Other filters	Download date	Number of hits
(sustainable OR climate) AND (aviation OR airline OR airport) AND (techno* OR operation*) AND (passenger OR freight* OR commercial)	Environment Complete (EBSCOhost)	2015-Present	Academic journals and magazines	3/4/2025	356
	GreenFILE (EBSCOhost)	2015-Present	Academic journals and magazines	3/4/2025	
	Google Scholar	--	--	3/4/2025	200*
Climate-friendly routing of aircraft	Google Scholar	--	--	3/4/2025	100*
Aviation non-carbon dioxide emissions technology	Google Scholar	--	--	3/4/2025	100*
Airport simulation technology	Google Scholar	--	--	3/4/2025	100*
Aviation carbon footprint tracking	Google Scholar	--	--	3/4/2025	100*

Notes:
We used multiple search strings in Google Scholar to match specific aspects of the legislative assignment. An asterisk **(*)** denotes that researchers retrieved the first 200 (or 100) citations using the free software, Publish or Perish.

Inclusion and Exclusion Criteria

Similar to the approach used for the systematic literature review in the previous section, we developed inclusion and exclusion criteria to filter research based on its relevance to the legislative assignment. For this review, we included any study that assessed an existing or emerging enhancement intended to reduce the environmental impacts of commercial aviation (e.g., reductions in CO_2 and non-CO_2 emissions, noise, pollution, waste).

To further focus the review, we limited the scope to assessments that compared an enhancement to a conventional aviation practice. This still produced a broad set of eligible study designs, including full life-cycle assessments (evaluating impacts across the entire life cycle), partial life-cycle assessments (evaluating one or more life-cycle stages), outcome evaluations, and simulations. Exhibit A8 below summarizes all inclusion and exclusion criteria.

Exhibit A8

Environmental Literature Review—Inclusion and Exclusion Criteria

Dimension	Inclusion criteria	Exclusion criteria
Publication year	-2015 to March 2025	-Pre-2015 -Articles published after our search in March 2025
Geography	-All countries	
Language	-Published or translated in English	
Context	-Commercial aviation (e.g., passengers, cargo, or both)	-General aviation -Military aviation
Study design	-Life-cycle assessment (e.g., well-to-wake analyses) -Partial life-cycle assessments (e.g., well-to-tank or tank-to-wake analyses) -Outcome evaluations -Models (ex-ante studies) and simulations	-Reviews and meta-analyses -Willingness-to-pay or contingent valuation studies -Opinion pieces -Studies quantifying the environmental impacts of aviation without assessing the advent of a technological innovation or operational enhancement
Intervention	-Existing or emerging technological and operational enhancements in aviation	
Intent of intervention	-Enhancements intended to decrease environmental impacts from air travel	-Strategies intended to decrease emissions from air travel through behavioral change (demand-reduction) and not technological innovation or operational enhancement
Outcomes	-Environmental impacts (e.g., CO_2 and non-CO_2 emissions, noise, pollution, waste, etc.)	-Efficiency -Profitability

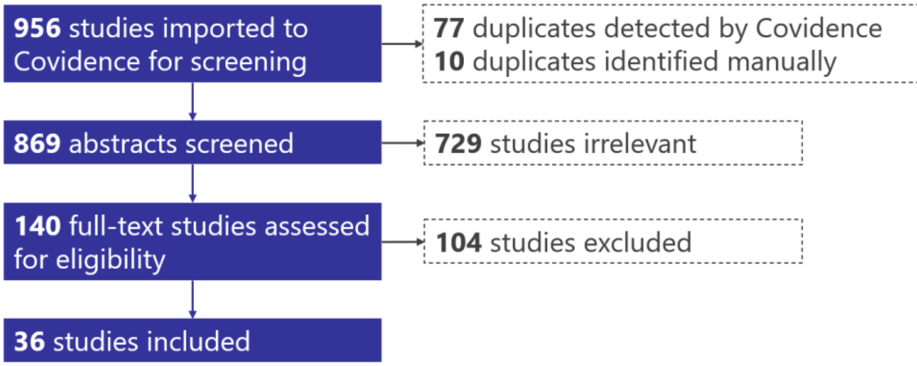
Notes:
We applied our inclusion and exclusion criteria to all articles returned by the systematic database search. Any article that met one or more exclusion criteria was removed from the review.

