Augustine's Law:
Are We Really Headed for the $800 Billion-Dollar Fighter?

Brent M. Johnstone

Abstract: Augustine's Law famously proposed fighter aircraft costs are growing so rapidly that by 2054 buying a single tactical aircraft will consume the entire defense budget. Is the situation really so dire? This paper examines the trend in U.S. fighter costs and relates them to generational changes in aircraft design and manufacture. It also examines the new jet fighters of the 2000s to see if Augustine's Law is really unfolding as its author originally thought.

Key words: Augustine's Law, cost analysis, fighter aircraft, government procurement, cost effectiveness, cost estimates, mathematical models, planning

> *"In the year 2054, the entire defense budget will purchase just one aircraft. This aircraft will
> have to be shared by the Air Force and Navy 3 ½ days each per week except for leap year,
> when it will be made available to the Marines for the extra day." – Augustine's Law XVI.*

Introduction

In his book, *Augustine's Laws*, former aerospace executive Norman Augustine proposed a series of "laws" – more accurately, a series of tongue-in-cheek empirical observations -- about management behavior in the spirit of the late C. Northcote Parkinson. The mostly widely quoted of these is Augustine's assertion (quoted above) that the rate of increase in military tactical aircraft costs over time would eventually exceed the cost of the overall defense budget and even (past 2100) the gross national product (GNP) of the United States.

This seemingly absurd conclusion nonetheless had empirical justification, which Augustine produced in his book. Beginning with the Wright Brother's Model A in 1910, Augustine tracked the cost of U.S. tactical aircraft through the release of the F-18A/B in the early 1980's and observed an exponential growth over time. Figure 1, reproduced from Augustine's book, shows the then-year average unit cost increasing by a factor of four every decade.
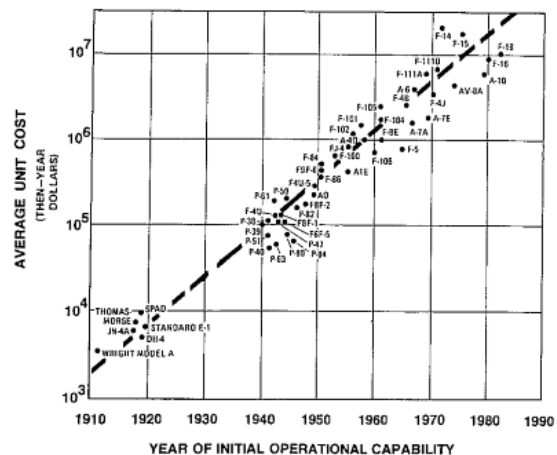

Figure 1: Reprinted with Permission of Norman Augustine

Extrapolating this trend into the future – as well as extrapolating the projected growth in the Defense Department budget and the nation's GNP – Augustine calculated that the price of a single tactical aircraft would equal the entire projected defense budget by 2054. This is shown in Figure 2, as well as the astonishing conclusion that the price of our single aircraft would eventually exceed the GNP sometime around the year 2150:
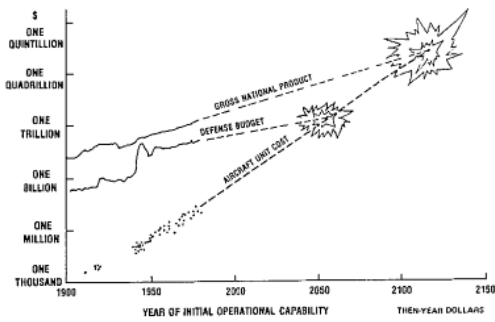
Figure 2: Reprinted with Permission of Norman Augustine

Augustine's book does not provide absolute numbers, but useful approximations can be made from reading the charts themselves. Cost increases for tactical aircraft by a factor of four every decade translates into a 15% increase per year. Likewise, from the chart, it is apparent that the defense budget is assumed to increase by 2.5% per year and the nominal GNP by 5.5% per year. This produces an intersection by 2054 where the defense budget and the cost of a single aircraft meet at approximately $800 billion. Likewise, by 2114 the GNP and the cost of a single aircraft meet at approximately $3.6 quadrillion.

Augustine's prediction first appeared in written form (Augustine, 1979) several years earlier as an article in the *Defense Systems Management Review*. When asked in 2016 about his prediction, Augustine not only confirmed his original prediction but gave it an exact date: "It was 2054.

I've refined it actually to July 23, 2054. The *Economist* just came out with [an] update to my law and I'm sorry to say we're right on track." (Aitoro, 2016.)

Along the same vein, another "law" authored by Augustine relates time against months to first flight (reference Figure 3) and concludes that there has been no change in aircraft design and development spans despite the increasing complexity of military and commercial aircraft design and build over time:

> The duration of the design and build phase of aircraft development programs has remained virtually unchanged for 40 years. This period is approximately the same for government projects, commercial projects, and, for that matter, projects undertaken in the Soviet Union. (Augustine, 1983.)

