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Thunder Versus Lightning: A Performance and Cost Analysis of the A-10 "Warthog" Versus the F-35 Joint Strike Fighter

Abstract: For decades, the U.S. Air Force has contemplated replacing the A-10 Thunderbolt II "Warthog" with a newer fighter aircraft. However, a quantitative analysis comparing the Warthog's performance and costs with those of its intended replacement, the F-35 Lightning II Joint Strike Fighter, shows that retiring the Warthog would be operationally unsound and fiscally imprudent. The rationale for the replacement is that it would increase airpower capability while controlling costs. That rationale does not withstand scrutiny. An effectiveness analysis based on results from a survey of joint terminal attack controllers indicates that the A-10 vastly outperforms the F-35 in providing close-air support (CAS), a critical requirement for future conflicts against terrorists and insurgents. A cost analysis demonstrates that replacing the A-10 before its service life ends in 2035 would cost at least $20.9 billion. The replacement plan would waste substantial resources and seriously impair U.S. military capabilities. Given that constrained future budgets and low-intensity conflicts requiring precision CAS can be expected, the U.S. air fleet should include the A-10 Thunderbolt II.

Keywords: A-10; close-air support; cost-benefit analysis; cost-effectiveness analysis; F-35; procurement; Warthog.

JEL classifications: D61; D69; H56; H57.

1 Introduction

Policy analysis got its start in government in the early 1960s with the Planning, Programming, and Budgeting System (PPBS) developed in the Pentagon by Alain Enthoven and his handpicked team of young defense analysts dubbed the "Whiz Kids." PPBS was "based on the six deceptively simple fundamental ideas: decisions should be based on explicit criteria of national interest, not on compromises among

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institutional forces. Needs and costs should be considered simultaneously. Major decisions should be made by choices among explicit, balanced, feasible alternatives. The Secretary of Defense should have an active analytic staff to provide him with relevant data and unbiased perspectives. A multiyear force and financial plan should project the consequences of present decisions into the future. Open and explicit analysis, available to all parties, should form the basis for major decisions. We submit that these principles constitute the foundation for sound management of any public institution, …" (Enthoven & Smith 2005, p. ix–x). Policy analysis has been extended into a vast array of realms in the intervening years. Its use in defense procurement decisions, however, appears to have declined. This study applies the cost-effectiveness measures that are foundational to policy analysis to the critical question of how the USA should assure its capability for close-air support (CAS).

The A-10 Thunderbolt II is the best CAS aircraft of its kind in the U.S. arsenal. Nevertheless, after many years of ambivalence, the Air Force nearly retired it permanently in 2015. Facing tight budgets, the Air Force decided that the A-10 fleet was unaffordable, given the planned purchase of new F-35 Lightning II Joint Strike Fighters over the next two decades. The F-35 alone, senior officials argued, could fully meet the requirements of all foreseeable conflict scenarios (Marshall, 2014). The likelihood of U.S. involvement in low-intensity conflicts, as well as the A-10's unique ability to provide the specialized CAS such fighting requires, undermine this assertion. This article considers the nature of different conflict scenarios facing the USA and their likelihoods. It then analyzes the performance of the A-10 and F-35 given these scenarios, and then compares their costs. The analysis shows that the A-10 is essential to an effective and efficient U.S. air fleet through 2035.

The A-10 differs dramatically from multirole fighters such as the F-15, F-16, F/A-18, and the newer and more sophisticated F-22 and F-35. These fighter aircraft are designed primarily to shoot down other aircraft. Striking ground targets is a secondary capability (U.S. Air Force, 2005). The A-10, in contrast, is highly specialized to perform CAS. The training and experience of Warthog pilots reflect their aircraft's specialized function, making them CAS experts (U.S. Air Force, 2015*a*). A 2016 Government Accountability Office (GAO) report found that, compared to multirole fighter pilots, A-10 pilots perform two to three times as many training sorties to become proficient at CAS (Government Accountability Office, 2016, p. 49).

The 281 A-10s in the U.S. inventory have been upgraded numerous times during their more than 30 years of service (U.S. Air Force, 2015*a*). As of 2018, the Air Force had purchased new wing sets for at least 172 of these aircraft, extending their service lives through 2035 (Boeing, 2013; Insinna, 2018*c*).

The plan to retire the A-10 identified modernization and the defeat of emerging threats as the core objectives of U.S. defense forces, thus requiring a fleet of multirole aircraft designed primarily for stealth, speed, and range (SSR; U.S. Department of Defense, 2014). Advocates of the retirement plan concede that it would sacrifice CAS capability, but argue that the versatility gained would make the loss worthwhile. In 2012, Adm. James Winnefeld, then Vice Chairman of the Joint Chiefs of Staff, explained: "Is the F-35 going to be as good a CAS platform as an A-10? I don't think anybody believes that. But is the A-10 going to be the air-to-air platform that the F-35 is going to be? So again, the Air Force is trying to get as much multimission capability as possible into the limited number of platforms it's going to have" (James Winnefeld, quoted in Schogol, 2012). This concession is critical to the rationale for the retirement plan: that trading the A-10 fleet for more F-35s involves a small and acceptable loss of CAS capability that is more than offset by gains in versatility and stealth, so that overall airpower capability would increase. This represents a fatal error within the proposed replacement plan: a performance analysis of the two aircraft indicates that the loss of CAS capability would be vast, decreasing overall airpower.

As the close attention to troop levels in Afghanistan and the carefully calibrated operations against the Islamic State in Iraq and Syria (ISIS) have shown, the USA is increasingly circumspect about the use of military force. In the low-intensity conflicts of the future, special operations forces will play a central role, given their precision, flexibility, and light signature.

When special operations units and other ground forces are sent into combat, highly capable CAS must support them. Air support is essential to protect ground forces from attack; it significantly enhances their effectiveness. U.S. aircraft also provide CAS support to allies and coalition partners that fight common adversaries such as the Taliban, al Qaida, and ISIS. Any use of CAS by the USA, whether or not U.S. troops are on the ground, must minimize harm to civilians. This requires extremely precise strikes based on careful surveillance from the air, thus enabling maximum target discrimination.

In the decades ahead, the demand for CAS on actual battlefields supporting U.S. and allied troops will remain high. The demand for precision in every strike will likewise remain high. Consequently, a large degradation in CAS capability would unacceptably put national security objectives and lives at risk. A cost effectiveness analysis shows that the plan to replace the A-10 fleet with F-35s would both dramatically reduce CAS capability and cost considerably more than available alternatives. Thus, this plan is strictly dominated and should be abandoned.

2 Background

The A-10 is the only single-purpose attack jet in the U.S. Air Force, as reflected in its "A" designation indicating "attack" (U.S. Air Force, 2005). Its 30 mm cannon protrudes downward from its blunt nose like a tusk, prompting its affectionate nickname of "Warthog." The A-10 entered service in 1975 and saw extensive action in the 1990–1991 Gulf War, the no-fly zones enforced against Saddam Hussein's regime following that conflict, NATO's no-fly zone over Bosnia and Herzegovina and its 1999 air campaign in Yugoslavia, the Afghan War, the second Iraq War, and operations against ISIS (U.S. Air Force, 2015*a*). In all these conflicts, the A-10's primary role has been CAS.[1]

When the air campaign to defend Kosovo required close-in targeting, NATO commanders preferred A-10s to AH-64 Apache helicopters due to the latter's vulnerability to antiaircraft fire (Lambeth, 2001, p. 28–29, 51, 55). In fact, two A-10s survived direct hits from antiaircraft artillery (Lambeth, 2001, p. 108–109). During Operation Anaconda, in the Tora Bora region of Afghanistan in early 2002, AH-64 Apache helicopters again proved excessively vulnerable to fire from the ground. A-10s were deployed to fill this capability gap due to their unique survivability while providing highly precise CAS (Cordesman, 2003, p. 68). A-10s were a cornerstone of CAS capability during the 2003 invasion of Iraq, performing the vast majority of precision strafing runs and again replacing attack helicopters after disastrous losses from ground fire (Lambeth, 2013, p. 263–264, 383). In late 2014, a small number of A-10s were transferred from Afghanistan to support Iraqi forces battling ISIS (Clark, 2014). In the conflict with ISIS, the A-10 has remained unchallenged in its ability to strike a large number of targets and make multiple attack runs with great precision (Pellerin, 2016).