Reference Screening

We screened references in Covidence using a two-stage process: first by reviewing article titles and abstracts, and then by screening the full text. For this literature review, we used a single screener for each article. The screening process resulted in 36 in-scope articles for data extraction. We provide a diagram summarizing our review and screening process in Exhibit A9.

Exhibit A9

Environmental Literature Review—Screening PRISMA Diagram



Data Extraction

We collected information on several key dimensions, including the technological or operational enhancement, the assessment conducted (e.g., life-cycle assessment, partial life-cycle assessment), the conventional practice used as the point of comparison, the environmental impacts of the enhancement relative to that practice, any feasibility considerations, and whether the enhancement is currently used in commercial aviation or is expected to be introduced in the future. We summarize the full list of in-scope articles used for data extraction in Exhibit A10.

Exhibit A10

Environmental Literature Review—In Scope Studies by Enhancement Category

Study	Technologies reviewed
Innovative aircraft design	
Oguntona, O. (2020). Longer-term aircraft fleet modelling: Narrative review of tools and measures for mitigating carbon emissions from aircraft fleet. *CEAS Aeronautical Journal, 11*, 13-31.	-Strut-braced wing -Boundary layer ingestion -Double-bubble fuselage -Counter-rotating open rotor
Zaporozhets, O., Isaienko, V., & Synylo, K. (2020). Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment. *Energy, 211*, 118814.	-Newer generation aircraft (e.g., Boeing 787)
Malina, R., Abate, M., Schlumberger, C., & Navarro Pineda, F. (2022). *The role of sustainable aviation fuels in decarbonizing air transport.* Mobility and Transport Connectivity Series. World Bank.	-Blended wing body -Boundary layer ingestion -Double-bubble fuselage -Counter-rotating open rotor
Stauch, A., & Müller, A. (2022). Overview of current and future propulsion technologies for sustainable aviation. In J. L. Walls & A. Wittmer (Eds.), *Sustainable aviation: A management perspective* (Chapter 1). Springer.	-Blended wing body -Strut-braced wing
Abrantes, I., Ferreira, A. F., Magalhães, L. B., Costa, M., & Silva, A. (2024). The impact of revolutionary aircraft designs on global aviation emissions. *Renewable Energy, 223*, 119937.	-Blended wing body -Strut-braced wing
Electric and hybrid aircraft	
Schäfer, A. W., Evans, A. D., Reynolds, T. G., & Dray, L. (2016). Costs of mitigating CO2 emissions from passenger aircraft. *Nature Climate Change, 6*(4), 412-417.	-Hybrid aircraft
Goldberg, C. (2017). *Techno-economic, environment and risk analysis of an aircraft concept with turbo-electric distributed propulsion* (Doctoral dissertation). Cranfield University.	-Fully electric aircraft
Stauch & Müller (2022)	-Fully electric aircraft
Niklaß, M., Lührs, B., & Swaid, M. (2023). Note on the non-CO2 mitigation potential of hybrid-electric aircraft using "Eco-Switch." *Journal of Aircraft, 60*(1).	-Hybrid aircraft
Routing optimization	
Yamashita, H., Grewe, V., Jöckel, P., Linke, D., & Schaefer, M. (2015). Towards Climate Optimized Flight Trajectories in a Climate Model: AirTraf.	-Wind-optimized routing
Grewe, V., Dahlmann, K., Flink, J., Frömming, C., Ghosh, R., Gierens, K., Heller, R., Hendricks, J., Jöckel, P., Kaufmann, S., Kölker, K., Linke, F., Luchkova, T., Lührs, B., van Manen, J., Matthes, S., Minikin, A., Niklaß, M., Plohr, M., ... Ziereis, H. (2017). *Mitigating the climate impact from aviation: Achievements and results of the DLR WeCare project* (Project Report). Deutsches Zentrum für Luft- und Raumfahrt (DLR).	-Intermediate stop operations
Grewe, V., & Linke, F. (2017). Eco-efficiency in aviation. *Meteorologische Zeitschrift, 26*(6), 689-696.	-Intermediate stop operations
Niklaß, M., Gollnick, V., Lührs, B., Dahlmann, K., Froemming, C., Grewe, V., & van Manen, J. (2017). Cost-benefit assessment of climate-restricted airspaces as an interim climate mitigation option. *Journal of Air Transportation, 25*(2).	-Climate-restricted airspaces
Niklaß, M., Lührs, B., Grewe, V., Dahlmann, K., Luchkova, T., Linke, F., & Gollnick, V. (2019). Potential to reduce the climate impact of aviation by climate restricted airspaces. *Transport Policy, 83*, 102-110.	-Climate-restricted airspaces
Baxter, G. (2021). Decarbonizing international air cargo transportation's carbon footprint: A review of the world air cargo–carrying airlines' current and potential environment-related measures and strategies. *International Journal of Environment, Agriculture and Biotechnology, 6*(6), 265-276. **Shorthand citation:** Baxter (2021a)	-Continuous descent operations

