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Foreign Object Debris Detection System Cost-Benefit Analysis

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16. Abstract

Foreign object debris (FOD) poses significant safety and financial threats to aviation. Estimates of the annual global costs of FOD range up to $22.7 billion in current United States dollars. The Federal Aviation Administration (FAA) recognizes that airport FOD detection systems can help reduce FOD risks. The FAA Airport Technology Research and Development Branch research team reviewed a recent cost-benefit analysis (CBA) of such systems. Inputs to this analysis included stakeholder interviews, literature review, safety and operational databases, and airport FOD detection records.

The research team created six CBA models with varied component cost models for underlying expenses. All six models showed a net financial benefit and break-even within 1–9 years. With only modest estimates for indirect cost (1x direct costs) and a partial estimate for fringe costs, CBA showed a benefit of $15.4 million and a break-even in Year 3.

This report discusses related issues, including fringe benefits, cost-sharing structure between stakeholders, and tailoring of these results to individual airports.

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LIST OF ACRONYMS AND ABBREVIATIONS

A-SMGCS	Advanced Surface Movement Guidance and Control System
AC	Advisory circular
AGL	Above ground level
ASRS	Aviation Safety Reporting System
ATA	Air Transport Association of America
B	Billion
B/C	Benefit/cost
B/D	Discounted benefit
Bdc	Cumulative discounted benefit
BOS	Boston Logan International Airport
BTS	Bureau of Transportation Statistics
C	cost
CBA	Cost benefit analysis (a.k.a. benefit cost analysis)
Cdc	Cumulative discounted cost
COVID-19	Coronavirus disease 2019
CPI	Consumer Price Index
DOT	U.S. Department of Transportation
FA	Financial analysis
FAA	Federal Aviation Administration
FBO	Fixed-base operator
FOD	Foreign object debris
FODDS	Foreign object debris detection system
IATA	International Air Traffic Association
K	Thousand
LCCA	Life-cycle cost analysis
LHR	Heathrow Airport
M	Million
MAIS	Maximum Abbreviated Injury Scale
MCAS Yuma	Marine Corps Air Station Yuma
mph	miles per hour
MTBF	Mean time between failure
MTBO	Mean time between outage
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NPV	Net present value
NTSB	National Transportation Safety Board
NYL	MCAS Yuma/Yuma International Airport
OGG	Kahului Airport
OMB	Office of Management and Budget
ORD	O’Hare International Airport
PV	Present value
QALY	Quality of life years
ROI	Return on investment
SA	Sensitivity analysis

SEA	Seattle-Tacoma International Airport
USDA	U.S. Department of Agriculture
USN	U.S. Navy
VSL	Value of statistical life
VTT	Value of travel time
YVR	Vancouver International Airport

EXECUTIVE SUMMARY

Foreign object debris (FOD) poses significant safety and financial threats to aviation. Estimates of the annual global costs of FOD range up to $22.7 billion in current United States dollars. Beyond the direct costs of FOD damage (e.g., destroyed tires, damaged engines) are the indirect or secondary costs (e.g., delays and cancellations). By some estimates, these indirect costs can run 10–12 times higher than direct costs.

The Federal Aviation Administration (FAA) recognizes that airport FOD detection systems can help reduce FOD risks. The FAA Airport Technology Research and Development Branch research team reviewed a recent cost-benefit analysis (CBA) of such systems. This analysis centered on a bottom-up, objective, and traceable comparison of the associated direct and indirect costs and benefits. Inputs to this analysis included stakeholder interviews (with airports, airlines, and system manufacturers), literature review, and database analysis. Additionally, airport FOD detection data were analyzed to help validate base rate assumptions for the current CBA modeling.

Researchers created six CBA models with varied component cost models for underlying expenses. Analysis showed that, even with the most conservative projections (intentionally disregarding, for example, personal injury and passenger delay impacts), such systems can be expected to provide a financial benefit over the return-on-investment horizon, which was based on a lifecycle estimate of 12 years.

The most conservative (direct benefits only) CBA model showed a $2.1 million (M) net benefit and an investment break-even by Year 9 of 12. With modest estimates for indirect costs (1x direct costs) and a partial estimate for fringe costs, CBA showed a benefit of $15.4M, and break-even by Year 3.

Several related lessons can be taken from this work. First, FOD damage costs are not borne equally across airports or airlines. Second, fuller consideration should be made of potential fringe benefits such systems can provide, for example in terms of wildlife management, security monitoring, and incident recording. Finally, the results of this CBA will need to be tailored to specific airports. This can be done via simple mathematical adjustment of assumed traffic parameters and site-specific assessment of FOD risk profile and fringe benefits.

1. INTRODUCTION

1.1 SCOPE OF THE FOREIGN OBJECT DEBRIS PROBLEM

Foreign object debris (FOD) is an ongoing concern at United States (U.S.) airports. FOD poses significant safety and financial threats to aviation, especially during critical phases of flight such as takeoff and landing rollout. For example, the July 25, 2000, crash of Air France 4950 was triggered by a runway FOD strike on takeoff, which resulted in the loss of 113 lives (Gamauf, 2010).

The annual global costs of FOD to the aviation community have been estimated at up to $19 billion (B) {$22.7B}[1] U.S. dollars[2] (Fechushak, 2010). Other estimates place the total cost at $4B {$6.4B} globally (Bachtel, 1998), with $504 million (M) {$601M} at the top 10 U.S. airports (McCreary, 2010) and $35M {$44M} for a single U.S. air carrier, Delta Air Lines (Patterson, 2007). Sides (2020) recently calculated total FOD costs at top 10 U.S. airports, as shown in Table 1.

Table 1. Total Annual FOD Costs at Top 10 U.S. Airports (source: Sides, 2020)

Airport	Annual FOD Cost
Hartsfield-Jackson Atlanta International Airport (ATL)	{$58M}
O'Hare International Airport (ORD)	{$58M}
Los Angeles International Airport (LAX)	{$43M}
Dallas Fort Worth International Airport (DFW)	{$42M}
Denver International Airport (DEN)	{$38M}
John F. Kennedy International Airport (JFK)	{$29M}
San Francisco International Airport (SFO)	{$29M}
Seattle-Tacoma International Airport (SEA)	{$28M}
McCarran International Airport (LAS)	{$24M}
Orlando International Airport (MCO)	{$21M}

McCreary (2008) reported that a single U.S. air carrier at a single airport (both were anonymous) experienced a total of 117 FOD engine strikes in a single year, an average of 1 every 3 days. These strikes resulted in 57 technical inspections (e.g., involving engine borescope, fluorescent dye, eddy check), and replacement of 65 fan blade pairs.

1.2 DIRECT AND INDIRECT FOD COSTS

Beyond the direct costs of FOD (primarily tire and engine damage to aircraft [McCreary, 2010]) are potential indirect costs such as passenger delays, personnel overtime, and aircraft reroutes. Between them, Flight Safety Foundation (1994) and McCreary (2008) identified more than 50 potential indirect costs, including the following:

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[1] Throughout this report, {braces} indicate inflation-corrected 2020 values, using www.usinflationcalculator.com

[2] Unless otherwise stated, all currency figures in this report are U.S. dollars.

- Airport efficiency losses
- Carbon/environmental issues
- Change of aircraft
- Airport closure
- Runway closure
- Criminal liability
- Cost of corrective action
- Cost of hiring and training replacement
- Rental or lease of replacement equipment
- Restoration of order
- Investigation costs
- Airborne delays
- Schedule disruption
- Gate delays
- Fines and citations
- Fuel efficiency losses
- Hotels
- Go arounds
- Increased insurance premiums
- Insurance deductibles
- Legal fees
- Excess liability claims
- Loss of business/damage to reputation
- Lost time and overtime
- Missed connections

Delays and cancellations seem the root cause of most indirect FOD damage costs. As one of the airlines reported in a data collection interview, if the airline has to cancel their last departure of the day out of Kahului Airport (OGG) in Maui, total costs can easily reach $30,000 including crew, accommodation, meal vouchers, rebooking, onboard (re)catering, and other secondary costs related to the direct FOD damage.

As discussed in Section 2, estimates of indirect FOD costs vary widely. The highest estimate seems to be that of McCreary (2008), who proposed a 10x–12x multiplier for indirect FOD costs. If accurate, this would drive the 3 thousand (K)-dollar parts-and-labor costs of a B737 tire change to $33K–$39K, including indirect costs.

1.3 POTENTIAL SOLUTIONS

Recent automation advances have greatly enhanced the capabilities of airport surface FOD detection equipment. There are several available systems that enable continuous FOD monitoring and detection on runway and other aircraft movement surfaces. The Federal Aviation Administration (FAA) recognizes that FOD hazards can possibly be reduced through the effective deployment of such systems and associated management programs. FAA Advisory Circular (AC) 150/5210-24 (FAA, 2010a) provides guidance for developing and managing an airport FOD program and outlines specifications for FOD removal operations and equipment.

1.4 AIMS OF THE CURRENT ANALYSIS

The main objective of the current work was to conduct a cost-benefit analysis (CBA) of airport FOD detection systems (FODDSs). As discussed in Section 2, the FAA Airport Technology Research and Development Branch research team's analysis was aimed at evaluating generic FODDS capability, not any system in particular. There are a few manufacturers of such systems that use different technologies.

1.5 STRUCTURE OF THIS REPORT

Section 2 covers the methods used in this analysis, including data sources and data collection and analysis procedures. Section 3 covers the results of CBA and highlights various CBA models, which were built up through literature review and extracted operational and safety data and based on different underlying quantitative assumptions. Section 4 presents the conclusions of this analysis, including discussion around lessons learned and remaining knowledge gaps in the literature on FOD damage costs and their mitigation. Finally, appendices A–C present the following, respectively:

- Data collection materials, including worksheets and interview guides
- Analysis details of wildlife strike data from FAA databases
- Literature review summary findings with reference citations

2. METHOD

This section reviews the approach the research team used to conduct the CBA, including the assumptions made. This review covers the participating stakeholders, data sources, and procedures used for data collection and analysis.

This approach rests on four main assumptions, as follows:

- Documented, objective cost estimation—As noted, estimates of FOD strike costs vary widely. Estimates of indirect FOD costs seem especially non-robust. On the basis of literature review, the research team adopted a conservative, building-block approach to deriving cost estimates and prioritized empirical operational and safety data where available. This meant, in the first instance, disregarding the widely quoted 10x–12x indirect multiplier of McCreary (2008).

- Broad stakeholder group—Based on preliminary literature review, airlines (and other aircraft operators) appear to be in the best position to estimate the direct and indirect costs of FOD damage. The stakeholder group, therefore, included airports, FODDS manufacturers, and airlines.

- System-agnostic evaluation—Technical comparison of FODDSs was beyond the scope of this task. This analysis was intended to be system-agnostic and not a comparison of specific FODDSs.

- Use of a standardized airport metric—FOD costs are generally expressed on a per-operation basis and are often scaled up to an annualized airport cost. To permit meaningful comparison, a standardized airport metric of 440,000 operations a year was adopted, based on the 2019 mean of Core 30 operations (FAA, 2020). Derived costs can be tailored to a given airport by simple multiplication.

2.1 COST-BENEFIT ANALYSIS METHODOLOGY

The FAA's main guidance on conducting CBA (FAA, 1999) is now more than 20 years old, although summary economic values and partial updates have been issued in the interim (GRA, 2007; FAA, 2010b).

CBA is straightforward in principle, if not always in practice (Landau & Weisbrod, 2009). Initial and ongoing costs of an investment are summed to arrive at a total cost (*C*) over a specified return-on-investment (ROI) horizon. Total benefits (*B*, expressed as costs saved over the same horizon) are also summed. A benefit-to-cost ratio is then derived. Figure 1 depicts weighing benefits against costs. If the ratio is above 1.0, benefits outweigh costs (Boardman et al., 2017). This approach is an accepted one and is required for certain categories of FAA capital projects above $10M (GRA, 2007; FAA, 2010b).

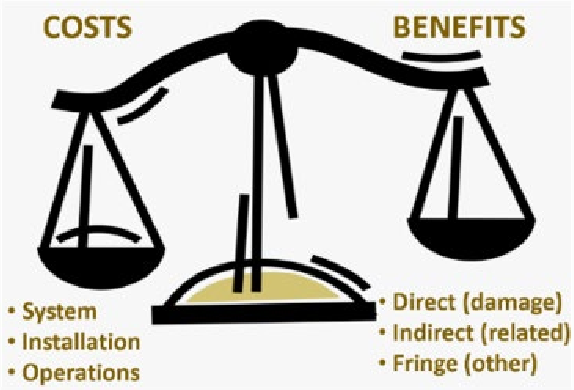

Figure 1. Weighing Costs and Benefits of FODDSs

2.1.1 Cost-Benefit Analysis vs Financial Analysis

The FAA's primary document on airport CBA distinguishes CBA from *financial analysis* (FA) (FAA, 1999). In many public investments, costs are borne by one party, but benefits accrue to another. Note that CBA focuses on the net social benefit, or social ROI, regardless of who pays and who benefits (Landau & Weisbrod, 2009). FA, however, considers only the costs and benefits accruing to the investor. Assessing the cost-benefit ratio of FODDS, only as it impacts airports, therefore implies the use of FA.