Augustine's ironic projections have been seized upon by critics of the defense establishment as proof of wasteful spending, "gold plate" requirements and an industry which has little to no concern about controlling costs. Summarizing much of the published criticism, Franck writes: "The most commonly held belief (the 'conventional wisdom') regarding quality versus quantity choices is that the major weapon systems are laden with technological bells and whistles that add much to cost but little, if anything, to military effectiveness." (Franck, 1992). In
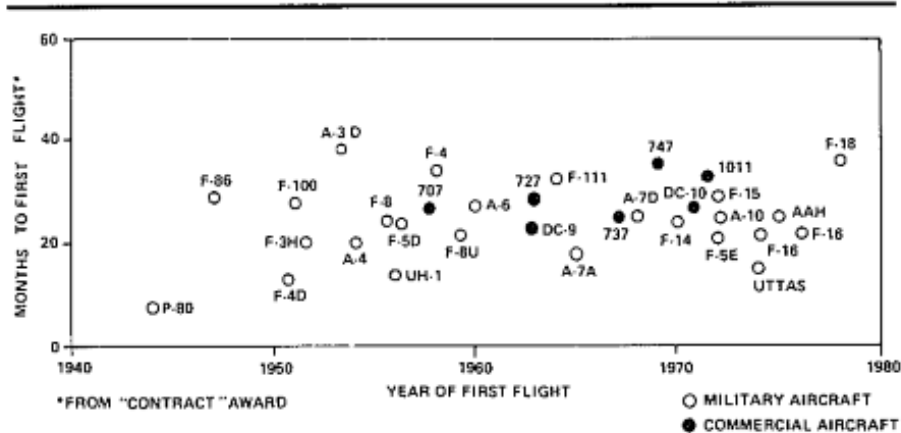

Figure 3: Reprinted with Permission of Norman Augustine

Augustine's view, the observed cost growth over time is not adequately explained by improvements in aircraft performance but is more closely linked to an engineering mindset that values technology for technology's sake – a mindset that has created a cost growth that is unsustainable over time:

> This rate of growth seems to be an inherent characteristic of such systems, with the unit cost being most closely correlated with the passage of time rather than with changes in maneuverability, speed, weight, or other technical parameters. The same inexorable trend can be shown to apply to commercial aircraft, helicopters, and even ships and tanks, although in the last two somewhat less technologically sophisticated instances, the rate of growth is a factor of two every ten years. Automobiles, houses, and certain other commercial products more nearly approximate this latter case. The point is not, of course, that new technology is inevitably more expensive than old technology; the opposite is often the case. But what happens is that…new technology opens vast new capability vistas which are then crammed into each new generation of a product. (Augustine, 1983.)

While Augustine's laws have been widely (and approvingly) quoted over the subsequent three decades, there have been criticisms of this analysis. Eskew (2000) pointed out three methodological issues in Augustine's analysis:

- His projection is based on then-year (inflated) dollars instead of adjusting all values back to a constant dollar base. A substantial portion of the cost growth is therefore due to the larger trend in monetary inflation over time. The Bureau of Labor Statistics on-line Consumer Price Index (CPI) inflation calculator shows that $10,000 in January 1913 would now be worth $261,370 in June 2019 – an increase of 2,514%. (BLS, 2019.)

- The analysis does not consider the total number of aircraft procured. All else being equal, the larger the production buy, the lower the average unit cost – the familiar learning curve effect. If the size of production buys has decreased over time, this could produce a systemic bias toward higher aircraft unit prices over time.

- Likewise, the analysis does not consider the number of aircraft produced in a single year. Larger lot buys are typically associated with lower costs due to the overhead savings due to larger business bases and the allocation of fixed support labor costs across larger quantities. Once again, smaller lot quantities over time could produce a systemic bias toward higher aircraft unit prices.

To Eskew's list, we can add:

- The definition of "average unit cost" as used by Augustine is a nebulous one. This could represent unit recurring flyaway (URF), or production average unit cost (PAUC); or average procurement cost (AUPC) – each of which would reveal a substantially different answer. It is unclear what definition is used by Augustine, or if it is applied consistently over time.

We come then to the purpose of this paper, which is to explore the following questions:

- If fighter aircraft are compared over time using a standardized definition of unit cost, after normalization for inflation and learning curve impacts, are the trends Augustine observed still apparent?

- Since Augustine's initial publication, three major fighter programs have been introduced (F-18E/F, F-22 and F-35). If we introduce this new data, does it change or confirm Augustine's projections?

- Fighter jet aircraft are substantially more complex than their post-World War II predecessors. What is the relationship between cost and each successive generation of fighter aircraft? How much do advances in capability cost historically?

- Regarding Augustine's assertion regarding the unchanging length of development programs, what does history for the most recent fighter programs (F-18E/F, F-22 and F-35) tell us?

Method of Analysis

To examine these issues more closely, a cost database from public domain sources was assembled. The primary source for cost data is the *U.S. Military Aircraft Cost Handbook* (DePuy, 1983). The *Handbook* database represents Total Obligational Authority (TOA) requested by the services to procure attack, bomber and fighter aircraft. Values are reported in then-year dollars and normalized to FY1981 dollars. The *Handbook* uses FY buy average costs to calculate airframe, airframe and engine, and total flyaway unit cost curves, allowing the calculation of theoretical T-100 values. The *Handbook* presents data for aircraft in the active U.S. inventory during FY1960-FY1980 period. This eliminates some of the first-generation fighters such as the P-80. The most recently introduced fighter aircraft in the MCR database is the F-18A/B series. In this analysis, the FY1981 cost data was escalated to FY2018 dollars using December 2018 U.S. DoD aircraft procurement escalation indices.

To include more recent aircraft introduced into the fleet, a supplemental database was created from public domain reports such as U.S. DoD budget documents (USAF, 2010, USN, 1999, USN, 2000, USN, 2001, USN, 2002, USN, 2003, USN, 2004, USN, 2005, USN, 2006, USN, 2007, USN, 2008, USN, 2009, USN, 2010, USN, 2011, DoD, 2012a, DoD, 2013, DoD, 2014) as well as General Accounting Office (GAO) reports (GAO, 2019). This provides then-year flyaway cost data by FY buy for the most recent aircraft introduced to the fleet: F-18E/F, F-22, and F-35. After normalization to FY2018 dollars using the same DoD escalation indices, unit curves were drawn from unit flyaway data and T100 theoretical values calculated.