Despite this distinguished record on the battlefield, the U.S. Air Force has had an uncomfortable institutional relationship with the Warthog.[2] Critics assert that Air Force leaders have sought to terminate the A-10 since its inception because of an entrenched preference for high-technology fighters and indifference toward the CAS mission (Pierre Sprey, quoted in Wheeler, 2013). A 2003 op-ed in the New York Times alleged that the Air Force was planning to retire the entire fleet of A-10s, replacing them with F-16s and later with F-35s (Coram, 2003). The Air Force denied then that any such plan existed (Hornburg, 2003). The issue resurfaced in 2013, when the Air Force first went public with its proposal to terminate the A-10 (Mehta, 2013).

On March 4, 2014, the Pentagon formally announced plans to retire the entire A-10 fleet.[3] The Air Force Chief of Staff testified "painful budget cuts" in FY15

1 For a fuller account of the Warthog's history of service, see Appendix A, "Discursive Notes," Note 1 in supplementary material.

2 For an explanation of why the A-10 cannot feasibly be transferred from the Air Force to the Army or Marine Corps, see Appendix A, Note 2 in supplementary material.

3 According to this plan, the A-10 fleet would be placed in Type-1000 ready storage. See Mehta (2014) and also Schwartz (2012).

required retiring the A-10 (Marshall, 2014). The Pentagon projected savings of \$3.7 billion in future program costs, in addition to \$500 million to be saved on discontinued upgrades to the A-10s. The Air Force assessed three alternatives to achieve a similar budget reduction given the pressure of sequestration: reducing the number of F-15s, trimming the F-16 fleet, and delaying the procurement of F-35 Joint Strike Fighters (Marshall, 2014). These three options were rejected in favor of a fourth option, which the Air Force proposed and the U.S. Department of Defense (DOD) accepted: terminate the A-10 fleet outright. The F-35 was proposed to take on the A-10's traditional roles and functions, notably CAS (Marshall, 2014). Congress blocked the A-10's retirement in FY15, but the Air Force and DOD reintroduced this plan in the FY16 budget (Everstine, 2015, see also U.S. Department of Defense, 2015*a*). The GAO cast doubt on the A-10 retirement plan in a 2016 report to Congress, concluding that the Air Force had neither performed a credible analysis of CAS requirements nor provided a sound basis on which to compare alternatives to meet its budget targets (Government Accountability Office, 2016, p. 2).

The A-10's increasing significance in Syria and Iraq prompted a modest change in the FY17 budget submission: a recommendation to phase out the Warthog fleet over 5 years (U.S. Department of Defense, 2016). Secretary of Defense Ash Carter, testifying before Congress, cited the A-10's payload capacity for conducting large-scale strikes on ISIS as a reason for delaying the full retirement of the fleet until 2022 (Lendon, 2016). Nevertheless, this budget entailed the phased replacement of A-10s with F-35s, beginning in FY18 (Seligman, 2016*a*).

The FY18 budget proposal backtracked further. The Secretary of the Air Force offered this assurance: "When we look out 5 years, they're still in the Air Force inventory" (Machi, 2017). The FY19 budget similarly imposed no immediate threat of retirement. However, the A-10's place in the arsenal is hardly secure. There are good reasons to expect the replacement plan to resurface in future budget proposals. First, the Air Force has long considered this plan to be a pillar of modernizing its aircraft fleet; such institutional commitments are hard to reverse. Second, the Air Force has not abandoned its core argument in favor of replacement: that it would be a cost-efficient way to maximize airpower and is superior to acknowledged alternatives. Finally, the FY18 proposal was \$54 billion higher than the FY17 defense budget, a 10% increase that substantially reduced the need to economize (U.S. Department of Defense, 2017*a*). The FY19 budget was higher still at \$717B in total, thus reducing pressures to make hard tradeoffs on capabilities (U.S. Department of Defense, 2018*e*). The FY20 budget may be as high as \$750B (Hicks *et al.*, 2019). But, reason dictates that defense budgets cannot increase indefinitely. When austerity does strike, the plan to have F-35s supplant A-10s will likely resurface.

3 Methods

The methods employed in this article differ somewhat from traditional benefit cost approaches for two reasons. First, the choice is merely between two alternatives in conducting CAS: continue to use the A-10, or terminate the A-10 and conduct future CAS missions using the F-35. This vastly simplifies the analysis; the two alternatives need merely to be compared on cost and performance. If either wins on both grounds, then there is no need to attach dollar values to gains in performance. Second, there are no clear measurements that detail the performance of the two aircraft on many important dimensions.[4] Moreover, there is no tally of the choices of individuals who had to select one alternative or the other. Third, value of statistical life estimates are not useful because while the number of enemy casualties caused by an effective strike may be known, the number of friendly casualties prevented is generally indeterminate (Melese *et al.*, 2015). The lack of data in these realms makes the evaluation task more difficult. And it would be meaningless to ask ordinary individuals to choose between the two, in the spirit of contingent valuation studies.[5]

Given these analytic challenges, this article uses expert elicitation to (i) identify a set of relevant dimensions upon which to evaluate performance and (ii) to assign comparable utility values to the A-10 and F-35, and weight them, to allow for a rigorous performance comparison. The most relevant dimensions to evaluate CAS performance are not obvious, nor objectively determinable. Further, the practical performance of aircraft on these dimensions are complex matters, and their utilities cannot be determined directly from available data. (There are two exceptions, speed and range, noted in the analysis.) The subjective but knowledge-based responses of experts provide the best available data for a quantitative analysis of CAS performance. Where objective data are not available or determinable, expert elicitation may be the best means of closing information gaps (Pindyck, 2016). Expert opinion is particularly credible when it yields values that do not vary widely, as is the case here (Pindyck, 2016).

The experts we consulted were joint terminal attack controllers (JTACs), the highly specialized troops who call in aircraft and direct airstrikes. We also analyzed a data set describing the air support that a special operations task force received over a 9-month period in Afghanistan. A performance analysis based on these data shows that replacing the A-10 fleet with F-35s would significantly compromise the ability of the

4 When such measurements are available, rigorous estimates can be derived directly from the data, even in fairly complex multiattribute situations. See, for example, Cordes *et al.* (2006), which provides a thorough valuation of the multiple dimensions on the cost side of homeland security measures.

5 On methods relying on individual choices, see, for example Ready *et al.*, (1997), an early study that compares contingent valuation estimates and hedonic pricing methods for valuing farmland. That study finds quite consistent answers.

USA to accomplish important and likely future missions. This plan would involve a vast degradation of CAS capability, not the small loss that the plan's proponents claim. Thus, the plan is operationally unsound.

A cost analysis shows that the replacement plan is unsound fiscally, as well. The A-10s are relatively cheap to operate and have zero procurement costs because they are already in the inventory. By contrast, F-35s have staggeringly high procurement and operating costs. Slightly reducing the number of F-35s purchased over a multiyear period would pay for the continued operation of the entire A-10 fleet, and would additionally save tens of billions of dollars.

Replacing A-10s with F-35s would involve a double sacrifice: a large net loss of CAS capability required for the conflicts of the foreseeable future, and the unnecessary expenditure of vast amounts of taxpayer monies. A mixed arsenal of A-10s and F-35s would provide the balanced air fleet the USA requires, given the likely national security challenges of the next two decades.

4 Low-intensity conflicts: Their likelihood and CAS requirements

The 2018 National Defense Strategy (NDS) focuses on major power adversaries while acknowledging the continuing terrorist threat from groups such as ISIS (U.S. Department of Defense, 2018*f*). This strategy is intended to drive defense spending for the foreseeable future, and is the intellectual foundation of budget proposals through FY20 and counting (Hicks *et al.*, 2019). The NDS asserts "long-term strategic competitions with China and Russia are the principal priorities for the Department" (U.S. Department of Defense, 2018*f*). To counter modern-state adversaries like China and Russia, U.S. forces must deter them and, if deterrence fails, defeat them in high-intensity warfare. The possibility that competition and conflict in a range of realms could escalate into a major war clearly justifies investing in advanced weapons systems, of which the F-35 is a prime example. Similarly, to defeat ISIS and other terrorist groups, including new ones to emerge in the future, the U.S. military must be well equipped to fight low-intensity conflicts. The security of the USA and its allies requires effective preparation for both high- and low-intensity conflicts.