As a first step, the research team used a CBA approach to assess the total cost-benefit ratio (i.e., regardless of who pays and who profits). If there are no total benefits, there can be no individual benefits. If total benefits are shown, then FA can proceed. The FA ratio can differ by airport because factors like fee structure (can landing fees be adjusted?) and possible fringe benefits (does the system provide, for example, wildlife management savings?) are context-specific. Transferring these CBA results to an airport-specific FA can be done on a case-by-case basis, in view of that airport's specific cost and operational considerations.

Other methods related to CBA and FA (Discounting, 2009) include the following:

- *Cost-effectiveness analysis*—Rates or ranks competing solutions when financial benefits cannot be accurately estimated, or benefits cannot be expressed in monetary terms.

- *Life-cycle cost analysis* (LCCA)—Identifies the cost of investment options aimed at achieving a predefined objective.

2.1.2 Return on Investment Horizon

If an investment yields benefits, these benefits pay out over time. CBA assesses whether investment returns over a given period of time outweigh the total (initial and ongoing) costs over that same period. This period can be referred to as the ROI horizon, and, in the case of a FODDS, this is linked to the assumed lifecycle of the system. It is reasonable to assume that system lifecycle, and the decision to upgrade, would be driven by at least two factors:

- Technological advancement—If a system upgrade could provide markedly improved FODDS performance (e.g., lower cost, better detection, additional benefits), the operator would be motivated to invest in a system upgrade.

- System reliability degradation—If a system has become too unreliable and costly to maintain, or components are nearing the end of their useful life, the operator would also be motivated to consider system replacement.

Although technological advancement is difficult to predict, system reliability can already be estimated. One of the primary FODSS manufacturers, for example, claims a field-demonstrated mean time between failure (MTBF) of more than 100,000 hours for their system. This results in a component failure, under continuous operation, every 11 or more years. Given that such component failures do not necessarily cause system shutdown, the mean time between outage (MTBO) is higher still. Based on manufacturer operational experience (see Section 3.1.3), a system life expectancy of 12 years was selected as the ROI horizon. Analysis then addressed whether total benefits over this 12-year period would be expected to exceed total costs over the same period.

2.1.3 Inflation Correction and Related Assumptions

Literature and data on FOD damage costs now go back more than 20 years. As a result, some of the cited figures are due for inflation correction. Again, this report presents both the originally cited figure and inflation-corrected figure to 2020 using {brace} notation:

cited \$ figure {2020 \$ figure}

These literature review citations are straight Consumer Price Index (CPI) adjustments to 2020. Later, in calculating weighted CBA equations, outyear cost and benefit adjustments are based on a historical 2010–2019 CPI average of 1.77%.

Apart from inflation correction, there are potential confounds in extrapolating historical damage costs. Possible changes in the underlying event frequency (e.g., tires might be less damage-prone than 20 years ago) or unit costs (tire costs, in real dollars, might vary in the future) could complicate this analysis. For this reason, CBA often concludes with a tweaking of assumptions about underlying cost estimates. This is the role of sensitivity analysis (SA), as discussed in Section 2.1.7.

2.1.4 Discount Rate and Net Present Value Assumptions

For projects that span years, benefits accrue over time. Projecting cost-benefit ratios into the future, however, requires an additional adjustment. CBA generally does not use straight inflation correction for forward-projected benefits because this introduces uncertainty (Discounting, 2020). Even with inflation corrections, it is improper to compare 2020-dollar costs with, for example, 2030-dollar benefits. CBA needs an additional mechanism to assess the value of future money in currently relevant units. The *discount rate* provides this mechanism. Discount rate reflects the adjustment used to determine the present value of future money.

This discount rate adjustment has the effect of capturing present value (PV) as a decreasing marginal benefit with time, as compared to a straight inflation correction. The higher the discount rate, the lower the inflation-adjusted future cost or benefit. This helps determine whether the total monetary benefits of an investment will be worth more than the total investment cost. Again, using a high discount rate decreases (or “discounts”) the calculated benefit in outyears.

Assessing benefits over some future horizon relies on calculating the net present value (NPV) as the difference between discounted benefits and discounted costs over time

$$NPV = \frac{B_0 - C_0}{(1+i)^0} + \frac{B_1 - C_1}{(1+i)^1} \cdots + \frac{B_t - C_t}{(1+i)^t}$$

where t=year, B=benefits, C=costs, and i=discount rate.

2.1.5 An Example CBA

Table 2 and Figure 2 present the results of a hypothetical CBA calculation. Assume an investment with an initial cost of $1,000, ongoing costs of $100 per year, ROI horizon of 10 years, and estimated benefits of $300 per year. These ongoing costs and benefits each have an inflation correction of 2% per year. Benefits are, in effect, costs saved. The tire that would otherwise have been destroyed in 2024 would have cost more than the same tire in 2020. Discount rate is set to 4% for this example. The Office of Management and Budget (OMB, 2019) currently recommends a discount rate of 0.0% for Federal investment decisions with a 10-year ROI horizon. That is, the OMB currently recommends no discount adjustment.

The results of CBA can be expressed in a few useful ways:

- **Benefit/cost (B/C) ratio**—The ratio of total benefit to total cost. In the example of Table 2, both are discounted. A B/C ratio greater than 1.0 indicates a net financial benefit. In this example, the B/C ratio (expressed as cumulative discounted benefit divided by cumulative discounted cost) is $2,647.37/$1,843.99 = 1.44, a net gain over the 10 years.

- **NPV**—The sum of discounted net annual benefits. Whereas B/C shows direction (is there a net benefit or loss?), NPV quantifies the benefit or loss, in net dollars over the ROI horizon. In this case, NPV is $803.37—again, a net gain over the 10 years.

- **Break-even point**—If a positive benefit is shown, at what point in the ROI horizon do benefits first exceed costs? In the current example, this occurs by year 6 when cumulative discounted benefit (Bdc) first exceeds cumulative discounted cost (Cdc). Break-even is graphed as the intersection of the net cumulative cost line and the net cumulative benefit line, as shown in Figure 2.

Table 2. Hypothetical CBA Calculation (figures rounded to the nearest whole dollar)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
C: Cost (2% inflation)	$1,100	$102	$104	$106	$108	$110	$113	$115	$117	$120
B: Benefit (2% inflation)	$300	$306	$312	$318	$325	$331	$338	$345	$351	$359
B/C: Benefit-cost	-$800	$204	$208	$212	$216	$221	$225	$230	$234	$239
D: Discount factor (4%)	1.04	1.08	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.48
Cd: Discounted cost (C/D)	$1,058	$94	$92	$91	$89	$87	$86	$84	$82	$81
Cdc: Cumulative discounted cost	$1,058	$1,152	$1,244	$1,335	$1,424	$1,511	$1,597	$1,681	$1,763	$1,844
Bd: Discounted benefit (B/D)	$288	$283	$277	$272	$267	$262	$257	$252	$247	$242
Bdc: Cumulative discounted benefit	$288	$571	$849	$1,121	$1,388	$1,650	$1,906	$2,158	$2,405	$2,647
NBd: Discounted net benefit (Bd-Cd)	-$769	$189	$185	$181	$178	$175	$171	$168	$165	$161
NPV: Cumulative NBd	-$769	-$581	-$396	-$214	-$36	$138	$309	$477	$642	$803

The results of Table 2 are shown graphically in Figure 2.

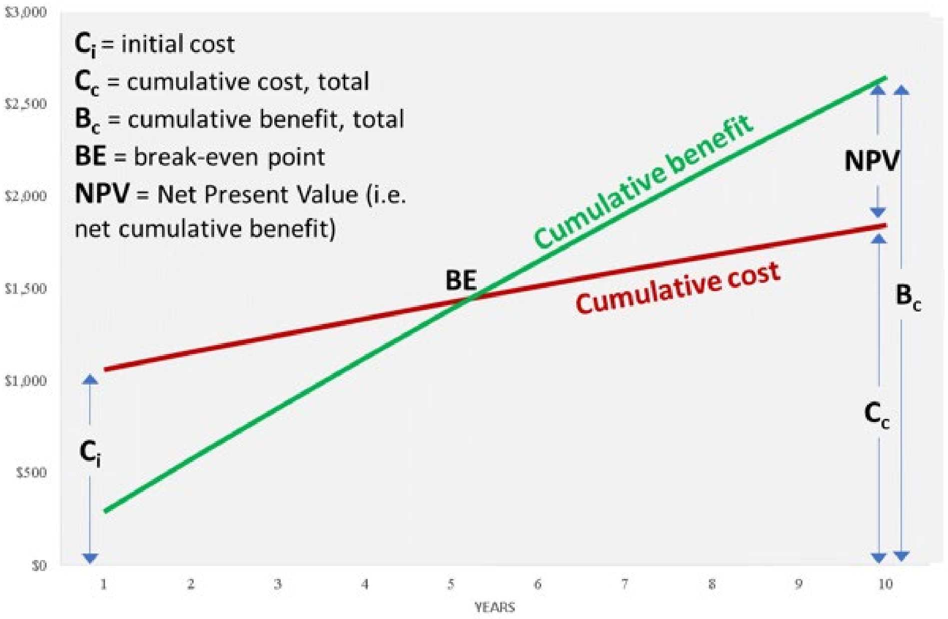

Figure 2. Graphical Example of CBA

2.1.6 Value of Statistical Life

CBA can sometimes reveal offsetting negative effects. For instance, the early CBA of setting the U.S. interstate highway speed limit at 55 miles per hour (mph) concluded (based on time series data for 1952–1979) that lowering the speed limit an average of about 5 mph would save 7,466 lives annually (Forester, McNown, & Singell, 1984). However, as a result, drivers would spend more time on the road, somewhat offsetting estimated benefits. Increased exposure by itself, along with a likely increase in fatigue- and frustration-related crashes, would increase fatalities. This forced the government into an enormous undertaking: assigning a monetary value to lives saved and determining the Value of Statistical Life (VSL)[3].

Valuating human life is challenging (Viscusi, 2000). The U.S. Department of Transportation (DOT) (2015) standardizes nonfatal injury costs proportional to VSL, using the Maximum Abbreviated Injury Scale (MAIS). The values of Table 3 refer to the highest-level injury, in cases where a victim suffers multiple injuries.

On the basis of both literature review and stakeholder interview, it seems that data on FOD-related injury and death are not robust enough to permit meaningful analysis. Analysis, therefore, is limited to damage-related costs.

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[3] Many now prefer the Quality Adjusted Life Year (QALY) metric over VSL.

Table 3. Department of Transportation Cost Estimates for MAIS Grade Injuries
(U.S. DOT, 2015)

MAIS Level	Severity	Fraction of VSL	Cost 2015 {2020}
1	Minor	0.003	$28K {$31K}
2	Moderate	0.047	$440K {$483K}
3	Serious	0.105	$1.0M {$1.1M}
4	Severe	0.266	$2.5M {$2.7M}
5	Critical	0.593	$5.6M {$6.2M}
6	Death	1.000	$9.4M {$10.3M}

2.1.7 Sensitivity Analysis

SA is an important final step in CBA (Boardman et al., 2017; Landau & Weisbrod, 2009; FAA, 1999). SA is a process of tweaking individual cost assumptions to determine their joint impact on the calculated B/C ratio. For example, if the cost of tires is assumed to be lower, the B/C ratio of a FODDS (everything else equal) would be lower. SA is especially useful when cost estimates vary widely for one or more elements. Individually adjusting the cost element estimates allows the user to perform "what-if" evaluations of the final B/C ratio, and tailor results to a specific context.