In addition, aircraft empty weight information was pulled from public domain sources, most coming from RAND studies (Hess, 1987) supplemented by Selected Acquisition Report (SAR) data or Air Force and/or industry press releases (DoD, 2012b, USAF, 2015, Lockheed

Martin, 2019). In all, cost and weight data were found for 23 U.S. fighter aircraft with Initial Operational Capability (IOC) dates ranging from 1949 to 2016.

A popular way to review military aircraft history is to talk of "generations" of fighter jet aircraft. F-22 and F-35 are commonly cited as "fifth generation" fighters, and their eventual replacements as "sixth generation." In truth there is no fully accepted definition of jet fighter generations. However, there is rough agreement on the timelines and characteristics associated with each fighter generation, although there may be disagreement on whether an individual aircraft should be classified as, say, second or third generation. Yoon (2004) suggests the following timeline to assess fighter development:

- First Generation Jet Fighters (circa 1945 to 1955) – Powered by the first turbojet engines, these post-World War II aircraft have capability like their piston engine predecessors. These aircraft are subsonic, usually do not carry radar and carry conventional weaponry such as machine guns and bombs but not guided missiles. First generation aircraft used in the sample were the North American F-86 and Northrop F-89. Unfortunately, other early examples from the U.S. inventory such as the Lockheed P-80 and F-94, Republic F-84, and the North American F-96 were eliminated because reliable T100 flyaway cost or weight data was not available.

- Second Generation Jet Fighters (circa 1955 to 1960) – This generation introduces the first supersonic combat aircraft. They also introduce radar and the use of guided missiles. Second generation aircraft used in the sample were the Douglas A-3; McDonnell A-4, F3H, and F-101; Convair F-102 and F-106; Lockheed F-104; and the Republic F-105.

- Third Generation Jet Fighters (circa 1960 to 1970) – This generation introduces multi-role fighters which combine air defense and ground attack missions in a single configuration. Third generation aircraft used in the sample were the McDonnell F-4, Grumman A-6, Vought A-7 and the General Dynamics F-111.

- Fourth Generation Jet Fighters (circa 1970 to 1990) – This generation continues the trend towards multi-role aircraft but improves capability with more advanced avionics and weapons systems. Greater emphasis is placed on maneuverability versus pure speed and incorporation of lessons learned from the Vietnam air war. Fourth generation aircraft used in the sample were the Grumman F-14, McDonnell Douglas F-15, F-18 and AV-8B, Fairchild A-10 and the General Dynamics F-16.

- Generation 4.5 Jet Fighters (circa 1990 to 2000) – This generation represents an upgrade to existing fourth generation aircraft but incorporates more advanced electronics and, to some degree, a reduced radar cross section (RCS) through the incorporation of limited stealth characteristics. The singular example of Generation 4.5 in the sample was the Boeing F-18E/F.

- Fifth Generation Jet Fighters (circa 2000 to Today) – This generation introduces low observable stealth, more powerful engines, and advanced integrated avionics. The F-35 also introduces shared battlefield awareness and the ability to work with a broad array of networked

systems. Fifth generation aircraft used in the sample were the Lockheed Martin F-22 and F-35A. For analysis purposes, only the Conventional Takeoff and Landing (CTOL) version of F-35 was used since it is the most commonly produced variant in lieu of the F-35B and F-35C versions.

Analysis – Military Fighter Aircraft

If we plot the T100 flyaway FY2018 dollars per unit – without performing any adjustment for aircraft weight -- against the initial fielding date of the aircraft, we get the result shown in Figure 4.

Based on the best fit line, the T100 dollars per unit have increased from $2M per unit in 1949 to $134M per unit in 2019 – an annualized increase of 6.6% in real (constant year) dollars. However, this may be slightly misleading since U.S. fighter aircraft have increased in size over time. Because we know from numerous prior studies (Hess, 1987, Resetar, 1991, Younossi, 2001, et al.) that aircraft flyaway cost is positively correlated with
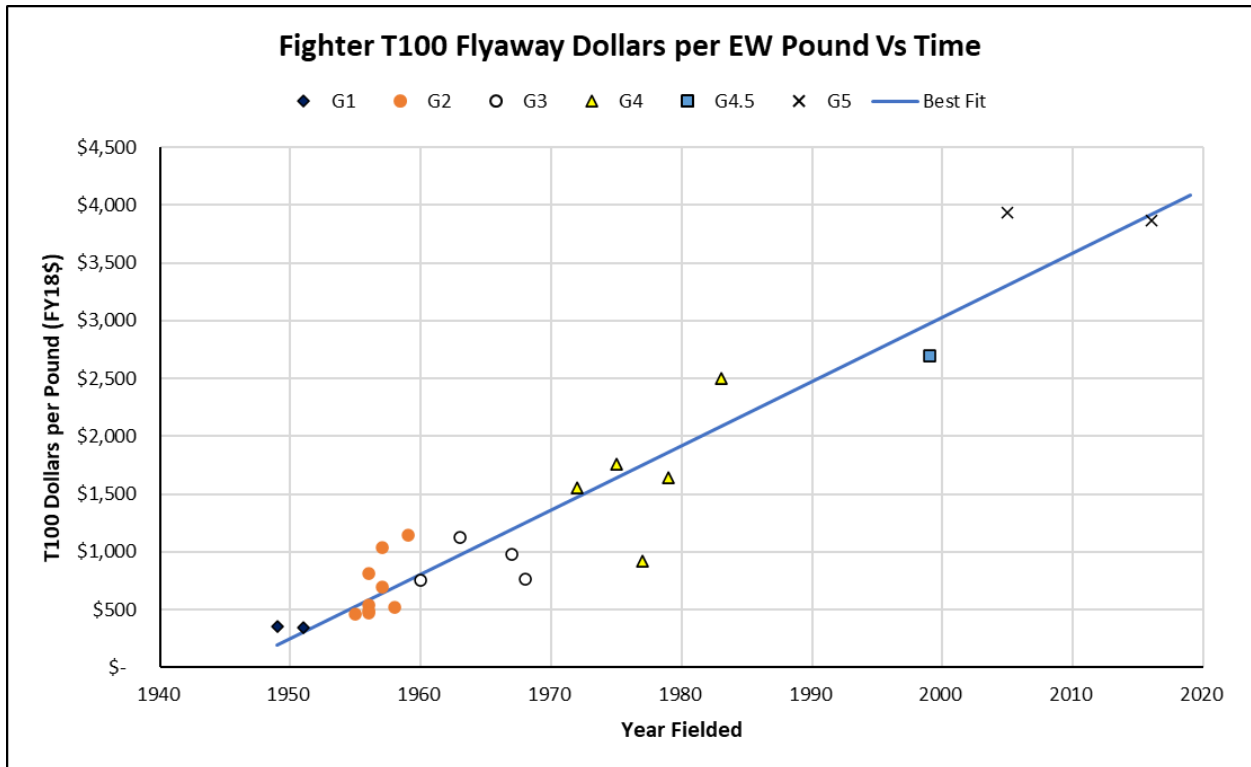

