Project Report
ATC-420

Terminal Flight Data Manager (TFDM) Environmental Benefits Assessment

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16. Abstract

This work monetizes the environmental benefits of Terminal Flight Data Manager (TFDM) capabilities which reduce fuel burn and gaseous emissions, and in turn reduce climate change and air quality effects. A methodology is created which takes TFDM "engines-on" taxi time savings and converts them to fuel and carbon dioxide (CO_2) emissions savings, accounting for aircraft fleet mix at each of 27 TFDM analysis airports over a 2016–2048 analysis timeframe. Total fuel reductions of approximately 300 million U.S. gallons are estimated, resulting in monetized benefits from all TFDM capabilities of $65m–$582m undiscounted, $23m–$310m discounted, depending on the Social Cost of CO_2 (SCC) and discount rate used. A similar methodology is used to estimate monetized benefits of reduced air quality emissions as well.

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EXECUTIVE SUMMARY

This work monetizes the environmental benefits of Terminal Flight Data Manager (TFDM) capabilities which reduce fuel burn and gaseous emissions, and in turn reduce climate change and air quality effects. A methodology is created which takes TFDM "engines-on" taxi time savings and converts them to fuel and carbon dioxide (CO_2) emissions savings, accounting for aircraft fleet mix at each of 27 TFDM analysis airports over a 2016–2048 analysis timeframe. Scenarios considered include "All TFDM" capabilities and "Departure Management (DQM) Only." Total estimates fuel and CO_2 emissions reductions are presented below. The DQM capability accounts for 93% of the total fuel and CO_2 savings.

Summary Fuel and CO_2 Emissions Savings across 27 TFDM Analysis Airports, 2016–2048

Scenario	Total Fuel Reduction	Total CO_2 Reduction
All TFDM	954,000 metric tons, 313 million U.S. gallons	3.0 million metric tons
DQM Only	889,000 metric tons, 291 million U.S. gallons	2.8 million metric tons

The carbon dioxide emissions savings are monetized using U.S. government inter-agency guidance on Social Cost of CO_2 (SCC) damage functions and recommended discount rates. The results are summarized below for both undiscounted and discounted cases. Significant monetized CO_2 benefits are seen to be enabled by deployment of TFDM at the analysis airports over the timeframe of interest. The grey highlighted results represent the "mid-case" estimates based on the "3% Average" SCC value and 3% and 7% discounting. The 3% discount rate is recommended for consistency with the 3% SCC value and appropriateness for CO_2 inter-generational effects. The 7% discount rate is included for consistency with investment analyses for other programs.

Summary Global CO_2 Monetized Benefits across 27 TFDM Analysis Airports, 2016–2048

	Undiscounted Monetized Benefit (2015$)				**Discounted Monetized Benefit (2015$)**				
Social Cost of CO_2	5% Av	3% Av	2.5% Av	3% 95th	5% Av	3% Av	3% Av	2.5% Av	3% 95th
Discount Rate	0%	0%	0%	0%	5%	7%	3%	2.5%	3%
All TFDM	$65m	$191m	$271m	$582m	$23m	$48m	$102m	$160m	$310m
DQM Only	$60m	$178m	$252m	$542m	$21m	$45m	$95m	$149m	$289m

The document details the approach used to generate these results, as well as global versus U.S.-only CO_2 impacts. An analogous approach is also presented for monetizing air quality benefits from TFDM which turn out to be of similar magnitude to the CO_2 monetized benefits. Because there is no agreed federal guidance on monetizing air quality impacts, these results are presented in an Appendix for information only, but do suggest that there are significant additional environmental benefits from TFDM beyond those from CO_2 alone.

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1. INTRODUCTION

1.1 TFDM PROGRAM BACKGROUND

The Terminal Flight Data Manager (TFDM) is a Federal Aviation Administration (FAA) program to develop an advanced automation platform for air traffic controllers to safely and efficiently manage aircraft operations on the airport surface and in the terminal area. TFDM will integrate with other FAA automation systems to provide decision support across flight domains. Planned TFDM capabilities include an enhanced surface situation display, an electronic flight data system and a suite of decision support tools [1]. In order to assess the suitability of TFDM to become an acquisition system for deployment in the air traffic control system, it is undergoing investment analysis consistent with the FAA Lifecycle Management Process shown in Figure 1.

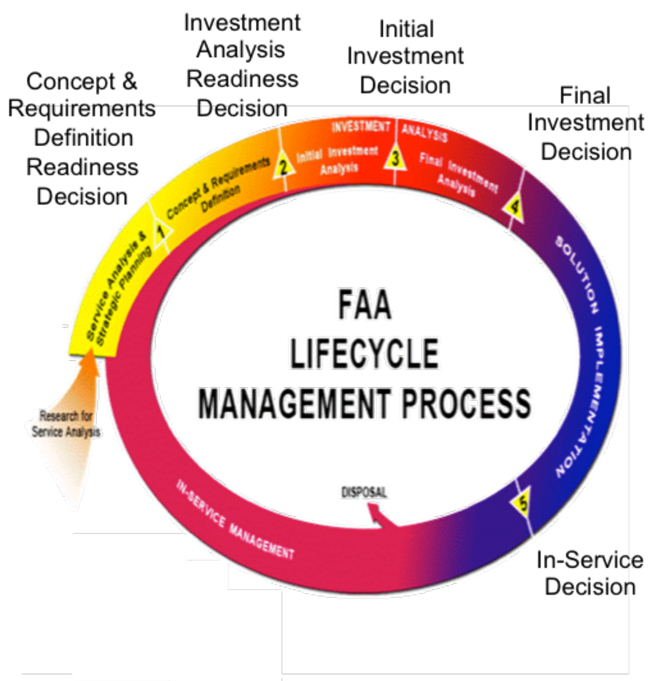


Figure 1. FAA lifecycle management process [source: FAA].

MIT Lincoln Laboratory has been supporting the TFDM Program Office in this process, including the design, implementation and test of a prototype TFDM system deployed to Dallas Fort Worth airport in 2010–11 to assist in concept development and requirements definition, and computer modeling and analysis to support the Investment Analysis Readiness Decision (IARD), Initial Investment Decision (IID) and Final Investment Decision (FID) activities. This document summarizes the environmental benefits assessment conducted in support of the FID activities.

1.2 TFDM ENVIRONMENTAL BENEFIT MECHANISMS

The capabilities provided by TFDM will have impacts to many system stakeholders, examples of which are shown in Figure 2.

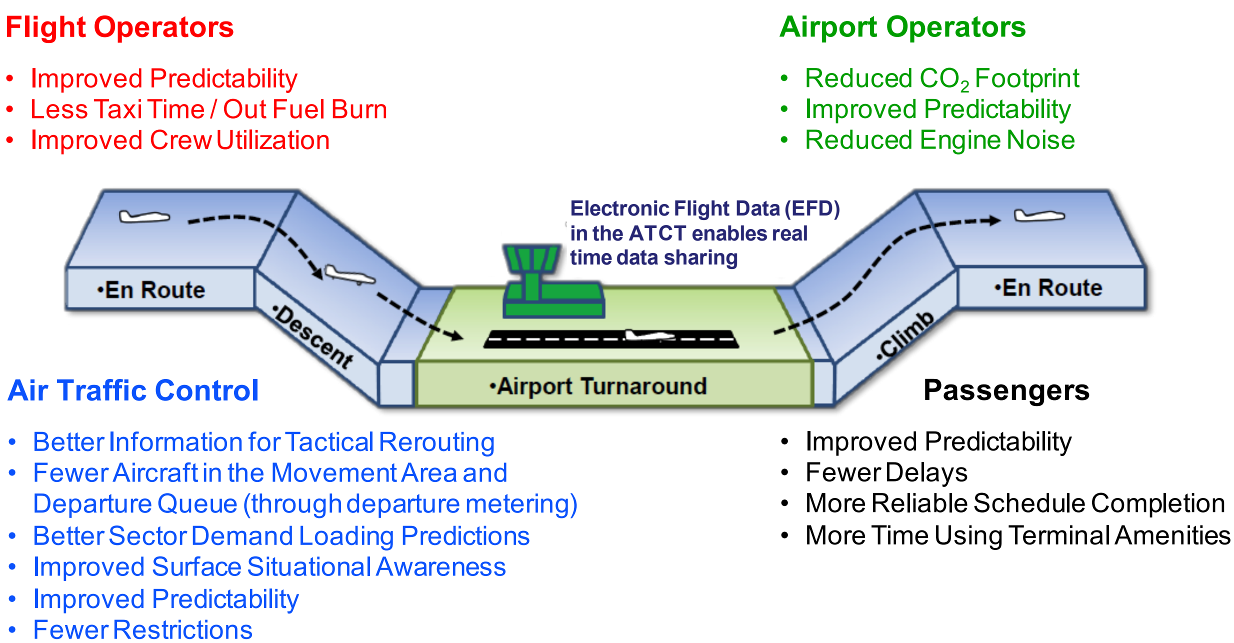


Figure 2. TFDM benefit mechanisms [source: FAA].