Fortunately, the likelihood of a high-intensity conventional war is low. The global economy intertwines the interests of states in ways that generally make high-intensity wars unappealing lose-lose scenarios, particularly given the potential for nuclear escalation leading to millions of fatalities. Therefore, the USA and its allies will presumably make every effort to avoid a war with a near-peer adversary such as China or Russia. Decision makers in those countries will likely be equally reluctant to provoke such a conflict, as they have been for decades. The primary purpose of advanced weapons systems such as the F-35 is to deter adversaries from initiating high-intensity wars or taking actions that could precipitate such wars.[6]

If a high-intensity war were to occur, advanced stealth aircraft would be indispensible. The F-35 is a prime example of a weapon this worst-case scenario would call for. In a conflict with a modern state, the F-35's advanced technology and signature characteristics of SSR would be critical for penetrating integrated air defenses, shooting down hostile aircraft, and clearing the way for ground forces and other airplanes like the A-10. The F-22 and F-35 are explicitly missioned to protect and support other aircraft in "advanced threat environments" where enemy air-to-air and ground-to-air threats are numerous and highly capable (U.S. Air Force, 2014, 2015*b*).

Although non-stealthy aircraft like the A-10 might not be able to operate independently in advanced threat environments, they could nonetheless perform critical functions in a high-intensity war. A full-scale war with North Korea is one example that the NDS considers as a serious possibility (U.S. Department of Defense, 2018*f*). Presumably, after an initial high-intensity battle for air superiority, attack aircraft would be required to find and destroy numerous ground forces, particularly tanks, dispersed and camouflaged in mountainous terrain (Project on Government Oversight, 2014). The A-10 was purpose-built to destroy armored vehicles and tanks, as well as human targets, and is exquisitely suited to this mission (U.S. Air Force, 2015*a*).

A combination of other aircraft including unmanned aerial vehicles (UAVs), gunships, and bombers, cannot provide an equivalent capability. These aircraft have characteristics and capabilities significantly different from those of A-10s and multirole fighters. Attack helicopters have excellent sense of the ground environment, which we may call "ground sense," but are lightly armed and vulnerable to direct fire (Project on Government Oversight, 2014). Gunships are heavily armed propeller-driven aircraft that lack speed and maneuverability. UAVs can orbit or "loiter" for long periods over a specific area, but lack the ground sense of manned aircraft and have limited strike capabilities. None of these platforms could replace the specialized CAS capability of the A-10, nor could a combination of them (Government Accountability Office, 2016, p. 1). The closest comparison and best replacement for the A-10, if it is to be replaced, is the one that the Air Force has proposed: a multirole fighter (U.S. Air Force, 2014). As the GAO noted, the loss of CAS capability involved in retiring the A-10 cannot be hand-waved away on a belief that a variety of other platforms will somehow make up the difference (Government Accountability Office, 2016, p. 16). Consequently, this analysis focuses on a one-to-one comparison of the A-10 and its proposed replacement, the F-35.

Low-intensity conflicts (U.S. Department of Defense, 2018*d*) include counter-terrorist operations, irregular warfare, and hybrid wars that blend conventional and

6 For a discussion of exceptions to the streak of low-intensity conflicts since Korea, notably the 1991 Persian Gulf War, see Appendix A, Note 3 in supplementary material.

unconventional elements (Hoffman, 2007). Unfortunately, the USA appears likely to continue to engage in low-intensity conflicts. Virtually no policymakers paid attention to ISIS half a dozen years ago. Yet, in August 2014, a new low-intensity conflict emerged in Iraq and Syria with the rise of ISIS. In Iraq, the USA provided special operations advisors and air support to the Iraqi Army and Kurdish Peshmerga forces (Landler & Gordon, 2014). In 2016, Iraq undertook a major operation to clear Mosul, its second largest city. Dug-in ISIS units refused to surrender in the face of overwhelming firepower and held out until the summer of 2017. Fighting to the death, ISIS troops had to be literally blasted out of their positions with airstrikes (Cooper, 2017).

In Syria, a U.S.-led coalition supported the Free Syrian Army, Kurdish militias, and other groups resisting ISIS (Lemmon, 2017). This proved to be a true hybrid war, given that ISIS conducted terrorist operations, such as car bombings, in addition to fielding regular forces including tanks and artillery. By late 2017, Kurdish-led forces had encircled ISIS' self-proclaimed capital of Raqqa and began clearing it block-by-block under the cover of coalition airpower (Lemmon, 2017). An entire squadron of A-10s was assigned to provide the extremely precise CAS required within the dense urban core of Raqqa, for example to strike point targets at the feet of five-story buildings (Rhynes, 2018). ISIS retreated after months of hard fighting, and by late 2018 had lost almost all territory.

The USA and its allies may need to engage in this type of warfare outside the Middle East. There are many other potential low-intensity threats. Gangs plague Central America and contribute to instability near the southern border of the USA (Jones, 2012). Al Qaida is weakened but remains a terrorist network with a global reach, and ISIS has spread well beyond the Levant (Kirkpatrick, 2015). Boko Haram, a jihadist group in northwest Africa, pledged allegiance to ISIS in 2015 (Callimachi, 2015). In 2017, ISIS militants ambushed a joint U.S.-Nigerien patrol in the remote Tongo Tongo region of Niger; they killed four U.S. special operations troops and five Nigerien soldiers (Searcey & Schmitt, 2017).

Russia's annexation of Crimea and its military support to separatists in Eastern Ukraine (Parfitt, 2015) represent major breaches of international norms within Europe (Mankoff, 2014). In response, NATO member nations have provided equipment and training to Ukrainian forces fighting the Russian-backed separatists (Gordon & Schmitt, 2015). Ukraine could become a flash point that precipitates a high-intensity conflict, or the current proxy war could simmer indefinitely. Moreover, the case of Ukraine demonstrates that low-intensity conflicts are dangers that can emerge anywhere, not just in the Middle East and Africa.

Conflicts with terrorists, insurgents, and other irregular adversaries remain highly likely; they reflect the military reality facing the USA and its allies for many years to come (Kilcullen, 2009, p. 2–27). The Trump administration recognizes terrorism as a prevailing threat to U.S. national interests (McMaster & Cohn, 2017). The NDS, in contrast, prioritizes building up advanced conventional forces to widen the competitive advantage over China and Russia (U.S. Department of Defense, 2018*f*). It follows that the defense budget invests in weapons of high-intensity war at record levels (U.S. Department of Defense, 2018*c*). This strategy risks over-investing in forces and capabilities suited to potential mission requirements, at the expense of concrete ones. The plan to retire the A-10 fleet to buy a few more F-35s exemplifies this misalignment in the NDS: it does not rationally balance the valid need for high-end deterrence against the reality of the low-intensity wars the USA will surely keep fighting.

Low-intensity conflicts invariably require extremely precise airstrikes, but seldom entail much air-to-air combat. Terrorist and insurgent groups usually do not have aircraft (Lambeth, 2005, p. 84–87). Advanced weaponry and overwhelming military power seldom deter irregular adversaries. Deterrence fails because these groups rarely have a physical center of gravity that can be captured or destroyed.[7] They are usually ideologically motivated and resigned to deaths among their members. Moreover, they can easily disperse into local populations. Al Qaida continues to actively threaten the USA, although much of its leadership has been eliminated. Although ISIS highly valued and fought desperately to retain its core territory in the Levant, it is unbowed by severe losses (Cooper, 2017). The logic of deterrence simply does not apply to groups that are prepared to fight to the death. The successful prosecution of low-intensity conflicts involves actual operations, not deterrence.

In the current political and strategic environment, U.S. policymakers plan to leverage increasingly the precision, stealth, flexibility, and relatively low cost of special operations forces to perform these operations (McRaven, 2013). The United States Special Operations Command (SOCOM) expanded at an unprecedented pace between 2001 and 2017, from 45,690 to 70,000 troops and from a $2.3 billion to an $8 billion budget (Lohaus, 2014, p. 31; see also SOCOM, 2000, p. 93; Thomas, 2017; SOCOM, 2016, p. 3). This vast increase in resources for SOCOM reflects its role as the primary U.S. force for low-intensity conflicts, particularly those against insurgent and terrorist groups (Thomas & Dougherty, 2013, p. 4–5, 45, 46, 77).