Study	Technologies reviewed
Matthes, S., Lim, L., Burkhardt, U., Dahlmann, K., Dietmüller, S., Grewe, V., Haslerud, A. S., Hendricks, J., Owen, B., Pitari, G., Righi, M., & Skowron, A. (2021). Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. *Aerospace, 8*, 36.	-Changing the altitude
Rosenow, J., Lindner, M., & Scheiderer, J. (2021). Advanced flight planning and the benefit of in-flight aircraft trajectory optimization. *Sustainability, 13*, 1383.	-In-flight trajectory optimization
Rao, P., Yin, F., Grewe, V., Yamashita, H., Jöckel, P., Matthes, S., Mertens, M., & Frömming, C. (2022). Case study for testing the validity of NOx-ozone algorithmic climate change functions for optimising flight trajectories. *Aerospace, 9*(5), 231.	-Changing the altitude
Zengerling, Z., Linke, F., Weder, C., & Dahlmann, K. (2022, September). A comparison of climate-optimised and fuel-optimised intermediate stop operations for selected case studies. In Proceedings of the 33rd Congress of the International Council of the Aeronautical Sciences (ICAS 2022).	-Intermediate stop operations
Zengerling, Z. L., Dal Gesso, S., Linke, F., Clococeanu, M., Gollnick, V., Peter, P., Matthes, S., Baspinar, B., Ozkol, I., Noorafza, M., & Baspinar, B. (2023). Operational improvements to reduce the climate impact of aviation—A comparative study from EU project ClimOP. *Applied Sciences, 13*, 9083.	-Intermediate stop operations
Airport design and electrification	
Baxter, G. (2021). Mitigating an airport's carbon footprint through the use of "green" technologies: The case of Brisbane and Melbourne Airports, Australia. *International Journal of Environment, Agriculture and Biotechnology, 6*(6), 29-38. **Shorthand citation:** Baxter (2021b)	-On-site power generation
Liu, X., Zhang, T., Liu, X., Li, L., Lin, L., & Jiang, Y. (2021). Energy saving potential for space heating in Chinese airport terminals: The impact of air infiltration. *Energy, 215*(Part B), 119175.	-Heating, ventilation, and air-conditioning
Alruwaili, M. (2022). *Sustainable airports: Green energy solutions to achieve carbon neutrality* (Doctoral dissertation). Cardiff University.	-On-site power generation
Zengerling et al. (2023)	-Insulation of exterior walls, optimization of windows, and use of LED lights
Ground operations optimization	
Schäfer et al. (2016)	-Single-engine taxiing -Optimized departure and approach procedures
Soltani, M., Ahmadi, S., Akgunduz, A., & Bhuiyan, N. (2020). An eco-friendly aircraft taxiing approach with collision and conflict avoidance. *Transportation Research Part C: Emerging Technologies, 121*, 102872.	-Using towing vehicles to taxi planes
Zengerling et al. (2023)	-Using towing vehicles to taxi planes
Alternative jet fuels	
Bicer, Y., & Dincer, I. (2017). Life cycle evaluation of hydrogen and other potential fuels for aircrafts. *International Journal of Hydrogen Energy, 42*(16), 10722-10738.	-Hydrogen -Ethanol -Ammonia -Liquefied natural gas -Methanol
Bosch, J., de Jong, S., Hoefnagels, R., & Slade, R. (2017). *Aviation biofuels: Strategically important, technically achievable, tough to deliver* (Grantham Briefing Paper No. 23). Imperial College London, Grantham Institute.	-Hydroprocessed esters and fatty acids -Alcohol-to-jet -Fischer-Tropsch -Direct sugars to hydrocarbons -Pyrolysis