2.2 DATA SOURCES

Data sources included the following:

- Historical airport FOD data—FOD data collection logs were obtained from Boston Logan International Airport (BOS) and SEA airports for the period after FODDS installation in 2013 and 2015, respectively.
- Written surveys—Based on preliminary review, separate questionnaires were developed for airports, airlines, and manufacturers.
- Interview sessions—Videoconference interview sessions were held with a number of stakeholders among the airline-, airport-, and FODDS-manufacturer communities, as shown in Table 4.
- Academic and operational literature—Keyword searches were used to drive literature review into FOD types and criticalities, damage costs, CBA methods, airport investment calculations, airline financial and operational data, and other areas.
- Statistical databases—Several statistical databases were referenced as data sources, including the following:
  - Bureau of Transportation Statistics (BTS) T100 Market and Segment data
  - National Transportation Safety Board (NTSB) accident/incident database
  - National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) database
  - FAA wildlife strike database

- International Air Traffic Association (IATA) incident data exchange (IDX), flight data exchange (FDX), and accident data exchange (ADX)
- FAA operations and performance data, including
  - Aviation System Performance Metrics (ASPM)
  - Airline Service Quality Performance (ASQP)
  - Operations Systems Network (OPSNET)
  - Traffic Flow Management System Counts (TFMSC)
- International databases from EUROCONTROL and the Australian Transport Safety Bureau (ATSB)

As shown in Table 4, different stakeholders bring different perspectives on the costs of FOD strike damage. In terms of system hardware, manufacturers have the best information on list- and discount-system price. Airports are a fairly good secondary source of information on system costs, but a given airport might have negotiated an unrepresentative price. Initial costs also include the costs of installation, and individual airports have the best view on actual installation costs, as these can vary by airport. Similarly, manufacturers have a good overview of ongoing maintenance costs (especially as some are going to a fixed-price subscription model for maintenance support), but the airports have the most accurate view of total operational costs.

In terms of FOD strike damage costs, the airlines are the best source of information.[4] Airports have a fairly good view of FOD strike frequency, but not all strikes are reported to the airport (airlines often discover FOD strike damage after the fact and cannot always link damage to a specific airport). Moreover, all interviewed airlines reported that they had never made a damage claim against an airport. As discussed in Section 3, these costs are generally handled internally at the airlines. Two airlines reported that high insurance deductibles mean that FOD damage claims are almost never submitted to an insurer. For this reason, insurance carriers were specifically excluded from this analysis.

Table 4. Cost Item Data by Potential Stakeholder

	Manufacturers	Airports	Airlines	FBOs	Military
System hardware costs	✓✓				
Installation	✓	✓✓			
Ongoing operating costs	✓	✓✓			
FOD strike costs		✓	✓✓	✓	✓

The research team initially considered fixed-base operators (FBOs) as a source of data on general aviation and Title 14 CFR Part 135 (commuter and on-demand operator [Air Carrier and Operator Certification, 2021]) FOD strike costs. After initial informal discussions, FBOs were excluded from analysis. It seems that FBOs have few encounters with FOD outside the FBO ramp area and

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[4] Maintenance, including “power-by-the-hour” engine service agreements. For smaller airlines, their maintenance organizations might have the most accurate data.

tend to have very limited awareness of runway FOD contamination. Finally, incidental interviews with U.S. Naval aviation (flight operations and engineering) experts provided background on the scope of the military FOD problem. Although military aircraft and operations differ from their civilian counterparts in some fundamental ways (e.g., some branches of the military fly the FOD-prone AV8B Harrier, and military operations are generally less cruise-oriented), there are some important lessons that can be drawn for the civilian FOD problem, as discussed in Section 4.2.8.

Table 5 shows the stakeholders that took part in survey and interview data collections.

Table 5. Stakeholder Organizations Contacted

Organization	Written Survey	Formal Interview
Airports		
London Heathrow (LHR)		✓
Seattle-Tacoma International (SEA)	✓	✓
Vancouver International (YVR)	✓	✓
Marine Corps Air Station Yuma (MCAS Yuma) and Yuma International (NYL)		✓
Manufacturers		
Moog/Tarsier	✓	✓
Xsight Systems	✓	
Airlines		
Alaska		✓
Emirates		✓
United		✓
Military Ops/Engineering		
U.S. Navy CFM56 Engineering	✓	

2.3 DATA COLLECTION PROCEDURES

The research team distributed written surveys (Appendix A) to stakeholders, and responses were received from two airports (SEA and YVR) and two manufacturers of fixed-base FOD systems (Moog and Xsight). The research team conducted data collection interviews with four airports (LHR, SEA, YVR, and NYL) and one manufacturer (Moog). The system costs worksheet (Appendix A.1) and FOD damage costs worksheet (Appendix A.2) were distributed in advance of interviews. Given the low initial response rate to mail-out surveys and worksheets, these served in the end as additional interview prompts (see Appendices A.3–A.5) to help guide interviews.

Total interview time ranged from about 2 to 3 hours per organization, and most interviews took multiple sessions to complete. The research team audio-recorded interviews, and later transcribed, anonymized, and summarized each session.

3. INTERVIEW RESULTS

The research team structured interviews around the worksheet and prompt items of Appendix A. Beyond system and FOD cost data (see Sections 3.1 and 3.2), respondents provided wide-ranging information on a number of topics. Some of these major topics included:

- System performance and reliability
- Hidden costs of FOD
- Business case for the system
- Fringe benefits
- Anecdotal benefits, including system ‘saves’
- Airport liability and insurance issues
- The relationship between airports and airlines
- Operational issues in the use of FODDS
- General FOD management program considerations
- Prepurchase considerations

3.1 SYSTEM COSTS

The research team identified system costs via interviews and written surveys with two manufacturers (Moog and Xsight) and four airports (SEA, YVR, LHR, and NYL). Moog is currently installed at YVR, LHR, and NYL, among others. Xsight is currently installed at SEA, BOS, and international airports including Suvarnabhumi Airport (BKK), Hamad International Airport (DOH), and Beijing Capital Airport (PEK). As shown in Appendix A.1, total system cost includes both initial expenses (system acquisition and installation) and ongoing annual expenses. Initial costs (13 items) consist of hardware, financing, and installation expenses, and ongoing costs (nine items) consist of personnel, maintenance, and other operational expenses.

3.1.1 Initial Costs

System costs are airport-specific and can vary by factors, such as runway count, length, and configuration (which drive the required number of sensors); site preparation costs; financing terms; customer tailoring; and optional capabilities. (For example, Xsight offers its optional BirdWize™ module for wildlife management.)

At the three airports where total initial costs could be determined, totals ranged from $1.7M to $6.4M:

- YVR—Four-tower Moog system installed in 2007
- SEA—Xsight system (including BirdWize™) installed in 2015
- NYL—Five-tower Moog system installed in 2020

Both YVR and SEA use their FODDS in single runway mode, whereas NYL uses its system to cover intersecting runways (notice the sensor blind spot on Runway 8/26), as shown in Figure 3.

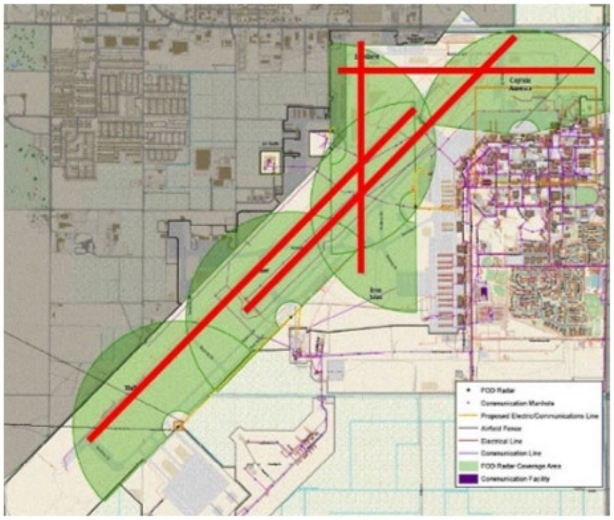

Figure 3. Five-Tower FODDS Installation at NYL

Based on Section 3.1.1, this analysis assumes a total initial cost of $5.75M.

3.1.2 Ongoing Annual Costs

In terms of recurring annual operational costs, information provided by stakeholders in this study resulted in a mean average of $275K per year in operation. Analysis assumes inflation adjustment over ROI horizon.

3.1.3 Lifecycle Assumptions

Both Xsight and Moog estimated lifecycles of more than 10 years. Both manufacturers claimed that replacement of their solid-state components is quick and easy. Further, existing infrastructure will likely lower system replacement cost at lifecycle end. Moog estimated a 75% savings on system replacement, assuming reuse of infrastructure such as towers, footers, and cabling.

Based on interviews, it seems that 12 years is a reasonable system life expectancy.

3.1.4 Total Initial System Cost Amortized Over 12 Years

Assuming outright purchase, uncorrected annual system cost over 12 years is:

$$[\ \{\$5.75M\} + [12 \times \{\$275K\}]\ ]/12 \approx \{\$754K\}$$

Using a historical 2010–2019 average CPI rate of 1.77%, Table 6 presents the inflation-adjusted (undiscounted) total system cost over 12 years. Data for Years 3, 5, 7, 9 and 11 are not shown in Table 6 but are included in the 12-year total.

Table 6. Inflation-Adjusted Total System Cost Over 12 Years

	Year 1	Year 2	Year 4	Year 6	Year 8	Year 10	Year 12	Total
Initial Cost	5,750,000							$5,750,000
Ongoing Cost	275,000	279,868	289,862	300,124	310,936	322,041	333,542	$3,640,986
Total Cost								$9,390,986

The inflation-adjusted total system cost over 12 years, including ongoing annual cost, is {$9,390,986}.

3.2 COSTS OF FOD DAMAGE

Quantifying system costs is fairly straightforward. However, quantifying benefits (expressed as FOD damage costs saved) is more complex. This becomes more challenging as analysis addresses indirect and fringe benefit categories, as data seem less robust, and estimates vary widely. McCreary (2010) appears to have done the first (and still most widely accepted) bottom-up analysis of FOD costs. Based on anonymous interviews and log inspections at a U.S. legacy carrier's hub maintenance operation, McCreary (2010) compiled statistics on FOD strike rates and costs.

Sections 3.3.1–3.3.6 build six CBA models. Model 1 uses derived costs for direct FOD damage only. Models 2–5 add rough multipliers for indirect costs and derived fringe benefits to the CBA equation. Model 6, the final direct-cost CBA model, is constructed based on recent FOD strike data obtained from the airline, Emirates.

3.2.1 Indirect Costs

Based on literature review and stakeholder interviews, the largest single contributor to indirect FOD costs is delay/cancellation (see Section 1.2 and Appendix C). To reiterate, according to one airline, the knock-on costs of a single cancellation can easily reach $30,000.

BTS T-100 data and FAA (2020) both capture National Airspace System (NAS) air traffic delays. Delays cost not only the airlines and airports, but also the traveler. The DOT defines a value-of-travel-time (VTT) metric that values personal and business travel at {$40.12}and {$70.23} per hour, respectively. For a typical narrow-body aircraft, this results in approximately $7,300 in VTT per hour of delay (see Section 4.2.6 for the calculation).

Data on FOD-specific delay did not seem robust enough to permit meaningful analysis. For this reason, the research team adopted a rough cost multiplier to estimate delay (and other indirect) costs.

3.2.2 Fringe Costs

Airports with operational FODDS all reported that their systems are adding capability beyond FOD detection. Functionality for perimeter security monitoring, pavement degradation monitoring, incident recording, and wildlife management are all part of the business proposition reported by manufacturers. Both SEA and YVR claimed added value, in particular, in terms of wildlife management capabilities. (SEA uses Xsight; YVR uses Moog.)

Wildlife management capabilities seem the largest current fringe benefit of FODDS. As a first approximation of fringe benefits, runway wildlife strike costs were added to the CBA model, as discussed in Sections 3.3.3 and 3.3.4.

3.3 WEIGHTED CBA MODELS

Sections 3.3.1–3.3.6 present the following six CBA models, respectively:

- **Model 1: DIR**—Direct cost only, for standard airport
- **Model 2: DIR IND1**—Direct plus assumed indirect cost (equal to direct cost) for standard airport
- **Model 3: DIR FRI**—Direct plus fringe (runway wildlife strike) cost for standard airport
- **Model 4: DIR IND1 FRI**—Direct plus assumed indirect cost (1x direct cost) plus fringe (runway wildlife strike cost) for standard airport
- **Model 5: DIR IND5**—Direct plus assumed indirect cost (5x direct cost) for standard airport
- **Model 6: DIR EMI**—Derived direct cost of FOD strikes for standard airport based on FOD strike data from Emirates

Table 7 shows an overview of the six CBA models, including how direct, indirect, and fringe elements were derived.

Table 7. Cost-Benefit Analysis Models 1–6 and Underlying Cost (Benefit) Elements

CBA Model	Direct	Indirect	Fringe
1. DIR	Derived from McCreary (2010)		
2. DIR IND1	Derived from McCreary (2010)	1x direct	
3. DIR FRI	Derived from McCreary (2010)		Computed runway strike benefit
4. DIR IND1 FRI	Derived from McCreary (2010)	1x direct	Computed runway strike benefit
5. DIR IND5	Derived from McCreary (2010)	5x direct	
6. DIR EMI	Based on Emirates FOD strike rate		

Again, the standard airport is defined by the 2019 average number of operations at the Core 30 airports (440,000, per FAA, [2020]).