Given the environmental benefits focus of this report, the primary mechanisms of interest are those TFDM capabilities which reduce engines-on taxi time and fuel burn, which in turn affects greenhouse gas emissions, local air quality pollutants and noise. The main TFDM capability which lead to reduced engines-on time and fuel burn is the Departure Queue Management (DQM) feature, which predicts surface congestion and collaboratively meters departures into the active movement area to reduce surface congestion. This enables taxi-out delay to be shifted from the movement area with engines on to the gate or other appropriate area where it can be accommodated with engines-off. Savings are also enabled by

TFDM through the increased opportunity to take Call For Release (CFR) delay at the gate, improved OFF-time compliance related to controlled departure times and improved capacity (and hence reduced taxi-out delay) from a Runway Balancing capability.

1.3 ENVIRONMENAL BENEFIT ASSESSMENT OBJECTIVES

The primary objective of the work outlined in this report was to monetize the environmental benefits of TFDM capabilities that reduce taxi-out fuel burn to contribute to the overall benefits assessment. In order to do this, methodologies were required to estimate the environmental impacts of relevant capabilities, and then convert those impacts into monetized benefits estimates.

The three main environmental impact areas considered in aviation system analysis are [2]:

- **Climate**: Reductions in fuel burn lead to reductions in greenhouse gas emissions which contribute to climate change effects. Methodologies can be developed for estimating fuel burn savings from given taxi time reductions by accounting for taxi fuel burn rates of a known fleet mix of aircraft at analysis airports of interest. Conversion of fuel savings to greenhouse gas emissions reductions is well understood for many relevant gaseous species, especially carbon dioxide (CO_2) which is one of the main climate-impacting pollutants. Methodologies and federal guidance to monetize emissions reductions for policy-making is also well-defined for CO_2, but such guidance is lacking for non-CO_2 climate-impacting pollutants such as nitrogen and sulphur oxides.

- **Air quality**: Reductions in fuel burn lead to reductions in pollutant emissions which contribute to air quality effects which impact human health. Conversion of fuel savings into air quality emissions reductions is also well understood for many relevant particulate and gaseous species, but in a much more complicated way than a simple multiplier on fuel burn. Although federal guidance does not exist on how to monetize air quality emissions reductions for policy-making, methodologies which mirror those for climate impact monetization do exist in peer-reviewed literature.

- **Noise**: Reduced engines-on time will lead to noise reductions and associated human welfare and economic benefits, especially for communities near to taxiway and runway queue locations where congestion is being reduced. Unfortunately, standard aircraft noise models (such as the FAA's Integrated Noise Model (INM) and Aviation Environmental Design Tool (AEDT)) are currently designed for assessing impacts from airborne flight phases and are not well-suited for assessing aircraft operations on the airport surface. Research is ongoing to develop improved models for this domain, but they are not available to support the TFDM FID analyses. Established noise impact monetization approaches (such as the Noise Depreciation Index (NDI)) are commonly used to assess the noise effects of modified airborne procedures, but the inability to model noise contour impacts from surface operations inhibits the ability to use these monetization approaches for this TFDM analysis. Therefore, TFDM noise assessment is limited to the qualitative statement that TFDM will enable noise reductions through reduced surface congestion.

Based on these factors, the objectives for the study documented in this report are as follows:

- Develop a TFDM environmental impact assessment methodology, including ways to estimate fuel burn reductions at appropriate study airports over suitable time horizons and techniques to convert these fuel savings into monetized CO_2 and air quality benefits (see Section 2).
- Apply the methodology to estimate monetized TFDM CO_2 climate benefits (see Section 3).
- Apply the methodology to estimate monetized TFDM air quality benefits (see Appendix A).

2. TFDM ENVIRONMENTAL BENEFITS ASSESSMENT METHODOLOGY

2.1 GENERAL METHODOLOGY

The general methodology for the TFDM climate and air quality environmental benefit assessment is shown in Figure 3. Analysis was conducted for a set of 27 major U.S. airports shown in Figure 4 where TFDM is expected to be deployed with full decision support capabilities, covering an analysis period 2016–2048. Note, although the analysis period starts in 2016, benefits do not begin until 2022 when TFDM deployment is expected to begin.

Each block of the methodology is discussed in the sections that follow.

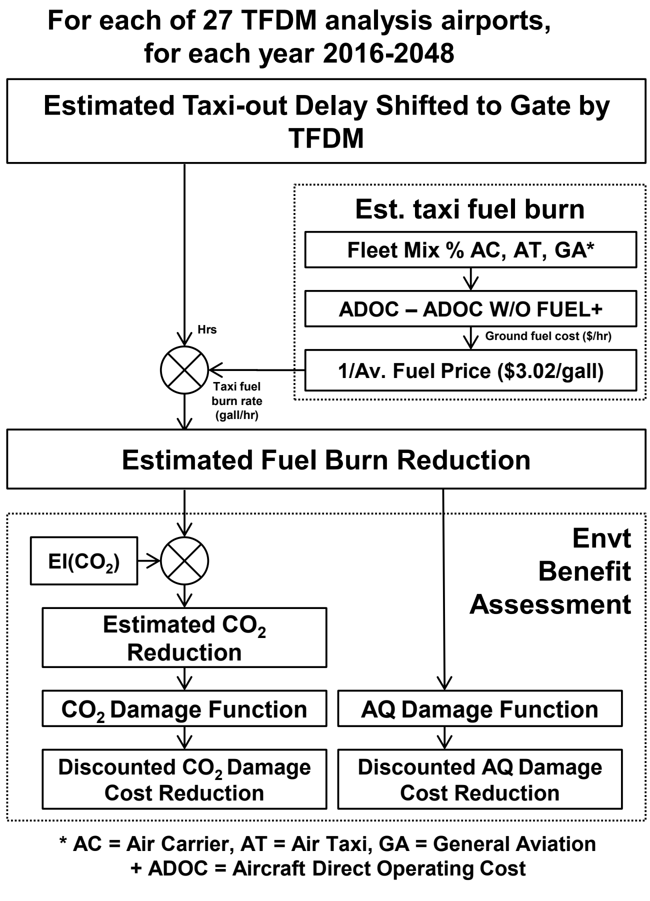


Figure 3. TFDM environmental benefit assessment methodology.

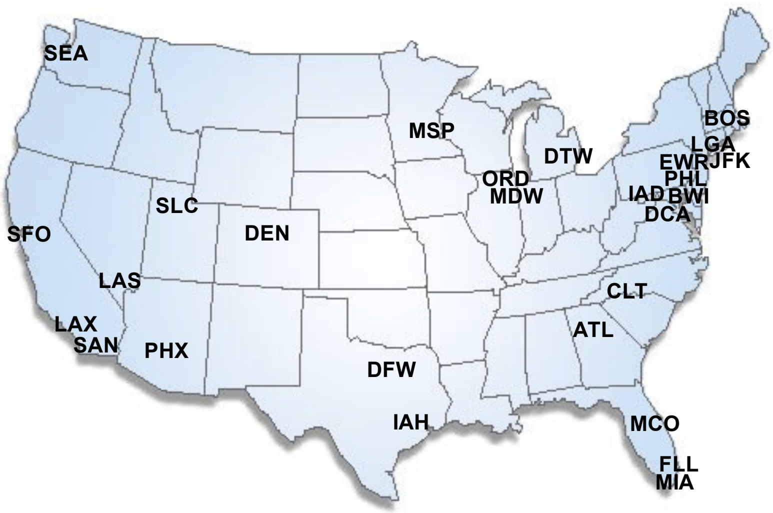
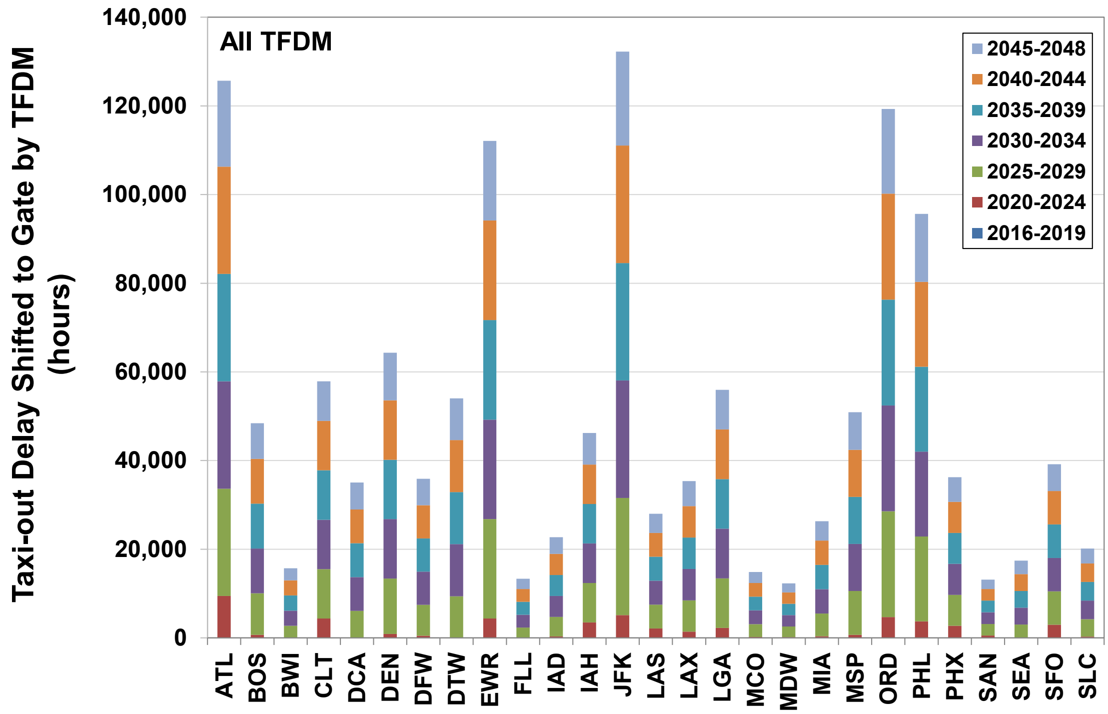


Figure 4. TFDM analysis airports.