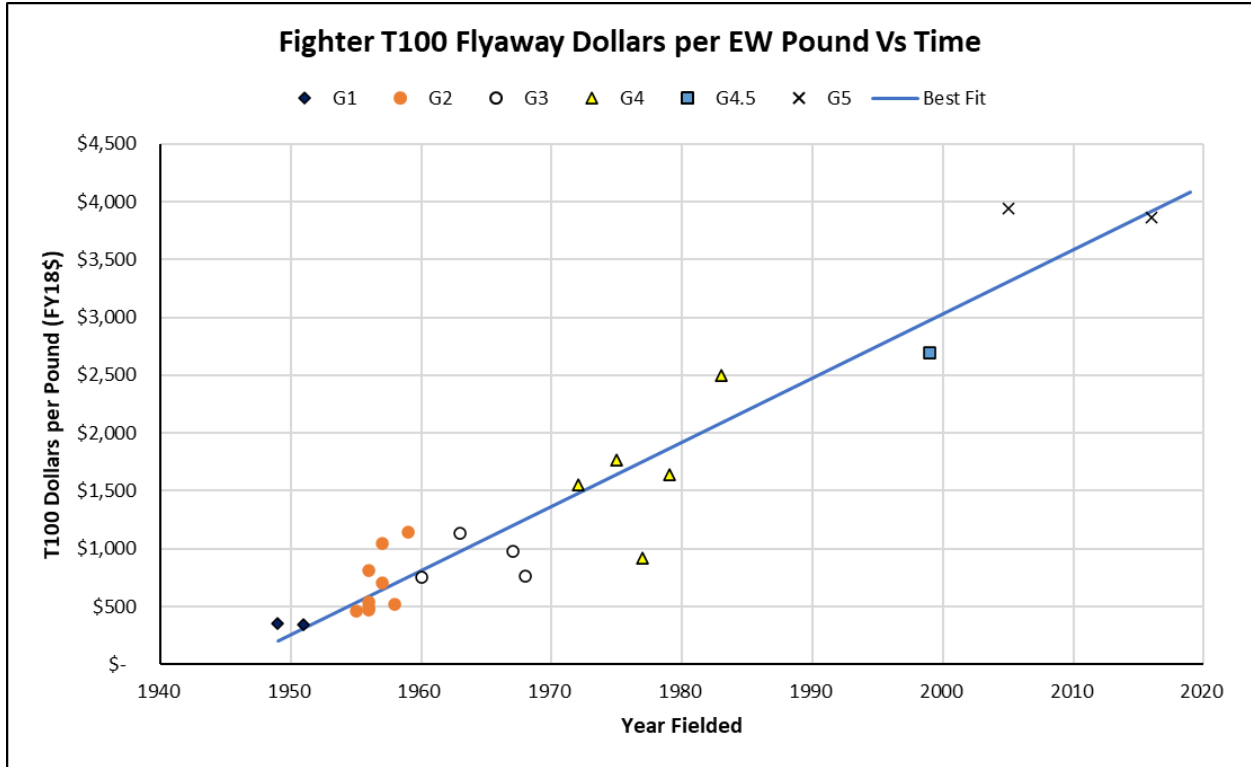*Figure 4. Fighter T100 Flyaway Dollars (FY18$) per Unit Over Time*

Figure 5. Fighter T100 Flyaway Dollars (FY18$) per Empty Weight Pound Over Time

aircraft weight (all else equal, the heavier the aircraft, the more it costs to build), it is more illuminating to plot the T100 flyaway dollars per pound against the initial fielding date of the aircraft, as shown in Figure 5.

The plot confirms Augustine's general thrust: that cost of fighter aircraft has increased significantly over time even after normalizing for inflation, position on the learning curve and overall aircraft weight. It is also apparent that each generation of aircraft has increased in cost over the prior one. Based on the best fit line, the T100 dollars per pound have increased from $198 per pound in 1949 to $4,087 per pound in 2019 – an annualized increase of 4.4% in real (constant year) dollars.