Special operations forces sometimes act alone. More often, they work alongside complementary ground forces, such as soldiers and Marines, in joint operations. In conflicts requiring a mass effort across a large and populous nation, conventional units will predominate with special operations in supporting roles: the counterinsurgency in Iraq following the 2003 invasion is a prime example (Lohaus, 2014, p. 38–43). In low-intensity conflicts that require a less obtrusive U.S. presence, special operations units perform most, if not all, combat operations.

7 ISIS may prove to be a partial exception to this rule, given that it appears to value highly the control of territory and populations.

Foreign partner forces supported by U.S. troops and air power also rely heavily on CAS.[8] Although U.S. forces have not engaged in direct ground combat in Iraq and Syria, they have provided extensive assistance from just behind the front lines. This includes directing CAS for Iraqi troops, Syrian Kurdish militias, and other partners engaging ISIS in close combat (Nordland & Cooper, 2015, Yan *et al.*, 2014). In both countries, U.S. and coalition aircraft have struck hundreds of targets in close proximity to friendly forces, civilians, or both (Nordland, 2015, see also Yan *et al.*, 2014). In 2015, these strikes successfully removed 1,000 ISIS irregulars from the battlefield each month (John W. Hesterman III, quoted in Marshall, 2015). The coalition sustained this blistering pace of CAS success through the ensuing 2 years (Cooper, 2017). There is anecdotal evidence that A-10s have been outperforming multirole fighters in this conflict, where the CAS requirement includes both high volume and high precision. By 2016, a small number of A-10s were accounting for nearly one-third of U.S. strikes in Iraq and Syria (Pellerin, 2016), and had dropped 13,856 total weapons (Woody, 2018).[9] These strikes are reported to have been highly accurate against, for example, point targets in the heavily populated city center of Raqqa (Rhynes, 2018). In future low-intensity conflicts, highly accurate CAS in support of foreign partner forces will remain a critical requirement, whether those forces operate on their own or with U.S. special operations troops directing airstrikes for them.

Low-intensity conflicts present unique and intense CAS requirements. Ground troops fighting terrorists and insurgents need aircraft to strike individual human targets that are fleet, mobile, disguised, and dangerously close to civilians and/or friendly forces. Insurgent needles must be picked out of civilian haystacks; in short, precision CAS is required.

Skilled irregular adversaries like the Taliban employ elaborate systems of lookouts to spot aircraft with the naked eye or to identify the sound of their engines. When approaching aircraft are detected, the Taliban know to go to ground. Given favorable conditions, they will open fire from bunkered positions against low-flying aircraft. Helicopters, especially vulnerable to this form of attack, are a favorite target.

Insurgents are hard to pinpoint from the air. They skillfully blend into civilian populations; they appear and disappear suddenly on the battlefield. They often stage attacks from civilian homes, hoping that excessive firepower and imprecise airstrikes from counterinsurgents will unintentionally harm civilians, undermining the counterinsurgents' legitimacy. A March 17, 2017, airstrike in Mosul resulted in 105 civilian deaths. An investigation found that ISIS had baited the coalition into

8 For a discussion of U.S. airpower in support of foreign partner forces from 1999 to 2011, see Appendix A, Note 4 in supplementary material.

9 Only one aircraft type was more prolific during this critical phase of the conflict: the F-15E released 14,995 total weapons during these 2 years.

bombing a building where displaced civilians had been deliberately gathered as targets.[10] This tactic permits one poorly placed bomb to unravel months of careful counterinsurgency work, thereby promoting strategic defeat.[11] Disciplined irregular troops will also "hug the belt," attacking from extremely close range so that airstrikes endanger counterinsurgent forces (Hackworth & Sherman, 1989, p. 488). Such risks from friendly fire became evident when an errant airstrike from a B-1B bomber accidentally killed five U.S. servicemen in Afghanistan in 2014 (Londoño & Salahuddin, 2014).

Precision CAS under these conditions requires a highly effective ground-air team, a super-system composed of two separate and distinct systems: a ground force and an aircraft with its pilot. Ground troops in heavy combat are usually sweaty, dusty, exhausted, and extremely stressed. Hearing the unflappable calm of pilots on the radio, sometimes referred to as the "voice of God" (Wheeler, 2013), reassures them. Pilots see the big picture of the battlefield and can relay what they observe over a wall or beyond a rise in the terrain. On the ground, troops have a close-up view and a nuanced feel for what is happening, identifying detail not visible or not interpretable from the air. The experience and information acquisition of these two "systems" effectively complement one another.

Specially trained JTACs link the two components of the ground-air super-system. In some units, they are full-time specialists, such as Air Force combat controllers. In other units, such as SEAL Teams, they have been cross-trained to control aircraft in addition to other duties. JTACs provide air expertise to commanders, control the airspace over ground forces, and call in strikes. Given their training, experience, and responsibilities, they are acknowledged experts on the use and effectiveness of CAS. Therefore, we surveyed JTACs for their views on the requirements for precision CAS and on the performance of various U.S. aircraft.

5 JTAC Survey

5.1 Method

To identify the critical factors affecting CAS effectiveness in low-intensity conflict, we consulted JTACs with combat experience controlling aircraft and calling in airstrikes in Iraq and Afghanistan. These "consumers" of CAS are recognized experts on its use and effectiveness.

10 In fact, the investigation led by Air Force General Matthew Isler found that ISIS planted explosives to amplify the effects of the strike and collapse the building on the families inside. See Snow (2017).

11 On the strategic impact of inaccurate airstrikes in undermining the legitimacy of U.S. forces in Afghanistan, see O'Hanlon and Sherjan (2010, p. 27).

This survey tested our two major claims. First, we claim that CAS performance requires five dimensions of capability: ground sense, loiter time, low noise signature, gun effectiveness, and survivability against direct fire. Second, we claim that the A-10 dramatically outperforms both current generation multirole fighters and the F-35 in the CAS role.

Sixty individuals who were prescreened for qualification as special operations JTACs received a survey link forwarded by a special operations air officer.[12] Forty-two respondents completed the survey.[13] The survey[14] presents a short narrative describing a low-intensity conflict scenario designed to mirror the reality of contemporary active conflicts:

You are a JTAC assigned to a special operations unit. Your unit is supporting a joint task force engaged in a low-intensity conflict, which has both counter-terrorism and counterinsurgency elements. Specific conditions of the conflict are:

1. *Friendly forces have air supremacy.*
2. *Enemy personnel blend into the civilian population making them hard to identify and target.*
3. *Collateral damage to innocent parties would have high adverse consequences, and has to be avoided even at significant cost.*
4. *Enemy forces are motivated and skilled, often engaging your unit in intense firefights that carry a significant risk of injury or death.*

The survey then poses seven questions referring to the scenario.

Question 1 asked participants to score the relevance of eight dimensions of capability: loiter time, radar stealth, ground sense, low noise signature, survivability against direct fire, speed, gun effectiveness, and range.[15] The capabilities were listed in this order so that no preference could be inferred from the design of the question. Capabilities were scored on a 1–7 Likert scale for importance (1 = completely irrelevant; 2 = minimally relevant; 3 = slightly important; 4 = somewhat important; 5 = very important; 6 = critical; 7 = extremely critical).

Questions 2–7 asked participants to compare the six possible pairings of these aircraft (F-15E, F-16C, F-35, and A-10) for CAS capability, again on a 1–7 Likert

12 For the complete text of the survey, see Appendix B, "CAS Survey 2014" in supplementary material.
13 Thirty respondents had at least one combat deployment as a JTAC. The 42 respondents averaged 1.8 combat deployments as a JTAC.
14 The survey, as it appeared to the respondents, is provided in Appendix B in supplementary material.
15 The wording in the survey differed slightly from the terms used in this article; the authors consider the differences in terminology to be insignificant. For a detailed account of the differences, see Appendix A, Note 5 in supplementary material.

Table 1 Dimensions of CAS capability and importance (question 1).

Question 1: How important are the following qualities in close air support aircraft on a 1–7 scale (least important to most important)?