3.3.1 Model 1: DIR (Direct Costs Only)

3.3.1.1 Runway FOD Strike Frequency

McCreary (2010) calculated FOD strike rate at 4.0 events per 10K operations (movements), runway FOD strike rate at 2.1 per 10K operations, and damaging runway FOD strike rate at 1.6 per 10K operations. This yields a risk of damaging runway FOD strike of 0.00016 per operation.

3.3.1.2 Runway FOD Strike Cost

Following McCreary (2010), the mean cost of a FOD strike is $10,336 {$12,335}, reflecting an 80/20 split between tire and engine damage (hull and other damage was negligible). This is a claimed direct-only repair cost of parts and labor.

Assuming that mean runway FOD strike costs parallel overall FOD strike costs, this results in a mean direct cost of $10,336 {$12,335} per runway FOD strike.

3.3.1.3 Runway FOD Strike Cost Per Operation

Combining the previous calculations leads to {$12,335} x 0.00016 = {$1.97} direct runway FOD strike cost per operation.

3.3.1.4 Runway FOD Strike Cost per Airport

For the adopted standard-airport metric (440,000 operations/year), this yields an annual FOD direct runway damage cost of 440,000 * $1.97 = {$866,800}. Core 30 operation numbers range from 214K at Tampa International Airport (TPA) to 914K at ORD in 2019 (FAA, 2020), which yields a Core 30 range of $422K to $1.8M per year per airport in direct runway FOD strike costs.

Table 8 presents CBA Model 1, which is based on the preceding calculations of:

- Initial system price = {$5.75M}
- Ongoing annual costs = {$275K)
- ROI horizon = 12 years
- Per-operation direct cost = {$1.97}
- Standard-airport number of operations = 440,000/year

CBA Model 1, shown in Figure 4, shows a B/C ratio of 1.22, indicating a 22% inflation-adjusted return over the 12-year ROI horizon, with a NPV (or net benefit) of $2.1M, and a break-even point (when cumulative benefits begin to exceed cumulative costs) in Year 9.

Table 8. Model 1: DIR (Direct Cost Only)

Model 1: DIR	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$866,800	$882,142	$897,756	$913,647	$929,818	$946,276	$963,025	$980,071	$997,418	$1,015,072	$1,033,039	$1,051,324
Cumulative savings benefit	$866,800	$1,748,942	$2,646,699	$3,560,345	$4,490,163	$5,436,439	$6,399,464	$7,379,535	$8,376,952	$9,392,025	$10,425,063	$11,476,387
Net annual benefit [B-C]	-$5,158,200	$602,275	$612,935	$623,784	$634,825	$646,061	$657,497	$669,134	$680,978	$693,031	$705,298	$717,782
Cumulative net annual benefit	-$5,158,200	-$4,555,925	-$3,942,990	-$3,319,206	-$2,684,381	-$2,038,319	-$1,380,823	-$711,688	-$30,710	$662,321	$1,367,619	$2,085,401
Discounted net annual benefit (r = 0.0%)	-$5,158,200	$602,275	$612,935	$623,784	$634,825	$646,061	$657,497	$669,134	$680,978	$693,031	$705,298	$717,782
Cumulative discounted net annual benefit	-$5,158,200	-$4,555,925	-$3,942,990	-$3,319,206	-$2,684,381	-$2,038,319	-$1,380,823	-$711,688	-$30,710	$662,321	$1,367,619	$2,085,401

Y = Year
B/C ratio: 1.22
NPV: $2.1M
Break-even: Year 9

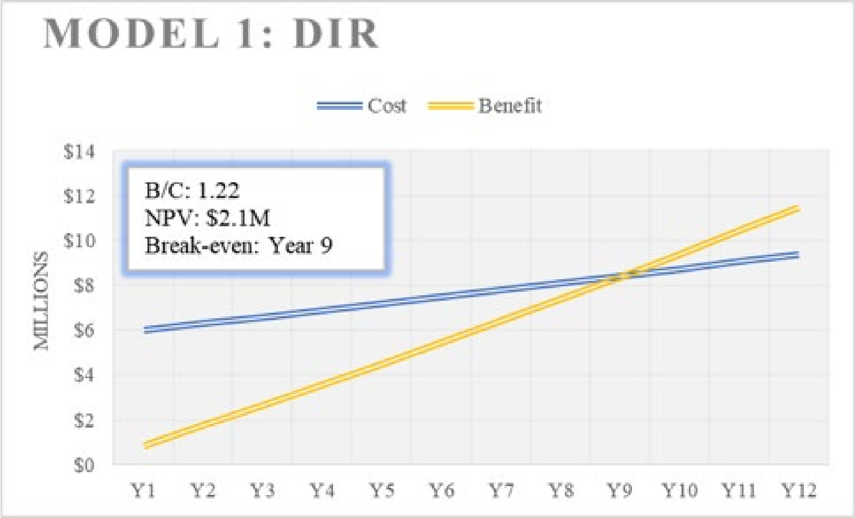

Figure 4. Model 1: DIR (Direct Cost Only)

3.3.2 Model 2: DIR IND1 (Direct + 1x Indirect Cost)

CBA Model 2 (DIR IND1) shown in Table 9 adds an estimate for indirect costs, equal to 100% of direct FOD damage costs. Based on literature review and interview consensus, this seems to be a conservative estimate.

Table 9. Model 2: DIR IND1 (Direct +1x Indirect Cost)

Model 2: DIR IND1	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$1,733,600	$1,764,285	$1,795,513	$1,827,293	$1,859,636	$1,892,552	$1,926,050	$1,960,141	$1,994,836	$2,030,144	$2,066,078	$2,102,647
Cumulative savings benefit	$1,733,600	$3,497,885	$5,293,397	$7,120,690	$8,980,327	$10,872,878	$12,798,928	$14,759,069	$16,753,905	$18,784,049	$20,850,127	$22,952,774
Net annual benefit [B-C]	-$4,291,400	$1,484,417	$1,510,691	$1,537,431	$1,564,643	$1,592,337	$1,620,522	$1,649,205	$1,678,396	$1,708,103	$1,738,337	$1,769,105
Cumulative net annual benefit	-$4,291,400	-$2,806,983	-$1,296,291	$241,139	$1,805,782	$3,398,120	$5,018,642	$6,667,846	$8,346,242	$10,054,346	$11,792,683	$13,561,788
Discounted net annual benefit (r = 0.0%)	-$4,291,400	$1,484,417	$1,510,691	$1,537,431	$1,564,643	$1,592,337	$1,620,522	$1,649,205	$1,678,396	$1,708,103	$1,738,337	$1,769,105
Cumulative discounted net annual benefit	-$4,291,400	-$2,806,983	-$1,296,291	$241,139	$1,805,782	$3,398,120	$5,018,642	$6,667,846	$8,346,242	$10,054,346	$11,792,683	$13,561,788

Y = Year
B/C ratio: 2.44
NPV: $13.6M
Break-even: Year 4

Model 2, shown in Figure 5, shows a B/C ratio of 2.44, NPV of $13.6M, and break-even in Year 4.

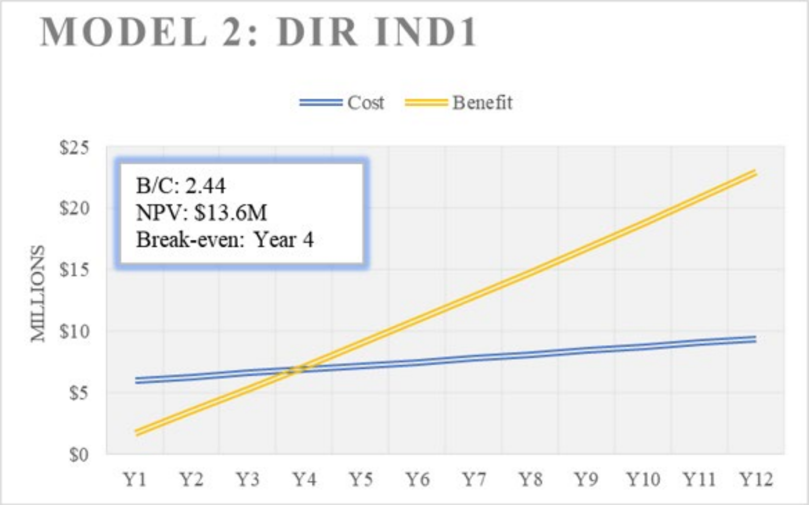

Figure 5. Model 2: DIR IND1 (Direct + 1x Indirect Cost)

3.3.3 Model 3: DIR FRI (Direct + Fringe)

Literature review suggests that wildlife management is a critical element of runway safety. The first bird strike-related aviation fatality (apart from the birds) occurred in 1912 (Cleary & Dolbeer, 2005; Dukiya & Ahmad, 2014). Cleary et al. (2004) estimated that wildlife strikes (98% involving birds) cost the U.S. civil aviation industry about $500M per year between 1990 and 2003. Allan and Orosz (2001) estimated that bird strikes cost commercial air carriers more than $1.2B worldwide annually.

The majority of wildlife strikes occur within the immediate airport environment, with 74% of all strikes occurring at or below 500 feet above ground level (AGL) (Cleary & Dolbeer, 2005). Ground-based FODDSs can help with a portion of these wildlife strikes.

McCreary (2010, Table 48) analyzed runway bird strike data for U.S. legacy carriers (American Airlines/American Eagle, United Airlines, Delta Air Lines, Southwest Airlines), and calculated a potential per-flight direct cost of {$3.46}.

To follow up literature review with an updated, fine-grained analysis, the research team extracted and processed records from the FAA wildlife strike database (https://wildlife.faa.gov) for 2010–2019. See Appendix B for details of this analysis, including supporting calculations and caveats.

As shown in Figure 6, the number of reported wildlife strikes increased steadily between 2010 and 2019. Superimposing number of wildlife strike reports on the number of scheduled civil flights (from the BTS T-100 Market database), it is clear that the increase in wildlife strike reports has outpaced scheduled civil traffic growth.

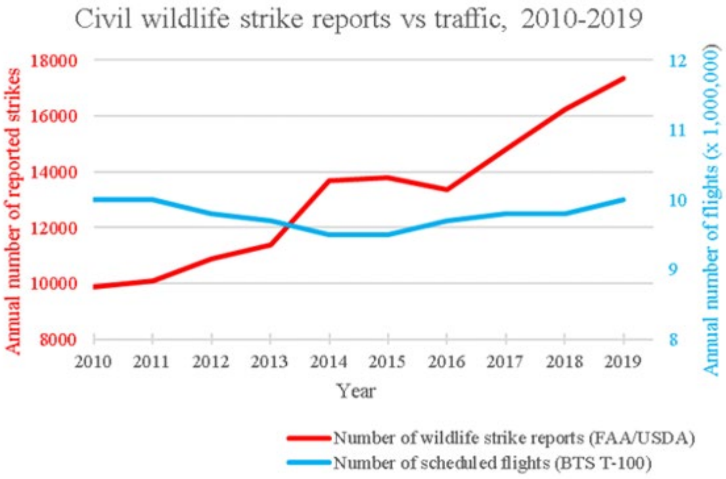

Figure 6. Wildlife Strike Reports Versus Traffic (2010–2019)

By merging data from the two databases (see Appendix B for details), the research team derived an approximate cost-per-operation of reported runway wildlife strikes (a FODDS would only be expected to help with the runway area). This permits calculation of the per-operation potential benefit of a FODDS, expressed as:

Total cost of reported runway wildlife strike damage/total number of operations

BTS T-100 data show a total of 97.8M scheduled flights for 2010 through 2019. Based on 2019 BTS T-100 segment data, 16.3% of operations were international (with a departure or arrival outside the United States, these reduce the number of NAS operations). Assuming this same rate for the past decade, this yields 97.8M + (0.837 * 97.8M) ≈ 180M total domestic operations, over the 10-year period. This results in an average of {$55.8M}/180M, or a potential runway wildlife strike benefit of {$0.31} per operation.