The plot also reveals the time between each fighter generation has been progressively increasing since the jet age began. Fueled by "hot" wars in Korea and Vietnam, the pace of innovation in the 1950's and 1960's was especially quick

with the introduction of supersonic flight and the capability to carry radar and guided missiles (second generation) and the ability to perform multi-role missions (third generation). The pace of innovation has slowed substantially since the end of the Cold War with 34 years between the fourth and fifth generations:

	Average Year of IOC	Years Between Generation
Generation 1	1950	N/A
Generation 2	1957	7
Generation 3	1965	8
Generation 4	1977	12
Generation 4.5	1999	22
Generation 5	2011	12

Table 1. Average Year of IOC by Fighter Generation

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.965
R Square	0.932
Adjusted R Square	0.907
Standard Error	0.306
Observations	23

ANOVA

	df	SS	MS	F	Significance F
Regression	6	20.62	3.44	36.60	0.00
Residual	16	1.50	0.09		
Total	22	22.13			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	(9.81)	1.74	(5.65)	0.00	(13.49)	(6.13)	(13.49)	(6.13)
Empty Weight	1.19	0.18	6.67	0.00	0.81	1.57	0.81	1.57
Generation 2	0.57	0.24	2.34	0.03	0.05	1.08	0.05	1.08
Generation 3	0.83	0.28	2.93	0.01	0.23	1.43	0.23	1.43
Generation 4	1.44	0.26	5.44	0.00	0.88	2.00	0.88	2.00
Generation 4.5	1.90	0.40	4.81	0.00	1.06	2.74	1.06	2.74
Generation 5	2.25	0.34	6.59	0.00	1.52	2.97	1.52	2.97

Table 2. Multiple Regression Outputs

To get a better understanding of the impact that the introduction of each fighter aircraft generation has had on cost multiple variable regression model was constructed using T100 flyaway dollars as the dependent variable and empty weight as an independent variable. In addition, five dummy variables were assigned for second, third, fourth, fifth and Generation 4.5 aircraft. These dummy variables were set at either one (aircraft model included in that generation) or zero (aircraft model not included in that generation). The results of that regression (performed in Microsoft Excel) were as shown in Table 2.

The resulting equation is:

$$T100 = 0.0001 * EW^{1.19} * 0.765^{G2} * 1.285^{G3} * 3.227^{G4} * 5.701^{G4.5} * 8.443^{G5}$$

Where:

T100 = T100 unit flyaway cost (FY2018$ millions)

EW = Empty weight (pounds)

G2 = Second generation aircraft (1 if yes, 0 if no)

G3 = Third generation aircraft (1 if yes, 0 if no)

G4 = Fourth generation aircraft (1 if yes, 0 if no)

G4.5 = Generation 4.5 aircraft (1 if yes, 0 if no)

G5 = Fifth generation aircraft (1 if yes, 0 if no)

The regression demonstrated a R-square value of 93.2%, suggesting the combination of empty weight and aircraft generation explains greater than 90% of the variation observed in the data. All the independent variables were positively correlated with T100 hours per pound as
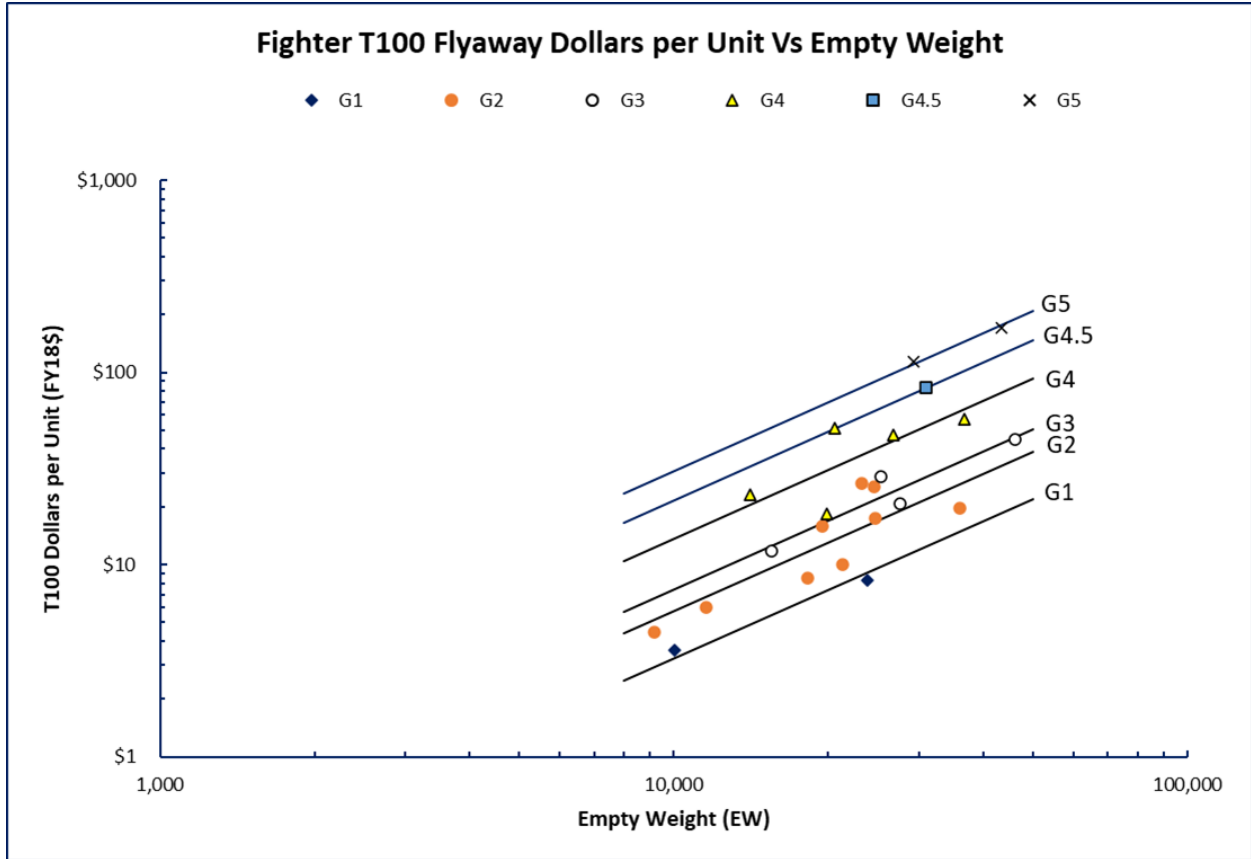
Figure 6. Fighter T100 Flyaway Dollars (FY18$) per Unit v. Empty Weight