No.	Question	Completely irrelevant [1]	Minimally relevant [2]	Slightly important [3]	Somewhat important [4]	Very important [5]	Critical [6]	Extremely critical [7]	Total responses	Mean
1	Loiter time	0	0	1	3	18	7	13	42	5.67
2	Radar stealth	14	17	5	4	1	0	1	42	2.17
3	Detailed sense of the ground environment	0	0	0	3	6	12	21	42	6.21
4	Low audible noise signature	1	2	4	11	16	5	3	42	4.57
5	Survivability against small arms fire from the ground	0	0	4	5	13	9	11	42	5.43
6	Speed	0	6	11	11	12	1	1	42	3.86
7	Accuracy of gun/cannon; low risk of collateral damage	0	0	0	1	3	6	32	42	6.64
8	Range	0	0	7	7	11	14	3	42	4.98

Statistic	Loiter time	Radar stealth	Detailed sense of the ground environment	Low audible noise signature	Survivability against small arms fire from the ground	Speed	Accuracy of gun/cannon; low risk of collateral damage	Range
Min value	3	1	4	1	3	2	4	3
Max value	7	7	7	7	7	7	7	7
Mean	5.67	2.17	6.21	4.57	5.43	3.86	6.64	4.98
Variance	1.15	1.65	0.90	1.71	1.62	1.44	0.53	1.49
Standard deviation	1.07	1.29	0.95	1.31	1.27	1.20	0.73	1.22
Total responses	42	42	42	42	42	42	42	42

scale, from *strongly prefer the first* to *strongly prefer the second.* The pairs of multirole fighters were included to conceal our focus on the A-10 versus these fighters.[16]

The next questions asked participants to compare A-designated attack aircraft in general, as exemplified by the A-10, to F-designated multirole fighters. Participants were instructed to consider all types of potential conflicts the USA may face in the future, including low-intensity and high-intensity conflicts. Subsequent questions asked participants to self-report their years of active service, years as a JTAC, and experience controlling aircraft and calling in airstrikes in Iraq and Afghanistan. The final question was narrative, soliciting general comments on the "subject of CAS and its application to future U.S. conflicts."

5.2 Results

The survey results indicated that the five dimensions of capability we identified above are essential for precision CAS in low-intensity conflict. Their mean Likert scores were gun effectiveness (6.64), ground sense (6.21), loiter time (5.67), survivability (5.43), and noise signature (4.57). Among the three SSR, only range (4.98) scored higher than any of the five identified dimensions, and then just one.[17] Speed (3.86) and stealth (2.17) scored distant lows.

Are these differences in the assessment of the eight capabilities for CAS statistically significant?[18] A Wilcoxon Sum-Rank Test provides the answer. The difference between the first (accuracy of gun/cannon) and second (detailed sense of the ground environment) scoring capabilities is significant at the 0.05 level, as was the difference between the rankings of the second and third capabilities. The results for the next three capabilities, 3 to 4, 4 to 5, and 5 to 6, fell short of significance. Thus, we compare 3 and 5, 4 and 6, and 5 and 7. The first was significant at the 0.05 level. The next two at the 0.01 level. Capabilities 6 to 7 and 7 to 8 differed at well beyond the 0.01 levels. In short, there were statistically significant differences among the rankings of capabilities.

Given a low-intensity conflict scenario, the JTACs vastly preferred the A-10 to the fighters. 93, 98, and 98% preferred the A-10 to the F-15E, F-16C, and F-35, respectively. No participant preferred any multirole fighter to the A-10. These survey results clearly identify the A-10's superior capabilities for CAS.[19]

16 See Appendix B in supplementary material.

17 The A-10 outperforms the fighters in terms of range based on U.S. Air Force fact sheets; see U.S. Air Force (2014, 2015*a*, *b*).

18 We thank a referee for requesting the statistical analyses in this article.

19 Complete survey data are provided in Appendix C, "CAS Survey 2014 Results" in supplementary material.

Table 2 F-35 and A-10 head-to-head comparison (question 6).

Question 6: Would you prefer to receive support from an F-35 or A-10?			
No.	**Answer**	**Response**	**%**
1	Strongly prefer F-35	0	0
2	Somewhat prefer F-35	0	0
3	Slightly prefer F-35	0	0
4	Makes no difference	1	2
5	Slightly prefer A-10	3	7
6	Somewhat prefer A-10	4	10
7	Strongly prefer A-10	34	81
	Total	42	100

Statistic	**Value**
Min value	4
Max value	7
Mean	6.69
Variance	0.51
Standard deviation	0.72
Total responses	42

Questions 6, 12, 14, and 15 all have 7 responses that are symmetric between the A-10 and either the F-35 or a multirole fighter. Thus a 1 and a 7 would both be "much more capable" or "strongly prefer." The null hypothesis would be no difference between the airplanes, so that on average there would be as many 7s as 1s, 6s as 2s, and 5s as 3s. The alternative hypothesis would be that the higher numbers would be more frequent. In fact, for none of these tables were there any values below 4. Thus, for question 6, there are 41 observations favorable to the alternative hypothesis. Each was 1/2 likely given the null. The statistical significance is thus ($1/2^{41}$), implying significance at an extreme level. That is true for questions 12, 14, and 15 as well.[20]

Asked to assess the importance of single-purpose fixed-wing aircraft specifically designed to conduct ground strikes, *in addition to* multirole fighters, the vast majority of respondents considered it "extremely important."

Question 8 has only five answers, and they are not symmetric. However, 35 of 42 answers were Extremely or Very important, indicating that a null of as likely as not to be no more than Somewhat important would be rejected at the 0.00001 level.

Extending the analysis to all possible future conflicts, including high-intensity warfare, participants judged the A-10 to be markedly more capable at CAS than fighters. The questions and the percentages of respondents who found the A-10 more

20 Note, this is a very conservative test, since it takes no account of the more powerful implications of answers such as strongly prefer or much more capable.

Table 3 Importance of fixed-wing aircraft for ground strikes in addition to multirole fighters (question 8).

Question 8: Looking to our nation's future security, how important is it that its arsenal include single purpose fixed-wing aircraft specifically designed to conduct ground strikes in addition to multirole fighters?

No.	Answer	Response	%
1	Extremely important	23	55
2	Very important	12	29
3	Somewhat important	5	12
4	Slightly important	1	2
5	Not important	1	2
	Total	42	100

capable were: "Which is better at destroying point targets, most importantly individual human enemies?" (95%), "Which is better at avoiding collateral damage to innocent or uninvolved civilians?" (81%), "Which has a better feel for what is happening on the ground?" (95%). Although a small percentage judged equality, no participant rated the multirole fighter as more capable at any of these tasks. Responses to the narrative item at the end of the survey reinforced these quantitative results (see Appendix C in supplementary material).

The JTACs in the survey group express an intense preference for CAS-specialist attack aircraft over multirole fighters across a range of conflict scenarios. Although the F-35 was not operational as of the survey, the JTACs' experience with current generation fighters allows them to make an informed assessment of its expected CAS capability.

6 Data set: Afghanistan Airstrikes 2011

6.1 Method

We cross-referenced the results of this survey with data from a special operations task force that operated in Afghanistan in 2011. The force consisted of more than a dozen tactical units that conducted 195 counterinsurgency missions over a 9-month period (Dalton, 2011).[21] These missions used CAS extensively, as is the norm in

21 Bale Dalton, "SOTF-XX CAS Data 2011." This data set is a Microsoft Excel spreadsheet. Unit names and JTAC call signs have been modified to preserve security and privacy. The data set is available upon request as Appendix D, "SOTF-XX CAS Data 2011" in supplementary material.

Table 4 A-10 and multirole fighter capabilities comparison (questions 12, 14, and 15).

Question 12: Which is better at destroying point targets, most importantly individual human enemies?

No.	Answer	Response	%
1	A multirole fighter is much more capable	0	0
2	A multirole fighter is somewhat more capable	0	0
3	A multirole fighter is slightly more capable	0	0
4	About the same	2	5
5	An A-10 is slightly more capable	6	14
6	An A-10 is somewhat more capable	7	17
7	An A-10 is much more capable	27	64
	Total	42	100

Statistic	Value
Min value	4
Max value	7
Mean	6.40
Variance	0.83
Standard deviation	0.91
Total responses	42

Question 14: Which is better at avoiding collateral damage to innocent or uninvolved civilians?