2.2 ESTIMATED TAXI-OUT DELAY SHIFT TO GATE

The methodology begins with the estimated taxi-out delay time shifted to the gate by TFDM for each airport and year included in the analysis. Prior analysis used forecast demand and capacity at each airport for each year, along with assumptions on the effectiveness of the departure queue management and other relevant capabilities, to develop these taxi time saving estimates. This included scenarios covering "All TFDM" (primarily DQM, CFR delay at the gate, improved OFF-time compliance, and Runway Balancing) and "DQM Only" capabilities. Full details of the taxi time saving analysis can be found in [3], and the results of that work are simply taken as inputs for this environmental benefit analysis. Risk adjustments were already applied in the input data to account for "cultural risk" associated with, for example, lack of availability of accurate airline input data, lack of compliance to TFDM recommendations on push-back times, lack of gate or other hold area availability and overlap with other programs.

Figure 5 presents the estimated taxi-out delay shifted to the gate for each of the 27 analysis airports, for five-year time bins for these two scenarios. Total taxi time savings of over 1.3 million hours are estimated over the 27 airports over the 2016–2048 timeframe for the "All TFDM" case. Benefits only start coming online with the 2020–2025 time bin as TFDM deployments begin. It is evident that the estimated taxi-out delay shift from TFDM vary significantly between the airports, with 5 of the 27 airports (Hartsfield-Jackson Atlanta International Airport (ATL), Newark Liberty International Airport (EWR), John F. Kennedy International Airport (JFK), Chicago O'Hare International Airport (ORD) and Philadelphia International Airport (PHL)) accounting for nearly half (44%) of the total taxi-out delay savings. Note that TFDM is assumed to be deployed starting at different years depending on the airport and that many of the analysis assumptions used to estimate the taxi-out delay shift were capped, and hence similar taxi-out delay estimates are observed for each time bin after deployment for a given airport.



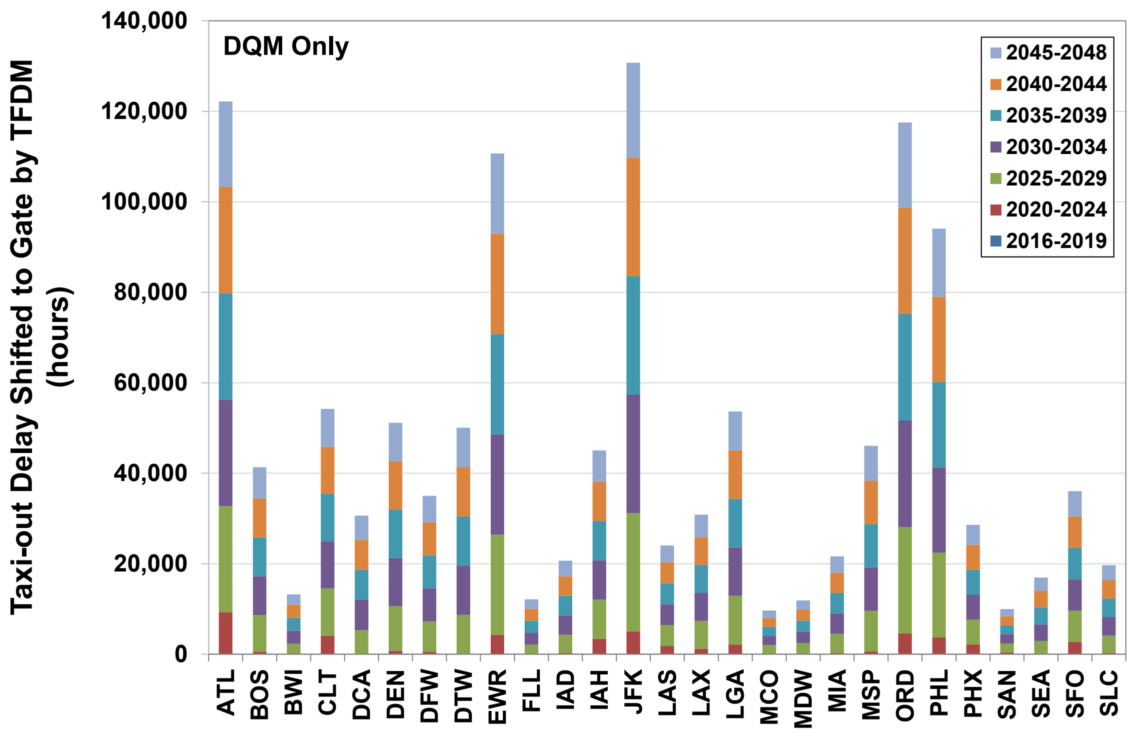


Figure 5. Estimated "All TFDM" and "DQM Only" taxi-out delay reductions.

2.3 ESTIMATED TAXI FUEL BURN RATES

In order to convert the taxi time estimates from Figure 5 into fuel savings, it was necessary to determine taxi fuel burn rates considering the fleet mix at each airport for each year. The official FAA traffic forecast is the Terminal Area Forecast (TAF) [4]. The edition used for this analysis covered the period 2014–2040. It provides estimates of the fleet mix at each airport during this period in terms of percentage of the fleet within air carrier, air taxi and general aviation categories. FAA investment analysis guidance [5] can be used to establish taxi fuel burn rates for each of these categories using Aircraft Direct Operating Cost (ADOC) with and without fuel burn per ground hour taxiing. The difference between the two gives an implied fuel cost rate per ground hour for each category. This can be converted to an implied fuel burn rate using the FAA-recommended fuel price value ($3.02 on average over the period 2015 to 2035 in $FY15 [5]). These parameters for each aircraft category are shown in Table 1.

Table 1

Taxi Fuel Burn Rate Estimates by Aircraft Category

Aircraft Category	Assumed ADOC with Fuel/Ground Hour	Assumed ADOC without Fuel/Ground Hour	Implied Fuel Cost/Ground Hour	Implied Fuel Burn Rate (U.S. gallons/hr @$3.02/gallon)
Air Carrier (Passenger)	$2364	$1546	$817	270.6
Air Taxi	$639	$416	$223	73.9
General Aviation	$365	$238	$128	42.3

The resulting estimated taxi fuel burn rates at each analysis airport and year accounting for the fraction of each aircraft category are shown in Figure 6. It is seen that there is variation between airports given differences in fleet mix, as well as changes over time at an airport due to evolving fleet mix distributions. These changes over time are relatively large in the period 2015–2030 (driven by increasing fractions of air carrier category aircraft in the fleet mixes from the TAF forecasts), but changes 2030–2040 are negligible. Given the TAF forecasts only go out to 2040, fleet mixes are kept constant after this year.

One concern about using this approach to estimate taxi fuel burn is that the generic aircraft categories contain a wide range of different types. For example, the air carrier category contains aircraft from small regional jets up to four engine wide-body jet aircraft which have very different taxi fuel burn rates in reality. In order to assess the impact of making the simplifying assumption of generic fuel burn rates by category across all airports, Figure 7 presents a comparison of the estimated fuel burn when accounting for the specific aircraft types at each airport in 2010 (using taxi fuel burn estimates from the ICAO certification database [6] for each specific aircraft type in the fleet mix) compared to the estimate using the generic fuel burn assumption.

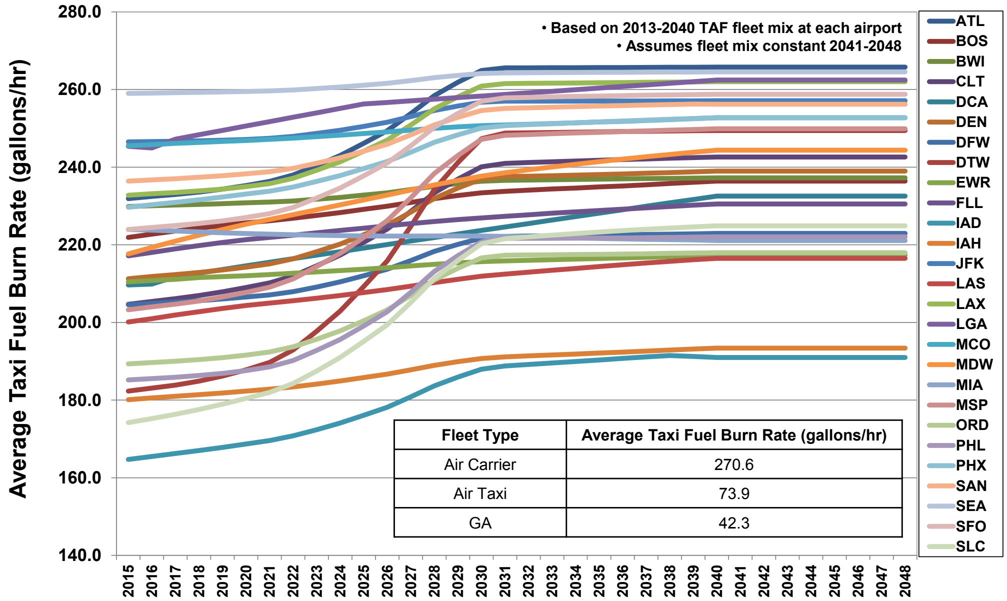


Figure 6. Estimated taxi fuel burn rates at TFDM analysis airports.