expected, and all the resulting coefficients were statistically significant at the 5 percent level of error. Visually, this is shown in Figure 6.

The graph shows us the clear stairstep pattern of increasing cost from generation to generation of fighter aircraft. It also allows us to quantitatively measure that growth. Assuming an aircraft with an empty weight of 30,000 pounds:

If a 30,000 lb fighter was….	T100 FY2018$ Flyaway ($M per Unit)
Generation 1	$12.00
Generation 2	$21.20
Generation 3	$27.40
Generation 4	$50.70
Generation 4.5	$80.30
Generation 5	$113.20

Table 3. Estimated T100 Flyaway Dollars (FY18$) per Unit for 30,000 Pound Fighter

Overall, the growth in cost has been 57% between each generation.

We can see that tactical fighter aircraft have grown in cost over each generation. Now the question is: are they more capable? Intuitively, the answer is "yes" -- clearly, today's fourth and fifth generation fighter aircraft could easily defeat its first-generation counterparts, laboring as they did at subsonic speeds without radars or missiles. Is there any way to measure this increased capability and relate it to the cost?

As it turns out, the *U.S. Military Aircraft Cost Handbook* was developed as a companion volume to a larger study by TASC to develop relative measures of U.S. tactical aircraft capability (TASC, 1980.) One of the results was an Aircraft System Performance (ASP) metric, which considers a variety of factors including payload, range, maneuverability, speed, target acquisition/
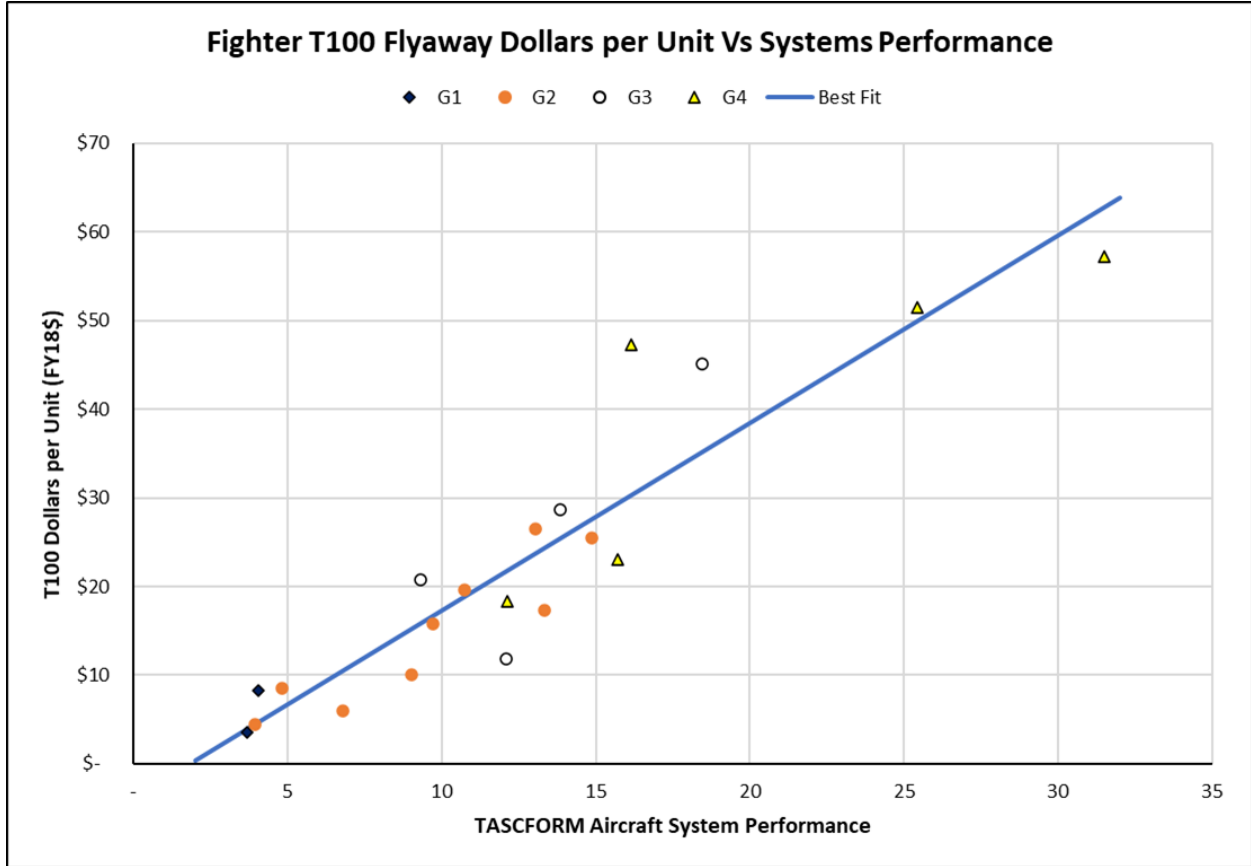
Figure 7. Fighter T100 Flyaway Dollars (FY18$) per Unit v. TASC Aircraft System Performance

engagement capability, navigational capability and survivability. The resulting numerical score can be interpreted against a baseline score for the F-4B (at 10). A tactical aircraft with an ASP score of 20 can be interpreted as a single aircraft is equivalent to two F-4Bs performing the same mission (Hildebrandt, 1986.)