No.	Answer	Response	%
1	A multirole fighter is much more capable	0	0
2	A multirole fighter is somewhat more capable	0	0
3	A multirole fighter is slightly more capable	0	0
4	About the same	8	19
5	An A-10 is slightly more capable	5	12
6	An A-10 is somewhat more capable	10	24
7	An A-10 is much more capable	19	45
	Total	42	100

Statistic	Value
Min value	4
Max value	7
Mean	5.95
Variance	1.36
Standard deviation	1.17
Total responses	42

Question 15: Which has a better feel for what is happening on the ground?

No.	Answer	Response	%
1	A multirole fighter is much more capable	0	0
2	A multirole fighter is somewhat more capable	0	0
3	A multirole fighter is slightly more capable	0	0
4	About the same	2	5

(Continued)

Table 4 (Continued).

Question 15: Which has a better feel for what is happening on the ground?

No.	Answer	Response	%
5	An A-10 is slightly more capable	4	10
6	An A-10 is somewhat more capable	10	24
7	An A-10 is much more capable	26	62
	Total	42	100

Statistic	Value
Min value	4
Max value	7
Mean	6.43
Variance	0.74
Standard deviation	0.86
Total responses	42

contemporary low-intensity conflicts.[22] The units had CAS aircraft assigned to support their missions (as opposed to on-call) 89% of the time. They were supported by 2.3 aircraft per mission on average. In one case, a fleet of 12 aircraft supported a single unit (Dalton, 2011).

These units called in 62 airstrikes. For each strike, the data set lists the aircraft used; the weapon used; the number of rounds, bombs, or passes; and a battle damage assessment briefly describing the result of the strike. Forty-six strikes were against human targets; 16 were against area targets such as vehicles or fighting positions (Dalton, 2011).

6.2 Results

When A-10s were available, JTACs used them against human targets 100% of the time, and never against area targets. When multirole fighters were available, JTACs used them against human targets 33% of the time, and against area targets 67% of the time. Thus A-10s were sorted to strike challenging human targets.[23] Humans are the primary intended targets of most uses of CAS against terrorist and insurgent groups. This data set is consistent with the finding that the A-10 overwhelmingly outperforms multirole fighters at the CAS mission.

Defense officials have publicly acknowledged the superiority of the A-10 to multirole fighters, including the F-35, in performing CAS (Schogol, 2012).

22 For the central role of CAS in the U.S. conflict with ISIS, see U.S. Department of Defense (2015*a*).
23 Other aircraft in this data set include attack helicopters, gunships, and unmanned aerial vehicles (UAVs).

The replacement plan assumes that the difference in CAS performance is modest, making the loss in capability acceptable. However, the expert judgment of the 42 surveyed JTACs and data from 195 missions in Afghanistan generate a quite different conclusion: the difference in capability is vast.

7 Performance analysis: The A-10 versus the F-35

A quantitative analysis comparing the A-10 and the F-35 measured the difference in performance. Results from survey questions 12–15 and Air Force fact sheets were used to determine the performance of the two aircraft on the eight attributes identified above. The A-10 has the advantage on the six most important attributes. The F-35 has the advantage in speed and stealth. The A-10 also has the advantage in range, based on U.S. Air Force fact sheets (U.S. Air Force, 2014, 2015*b*; fact sheet data are summarized in Table 5).

We assigned a utility score of 3 to the aircraft with the advantage. On each objective, the lesser aircraft received a utility score of 2 if the difference in capability was small and of 1 if the difference was large.[24] The A-10 received a 0 for stealth because it has no radar stealth capability.

These raw effectiveness scores for each attribute were weighted with respect to importance for low-intensity conflict (weight), using the mean value provided by the JTACs in question 1 of the survey.[25] This approach followed the direct assessment method described by Melese *et al.*, treating the JTACs as the "decision makers" for purposes of weighting (Melese *et al.*, 2015). A distinction is that our weights are on a 1–7 scale (see Table 1). The weighted scores were then summed to yield a total low-intensity conflict score for each of the two aircraft (A-10 utility score and F-35 utility score).[26]

24 To determine which aircraft has the advantage and by how much, we compared the relevant U.S. Air Force fact sheets and reviewed publicly available information on the capabilities of both aircraft. See U.S. Air Force (2014, 2015*a*); see also Appendix A, Note 6 in supplementary material. The authors also consulted the expert judgment of a highly experienced JTAC who has called in a large number of airstrikes in Iraq and Afghanistan; the authors then cross-checked with the surveyed JTACs' responses to Questions 12–15 and 21. For example, the results of Question 15 support a conclusion that the difference in ground sense between the A-10 and F-35 is large, and in the A-10's favor. See Appendix C in supplementary material.

25 The mean values from Question 1 of the survey reveal the relative importance the JTACs place on each attribute for CAS in a low-intensity conflict. Thus, they can be used as the weights for each attribute.

26 This analysis implicitly assumes that the scores for the various features of the aircraft are independent and can be added in gauging overall effectiveness. If they complemented each other—for example, by being to some extent multiplicative—that would increase the CAS advantage of the A-10. The 0–3 scores implicitly represent cardinal utilities for each attribute so that an increase from 1 to 2 is as valuable as one from 2 to 3. Although a 0–3 scale is arbitrary, the differences between the A-10 and F-35 are extremely clear for the six most important attributes for CAS. Hence, no plausible scaling could have eliminated the A-10's significant advantage for CAS.

Table 5 U.S. Air Force fact sheet data.

Data	A-10	F-35
Stealth	N/A	Yes
Speed	Mach 0.75	Mach 1.6
Range	2580 mi	1350+ mi

Table 6 Overall effectiveness of A-10 and F-35 in low-intensity conflict (LIC).

Attribute	Weight	A-10	F-35	A-10 utility score	F-35 utility score
Ground sense	6.21	3	1	18.63	6.21
Loiter time	5.67	3	2	17.01	11.34
Noise sig.	4.57	3	1	13.71	4.57
Gun eff.	6.64	3	1	19.92	6.64
Survivability	5.43	3	1	16.29	5.43
Stealth	2.17	0	3	0	6.51
Speed	3.86	1	3	3.86	11.58
Range	4.98	3	2	14.94	9.96
Total	–	–	–	104.36	62.24

The A-10 dramatically outscored the F-35, 104.36–62.24. This was inevitable, given its superiority on the six most important characteristics, and its notable superiority (scoring 3 versus 1) on the two most important. This analysis indicates that cancelling the A-10 would significantly and unacceptably hurt the U.S. CAS capability.

To check whether our results were robust to plausible alternate performance scores, the authors provided a questionnaire to additional highly experienced JTACs asking them to provide their own scores. Three JTACs completed the questionnaire; their scores are shown in Table 7.[27] JTAC no. 1 was much more favorable to the F-35, giving it the advantage on six of eight attributes. However, he scored the A-10 higher, 3-0, on ground sense and gun effectiveness, so that the A-10 beat the F-35, 85.17–80.04. JTAC no. 2's scores were somewhat more favorable to the F-35 than the authors', resulting in the A-10 winning 105.82–84.68. JTAC no. 3's scores were similar to the authors', resulting in the A-10 winning, 106.53–62. These results show that our analysis and its results are robust to alternate performance scoring of the two aircraft. The CAS performance of the A-10 under low-intensity conflict conditions is clearly superior to the F-35.

This interpretation is robust to changes in the weights of each attribute. Using the original performance scores in Table 6, if we increase the weight given to stealth

27 These JTACs did not know the weights and were asked to score the A-10 and F-35 on pure performance. See Appendix E in supplementary material.

Table 7 Alternate performance scores.