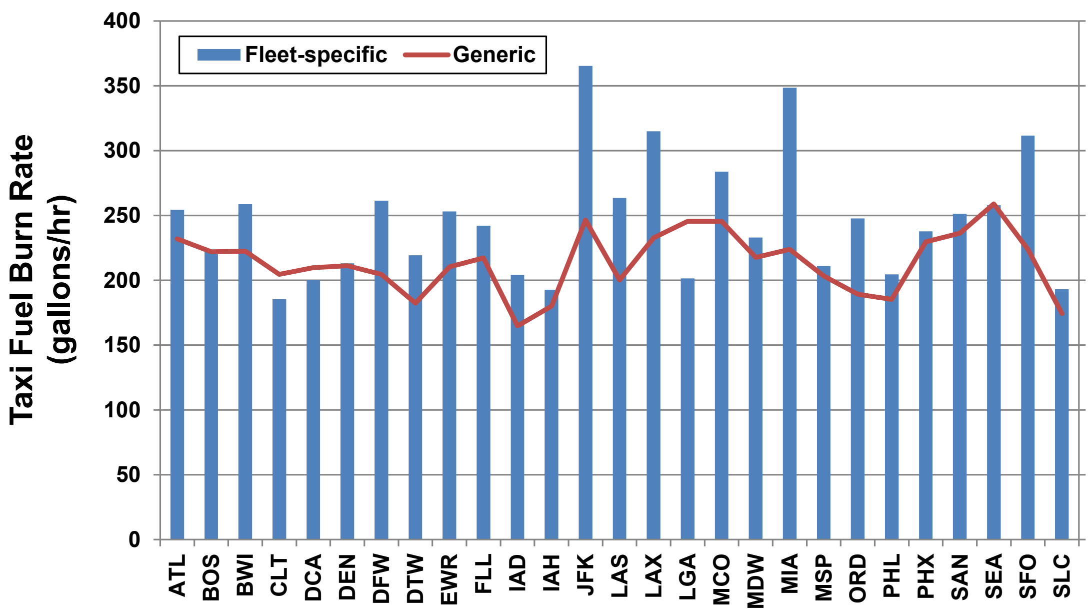


Figure 7. Fleet-specific vs. generic taxi fuel burn rates at TFDM analysis airports.

It is seen that at many airports the generic category assumption results in a reasonably good estimate of the average fuel burn rate. However, airports with a relatively large fraction of wide-body aircraft (e.g., Dallas/Fort Worth (DFW), Newark (EWR), John F. Kennedy (JFK), Los Angeles (LAX), Miami (MIA), San Francisco (SFO)) have significantly higher fuel burn rates when using the fleet-specific values, while the opposite is the case at airports with few larger types (e.g., LaGuardia (LGA)). The impact of these differences depend on the taxi time savings being predicted at each of the analysis airports. Figure 8 presents the total estimated fuel burn saving differences at each airport (over the total 2016–2048 study period) between the fleet-specific and generic values when scaled by the taxi time saving at each airport. It is seen that there is up to a 30% high or low difference between the two approaches at some airports (30% high at JFK, 30% low at LGA), but when aggregated over all airports the difference between the two approaches is approximately 5%. Therefore, the generic taxi fuel burn estimate values were carried forward in this analysis given their relative simplicity and grounding in the FAA-recommended values. However, this may not be appropriate for any future airport-specific studies.

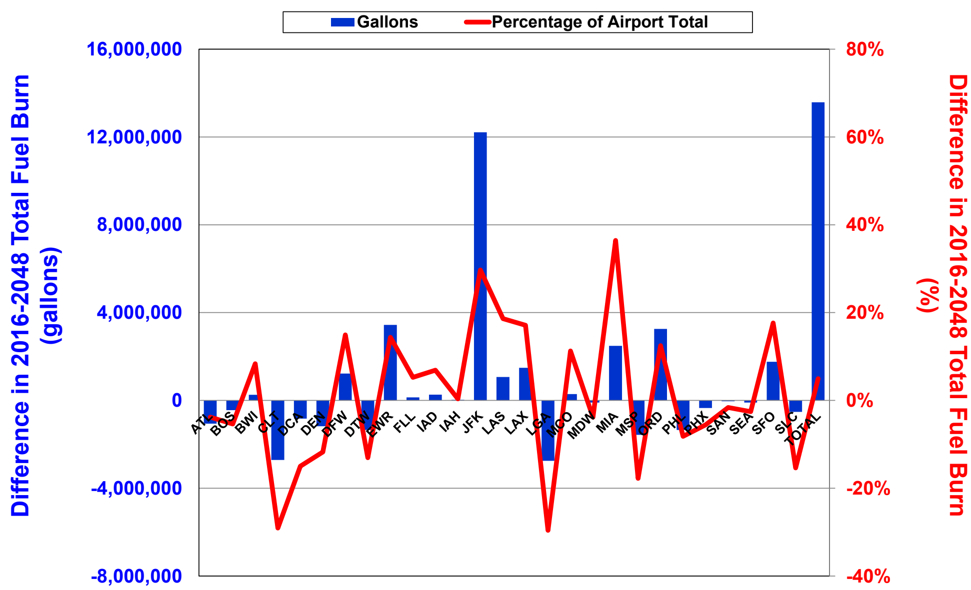


Figure 8. Total fuel burn comparison using fleet-specific or generic taxi fuel burn rates.

2.4 ESTIMATED FUEL BURN AND CARBON DIOXIDE REDUCTION

Fuel burn reduction estimates were calculated by simply multiplying the taxi time savings (from Figure 5) by the fuel burn rate (from Figure 6) for each year at each airport. Estimating carbon dioxide savings from fuel savings is also straightforward (given the stoichiometric production of CO_2 from jet fuel) using an Emissions Index, (EI)(CO_2) of 3.16 kg CO_2 produced per kg jet fuel burnt [7]. The results are shown in Figure 9, with the fuel savings referenced to the left axis, and CO_2 reductions referenced to the right axis. The total fuel and CO_2 savings are presented in Table 2.