Study	Technologies reviewed
Alam, A., Masum, M. F. H., & Dwivedi, P. (2021). Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeastern United States. *GCB Bioenergy, 13*(10), 1569-1583.	-Hydroprocessed esters and fatty acids
Alherbawi, M., McKay, G., Mackey, H. R., & Al-Ansari, T. (2021). A novel integrated pathway for jet biofuel production from whole energy crops: A *Jatropha curcas* case study. *Energy Conversion and Management, 229*, 113662.	-Hydroprocessed esters and fatty acids
Male, J. L., Kintner-Meyer, M. C. W., & Weber, R. S. (2021). The U.S. energy system and the production of sustainable aviation fuel from clean electricity. *Frontiers in Energy Research, 9*, 765360.	-Alcohol-to-jet
Mousavi-Avval, S. H., & Shah, A. (2021). Life cycle energy and environmental impacts of hydroprocessed renewable jet fuel production from pennycress. *Applied Energy, 297*, 117098.	-Hydroprocessed esters and fatty acids
Arter, C. A., Buonocore, J. J., Moniruzzaman, C., Yang, D., Huang, J., & Arunachalam, S. (2022). Air quality and health-related impacts of traditional and alternate jet fuels from airport aircraft operations in the U.S. *Environment International, 158*, 106958.	-Sustainable aviation fuel blends
Lai, Y. Y., Karakaya, E., & Björklund, A. (2022). Employing a socio-technical system approach in prospective life cycle assessment: A case of large-scale Swedish sustainable aviation fuels. *Frontiers in Sustainability, 3*, 912676.	-Fischer-Tropsch
Vardon, D. R., Sherbacow, B. J., Guan, K., Heyne, J. S., & Abdullah, Z. (2022). Realizing "net-zero-carbon" sustainable aviation fuel. *Joule, 6*(1), 16-21.	-Hydroprocessed esters and fatty acids -Alcohol-to-jet -Fischer-Tropsch
Bhatt, A. H., Zhang, Y., Milbrandt, A., Newes, E., Moriarty, K., Klein, B., & Tao, L. (2023). Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. *Energy Conversion and Management, 275*, 116441.	-Hydroprocessed esters and fatty acids
Akter, H. A., Masum, F. H., & Dwivedi, P. (2024). Life cycle emissions and unit production cost of sustainable aviation fuel from logging residues in Georgia, United States. *Renewable Energy, 228*, 120611.	-Alcohol-to-jet
Mourouzidis, C., Singh, G., Sun, X., Huete, J., Nalianda, D., Nikolaidis, T., Sethi, V., Rolt, A., Goodger, E., & Pilidis, P. (2024). Abating CO2 and non-CO2 emissions with hydrogen propulsion. *The Aeronautical Journal*, 1-18.	-Hydrogen
Bell, A., Mannion, L. A., Kelly, M., Ghaani, M. R., & Dooley, S. (2025). Life cycle CO2e intensity of commercial aviation with specific sustainable aviation fuels. *Applied Energy, 382*, 125075.	-Hydroprocessed esters and fatty acids

Notes:
We included 36 studies in our final review, three of which evaluated more than one relevant enhancement.
We present citations by enhancement category in order of publication date and the primary author's last name.

Appendix V. Feasibility Assessment of Interventions to Reduce the Environmental Impacts of Aviation

In this appendix, we provide additional detail for the feasibility assessment aspect of the legislative assignment. We offer further information on our interview procedures with industry professionals, including the types of professionals we contacted, the questions we asked, and the number of interviews conducted. For the remaining components of the feasibility assessment, which examined environmental initiatives undertaken by airports, airlines, and air cargo carriers, we cite the relevant reports in this appendix.

Interview Protocol

As part of the legislative assignment, we were tasked with assessing the feasibility of deploying various technologies and operational enhancements in Washington. Our approach included conducting interviews with industry experts such as regulators, airport personnel, manufacturers, and cargo carriers. We used a purposive sampling approach, contacting a targeted set of industry professionals based on our own research and organization referrals from the Washington State Department of Transportation (WSDOT) and the Commercial Aviation Workgroup (CAWG). From there, we also used a snowball sampling approach, soliciting additional contacts from those we interviewed. In total, we contacted 16 industry professionals and completed six interviews.

During the interviews, we followed a scripted introduction that outlined the purpose of the discussion. Two WSIPP researchers conducted each interview: one led the questioning while the other documented responses using a secure SurveyMonkey survey tool. We did not record interviews but rather used our survey tool to collect responses.

We asked a series of questions about existing and emerging practices that their organizations use to mitigate environmental impacts from air travel. We also asked about technologies and practices they had considered but not adopted, as well as barriers to implementing certain practices. Finally, we asked about any attributes specific to Washington that could limit feasibility, including geographic factors, climate considerations, infrastructure, or regulatory constraints. Exhibit A11 provides the complete list of interview questions.