Ideally, we would be able to update these metrics for the three aircraft added since the TASC study was completed: F-18E/F, F-22 and F-35. Unfortunately, the author has been unable to find ASP metrics developed for these aircraft. But we can still compare flyway costs to performance metrics through fourth generation aircraft.

A graph relating flyaway costs to TASC Aircraft System Performance is shown in Figure 7.

Examination of the linear best fit line demonstrates a R-square value of 85.2%, suggesting the increase in T100 flyaway dollars

per unit is highly correlated to increases in aircraft system performance. It is also apparent from the chart that each generation has a higher level of systems performance:

	Avg. ASP
Generation 1	3.9
Generation 2	9.6
Generation 3	13.4
Generation 4	20.2

Table 4. Average Aircraft Systems Performance Score by Fighter Generation

It is also clear that this contradicts Augustine's assertion that "…the unit cost being most closely correlated with the passage of time rather than with changes in maneuverability, speed, weight, or other technical parameters." On the contrary, the graph suggests that the increase in unit cost is *intimately* correlated to the technical
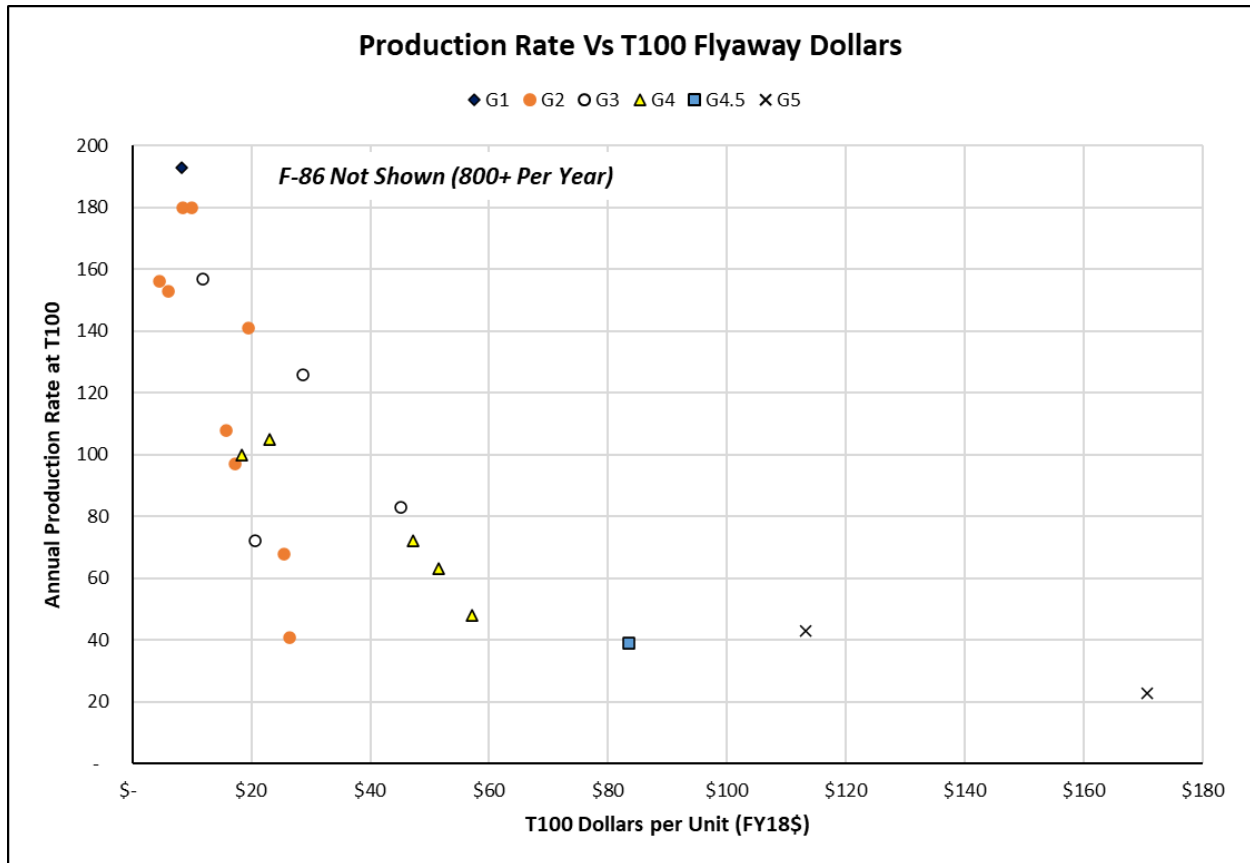
Figure 8. Production Rate v. T100 Flyaway Dollars (FY18$) per Unit

characteristics of the aircraft. While the ASP indices are only available through the fourth generation, it can be surmised that the equivalent systems performance values would be even higher for Generation 4.5 and 5 aircraft – as is, of course, the cost.

If we interpret the TASC systems performance as intended, this suggests a single fourth generation fighter jet is equivalent in performance to five (5) first generation aircraft. If this is correct, it helps explain another interesting fact that emerges from comparing U.S. fighter aircraft over time – the substantial decrease in production rates over time. This emerges vividly by plotting the annual production rate for the production lot in which the 100th unit delivers and correlating it to the flyaway cost, as shown in Figure 8.