Attribute	Weight	A-10	F-35	A-10 utility score	F-35 utility score
JTAC No. 1					
Ground sense	6.21	3	0	18.63	0
Loiter time	5.67	2	3	11.34	17.01
Noise sig.	4.57	1	3	4.57	13.71
Gun eff.	6.64	3	0	19.92	0
Survivability	5.43	2	3	10.86	16.29
Stealth	2.17	1	3	2.17	6.51
Speed	3.86	2	3	7.72	11.58
Range	4.98	2	3	9.96	14.94
Total	–	–	–	85.17	80.04
JTAC No. 2					
Ground sense	6.21	3	2	18.63	12.42
Loiter time	5.67	3	2	17.01	11.34
Noise sig.	4.57	2	3	9.14	13.71
Gun eff.	6.64	3	2	19.92	13.28
Survivability	5.43	3	2	16.29	10.86
Stealth	2.17	1	3	2.17	6.51
Speed	3.86	2	3	7.72	11.58
Range	4.98	3	1	14.94	4.98
Total	–	–	–	105.82	84.68
JTAC No. 3					
Ground sense	6.21	3	1	18.63	6.21
Loiter time	5.67	3	1	17.01	5.67
Noise sig.	4.57	3	1	13.71	4.57
Gun eff.	6.64	3	1	19.92	6.64
Survivability	5.43	3	2	16.29	10.86
Stealth	2.17	1	3	2.17	6.51
Speed	3.86	1	3	3.86	11.58
Range	4.98	3	2	14.94	9.96
Total	–	–	–	106.53	62

and speed, the two attributes where the F-35 has the advantage, to the maximum value of 7, the A-10 still retains its overall superiority. Indeed no plausible weighting, given a low-intensity conflict scenario, shows the overall CAS performance of the F-35 to be superior.[28]

Proponents of the replacement plan argue that the F-35's versatility, termed "multimission capability," outweighs other factors (Schogol, 2012). However, versatility is but one consideration. Multimission aircraft are not better by

28 Extreme weights that maximize stealth and speed and minimize the other six attributes will result in the F-35 winning. The authors do not dispute that the F-35 would be superior given high-intensity conflict scenarios where stealth and speed are paramount. For further discussion of how the performance attributes were scored and weighted, and the robustness of our findings to changes in these, see Appendix A, Note 10 in supplementary material.

Table 8 Cost comparison of A-10, F-22, and F-35.

Aircraft	Average per unit cost (APUC)	Cost per flight hour (CPFH)	Fleet
A-10	$18.8M	$19,736	281 (172 upgraded)
F-22	$143M	$58,059	183
F-35	$148–$337M	$67,550	1763 (planned)

definition. They are only better if they can perform the required set of tasks more effectively and efficiently than some set of single-purpose alternatives. Here that is not the case. Despite its impressive SSR, the multimission F-35 is markedly inferior in terms of CAS performance to the aircraft it would replace. The A-10 performs a single critical task, precision CAS, far better than the proposed alternative and at far lesser cost.

8 Cost comparison: The A-10 versus the F-35

Costs are a central consideration, the primary one stressed by the Air Force to justify cancelling the A-10 fleet. Given that replacing paid-for A-10s with to-be-purchased F-35s would be extremely expensive, as this section shows, claims of cost savings are not credible.

The Air Force has presented its plan as a cost-saving response to tight budget constraints (Marshall, 2014). The F-35's touted cost savings would theoretically emerge because large purchases would produce substantial economies of scale (U.S. Department of Defense, 2018*a*). Winslow Wheeler, a defense budget researcher and former Government Accountability Office analyst, determined that the cost of one F-35 would range between $148 million and $337 million depending on the variant, with an average cost of $178 million.[29] Lockheed Martin, which manufactures the F-35, has claimed this cost will drop to $65 million in future years (Stephen O'Bryan, quoted in Pike, 2014). Lockheed also forecasts that operating and support costs would fall sharply, to half those of current aircraft (Wheeler, 2011). Wheeler (2011) has argued persuasively that similar past claims have proved unfounded. The cost-per-flight-hour (CPFH) to operate the F-35 is $67,550, even more expensive than the F-22 at $58,059 CPFH, and more than three times the per-flight-hour cost of the A-10 at $19,736 CPFH (Bender & Nudelman, 2016; see also Project on Government Oversight, 2014).

29 This figure is staggering in part because the F-35 now costs more than the F-22, a twin-engine fifth generation fighter that is far stealthier and more powerful. See Wheeler (2014).

Table 9 Alternative air fleets and F-35/A-10 ratios.

Alternatives	A-10s	F-35s	Ratio F-35/A-10
Current	281	1763 (planned)	6/1
Divestiture	0	1763	N/A
Recommended	172 (upgraded)	1587	9/1

In the most optimistic scenario, sufficient quantities of F-35s would be produced to allow learning to bring down procurement costs (but not operating costs) from their current extremely high levels to those comparable to current-generation fighters. The claim, however, that the F-35 will ever be significantly more affordable than currently owned aircraft lacks both logic and precedent. High-technology aircraft almost always become more expensive with each new model. The F-22 cost more than four times as much per airplane, \$143 million, as the F-15 it was intended to replace (U.S. Air Force, 2005). The Air Force claimed that the F-22 “will have better reliability and maintainability than any fighter aircraft in history,” making it highly cost-efficient over time (U.S. Air Force, 2005). Yet the F-22 remains vastly more expensive to operate than aircraft such as the A-10, F-15, and F-16 (Project on Government Oversight, 2014).

Technological problems have persistently plagued the F-35, and continue to increase its cost. The Defense Department’s Office of the Director of Operational Test and Evaluation (DOT&E) 2017 report noted many weapons defects: its gun is inaccurate; it cannot engage moving targets; and it cannot correctly predict the “time on target” when a bomb will strike, a basic requirement for operating with ground forces (U.S. Department of Defense, 2018*b*, p. 43–45). Its automated maintenance system is vulnerable to cyber-attack and is underperforming, contributing to disappointing reliability well below program targets (U.S. Department of Defense, 2018*b*, p. 53, 55). Its advanced helmet-mounted display system has failed frequently and is being re-engineered (Smithberger, 2015). Aerodynamic flaws limit its ability to make aggressive maneuvers (Grazier & Smithberger, 2016). An upgrade plan to remedy these deficiencies is estimated to add \$16 billion to the F-35 program’s total cost (Insinna, 2018*a*).

Obviously, procuring F-35s at any price would be more costly than the continued operation of the 172 A-10s, refurbished with new wing sets, which are already on hand. Despite the A-10’s age, its CPFH is less than one-third of the F-35’s (Project on Government Oversight, 2014). The A-10 is a relatively simple, subsonic, non-stealthy aircraft. It is comparatively cheap to build and to fly. Replacements will be required in 2035 when these upgraded A-10s will have reached the end of their extended service lives. Until that time, however, replacement would be a profligate measure.

Let's put actual costs aside. The efficiency of the A-10 and F-35 could be compared using a hypothetical procurement scenario. Consider a case in which the

USA had to buy all new aircraft, and could only buy new A-10s or F-35s, and *procurement and operating costs for the two were equal.* Even given all new procurement, our effectiveness analysis shows that the varied capabilities of a mixed fleet of A-10s and F-35s would yield more military utility than would a fleet composed exclusively of F-35s. In a theoretical scenario where the USA could purchase only two aircraft, it would be most efficient to purchase one of each. The F-35 would be allocated to deterrence and air dominance roles for high-intensity conflicts; the A-10 would be allocated to precision CAS for low-intensity conflicts. Positing a more realistically sized fleet of many hundreds of aircraft, the USA, seeking efficiency, would purchase a mix of A-10s and F-35s. How many of each would depend on the estimated likelihoods of the two conflict scenarios, and on the performance of the fleet as the numbers of each type of aircraft increased. Given the A-10's substantial superiority in low-intensity conflict, as well as the far greater likelihood of this type of conflict, no objective analyst could recommend purchasing an all-F-35 fleet. Only if a low-intensity conflict were extremely unlikely could an all-F-35 fleet make sense.

The real procurement decisions facing the USA are much more agreeable than this hypothetical scenario. The USA already has all the A-10s it needs. Two hundred eighty-one of them are currently in service; 172 of those have been refurbished for a service life extension through 2035. The remaining 109 A-10s could be refurbished for much less than the cost of purchasing new A-10s, and for far less than the cost of purchasing new F-35s.[30]

Training CAS-specialist pilots is another important cost factor. A-10 pilots have been trained at great cost to perform their roles and functions within the aircraft-pilot system. Many have acquired substantial combat experience in Afghanistan, Iraq, and Syria (Adelan, 2017). Retraining them to fly F-35s would entail considerable start-up costs.

The A-10 provides substantially more capability for the critical mission of CAS than does the F-35, at a fraction of the cost, however it is tallied. This conclusion recognizes the possibility of a high-intensity conflict and concedes the F-35's vast superiority in that scenario. Given both conflict scenarios and the differences in capabilities of the two aircraft, our analysis demonstrates that a mixed fleet is the preferable option for the USA.