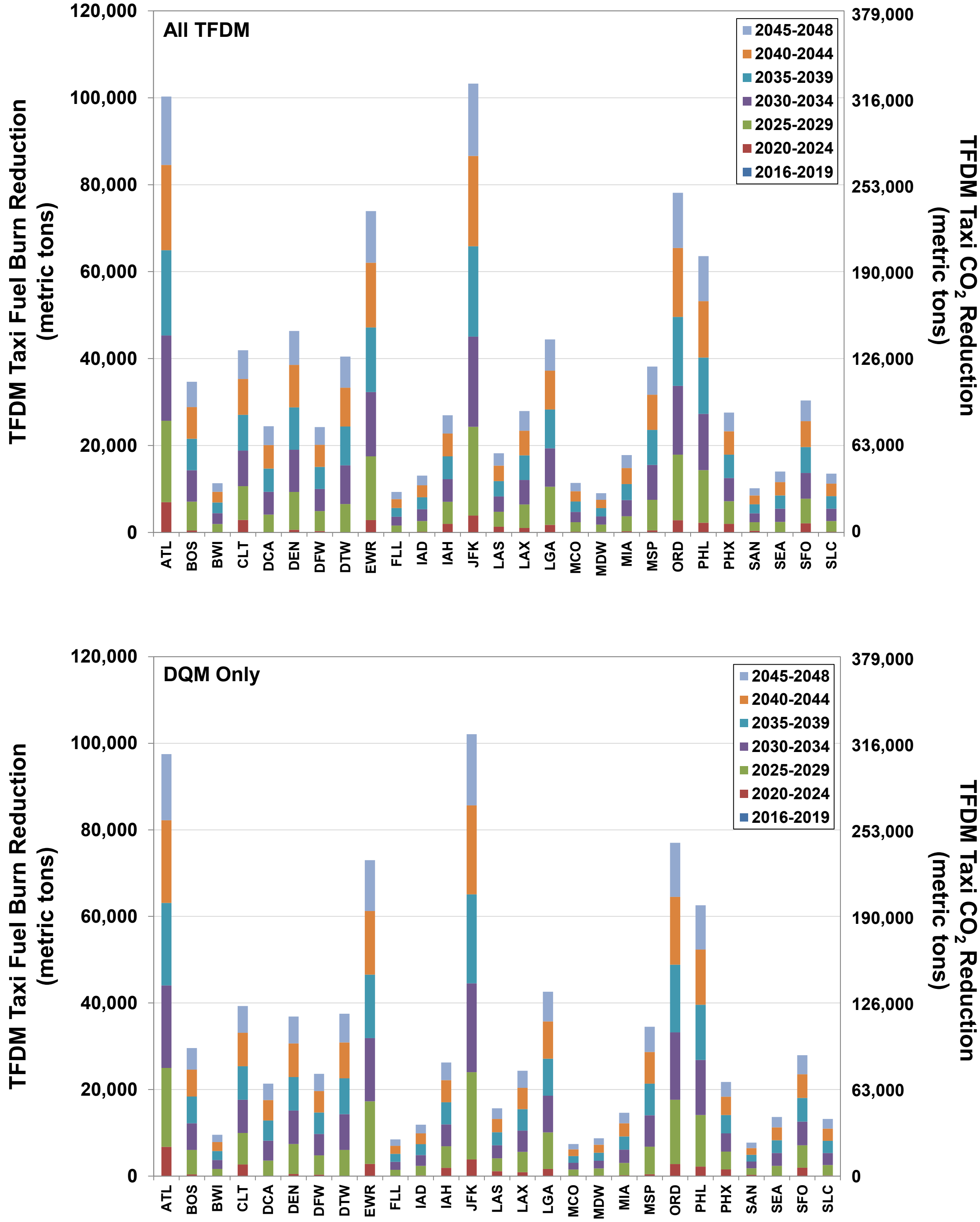


Figure 9. Estimated "All TFDM" and "DQM Only" taxi-out fuel and carbon dioxide reductions.

Table 2

Total Estimated Taxi-out Fuel and Carbon Dioxide Reductions

Year	Total Fuel Reduction (metric tons)		Total CO_2 Reduction (metric tons)	
	All TFDM	DQM Only	All TFDM	DQM Only
2015–2019	0	0	0	0
2020–2024	34,748	32,743	109,805	103,468
2025–2029	180,181	167,862	569,373	530,445
2030–2034	193,907	180,394	612,745	570,045
2035–2039	194,634	181,058	615,042	572,144
2040–2044	195,013	181,404	616,240	573,237
2045–2048	156,010	145,123	492,992	458,590
TOTAL	954,493 (312.9 million U.S. gallons)	888,585 (291.3 million U.S. gallons)	3,016,197	2,807,930

2.5 DAMAGE FUNCTIONS AND DISCOUNTING

Once estimates have been calculated for fuel and CO_2 emissions reductions, damage functions can be used to monetize the climate and air quality benefits at various years in the future. The damage functions are different for climate and air quality impacts, and hence they will be discussed separately in the next sections.

It is common to also apply discount rates, to bring benefits in future years back to a base year according to:

$$Total\ Benefit\ (Base\ Year) = \sum_{Base\ Year}^{Final\ Impact\ Year} \frac{Benefit\ (Impact\ Year)}{(1 + Discount\ Rate)^{Impact\ Year - Base\ Year}}$$

The discount rate reflects how much we value future year benefits: the lower the discount rate, the closer we value future benefits to how we would value the same benefit today.

3. TFDM CO_2 CLIMATE BENEFITS ASSESSMENT

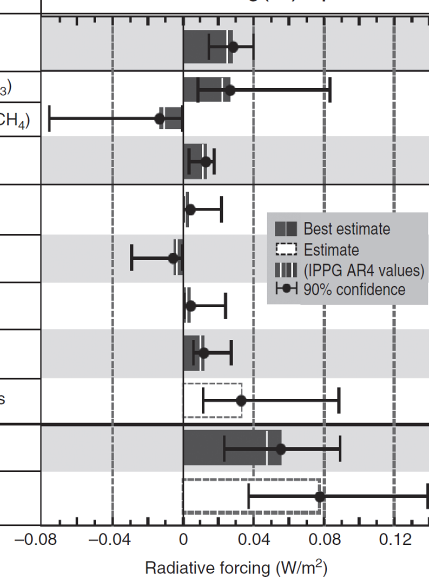
3.1 INTRODUCTION

Carbon dioxide (CO_2) is the dominant pollutant from the burning of jet fuel, accounting for over 70% of emissions by mass. It is also a long-lived pollutant, remaining in the atmosphere for many decades to centuries after being emitted. As a result of this long lifetime, CO_2 emissions get mixed in the atmosphere around the globe. The effects of CO_2 on the atmosphere are relatively well-understood. One way this impact is measured is in terms of Radiative Forcing (RF), a measure of the influence that a pollutant has in altering the energy balance of the Earth's atmosphere. RF is a convenient metric to use because it is directly proportional to the estimated temperature change impacts of a given pollutant (positive RF leads to a warming tendency, negative RF leads to a cooling tendency). Table 3 presents the RF impacts, as well as spatial, temporal and level of scientific understanding of impacts, of the main climate-changing pollutants from aviation.

Table 3

Radiative Forcing Impact Estimates of Aviation Emissions (adapted from [8])

Climate Change Source		Radiative Forcing (RF) Impact	Spatial Scale	Temporal Scale	LOSU*
Carbon dioxide (CO_2)			Global	10-100s years	High
Nitrogen oxides (NO_x)	Inc. Ozone (O_3)		Continental	Months-10s years	Med-low
	Dec. Methane (CH_4)		Global	Months-10s years	Med-low
Total NO_x			Global	Months-10s years	Med-low
Water vapor (H_2O)			Global	Days	Low
Sulphate (SO_x) aerosol			Local-global	Days-weeks	Low
Soot aerosol			Local-global	Days-weeks	Low
Linear contrails			Local-continental	Hours	Low
Induced cirrus cloudiness			Local-hemispheric	Hours-days	V. low
Total aviation (excl. induced cirrus)			Global	Hours-100s years	Low
Total aviation (incl. induced cirrus)			Global	Hours-100s years	Low



*Level of scientific understanding

As previously noted, the TFDM climate assessment was limited to CO_2 effects given it is the pollutant with highest level of scientific understanding, and hence for which established monetization guidelines exist for policy-making, but in future it may be appropriate to include non-CO_2 effects as well.

3.2 CARBON DIOXIDE DAMAGE FUNCTIONS AND DISCOUNTING

U.S. federal guidance on monetizing CO_2 emissions has been established by the Interagency Working Group on Social Cost of Carbon (SCC)[1], with the latest guidance summarized in [9]. The primary output of relevance to this study are recommended Social Cost of CO_2 values. Three integrated climate assessment models are used by the U.S. government to estimate these values (the DICE, FUND and PAGE models). These models consider the social and economic factors that drive the emission of greenhouse gases, the biogeochemical cycles and atmospheric chemistry that determines the fate of those emissions, and the resultant effect of greenhouse gas emissions on climate and human welfare. The latest monetization values are based on a range of updates to these integrated models run at a range of reference scenarios as fully described in [9]. One of the key scenario variables studied was discount rate, using recommended values of 2.5%, 3% and 5%. The global Social Cost of CO_2 values from these models are presented in Table 4. The "average" values represent the mean of the various model runs, while the 95th percentile from the 3% model was chosen to represent the higher-than-expected economic impact from climate change further out in the tails of the distribution. See Figure 10 for an illustration of these different discount rate cases and examples of the model run distributions from which they were determined.

Table 4

Global Social Cost of CO_2 Values ($/metric ton of CO_2 in 2007$) [9]

Year	Discount Rate			
	5% average	3% average	2.5% average	3% 95th
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

[1]Although the term Social Cost of Carbon is used in the Group's name, the damage functions are actually in terms of Social Cost of Carbon Dioxide. Technically they are different (in that a metric ton of CO_2 does not contain a metric ton of carbon), but the terms seem to be used interchangeably and equivalently in [9]. The term "Social Cost of CO_2" will be used in this analysis to avoid confusion.

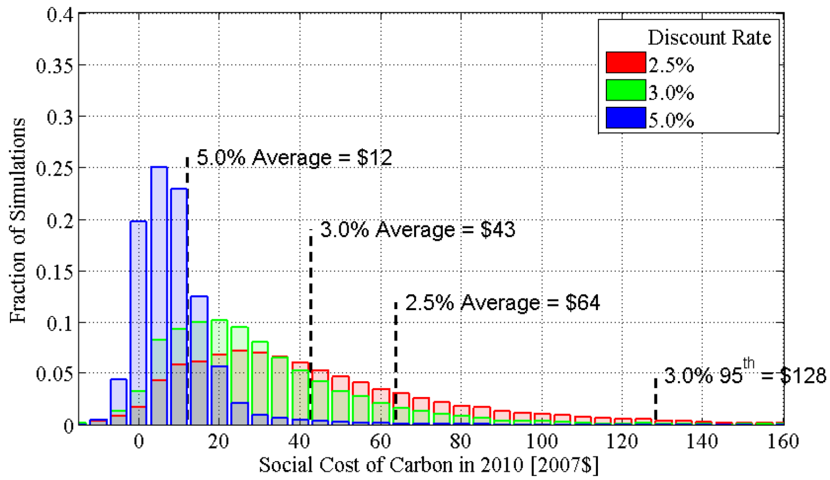


Figure 10. Sample social cost of carbon estimates from integrated assessment model runs [9].