As a first approximation of FODDS fringe benefits, a runway wildlife strike cost of {$0.31} per operation was added to arrive at CBA Model 3 shown in Table 10. CBA Model 3 includes direct costs (as previously calculated) and runway wildlife strike costs. This provides a standard-airport annual benefit of

> [{$1.97} (direct runway FOD strike benefit) + {$0.31} (runway wildlife strike benefit)] x 440,000 operations
>
> = {$1,003,200} in standard-airport annual benefit, including direct and fringe (runway wildlife strike) benefits

Table 10. Model 3: DIR FRI (Direct + Fringe)

Model 3: DIR FRI	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$1,003,200	$1,020,957	$1,039,028	$1,057,418	$1,076,135	$1,095,182	$1,114,567	$1,134,295	$1,154,372	$1,174,804	$1,195,598	$1,216,760
Cumulative savings benefit	$1,003,200	$2,024,157	$3,063,184	$4,120,603	$5,196,737	$6,291,919	$7,406,486	$8,540,781	$9,695,153	$10,869,957	$12,065,556	$13,282,316
Net annual benefit [B-C]	-$5,021,800	$741,089	$754,206	$767,556	$781,142	$794,968	$809,039	$823,359	$837,932	$852,764	$867,857	$883,219
Cumulative net annual benefit	-$5,021,800	-$4,280,711	-$3,526,504	-$2,758,949	-$1,977,807	-$1,182,839	-$373,800	$449,558	$1,287,491	$2,140,254	$3,008,112	$3,891,330
Discounted net annual benefit (r = 0.0%)	-$5,021,800	$741,089	$754,206	$767,556	$781,142	$794,968	$809,039	$823,359	$837,932	$852,764	$867,857	$883,219
Cumulative discounted net annual benefit	-$5,021,800	-$4,280,711	-$3,526,504	-$2,758,949	-$1,977,807	-$1,182,839	-$373,800	$449,558	$1,287,491	$2,140,254	$3,008,112	$3,891,330

Y = Year
B/C ratio: 1.41
NPV: $3.9M
Break-even: Year 7

CBA Model 3 (Figure 7) shows a B/C ratio of 1.41, NPV of $3.9M, and break-even near the end of Year 7.

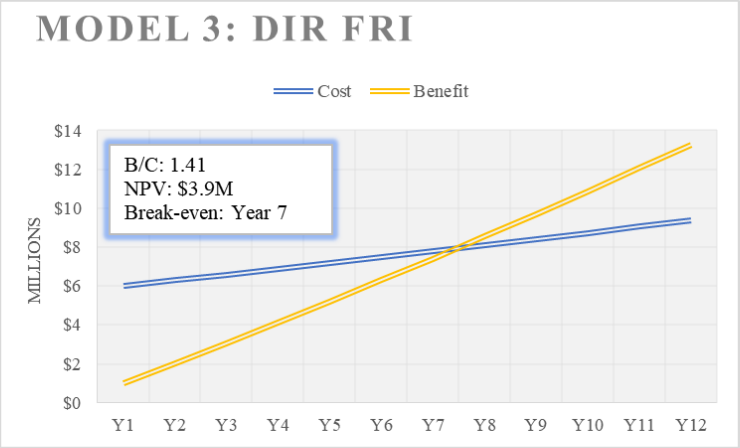

Figure 7. Model 3: DIR FRI (Direct + Fringe)

3.3.4 Model 4: DIR IND1 FRI (Direct + 1x Indirect + Fringe)

Combining the calculations of Models 2 and 3 provides a fourth model, which assumes equal (1x) indirect costs and a (runway wildlife strike) fringe, as shown in Table 11.

Table 11. Model 4: DIR IND1 FRI (Direct + 1x Indirect+ Fringe)

Model 4: DIR IND1 FRI	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$1,870,000	$1,903,099	$1,936,784	$1,971,065	$2,005,953	$2,041,458	$2,077,592	$2,114,365	$2,151,790	$2,189,876	$2,228,637	$2,268,084
Cumulative savings benefit	$1,870,000	$3,773,099	$5,709,883	$7,680,948	$9,686,901	$11,728,359	$13,805,951	$15,920,316	$18,072,106	$20,261,982	$22,490,619	$24,758,703
Net annual benefit [B-C]	-$4,155,000	$1,623,232	$1,651,963	$1,681,202	$1,710,960	$1,741,244	$1,772,064	$1,803,429	$1,835,350	$1,867,836	$1,900,896	$1,934,542
Cumulative net annual benefit	-$4,155,000	-$2,531,769	-$879,806	$801,397	$2,512,356	$4,253,600	$6,025,664	$7,829,093	$9,664,443	$11,532,279	$13,433,175	$15,367,717
Discounted net annual benefit (r = 0.0%)	-$4,155,000	$1,623,232	$1,651,963	$1,681,202	$1,710,960	$1,741,244	$1,772,064	$1,803,429	$1,835,350	$1,867,836	$1,900,896	$1,934,542
Cumulative discounted net annual benefit	-$4,155,000	-$2,531,769	-$879,806	$801,397	$2,512,356	$4,253,600	$6,025,664	$7,829,093	$9,664,443	$11,532,279	$13,433,175	$15,367,717

Y = Year
B/C ratio: 2.64
NPV: $15.4M
Break-even: Year 3

CBA Model 4 (Figure 8) shows a B/C ratio of 2.64, NPV of $15.4M, and break-even near in Year 3.

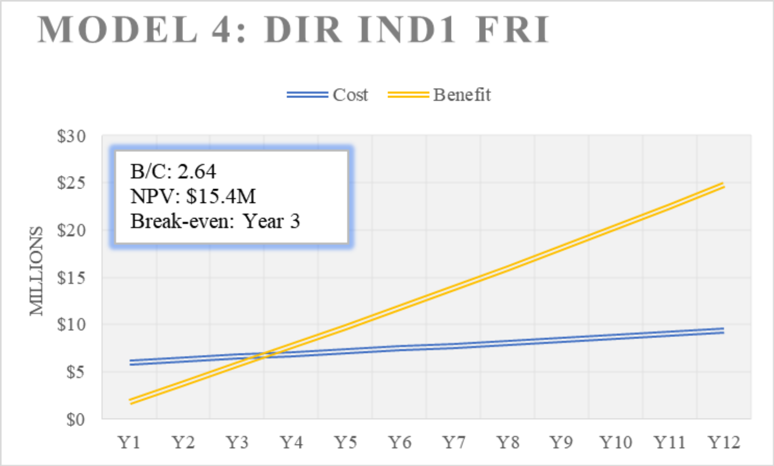

Figure 8. Model 4: DIR IND1 FRI (Direct +1x Indirect + Fringe)

3.3.5 Model 5: DIR IND5 (Direct + 5x Indirect)

Literature review (see McCreary, 2008, among others) and one airline interview suggest a 10x multiplier for indirect FOD damage costs. For the current analysis, an indirect multiplier was set to a relatively conservative maximum of 5x. This leads to CBA Model 5.

CBA Model 5, shown in Table 12 and Figure 9, shows a B/C ratio of 7.33, NPV of $59.5M, and break-even in Year 2.

Table 12. Model 5: DIR IND5 (Direct + 5x Indirect Cost)

Model 5: DIR IND1 FRI	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$5,200,800	$5,292,854	$5,386,538	$5,481,879	$5,578,909	$5,677,655	$5,778,150	$5,880,423	$5,984,507	$6,090,432	$6,198,233	$6,307,942
Cumulative savings benefit	$5,200,800	$10,493,654	$15,880,192	$21,362,071	$26,940,980	$32,618,635	$38,396,785	$44,277,208	$50,261,715	$56,352,147	$62,550,380	$68,858,322
Net annual benefit [B-C]	-$824,200	$5,012,987	$5,101,717	$5,192,017	$5,283,916	$5,377,441	$5,472,622	$5,569,487	$5,668,067	$5,768,392	$5,870,492	$5,974,400
Cumulative net annual benefit	-$824,200	$4,188,787	$9,290,503	$14,482,520	$19,766,436	$25,143,877	$30,616,498	$36,185,985	$41,854,052	$47,622,444	$53,492,936	$59,467,336
Discounted net annual benefit (r = 0.0%)	-$824,200	$5,012,987	$5,101,717	$5,192,017	$5,283,916	$5,377,441	$5,472,622	$5,569,487	$5,668,067	$5,768,392	$5,870,492	$5,974,400
Cumulative discounted net annual benefit	-$824,200	$4,188,787	$9,290,503	$14,482,520	$19,766,436	$25,143,877	$30,616,498	$36,185,985	$41,854,052	$47,622,444	$53,492,936	$59,467,336

Y = Year
B/C ratio: 7.33
NPV: $59.5M
Break-even: Year 2

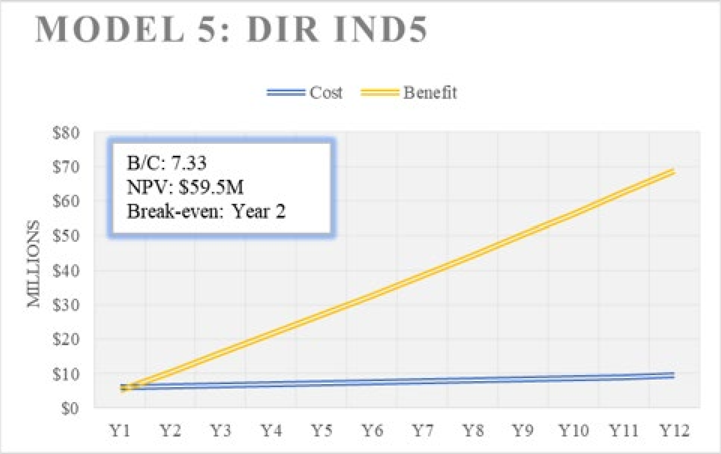

Figure 9. Model 5: DIR IND5 (Direct + 5x Indirect Cost)

3.3.6 Model 6: DIR EMI (Direct Costs Based on Airline Data)

One airline provided FOD strike data by city pair for their 36 most FOD-prone city pairs. Each city pair included the airline's hub airport as either departure or destination. The damage airport could not be determined from the data.

Figure 10 shows the number of FOD strikes (not all had damage costs) per 1,000 departures (flights) for January to August 2020. For the first half of 2020, through August 31, the airline experienced a mean average of 5.7 FOD strikes per 1,000 departures. This yields 5.7 x 2 (operations per flight) = 11.4/1,000, or 114 FOD strikes per 10,000 operations. Notice that the reporting period fell largely during the coronavirus disease 2019 (COVID-19) pandemic, which forced service cutbacks. It is not clear how this might have impacted the per-operation FOD strike rate.

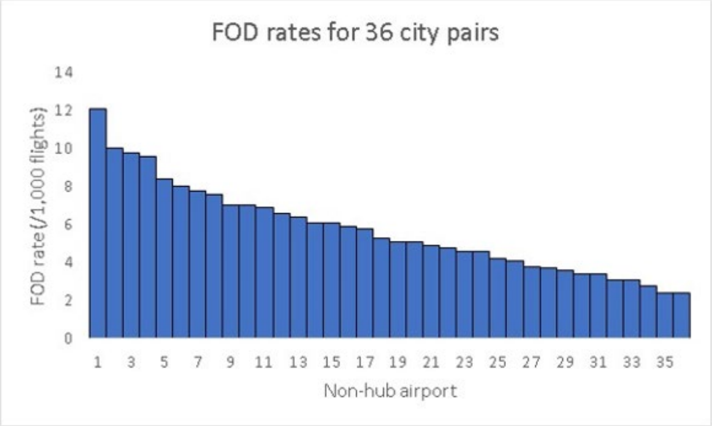

Figure 10. Airline City Pair FOD Strike Rate, January–August 2020

Combining the airline's FOD strike rate with McCreary's (2010) strike data (Section 3.3.1) yields a damaging runway strike rate of (1.6/4.0) x 114 ≈ 46 damaging runway FOD strikes per 10,000 operations on its 36 most FOD-prone city pairs.

Combined with the derived cost of {$12,335} per damaging FOD strike (Section 3.3.1), and assuming runway FOD strike costs parallel overall FOD strike costs, this yields 46 x {$12,335} = {$567,410}, {$567,410}/10,000 operations = {$56.74} per operation, or {$113.48} per flight that the airline theoretically spent in January–August 2020 on its 36 most FOD-strike-prone city pairs. The airline's actual cost data were not made available.

Applying airline data to the standard-airport 440K annual operations would suggest an annual direct runway FOD strike cost of about $25M per airport, which supports the calculations of Sides (2020), who computed a median annual FOD cost of $33.5M at the 10 busiest U.S. airports (see Table 13). Given that these data are from the airline's most FOD-prone city pairs, this is seen as an outside estimate of FOD damage costs.

The CBA Model 6 in Figure 11 shows a B/C ratio of 35.2, NPV of $321.2M, and break-even in Year 1.