Exhibit A11

List of Interview Questions for Interviews with Industry Professionals

Interview questions
Current practices
1. What technologies or operational practices are currently implemented at your organization?
2. What technologies or operational practices do you plan to introduce in the near future, if any?
Barriers to implementation
3. What technologies or practices have been considered but not adopted?
4. Why did your organization not implement these practices?
5. What barriers has your organization had to overcome to implement the technologies you already have in place?
6. Is there anything unique to Washington that would limit the feasibility of certain sustainable initiatives? For example, is there something about Washington's geography, climate considerations, commercial aviation infrastructure, or regulations that are barriers?
Other
7. Is there anything else that you'd like to share before we finish?

Note:
Interviews were not recorded; instead, responses were documented in a secure SurveyMonkey survey tool.

Citations for Initiatives Implemented by Airports and Airlines in the US

To further address the portion of the legislative assignment focused on assessing the feasibility of technological and operational enhancements in Washington, our team reviewed initiatives implemented by airports, airlines, and cargo carriers across the US. For this review, we primarily examined sustainability documents, noting which practices each entity had adopted. We cite the specific sustainability documents consulted for airlines, cargo carriers, and peer airports in Exhibit A12 below.

Exhibit A12

Sources for Ongoing Environmental Initiatives

Entity	Source
Airports	
Seattle-Tacoma International	Port of Seattle. (n.d.). *SEA Airport Climate and Air Programs*; Port of Seattle. (2024). *Driving a SEA Change for our Future: Environment and Sustainability 2024 Annual Report.*
Boston Logan International	Massachusetts Port Authority Strategic and Business Planning. (2024). *2022 Environmental Status and Planning Report.*
Chicago O'Hare International	Chicago Department of Aviation. (n.d.). *Environment.*
Dallas-Fort Worth International	Dallas Fort Worth International Airport. (2024). *DFW: A Bold Vision for Tomorrow: 2024 Environmental, Social, and Governance Report.*
George Bush Intercontinental (Houston)	Houston Airports. (n.d.). *Sustainable Management Plan*; Houston Airports. (April 2024). *Carbon Management Plan: Houston Airport System.*
Los Angeles International	Los Angeles World Airports. (2019). *LAWA: Boldly Moving to Zero.*
Miami International	Miami-Dade Aviation Department. (2025). *Fly Green at MIA.*
Phoenix Sky Harbor International	City of Phoenix Aviation Department. (2025). *Sustainability*: City of Phoenix Aviation Department. (n.d.). *Roadmap to Net Zero Carbon.*
San Francisco International	San Francisco International Sustainability Department (2023). *Your Gateway to Sustainable Travel.*
Washington Dulles International (Washington DC)	Metropolitan Washington Airports Authority. (n.d.). *Green Programs at the Airports Authority.*
Regular Carriers	
Alaska Airlines	Alaska Airlines. (2024). *2024 Corporate Impact Report.*
American Airlines	American Airlines. (2024). *American Airlines Sustainability Report 2024.*
Delta Airlines	Delta Airlines. (2024). *2024 Delta Difference Report.*
Hawaiian Airlines	Hawaiian Airlines. (2025). *Environmental Stewardship.*
United Airlines	United Airlines. (2025). *Corporate Impact Report 2024.*
Low-Cost Carriers	
Allegiant Air	Allegiant Air. (2023). *Destined for Sustainable Impact.*
Frontier Airlines	Frontier Airlines. (2025). *America's Greenest Airline.*
JetBlue	JetBlue. (2025). *Sustainability.*
Southwest Airlines	Southwest Airlines. (2025). *Planet.*
Spirit Airlines	Spirit Airlines. (2023). *Sustainability Report 2021/2022.*
Cargo Carriers	
Air Transport Services Group	Air Transport Services Group. (2025). *2024 Sustainability Report.*
Atlas Air	Atlas Air Worldwide. (2024). *Caring for the World We Carry.*
Federal Express	Federal Express. (2025). *Corporate Responsibility Report.*
Kalitta Air	Kalitta Air. (2024). *Environmental Strategy.*
United Parcel Service	United Parcel Services. (2025). *Global Reporting Initiative 2024.*

Note:
"Airport" is dropped from the end of each of the official airport names above.

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