The guidance documentation contains specific recommendations on how to use these Social Cost of CO_2 values, including:

- "…for the purposes of capturing the uncertainties involved in regulatory impact analysis, the interagency group emphasizes the importance and value of including all four SCC values" ([9], page 12)

- "The future monetized value of emission reductions in each year (the SCC in year *t* multiplied by the change in emissions in year *t*) must be discounted to the present to determine its total net present value for use in regulatory analysis…damages from future emissions should be discounted at the same rate as that used to calculate the SCC estimates themselves to ensure internal consistency." ([9] page 14)

In addition to following this guidance, it was also recommended by FAA stakeholders that the analysis include a 7% discount rate applied to the 3% average SCC value to simplify comparison with benefits analyses from other programs which use a standard 7% discount rate. The 3% discount rate is recommended in the inter-agency guidance given its internal consistency with the 3% average SCC value and appropriateness for CO_2 inter-generational effects, but the 7% discount rate is also included given the additional guidance received.

The values in Table 4 reflect the global monetized impact of climate change. An earlier version of the guidance document from the Interagency Working Group on SCC [10] goes into some detail regarding the use of global versus U.S.-only SCC values. It makes the case that the climate change problem is highly unusual (compared to other regulatory or investment considerations) in at least two respects:

- "…First, it involves a global externality: emissions of most greenhouse gases contribute to damages around the world even when they are emitted in the United States. Consequently, to address the global nature of the problem, the SCC must incorporate the full (global) damages caused by greenhouse gas emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. Other countries would also need to take action to reduce emissions if significant changes in the global climate are to be avoided.… When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable." ([10] page 10–11)

Although use of the global SCC values are recommended in [10], and are the only values presented in the updated guidance in [9], this work also considered the effect on the monetized estimates of using U.S.-domestic SCC values for comparison. Guidance for determining U.S.-only SCC values is contained in [10] as follows:

- "… the development of a domestic SCC is greatly complicated by the relatively few region-or country-specific estimates of the SCC in the literature. One potential source of estimates comes from the FUND model. The resulting estimates suggest that the ratio of domestic to global benefits of emission reductions varies with key parameter assumptions. For example, with a 2.5 or 3 percent discount rate, the U.S. benefit is about 7–10 percent of the global benefit, on average, across the scenarios analyzed. Alternatively, if the fraction of GDP lost due to climate change is assumed to be similar across countries, the domestic benefit would be proportional to the U.S. share of global GDP, which is currently about 23 percent. *On the basis of this evidence, the interagency workgroup determined that a range of values from 7 to 23 percent should be used to adjust the global SCC to calculate domestic effects. Reported domestic values should use this range.* It is recognized that these values are approximate, provisional, and highly speculative.… If more accurate methods for calculating the domestic SCC become available, the Federal government will examine these to determine whether to update its approach." ([10] page 11, italicized text made in this excerpt for emphasis).

Based on this guidance, U.S.-only SCC values of 15% (the mid-point of the 7–23% recommended range from [10]) of the equivalent global SCC values from [9] were estimated: see Table 5.

Table 5

Estimated U.S.-Only Social Cost of CO_2 Values Using 15% Multiplier on Global Values ($/metric ton of CO_2 in 2007$) [9,10]

Year	Discount Rate			
	5% Average	3% Average	2.5% Average	3% 95th
2010	1.5	4.65	7.5	12.9
2015	1.65	5.4	8.4	15.75
2020	1.8	6.3	9.3	18.45
2025	2.1	6.9	10.2	20.7
2030	2.4	7.5	10.95	22.8
2035	2.7	8.25	11.7	25.2
2040	3.15	9	12.6	27.45
2045	3.45	9.6	13.35	29.55
2050	3.9	10.35	14.25	31.8

3.3 ESTIMATED CARBON DIOXIDE MONETIZED BENEFITS

The guidance from [9] detailed above was used in conjunction with the CO_2 savings estimates (from Figure 9) to monetize the climate benefits from TFDM taxi time reduction. Figure 11 presents the cumulative monetized CO_2 benefits as a function of year into the future and the recommended global SCC values and discount rates aggregated across all 27 analysis airports. The solid lines provide undiscounted results for each of the four SCC categories from Table 4 (using linear interpolation of provided values for intermediate years and inflation to a 2015 base year using 2015$=1.12807*2007$ consistent with FAA guidance [11]), while the dashed lines represent results after discounting at the rate consistent with the Social Cost of CO_2 value in line with the guidance in [9]. The dotted green line represents the results for the additional case of 3% average SCC with 7% discount rate requested by the FAA for consistency with other investment analysis activities.

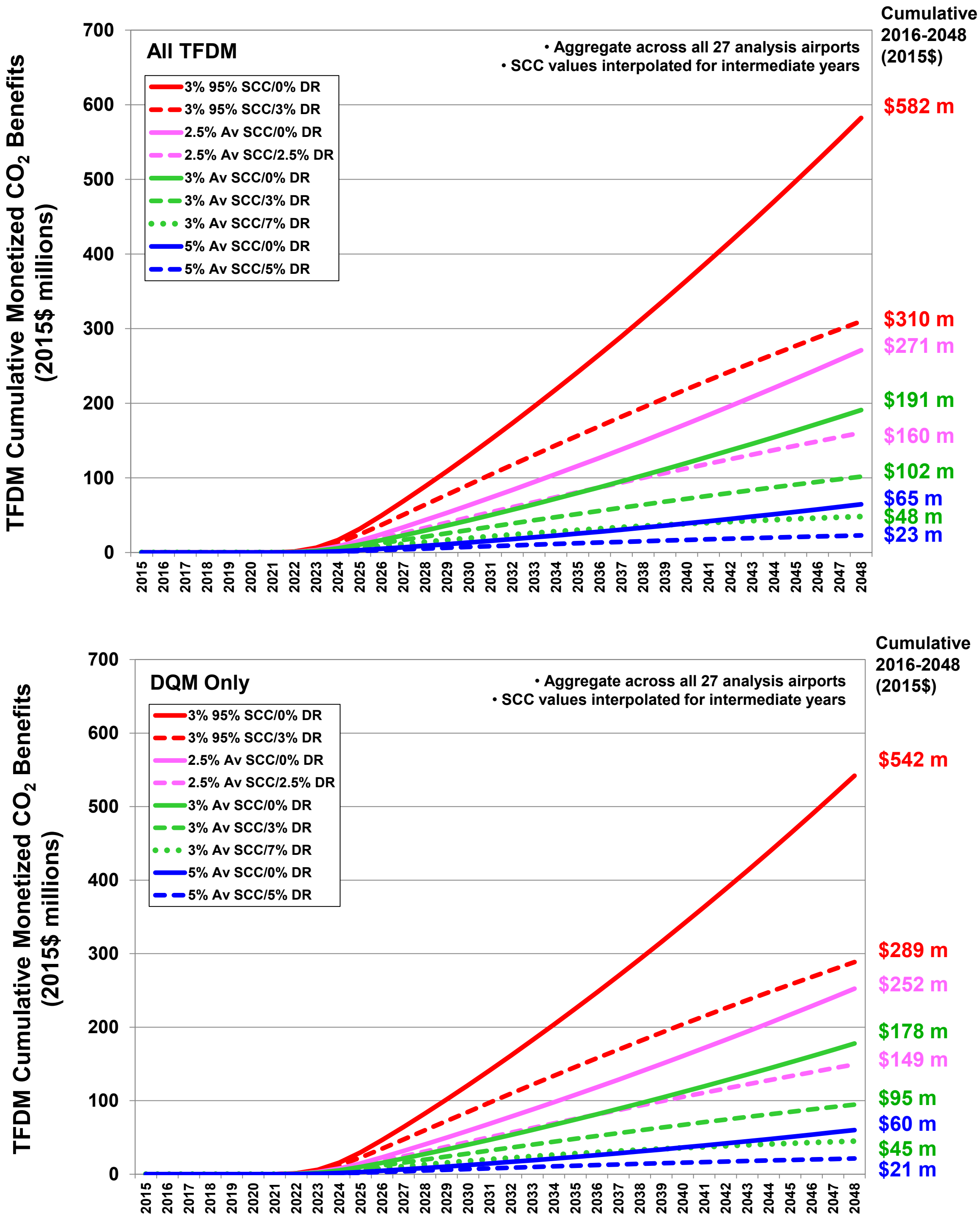


Figure 11. Estimated "All TFDM" and "DQM Only" monetized CO_2 benefits using global SCCs.

It is evident that the choice of Social Cost of CO_2 category makes an order of magnitude difference to the total cumulative benefits over the 2016–2048 timeframe, ranging from over $580 million for the 3% 95th percentile to $65 million for the 5% average value for the undiscounted “All TFDM” scenario. Discounting these values using rates consistent with the SCC further reduces the estimated benefits by 50–70%, producing a benefits range of $23 million to $310 million. The middle case of the 3% average SCCs result in estimated benefits of $191 million undiscounted, $102 million discounted at 3% and $48 million discounted at 7%. The difference between the “All TFDM” and “DQM Only” scenarios are small given DQM is the dominant benefit mechanism for fuel saving.