Table 13. CBA Model 6: DIR EMI (Direct Costs Based on Airline FOD Strike Data)

Model 6: DIR EMI	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Annual cost [C]	$6,025,000	$279,868	$284,821	$289,862	$294,993	$300,214	$305,528	$310,936	$316,440	$322,041	$327,741	$333,542
Cumulative cost	$6,025,000	$6,304,868	$6,589,689	$6,879,551	$7,174,544	$7,474,759	$7,780,287	$8,091,223	$8,407,663	$8,729,703	$9,057,444	$9,390,986
Annual savings benefit [B]	$24,965,600	$25,407,491	$25,857,204	$26,314,876	$26,780,650	$27,254,667	$27,737,075	$28,228,021	$28,727,657	$29,236,136	$29,753,616	$30,280,255
Cumulative savings benefit	$24,965,600	$50,373,091	$76,230,295	$102,545,171	$129,325,821	$156,580,488	$184,317,562	$212,545,583	$241,273,240	$270,509,376	$300,262,992	$330,543,247
Net annual benefit [B-C]	$18,940,600	$25,127,624	$25,572,383	$26,025,014	$26,485,656	$26,954,453	$27,431,546	$27,917,085	$28,411,217	$28,914,096	$29,425,875	$29,946,713
Cumulative net annual benefit	$18,940,600	$44,068,224	$69,640,606	$95,665,620	$122,151,276	$149,105,729	$176,537,275	$204,454,360	$232,865,577	$261,779,673	$291,205,548	$321,152,261
Discounted net annual benefit (r = 0.0%)	$18,940,600	$25,127,624	$25,572,383	$26,025,014	$26,485,656	$26,954,453	$27,431,546	$27,917,085	$28,411,217	$28,914,096	$29,425,875	$29,946,713
Cumulative discounted net annual benefit	$18,940,600	$44,068,224	$69,640,606	$95,665,620	$122,151,276	$149,105,729	$176,537,275	$204,454,360	$232,865,577	$261,779,673	$291,205,548	$321,152,261

Y = Year
B/C ratio: 35.2
NPV: $321.2M
Break-even: Year 1

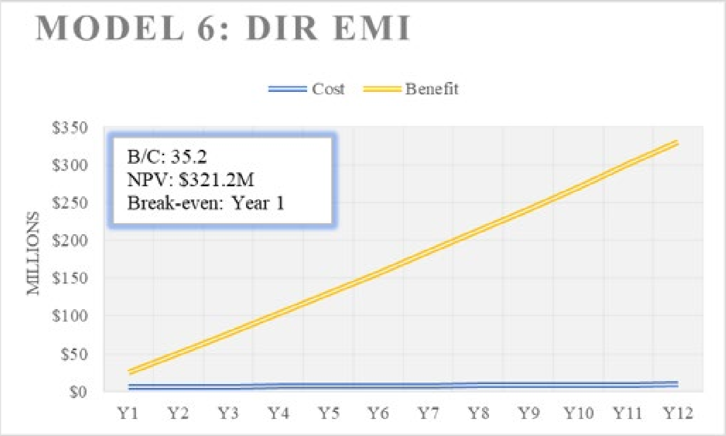

Figure 11. Model 6: Direct Costs Based on Airline FOD Strike Data

3.4 VALIDATING FOD RATE: EVIDENCE FROM FODDS-EQUIPPED AIRPORTS

The preceding calculations were based on McCreary's (2010) analysis of a U.S. carrier's hub airport maintenance logs. This analysis arrived at a FOD strike rate of 4 per 10,000 operations, 53% (2.1) of which were runway strikes, and 40% (1.6) were damaging runway strikes.

BOS management oversaw the installation of a FODDS in 2013, and SEA installed one in 2015. Both airports installed the Xsight system. (SEA purchased the optional BirdWize™ module for extended wildlife management capability.) Both airports generated FOD detection logs thereafter with an event report for each individual FOD detection. The research team analyzed these event logs. Notice that the two airports provided neither FOD strike nor damage cost data; they provided only FOD detection data. These data were used as an initial proxy for the potential FOD strike rate. The researchers hypothesized that the runway FOD detection rate would be relatively close (less than an order of magnitude difference) from McCreary's damaging FOD strike rate of 1.6 per 10,000 operations.

3.4.1 BOS Data

BOS data compared FOD detections across two runways: 9/27, which was FODDS equipped, and 4L/22R, which was unequipped. Other runways did not appear in the provided data set. Figure 12 shows runway FOD detection rate by source (i.e., FODDS vs vehicle/visual inspection) over the 45-month period for which data were provided. Few FOD detections were logged outside of July 2014–November 2015, and this 17-month sub-period was selected for analysis.

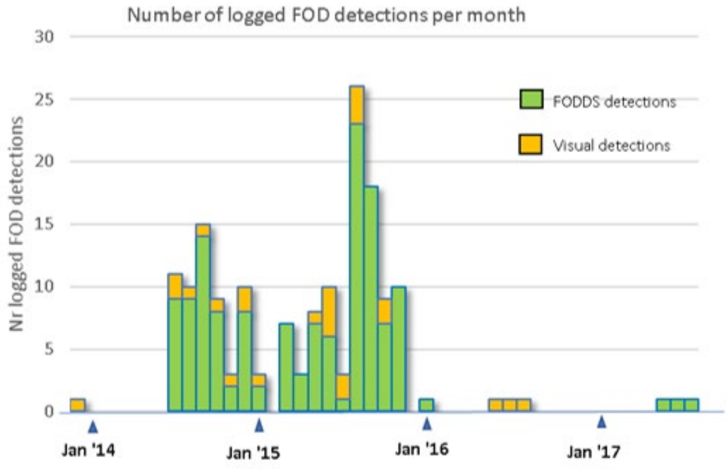

Figure 12. Logged FOD Detections per Month, by Source, 2013–2017 (BOS)

Between July 2014 and November 2015, a total of 155 FOD detections was logged (an average of 9.1 per month). Interestingly, 86% of these detections were via the FODDS, meaning that the FODDS found more than six times as much FOD as vehicle/visual inspection did. However, a base rate confound cannot be ruled out; that is, the FODDS would likely have been installed on the busier runway, which would, in turn, be expected to generate more FOD.

According to Massachusetts Port Authority (Massport) data (www.massport.com), BOS saw 343,658 operations over this 17-month period. This yields a FOD detection rate of 0.00044, or 4.4 detections per 10,000 operations. This is very close to McCreary's (2010) observed overall FOD strike rate of 4 per 10,000, and—more relevantly—well above McCreary's observed runway FOD strike rate of 2.1.

Of course, given the sensitivity of the FODDS, not all detected FOD would be high risk. Critical FOD (roughly defined as hard objects regardless of size) accounted for about 25%, or 1.1 detections per 10,000 operations.

Based on this limited sample, which was collected over 17 months at BOS, critical runway FOD was detected at a rate of 1.1 per 10,000 operations. This corresponds fairly closely to McCreary's (2010) rate of runway FOD damage of 1.6 per 10,000 operations. Further, this estimated detection rate understates the actual detection rate, because the equipped-runway-number-of-operations is smaller than the total number of operations.[5]

3.4.2 SEA Data

In 2015, SEA personnel installed a FODDS on Runway 16C/34C. After installing Xsight in 2015, SEA personnel logged automated FOD detections over a 48-month period (January 2016–December 2019). Provided data included only Xsight detections, not vehicle/visual inspections.

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[5] As of this writing, the number of operations for the equipped runway (9/27) was unknown.

Also, reports did not categorize FOD by mass. As a result, SEA data did not allow calculation of a critical runway FOD detection rate.

In terms of system detection rate, SEA's Xsight found between 0 and 25 pieces per month over the 48-month period, as shown in Figure 13.

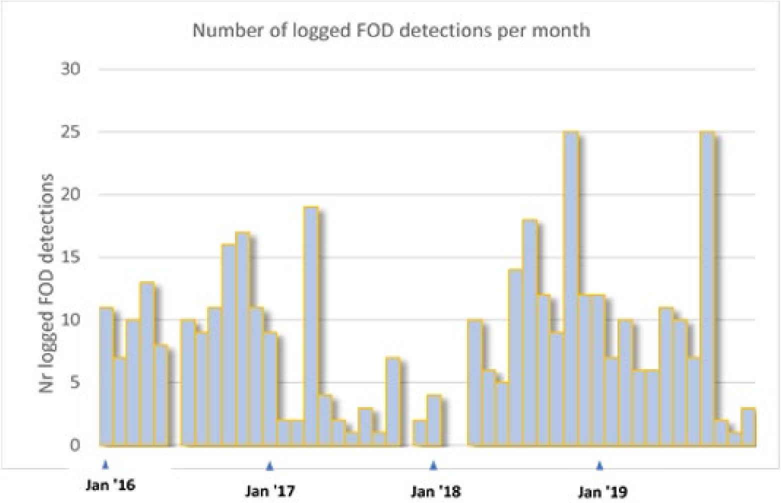

Figure 13. Foreign Object Debris Detections per Month, 2016–2019 (SEA)

A recent report by Brady (2020) compared FODDS vs visual detection rates for SEA between January 2019 and January 2020. Of the 33,140 detected items, 76.4% (n=25,316) were detected by FODDS, and 23.6% (7,824) were detected by vehicle/visual inspection. Notice the potential confound between runway and equipage: the FODDS-equipped Runways 16C/34C (9,426 feet long) and 16L/34R (11,901 feet long) might differ in traffic rate (and thus FOD base rate).

Of the 33,140 detected items, the research team classified 22.3% (n=7,406) as false alerts. Of the other 25,734 detected items, 43% were classified as "Other," 26% bird, 19% prey, 11% vegetation, and 1% plastic/paper. These results are shown in Figure 14. Metal, snow chunks, and tire chunks all accounted for less than 0.1% of detected objects and are not shown in the figure.

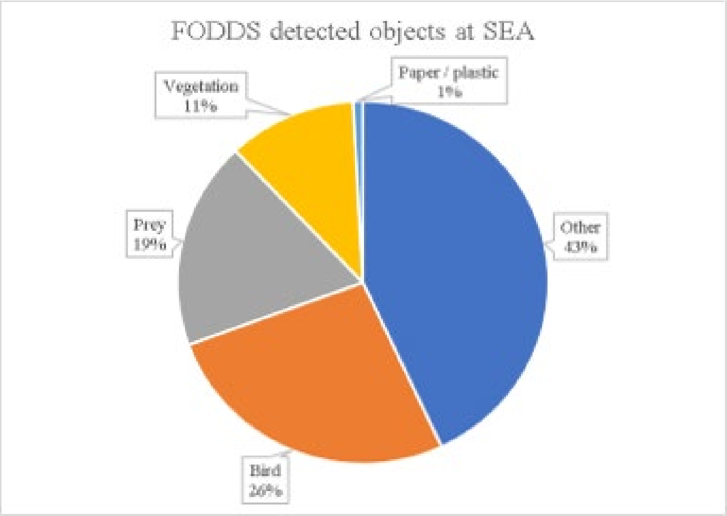

Figure 14. Detected Objects at SEA, January 2019–January 2020 (data from Brady, 2020)

Of all 33,140 detected items, a total of 132 items was collected. The majority of these collections (77.3%, n=102) were associated with the FODDS runway, and 22.7% (30) with the non-equipped runway.

SEA data (Brady, 2020) show that FODDS detection and collection rates were about three times the non-equipped rates.

4. FINDINGS

4.1 DISCUSSION

Literature review quickly revealed that FOD cost estimates vary widely, particularly with respect to the indirect costs of FOD strikes. For this reason, the research analysts aimed for a bottom-up, conservative, consistent, and traceable calculation of the associated direct and indirect costs of FOD.

To enable meaningful comparison, the research team defined a standard airport metric based on a Core 30 average of 440,000 annual operations (FAA, 2020). Using this standard-airport metric, all CBA models showed a net (NPV) benefit. Even the most conservative model, which excluded indirect and fringe benefits, showed a B/C ratio of 1.22, a net gain of $2.1M over a 12-year ROI horizon, and an investment break-even by Year 9.

The indirect costs of FOD damage are clearly not zero. Assuming even modest indirect costs (Models 2 and 4) makes the FODDS value proposition clearer. With a 1x multiplier for indirect FOD strike costs (Model 2), the standard-airport NPV benefit (B/C=2.44) equals $13.6M with break-even at Year 4. As a first approximation of potential fringe benefits, the researchers performed a fine-grained analysis of FAA's wildlife strike data to derive wildlife strike benefits. If such fringe benefits are added, the B/C ratio increases further.

As a secondary analysis, the research team reanalyzed FOD detection data from BOS and SEA airports. Using BOS FOD detection rates as a proxy for strike rates, analysis of runway FOD detection logs showed a critical FOD detection rate of 1.1 per 10,000 operations at BOS, following FODDS installation (pre- and post-comparison was not possible). This rate corresponds fairly closely to the damaging FOD strike rate of 1.6 per 10,000 operations of McCreary (2008). McCreary's rate was derived from empirical review of airline maintenance logs, and it formed the basis for strike rate calculations in the current CBA models. For this reason, the BOS-derived detection rate was seen as an important validation of the base-rate estimate underlying the current analysis.

4.2 LESSONS LEARNED

Other important lessons from this analysis are outlined in Sections 4.2.1–4.2.9.