30 Given that the Air Force purchased 56 new wing sets for \$212 million, if we assume proportionate costs, the estimated price to extend the service lives of the remaining 109 A-10s would be \$412 million. See Boeing (2013). At an average per-unit cost (APUC) of \$18.8 million, 109 new A-10s would cost \$2 billion. The same number of F-35s would cost at least \$12 billion.

9 Conclusion

The USA has not engaged in a high-intensity conflict of significant scope and duration since the Korean War ended in 1953. In the last 64 years, by contrast, the USA has engaged in low-intensity conflicts in Vietnam, Grenada, Panama, Somalia, Kosovo, Afghanistan, Iraq, Libya, Iraq once again, and Syria. Such low-intensity conflicts appear to be in the USA's future, with potential old and new adversaries located on most continents. Special operations forces, indeed any forces engaged in low-intensity conflicts, require precision CAS. That support, as the survey and data set show, is best provided by A-10s. Moreover, the USA currently has 281 A-10s in service, with 172 of them already refurbished to last another 16 years.

As of 2019, the U.S.-led coalition has cornered what remains of ISIS in dwindling redoubts in the desert of eastern Syria (O'Connor, 2018). The military defeat of this terrorist army, which once controlled much of Syria and Iraq, is imminent (Cronk, 2018). ISIS' global affiliates, as well as the risk of its resurgence in the Levant, remain serious threats to U.S. national security interests (Hassan, 2018). Reducing ISIS to its weakened state has required grinding down highly capable hybrid forces that present tough targets from the air, while avoiding harm to civilians. This has been a primary consideration for every air strike (John W. Hesterman III quoted in Marshall, 2015). In this CAS-intensive conflict, A-10s emerged as a cornerstone of the air campaign (U.S. Department of Defense, 2015*b*). By 2016, a small number of A-10s accounted for 30% of U.S. strikes in Iraq and Syria (Pellerin, 2016). Their heavy armament proved decisive in destroying ISIS fielded forces and equipment; in one major strike, A-10s partnered with AC-130 gunships to destroy 116 tanker trucks (Lendon, 2016). When pinpoint strikes were required to clear Raqqa, the exceptional precision of A-10s made them the preferred CAS provider (Rhynes, 2018).

Despite the Trump administration's isolationist tendencies, limited and judicious international commitments will remain necessary to secure U.S. security interests against terrorist and insurgent groups. Continued low-intensity conflicts will occupy the USA and its allies for many years to come in the Middle East, Africa, and elsewhere. To prevail will require the unique capabilities of the A-10 fleet.

The F-35 is a technological marvel of speed, stealth, and range, appropriately slated to be the backbone of the fighter fleet in the coming decades. It will be a critical component of the U.S. arsenal, given its ability to deter sophisticated enemies and, if necessary, defeat them in high-intensity battles. However, the F-35 falls well short of the precision CAS capability that the A-10 offers. At the direction of Congress, the DOT&E conducted a fly-off between the F-35 and the A-10 in 2018 (Insinna, 2018*b*). The results are under review and have not been released (Leoni & Remper, 2018). Proponents of the F-35 are optimistic that its advanced technology will offset the core advantages of the A-10 (Seligman, 2016*b*). This fly-off, if it were complete and objective, could put to rest questions about the comparative effectiveness of the two aircraft at CAS. In the best case, it would provide objective measures of performance to allow for a definitive cost-effectiveness analysis of the A-10 and F-35 as CAS platforms.[31] In the absence of these data, the expert judgment of experienced JTACs provides the best available information upon which to assess the comparative CAS performance of these aircraft. This expert judgment, as demonstrated in our survey, and substantial evidence from combat operations, indicate that the A-10's CAS capability surpasses that of its proposed replacement by a wide margin.

A sensible strategy is to use the already available A-10s for current and expected low-intensity conflicts through the end of their service lives, and to use newly procured F-35s as deterrents of high-intensity wars or, if necessary, as equipment for battle against a major power. Our analysis shows that the difference in CAS capability between these two aircraft is great. The argument for retiring the A-10 rested heavily on the false claim that this difference in capability would be small, making its loss acceptable. With the claim refuted, the rationale does not stand. Thus, the Air Force's recurring proposal to cut the A-10 fleet completely while simultaneously purchasing vast numbers of F-35s is poorly considered. The claim of budgetary savings has no factual basis.

The selected acquisition report for the F-35 proposes the purchase of 1,763 aircraft (U.S. Department of Defense, 2010). There is no data showing this to be an efficient quantity and it should not be accepted prima facie as an optimum or minimum number. It is plausible that reducing a marginal number of F-35s in the U.S. air fleet would not unacceptably compromise deterrence and readiness for high-intensity conflict. Posit that 10% of the 1,763 proposed F-35s – a very conservative estimate – would be used for CAS in low-intensity conflicts. Not building those 176 planes, over a 15-year period, would save a minimum of $25.1 billion.[32] The Air Force estimates that retiring all of the A-10s would save $4.2 billion. Posit that only the 172 A-10s whose service lives have been extended to 2035 were retained, virtually substituting one-for-one for the F-35s that were cut, and that cutting the other 109 A-10s saved no dollars. This budget would still save a minimum of $20.9

31 The authors thank a referee for noting the importance of this fly-off for future CAS cost-effectiveness analysis during pre-publication review of this article. As of publication, the results of the fly-off have not been publicly released. For a critical assessment of the fly-off, see Grazier (2018).

32 Projected discounted savings using FY19 base dollars and midpoint discounting at a 20-year interest rate of 0.5% (discount factor 0.9950), reducing the acquisition of F-35s by 12 aircraft per year from 2020 to 2033 and by eight aircraft in 2034. For this conservative calculation, we use the lowest currently estimated APUC for the F-35, $148 million. See U.S. Department of Defense (1995, pp. 11–12, 18–19), Office of Management and Budget (1992), and Office of Management and Budget (2016).

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billion.[33] Much more important, the USA would retain a far superior capability to fight low-intensity conflicts.

Benefiting from a substantial increase in its budget, the DOD is keeping the A-10 fleet in service for now. However, the Air Force has kept alive its core argument that retiring A-10s to buy more F-35s would be a cost-effective way to maximize airpower in response to tight budgets. In discussing the FY19 budget, Air Force General Mike Holmes hinted: "As far as exactly how many of the 280 or so A-10s that we have that we'll maintain forever, I'm not sure" (Insinna, 2018*c*). It seems highly likely that the replacement plan will resurface well before the end of the A-10's service life in 2035, once defense budgets again become tight.

This plan is vastly inferior to alternatives that the Air Force has already analyzed and found to be feasible. One of these alternative plans, delaying a fraction of F-35 procurement, has been analyzed in this article and found to be operationally and fiscally preferable. Our proposal to modestly reduce F-35 procurement over a 15-year period, demonstrates how a small tradeoff against the stealth inventory could underwrite a balanced fleet with superior air power capability and hedge against both low-intensity and high-intensity threats of the future. The modest cost of retaining the entire A-10 fleet ($4.2B), in contrast to the staggering cost of procuring the last 10% of F-35s ($25.1B), makes this tradeoff feasible and sensible.

The CAS-specialist A-10 presents a suite of capabilities that is essential for the likely conflicts of the foreseeable future, and cannot be effectively replaced by advanced multirole fighters or a patchwork of drones, gunships, and bombers. Beyond the A-10's current service life of 2035 looms a cost effectiveness problem for long-term CAS requirements. Will the Air Force further extend some A-10s, procure successor attack aircraft, or rely solely on advanced multirole fighters? Until then, retaining the battle-tested Warthog is a dominant solution. The A-10, alongside the F-35, will balance the U.S. air fleet to deter and defeat threats up to the mid-21st century. As policy analysis shows, retaining the A-10 Thunderbolt II is the best and most efficient solution for an effective air fleet.

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33 The Air Force estimates that cutting the A-10 fleet to zero would save $4.2 billion. Some fraction of this savings would certainly be achieved by retiring the 109 A-10s whose service lives have not been extended; however, for simplicity, this analysis assumes no fractional savings from the partial retirement. With 172 A-10s that need not be replaced by F-35s, the budget would reflect a savings of $25.1 billion in procurement costs. Thus, retaining the service-life-extended A-10s would, at a minimum, save $20.9 billion more than the Air Force plan.

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Supplementary Material

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