The equivalent results using the estimated U.S.-only SCCs from Table 5 are presented in Figure 12. All of the benefits are reduced by the 15% multiplier of global to U.S. domestic SCC values: the middle case now has estimated benefits of $29 million undiscounted and $16 million discounted at 3% for the “All TFDM” scenario.

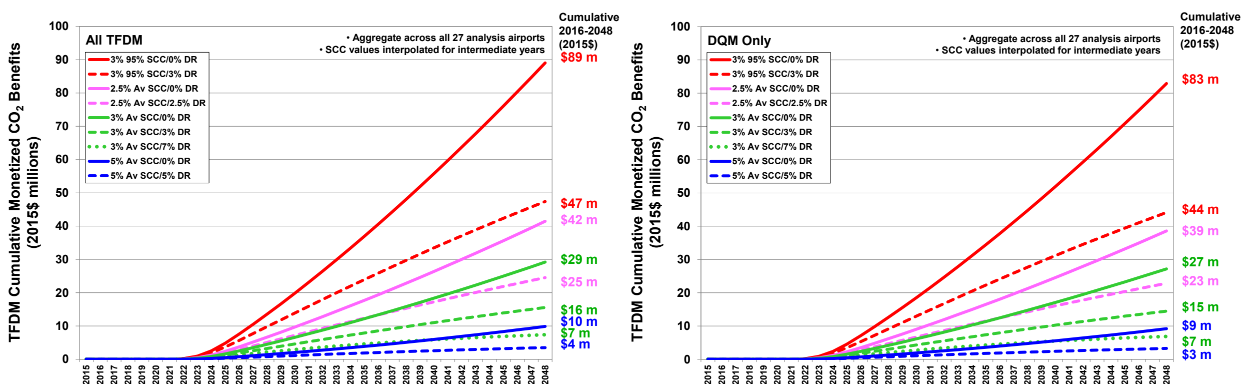


Figure 12. Estimated “All TFDM” and “DQM Only” monetized CO_2 benefits using U.S.-only SCCs.

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4. SUMMARY

This work has developed a methodology for estimating the monetized CO_2 benefits of TFDM-enabled shifting of taxi-out time delay from the taxi-ways with engines on to the gate or other designated location with engines off, thereby reducing fuel burn and emissions by the amounts estimated in Table 6.

Table 6

Summary Fuel and CO_2 Emissions Savings across 27 TFDM Analysis Airports, 2016–2048

Scenario	Total Fuel Reduction	Total CO_2 Reduction
All TFDM	954,000 metric tons, 313 million U.S. gallons	3.0 million metric tons
DQM Only	889,000 metric tons, 291 million U.S. gallons	2.8 million metric tons

This methodology was applied using official U.S. government inter-agency guidance using global and U.S. domestic Social Cost of CO_2 and recommended discount rates to monetize CO_2 benefits. The results are summarized in Table 7 below for both undiscounted and discounted cases. Significant monetized CO_2 benefits are seen to be enabled by deployment of TFDM at the analysis airports over the timeframe of interest. The grey highlighted results represent the "mid-case" estimates based on the "3% average" SCC value and 3% and 7% discounting. The 3% discount rate is recommended for consistency with the 3% SCC value and appropriateness for CO_2 inter-generational effects. The 7% discount rate is included for consistency with investment analyses for other programs.

Table 7

Summary Global CO_2 Monetized Benefits across 27 TFDM Analysis Airports, 2016–2048

	Undiscounted Monetized Benefit (2015$)				**Discounted Monetized Benefit (2015$)**				
Social Cost of CO_2	5% Av	3% Av	2.5% Av	3% 95th	5% Av	3% Av	3% Av	2.5% Av	3% 95th
Discount Rate	0%	0%	0%	0%	5%	7%	3%	2.5%	3%
All TFDM	$65m	$191m	$271m	$582m	$23m	$48m	$102m	$160m	$310m
DQM Only	$60m	$178m	$252m	$542m	$21m	$45m	$95m	$149m	$289m

An analogous approach is presented in Appendix A for monetizing air quality benefits from TFDM which turn out to be of similar magnitude to the CO_2 monetized benefits. Because there is no agreed federal guidance on monetizing air quality impacts, these results are presented for information only, but do suggest that there are significant additional environmental benefits from TFDM beyond those from CO_2 alone.

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APPENDIX A: TFDM AIR QUALITY BENEFITS ASSESSMENT

A.1 INTRODUCTION

Air quality impacts are generally harder to monetize because of their more complex generation and impact pathways. Unlike CO_2, which is globally mixed and has a well-understood relationship to fuel burn and impact on global temperature changes, air quality pollutants vary by engine and atmospheric conditions, impact on a regional scale over short timeframes and with more complex impact pathways over longer timeframes. The primary monetizable impact is via premature mortality (death) and morbidity (disease) health endpoints, especially from human exposure to Particulate Matter (PM), nitrogen oxides (NOx), sulphur oxides (SOx), unburned hydrocarbons, ozone and carbon monoxide [2]. Therefore, air quality impacts also vary strongly with local population densities and climatological conditions. Because of these complexities, there is no regulatory guidance on monetizing their effects as there is for CO_2. However, peer-reviewed journal publications, e.g., [12] have developed air quality damage functions which allow a similar methodology to be used as for the climate assessment in the previous section. These approaches are considered appropriate for larger scale aggregate analysis which remove some of the sensitivities to local issues associated with more airport-specific analyses. Although there is less consensus on the specific damage function values to use for air quality impacts, it is instructive to use the literature values to assess their order of magnitude impact relative to the climate case.

A.2 AIR QUALITY DAMAGE FUNCTIONS AND DISCOUNTING

The damage functions recommended in [12] are based on model runs of the Aviation environmental Portfolio Management Tool-Impacts (APMT-Impacts) which has been developed as part of a large research initiative by the FAA Office of Environment and Energy, National Aeronautics and Space Administration (NASA) and Transport Canada, as described in [13]. The APMT-Impacts Air Quality Module evaluates surface air quality impacts of aviation focusing on aircraft PM2.5 (PM having a diameter of 2.5 µm or less) including both direct emissions of non-volatile PM and secondary particulate matter formed from NOx and SOx emissions. It uses a surrogate model derived from a more complex chemical transport model to calculate changes in ambient PM2.5 concentration, thus accelerating the assessment process and enabling propagation of uncertainties using Monte Carlo analyses. Changes in population exposure are computed by multiplying the estimated changes in PM2.5 concentration by the affected population. Changes to population exposure are related to changes in health endpoints by means of Concentration Response Functions (CRFs) derived from epidemiological studies. Health impacts are monetized using the U.S. Department of Transportation-recommended Value of a Statistical Life (VSL) of $6.3 million with a standard deviation of $2.8 million, as well as willingness-to-pay (WTP) and cost-of-illness (COI) estimates from the literature.

The resulting air quality damage costs per metric ton of fuel burnt below 3000 ft above ground level are shown in Table 8. The different “lens” values reflect the range of values taken by key analysis variables (e.g., population growth, VSL growth, fuel burn, etc.) in an internally consistent way, with the “low lens” reflecting low environmental impact assumptions, the “mid lens” reflecting the nominal case, and the “high lens” reflecting a worst case environmental impact.

Table 8

Air Quality Damage Functions ($/metric ton of fuel in 2006$) [12]

	Low Lens	Mid Lens	High Lens
Total Fuel	29	230	1226

Given that these impacts are being monetized for future years, it is again necessary to apply discount rates, and [12] recommends that similar discount rates as for climate impacts are also used for the air quality analysis. Note that air quality damage costs are not provided for future years, and care needs to be exercised in their use due to this, to both reflect changes in perceived importance of air quality impacts, as well as background atmospheric changes which can modify the impacts of different pollution species. But for this analysis, constant air quality damage functions are used for all years.

A.3 ESTIMATED AIR QUALITY MONETIZED BENEFITS

The guidance from [12] was used in conjunction with the fuel savings estimates (from Figure 9) to monetize the air quality benefits from TFDM taxi time reduction. Figure 13 presents the cumulative monetized air quality benefits as a function of year into the future and the recommended air quality damage functions aggregated across all 27 analysis airports for the “All TFDM” scenario. As before, the solid lines provide undiscounted results for each of the damage function values from Table 8 (inflated to a 2015 base year using a 2015$=1.18*2006$ [11]), while the dashed lines represent results after discounting at the rates used previously in the climate analysis (with 5% used for the low lens, 3% used for the mid lens and 2.5% used for the high lens) in line with the guidance in [12].

The range of estimates for the air quality monetized benefits is even larger than for CO_2, ranging from a cumulative value of over $1.3 billion for the high lens undiscounted case (corresponding to biggest impact of air quality emissions and hence highest value of reducing those emissions) to $33 million for the low lens undiscounted. Discounting these values using rates consistent with the climate assessment reduces the estimated benefits by 50–70% as expected, producing a benefits range of $12 million to $831 million for the 2016–2048 period. Cumulative mid-case estimates are $259 million undiscounted, $142 million with a 3% discount rate and $69 million if a 7% discount rate is applied.