4.2.1 Benefits Vary by Airport

FOD strikes do not seem evenly distributed across airports, not even across the Core 30 airports. Anecdotal evidence from air carriers suggests that some airports are more FOD prone than others. Traffic (number of operations), construction projects, quality of FOD mitigation plans, and natural conditions all drive differences in the perceived FOD strike risk across airports. This could be because most FOD strikes are occurring at just a handful of airports (airlines often do not know where a given FOD strike occurred). Therefore, one avenue of future research is to identify those airports that seem to pose the greatest FOD risk, thereby maximizing ROI in FOD system installations.

On a related point, creating slots through delay reduction benefits the busiest airports, which are those that are currently near capacity. If an airport has 20–30 departures an hour, a 10-minute FOD cleanup can be absorbed into the schedule. However, an airport running 90 operations per runway per hour would experience cancellations. Such cancellations can ultimately represent lost landing slots and fees. LHR, for example, estimated the value of a lost slot at more than $13K (British pound sterling (£)10K).

4.2.2 Benefits Vary by Airline

One airline reported that a FOD-related flight cancellation at OGG can cost them $30K in hotels, meal vouchers, crew time, catering, and other costs. Another airline, however, claimed that FOD strike cancellations rarely impose indirect costs. This airline attributes this, in part, to their larger fleet size and route structure. For example, if a 4 p.m. departure is cancelled, the airline often has another departure scheduled at 6 p.m. Bumped passengers can generally be re-accommodated at minimal airline expense unless the cancellation involves the last flight of the day.

4.2.3 Foreign Object Debris Strike Rate: per Airport vs per Operation

Past research has generally quantified FOD strike costs in terms of per-aircraft operation. Even when analyses have derived a per-airport cost, these costs have generally been based on a per-operation cost, which is then multiplied by the number of operations at a given airport.

It is not clear that calculating FOD costs on a per-operation basis is the best approach. According to the research team's interviews of air carriers, airline safety management personnel feel that some airports (not always the busiest) are more FOD-prone than others. Weather patterns, construction, and other factors could possibly make one airport more FOD-prone than another. Available data were not robust enough to permit cross-airport comparison.

4.2.4 Who Pays and Who Profits

Installing an airport FODDS under the existing fee structure is a case where costs are borne by one party (the airport) and benefits largely accrue to another (airlines). Safety management personnel from two airlines reported that, given the high insurance deductible threshold (and the inherent difficulty in identifying damage sites), FOD damage claims are rarely brought against an airport.

4.2.5 Amortization Beyond 12 Years

The derived ROI horizon of 12 years is based on operational MTBF, but one FODDS manufacturer claimed a 75% reduction in replacement costs at that point, assuming reuse of infrastructure components (see Section 3.1.2). Airport financial analysis can tailor assumptions to a longer amortization schedule.

4.2.6 Value of Travel Time

The research team aimed this analysis for a conservative first estimate of potential FODDS benefits. As a result, researchers intentionally omitted some categories of peripheral expenses. One of these categories is passenger VTT (U.S. DOT, 2016), which the DOT recognizes as a significant cost of air travel delay. The DOT values travel time at {$40.12} and {$70.23} per hour for personal and business travelers, respectively. The DOT assumes a 60/40 split in aircraft load between the two types of travelers. To put this in perspective, the average narrow-body aircraft (assuming 170 seats and a 2019 average load factor of 0.82 [BTS T-100 data]) would cost travelers about $7,300 per hour of delay.

4.2.7 Unexplored Fringe Benefits

Some interviewed airport personnel had years of experience with installed FODDSs. One common observation was that the incidence of FOD was much higher than they had previously realized. A related observation was that the installed system had provided not only a FOD detection capability, but also a perimeter security tool and a predictive analytic and reporting tool. Using these tools, personnel at a given airport now could predict wildlife migration patterns, runway contamination issues, etc. If and when more airport FODDSs become available online and incident databases grow richer, it would be useful to try to quantify such fringe benefits more finely.

4.2.8 Learning from the U.S. Military's FOD Experience

Data collection involved discussions with U.S. Navy (USN) engineering experts on the topics of military flight operations, maintenance, and CFM56 turbofan engineering (see Appendices A.1 and A.5). Military and civilian flight clearly differ in a few fundamental ways. First, the two tend to involve different aircraft types. Military aircraft such as the Harrier AV8B and F35B are two examples that, because of their vertical flight profile and vulnerable exposed ducting design, are highly FOD-prone. Moreover, military flight tends to be less cruise-oriented with emphasis on flight cycles over flight hours. Greater runway exposure increases FOD risk.

Given its sensitivity to FOD damage, it is not surprising that the military maintains detailed data on FOD strike rates and damage costs. Further, unlike its civilian counterparts, the military can generally trace FOD damage back to its source airport. The FAA could benefit from transferring military knowledge in this area. One relevant example is the USN FOD incident database on the P8 Poseidon, a military variant of the B737-800.

4.2.9 Tailoring Results to an Individual Airport

As discussed in Section 2.1.1, the FA benefit equation will differ by airport. Results of these CBA models can be scaled to other airports by simple traffic adjustment. However, each airport will also need to assess their own FOD risk profile (location, climate, and airport layout can all impact FOD risk), and the potential fringe benefits (see Section 4.2.7) offered by a FODDS.

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APPENDIX A—DATA COLLECTION MATERIALS

A.1 WORKSHEET—SYSTEM COSTS

Initial costs:

Hardware:

1. Base system ____________
2. Options (explain) ______________
3. Tools___________
4. Spare parts_______
5. Other ___________

Installation:

6. Research / consultancy / due diligence ___________
7. Certification & permits ___________
8. Initial installation ___________
9. Required new equipment ___________
10. Initial training ___________
11. Other

Financing:

12. Loan (borrowing) costs ___________
13. Other ___________

Total initial costs (sum 1 through 13):____________

Ongoing annual costs:

14. Training (delta from pre-equipage) ___________
15. Personnel (delta from pre-equipage) ___________
16. Insurance (delta from pre-equipage) ___________

    Maintenance (MX)

    17. Preventive MX ___________
    18. Corrective MX ___________
    19. Other MX (conditional, timed, etc.) ___________
20. Spare parts ___________
21. Equipment (delta from pre-equipage) ___________
22. Other ______

Total ongoing annual costs (sum 14 through 22):____________

A.2 WORKSHEET—FOD DAMAGE COSTS

Direct costs:

☐ Loss of life
☐ Multiple loss of life
☐ Injury
☐ Loss of aircraft
☐ Aircraft engine damage
☐ Vehicle damage

Other / indirect costs

☐ Airport efficiency losses
☐ Carbon / Environmental issues
☐ Change of aircraft
☐ Airport closure
☐ Runway closure
☐ Corporate manslaughter / criminal liability
☐ Corrective action
☐ Hiring and training replacement
☐ Rental / lease of replacement equipment
☐ Restoration of order
☐ Investigation (accident / incident)
☐ Delay for planes in air
☐ Delays at gate
☐ Fines and citations
☐ Fuel efficiency losses
☐ Hotels
☐ Increased insurance premiums
☐ Increased equipment operating costs
☐ Insurance deductibles
☐ Legal fees
☐ Liability claims in excess of insurance
☐ Loss of business / damage to reputation
☐ Loss of productivity of injured personnel
☐ Loss of spares or specialized equipment
☐ Lost time and overtime
☐ Missed connections
☐ Schedule disruption
☐ Replacement flights on other carriers
☐ Unscheduled maintenance.
☐ Other: ______________________

A.3 INTERVIEW PROMPTS—MANUFACTURERS

- ☐ Please provide a short summary of your system and how it works
- ☐ How many installations do you have? Where is your system installed?
- ☐ How much does the system cost?
- ☐ What factors drive the system cost?
- ☐ What factors drive the installation cost?
- ☐ What factors drive the ongoing annual costs?
- ☐ Explain maintenance demands and costs
- ☐ What kind of warranty is provided?
- ☐ What is the life expectancy of the system?
- ☐ Are there any additional acquisitions that you think the airport needs to operate your system?
- ☐ Are there any specialized personnel / training that an airport might have to address in installing or operating your system?
- ☐ What limitations or requirements does your product currently have regarding:
    - Weather / climate?
    - Lighting?
    - Number and type of aircraft operating?
    - Number and size of surveillance areas (e.g., runways, taxiways, aprons)?
    - Location of surveillance areas (and their distance from the sensor)?
    - Detection equipment precision / sensitivity?
    - False alarms or misses?
- ☐ Have you found that the FODDS has enabled the airports to add capacity? Which airports? By how much?
- ☐ Is there an aspect of the FODDS, or the way that the FODDS is being used at airports, that can be improved along these lines?
- ☐ Can your system provide benefits beyond FOD detection (e.g., Advanced Surface Movement Guidance and Control System [A-SMGCS], wildlife management, perimeter fence management)? Please explain.

A.4 INTERVIEW PROMPTS—AIRPORTS

- ☐ Are there any unique characteristics of this airport / location, that would impact the cost or operation of a FODDS (e.g., climate, wildlife, traffic)?
- ☐ Are there any fringe benefits?
- ☐ Do you have any logged data on FOD events? May we obtain a copy?
- ☐ What are some of the most common FOD alerts you've experienced?
- ☐ What are some of the most critical FOD alerts you've experienced?
- ☐ Has your airport already done any cost / benefit or ROI analysis?
- ☐ What would you change in the system / current procedures?
- ☐ Does your system ever go down, for planned / unplanned purposes? Please elaborate.
- ☐ Can you discuss maintenance requirements and cost?

☐ What training do staff get in the use of the FOD system? Describe cost, duration, and currency requirements.
☐ Can you describe your FOD system, and how it differs from standard (e.g., options, extras)?
☐ Besides FOD detection, what else do you use the system for (e.g., snow, wildlife, A-SMGCS)?
☐ Can you discuss false alarms and misses (including frequency and causes)?
☐ Do you have an example of when the system demonstrated safety, money, or efficiency benefits?
☐ Can you compare before and after installation of the system, in terms of the above?
☐ Can you discuss any limitations of the system (aircraft, area, event context)?
☐ Any potential conflicts with airport communication, navigation, and surveillance (CNS) systems (e.g., instrument landing system [ILS])?
☐ Please discuss FOD management program (e.g., training, oversight, maintenance, research and development [R&D], appointed staff)
☐ Do you have formalized FOD response / removal procedures?
☐ How do you coordinate with carriers regarding FOD event responses? Awareness? Info sharing?

A.5 INTERVIEW PROMPTS—AIR CARRIERS

☐ How much does FOD cost your company annually?
☐ Can you distinguish / discuss direct and indirect costs?
☐ What are the most common FOD events?
☐ What are the costliest FOD events?
☐ Is there communication between airport and your company, regarding FOD issues and technology?
☐ Does your company feel it has a stake in airport FOD-related policy / procedure decisions?
☐ What do you do to address FOD avoidance?
☐ Can you compare airports with and without FODDSs? Can you assess the benefits of FODDSs on your company?
☐ Does your company maintain data on FOD damage?
☐ What proactive steps has your company taken with respect to FOD avoidance?
  - Preflight procedures
  - Recurrent training
  - Operational guidance
☐ How many company flights are impacted by FOD each year?
☐ Has your company noticed / quantified benefits at airports with FODDSs?

APPENDIX B—ANALYSIS OF WILDLIFE STRIKE COSTS

Cleary et al. (2004) estimated that wildlife strikes (98% involving birds) cost the United States (U.S.) civil aviation industry about $500M per year between 1990 and 2003. Allan and Orosz (2001) estimated that bird strikes annually cost commercial air carriers more than $1.2 billion worldwide.

The majority of wildlife strikes occur within the immediate airport environment, with 74% of all strikes occurring at or below 500 feet above ground level (Cleary & Dolbeer, 2005). Ground-based foreign object debris detection systems (FODDSs) can help with some percentage of these wildlife strikes.

McCreary (2010, Table 48) analyzed runway bird strike data for U.S. legacy carriers (American Airlines/American Eagle, United Airlines, Delta Air Lines, and Southwest Airlines), and calculated a potential per-flight direct cost of {$3.46} and total benefit (including a 10x multiplier for indirect costs) of {$38.06}.

Deriving wildlife strike costs

With input from the U.S. Department of Agriculture (USDA), the Federal Aviation Administration (FAA) maintains a database on civil and military aviation wildlife strikes (https://wildlife.faa.gov) that compiles data from voluntary reports (using form 5200-7, in either hard copy or online) and mandatory occurrence reports. The database includes reports involving Part 121 and 131 operators, military and civil operators, foreign and domestic carriers, and both cargo and passenger carriers, operating to, from, and within the United States. The database captures many details, including location, severity, and damage repair costs associated with each event. To follow up literature review with a more recent and fine-grained analysis, the FAA Airport Technology Research and Development Branch research team extracted 2010–2019 event records from the wildlife strike database.