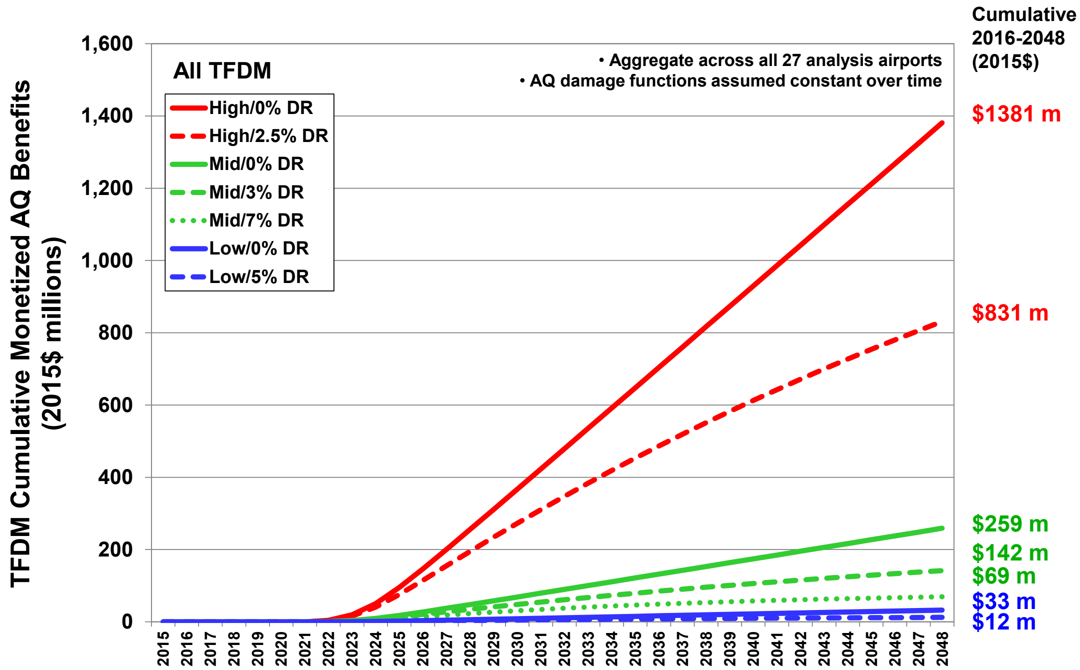

Figure 13. Estimated "All TFDM" cumulative monetized air quality benefits.

The results above reflect the monetized air quality benefits across all 27 of the analysis airports. Some of those airports are located inside designated "non-attainment areas." These are areas where air pollution levels of certain critical emissions species persistently exceed the National Ambient Air Quality Standards (NAAQS) as defined by the Clean Air Act [14]. Non-attainment areas must have and implement a plan to meet the relevant NAAQS for the violating pollutant, or risk losing some forms of federal financial assistance. Small particulate matter (PM2.5) and ozone (O_3) are the primary NAAQS pollutants of interest for this analysis: PM2.5 is the primary pollutant associated with premature mortality from adverse air quality, while O_3 has morbidity (disease-inducing) effects through lung function impairment and lowering resistance to respiratory infections [2]. Current NAAQS require concentrations of PM2.5 remain below 12 μg/m^3 for a three-year annual average, and below 35 μg/m^3 in any 24 hour period, and O_3 concentrations remain below 0.075 ppm for the annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years [14]. Figure 14 shows the PM2.5 and O_3 non-attainment areas as of 1/30/15, as well as the TFDM analysis airports located within these areas. Because these airports are inside non-attainment areas, they are in regions which are especially sensitive to air quality impacts and therefore air quality benefits from TFDM would be especially important. Figure 15 presents the cumulative monetized air quality benefits for the airports within PM2.5 or O_3 (the superset of the airports shown in Figure 14) and PM2.5 only non-attainment areas as a function of time.

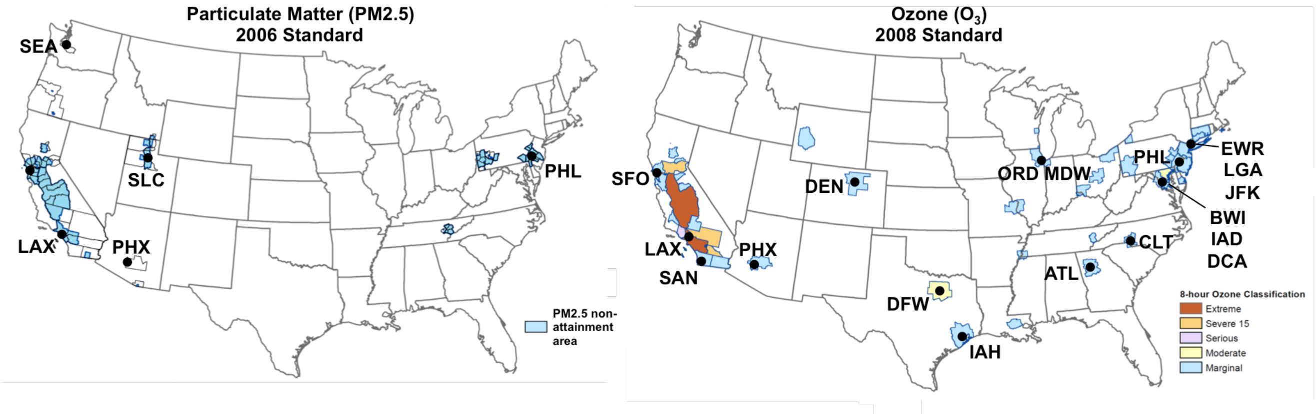

Figure 14. PM2.5 and O_3 non-attainment areas as of 1/30/2015 (adapted from [14]).

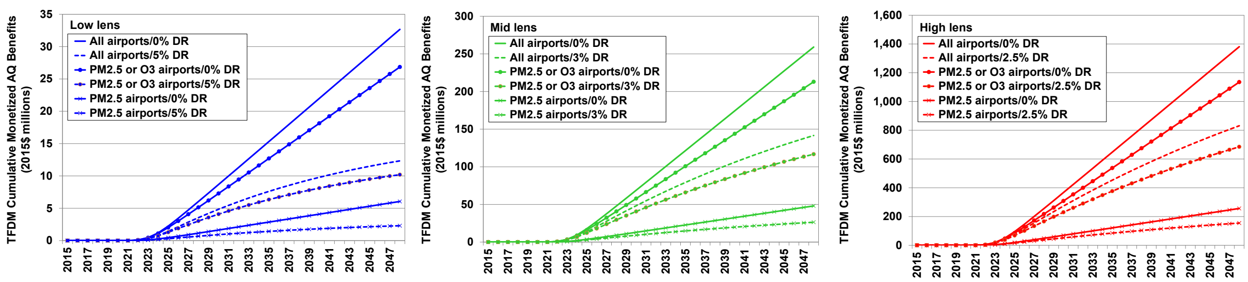

Figure 15. Estimated "All TFDM" monetized air quality benefits for non-attainment airports (note very different y-axis scales)

Table 9 presents the cumulative values at the end of the 2016–2048 time period for the "All TFDM" scenario. Approximately 80% of the total monetized air quality benefits are seen at airports within either O_3 or PM2.5 non-attainment areas, while approximately 20% of the total benefits are seen at airport within PM2.5 only non-attainment areas.

Table 9

Summary "All TFDM" Air Quality Monetized Benefits Estimates across 27 Analysis Airport, 2016–2048

	Undiscounted Monetized Benefit (2015$)			Discounted Monetized Benefit (2015$)			
Lens	Low	Mid	High	Low	Mid	Mid	High
Discount Rate	0%	0%	0%	5%	7%	3%	2.5%
All Analysis Airports	$33 m	$259 m	$1381 m	$12 m	$69 m	$142 m	$831 m
PM2.5 or O_3 Non-Attainment Area Airports	$27 m	$213 m	$1135 m	$10 m	$57 m	$117 m	$685 m
PM2.5 Non-Attainment Area Airports	$6 m	$48 m	$256 m	$2 m	$13 m	$26 m	$154 m

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GLOSSARY

ADOC	Aircraft Direct Operating Cost
AEDT	Aviation Environmental Design Tool
APMT	Aviation environmental Portfolio Management Tool-Impacts
ATL	Hartsfield-Jackson Atlanta International Airport
CFR	Call For Release
CO_2	Carbon Dioxide
COI	Cost-of-Illness
CRFs	Concentration Response Functions
DFW	Dallas/Fort Worth International Airport
DQM	Departure Queue Management
EI	Emissions Index
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FID	Final Investment Decision
IARD	Investment Analysis Readiness Decision
IID	Initial Investment Decision
INM	Integrated Noise Model
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
LGA	LaGuardia Airport
MIA	Miami International Airport
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NDI	Noise Depreciation Index
NOx	Nitrogen Oxides
O_3	Ozone
ORD	Chicago O'Hare International Airport
PHL	Philadelphia International Airport
PM	Particulate Matter
RF	Radiative Forcing
SCC	Social Cost of Carbon Dioxide
SFO	San Francisco International Airport
SOx	Sulphur Oxides
TAF	Terminal Area Forecast
TFDM	Terminal Flight Data Manager
VSL	Value of a Statistical Life
WTP	Willingness-to-Pay

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