Between 2010 and 2019, there were 131,491 reported wildlife strikes with nonmilitary aircraft (and another 2,235 with military aircraft). For civil aircraft, this results in an average of 1,096 strike reports per month, or (assuming 24/7 operations) one every 40 minutes.

As shown in Figure B-1, the number of reported wildlife strikes increased steadily between 2010 and 2019. Superimposed on the annual number of scheduled civil flights (from the Bureau of Transportation Statistics (BTS) T-100 market database), it is clear that the increase in wildlife strike reports has outpaced traffic growth.

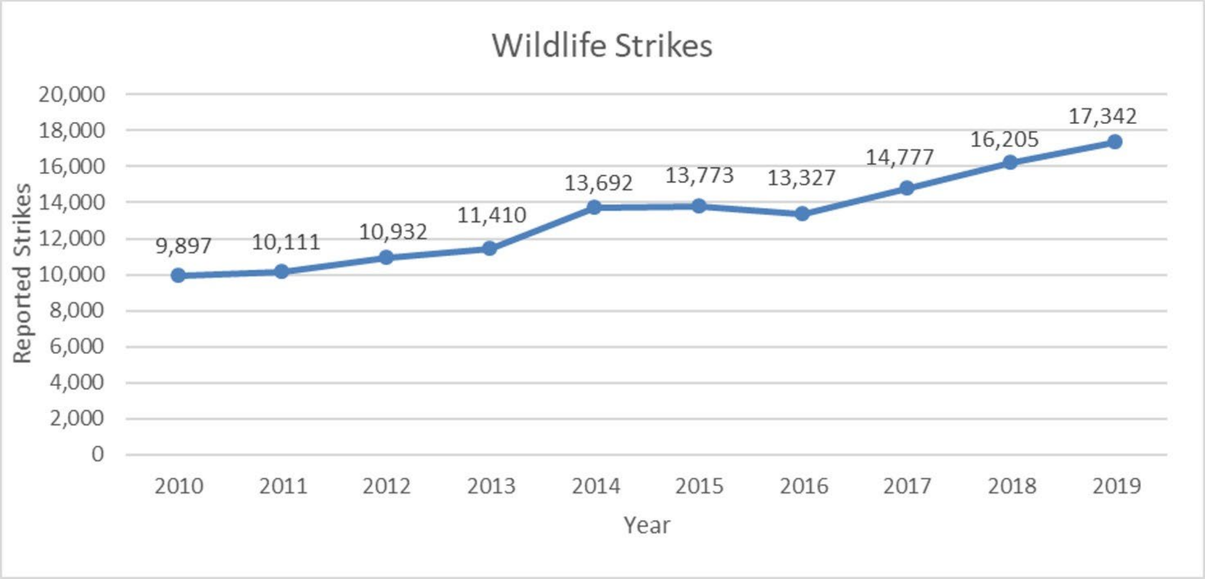

Figure B-1. Annual Increase in Reported Wildlife Strikes Between 2010 and 2019

From the wildlife strike database, 3,783 (2.9%) of the 131,491 reported strikes resulted in direct and/or indirect damage repair costs. Total cost (direct + indirect) was {$283.6M}, and per-event total costs ranged from {$1} to {$15.6M}, with a median of {$1,596} and a mean of {$74,975} (a small number of expensive repairs skews the mean).

The wildlife strike database distinguishes several phases-of-flight, which can be grouped as follows:

- Runway—Takeoff and landing rollout phases
- Arrival/departure/altitude change—Climb, descent, departure, arrival, and approach
- En route
- Taxi/ground—Parked and taxi

Of the 3,783 strike reports that listed nonzero damage costs, 2,734 had complete data sets (including location). These 2,734 strikes resulted in a total cost of {$222M}. Of these reported strikes, runway events accounted for 23.8% (n=652) of the total,[1] and 25.1% ({$55.8M}) of all costs. Figure B-2 shows the frequency and cost of wildlife strikes, by phase of flight, for 2010–2019.

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[1] McCreary (2010) claimed from Delta Airlines forensic analysis that about 50% of all FOD strikes occurred on the runway. Combining these results, about half of all FOD strikes, and a quarter of reported wildlife strikes, occurred on the runway.

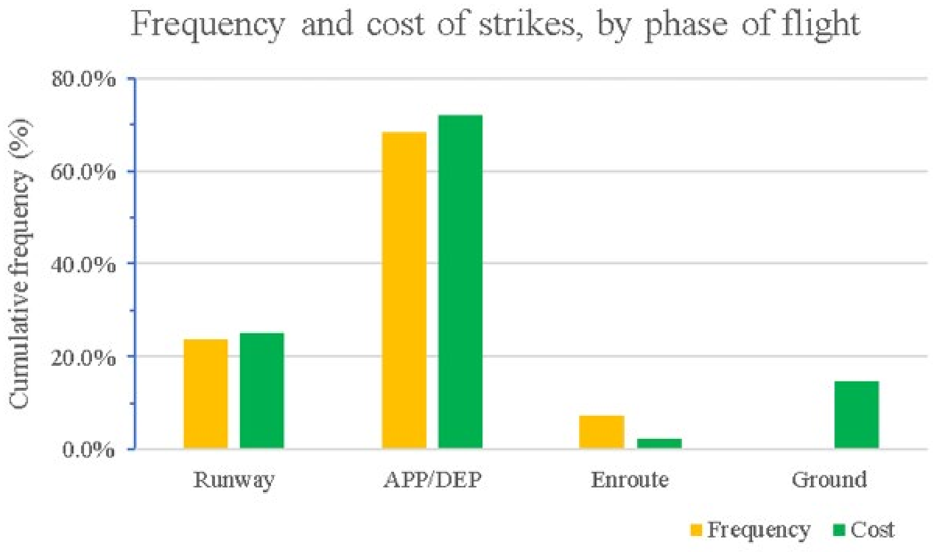

Figure B-2. Frequency and Cost of Wildlife Strikes by Phase of Flight (2010–2019)

It makes sense to focus only on runway events, since those are the ones that a runway-focused FODDS could address. Database events were filtered to include only takeoff and landing rollout phases. Again, the wildlife strike database identifies 652 runway strikes (i.e., those during takeoff or landing rollout) between 2010 and 2019 that resulted in damage costs. Total cost of these 652 strikes was {$55.8M}, and per-event costs ranged from {$5} to {$7.0M} with a median of {$1,732} and a mean of {$85.5K}. No reported runway wildlife strikes resulted in injury. (Three injury events logged as rollout injuries actually involved enroute or descent bird strikes and were disregarded for this analysis.)

From these data, it is possible to derive an approximate cost-per-operation of reported runway wildlife strikes (again, a runway-focused FODDS would only be expected to help with the runway area). This permits calculation of the per-operation potential cost benefits of a FODDS, expressed as:

Total costs of reported runway wildlife strike damage/total number of operations

BTS T-100 data show a total of 97.8M scheduled flights for 2010 through 2019. Based on 2019 BTS T-100 segment data, 16.3% of operations were international (with a departure or arrival outside the United States, these reduce the number of National Airspace System operations). Using this same rate for the past decade, this yields 97.8M + (0.837 * 97.8M) ≈ 180M total domestic operations, over the 10-year period. This calculates to an average of {$55.8M}/180M, or a potential savings of {$0.31} per scheduled operation.

To put that in perspective, the Core 30 airports each averaged 440,000 operations (214,000 to 914,000) in Fiscal Year 2019 (13.2M/30; FAA, 2020). This would mean a potential average annual FODDS benefit of {$136K}, per Core 30 airport, in helping avert runway wildlife strikes. There are a few caveats:

- First, the 2010–2019 average number of wildlife strike reports understates the increase since 2016.
- Second, there is anecdotal evidence that reporting increasingly outpaces actual strike numbers.
- Third, it is assumed that these wildlife strikes are not double counted in the overall runway strike rate. (This appears to be the case.)
- Fourth, BTS T-100 data are for scheduled flights only. Adding unscheduled flights would increase the denominator and decrease the calculated cost-per-operation.

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APPENDIX C—LITERATURE REVIEW EXTRACTS WITH SUPPORTING CITATIONS

C.1 FOREIGN OBJECT DEBRIS DAMAGE RATES

- Foreign object debris (FOD) strikes occur 4x per 10,000 operations (McCreary, 2010), with
    - 79% causing damage,
    - 52% occurring on the runway, and
    - 40% of runway strikes causing damage costs.
- United Kingdom Civil Aviation Authority found that 15% of all FOD was found on the runway (Thomas, 2010).
- Delta Air Lines found that runway FOD was 15% of the total, but 50% of all FOD damage cost (Thomas, 2010).
- Delta Air Lines found that the largest source of FOD was aircraft parts, 45% (Thomas, 2010).

C.2 FOD DAMAGE COSTS

- FOD accounts for billions of dollars in damage per year worldwide (Gamauf, 2010).
- FOD costs $380M {$453M} annually in direct costs at the world's 300 largest civil airports (Thomas, 2010).
- FOD costs Delta Air Lines $16.0M {$26.3M} annually based on 2006 analysis (Fechushak, 2010; as cited in McCreary, 2010).
- In 1996, the Air Transport Association of America (ATA) counted FOD events among 23 member airlines over 3 years and demonstrated an average annual loss of $7.4M per airline, with an average annual loss across all member airlines of $170M (Zhongda, Y., Mingguang, L. & Xiuquan, C., 2019; Procaccio, 2008).
- A total of 52.5% of all damaging FOD strikes are on the runway (McCreary, 2010).
- A total of 80% of FOD strikes are to tires, and 20% to engines (McCreary, 2010; Thomas, 2010).
- The world's 300 largest civil airports have 55M aircraft movements and 70K FOD incidents a year (Thomas, 2010).
- The direct cost of FOD damage is $90,161 {$107.6K} per 10,000 movements (Thomas, 2010).
- The direct cost of FOD damage is $32,333 {$38,586} per 10,000 movements (McCreary, 2010).

- A total of 78% of FOD strikes cause damage to the aircraft (Thomas, 2010).
- A large, anonymous U.S. airline reported 117 engine FOD events at a single airport in 1 year. During that same year, the airline replaced 65 blade pairs, blended 80 blades, and made more than 57 technical inspections (McCreary, 2010; Thomas, 2010).
- FOD damage costs the global airline industry more than $4B {$6.4B} a year, mostly through engine and airframe damage (Phillips, 2008).
- In 2008, one U.S. airline reported $1.8M {$2.2M} in FOD damage per month fleetwide (Phillips, 2008).
- U.S. airlines combined spend $35M {$43.9M} a year on FOD (Patterson, 2007).
- The cost to repair a FOD-damaged engine can exceed $1M {$1.6M} (Bachtel, 1998).
- Delta Air Lines spent $23M {$28.9M} annually on FOD damage (Patterson, 2007).

C.3 DELAY COSTS

- Delays caused an average of $40 {$48} per minute per aircraft (McCreary, 2010).
- A total of 90% of runway closure time at reporting European airports is due to FOD (McCreary, 2010).
- Reporting European airports average 220 minutes of FOD-related runway closure delays per month (McCreary, 2010).
- FOD-related delays at reporting European airports costs $26,740 {$31.9K} per 10,000 movements (McCreary, 2010).
- FOD-related delays cost large European airports more than $1M {$1.2M} annually (McCreary, 2010).

C.4 WILDLIFE STRIKE RATES AND COSTS

- A total of 97% of wildlife strikes are bird strikes (George, 2009).
- FAA statistics show that wildlife strikes cause $500M of damage to U.S. aircraft per year (George, 2009).
- FAA statistics show that wildlife strikes force aircraft out of service for about 500,000 hours per year (George, 2009).
- Insurers process 40 to 50 bird-strike-related engine FOD claims per year (George, 2009).
- The average bird-strike-related engine claim is $575K {$697K} (George, 2009).

- Most bird strikes occur below 3,000 feet (George, 2009).
- FOD damage costs the global airline industry more than $4B {$6.4B} a year, mostly through engine and airframe damage (Phillips, 2008).
- In 2008, one U.S. airline reported $1.8M {$2.2M} in FOD damage per month fleetwide (Phillips, 2008).
- The FAA funded $900K of Boston Logan International Airport's $1.7M system installation (Aviation Pros, 2014).
- "There may be hundreds of takeoffs and landings in between every manual inspection. An automated system scans continuously" (Aviation Pros, 2014).
- FOD damage costs the global aerospace industry $4B {$6.4B} annually (Bachtel, 1998).
- FOD costs the U.S. Navy an estimated $140M (Sides, 2020).
- Indirect costs include, for example (Bachtel, 1998):
    - Flight delays and cancellations, leading to a loss of customers.
    - Schedule disruption caused by the need to reposition planes and crews.
    - Potential injury-related liability.
    - Additional work time for airline management and staff.
- Wildlife strikes cost the U.S. civil aviation industry $500M {$642M} annually (Dolbeer, 2006)

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