Clearly, there has been a significant decrease in production rates with each generation of fighter aircraft at the 100th unit:

	Avg. Annual Rate (T-100)
Generation 1	510
Generation 2	125
Generation 3	110
Generation 4	78
Generation 4.5	39
Generation 5	33

Table 5. T-100 Annual Production Rates by Fighter Generation

It has been suggested (Eskew, 1990) that the reduced production rates are a factor in the increased costs over time. Many analysts suggest high production rates produce cost savings -- driven by material discounts associated with buying larger quantities, wider distribution of fixed support labor and overhead costs across the number of units produced, and steeper learning curve slopes (for a review of the literature, see Johnstone, 2017). Accordingly, the decrease in

production rates over time may potentially explain some of the increase in fighter aircraft costs.

The problem with this analysis is it asks the proverbial "chicken or the egg" question: Have lower production rates over time driven higher aircraft costs? Or have higher procurement costs forced the services to buy fewer and fewer fighters with each successive generation? Or (alternatively) have the improvements in capability of fighters allowed the services to simply buy less of them without sacrificing the ability to perform the mission? The answer to this question is beyond the scope of this paper; nonetheless, it is the author's intuition that the second and third answers are more plausible than the first.

Augustine's Law – True or False?

We return to Augustine's analysis of tactical aircraft and ask: are we really in danger of one day seeing the cost of a single aircraft equal the entire defense budget? The easiest way to answer this question is see how accurate Augustine's predictions – made almost forty years ago – have matched up against our most recent experience. Specifically, how have his extrapolations fared against reality not only for tactical aircraft cost,

2019 Values	Projected	Actual	Variance to Actual
Tactical Aircraft Unit Cost	$6.24B	$146M	4163%
U.S. Defense Budget	$351B	$689B	-49%
U.S. Gross Domestic Product (GDP)	$22.5T	$21.0T	7%

Table 6. Comparison of Projected v. Actual, CY2019

but for the defense budget and the gross national product as well?

As we noted earlier, Augustine's book does not provide absolute numbers, but we can work them out from his charts. In the formulation of his law, Augustine assumed a nominal 15% increase per year in tactical aircraft costs in nominal dollars. Likewise, he assumed the defense budget would increase by 2.5% per year and the nominal GNP by 5.5% per year. By the year 2019 (Budget, 2019a; Budget, 2019b), we should have had the data in Table 6.

Graphically, if we fill in the actual experience since 1980 for these three categories, we get the results in Table 6. Graphically, if we fill in the actual experience since 1980 for these three categories, we see the results shown in Figure 9.
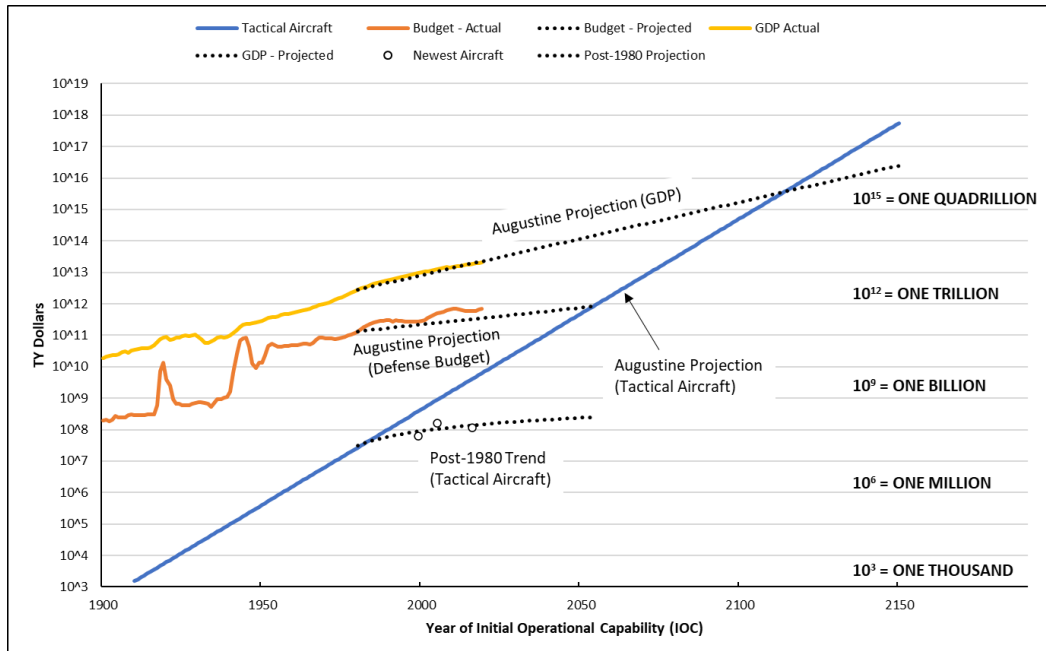

Figure 9. GDP, Defense Budget and Tactical Aircraft Trends, 1900-2050

Augustine's extrapolation for GDP was quite close to the eventual 2019 value. He overstated the actual amount by only 7%, an excellent mark for a projection forty years into the future. His projection for the defense budget, developed from the post-Vietnam War wind-down, did not anticipate either the Reagan era defense buildup or the Bush War on Terror and therefore was understated by 49%. But for tactical aircraft, Augustine's projection missed by four *thousand* percent. There is no six billion dollar fighter aircraft in 2019. Taking the F-18E/F, F-22 and F-35 unit cost into account, the Augustinian trend line seems to have deflected. Since 1980, the growth in tactical aircraft costs seem to have slowed to 4% nominal (then-year) growth per year. Based on this, the projected 2019 fighter cost is closer to $145 million per copy. Augustine's projections seem to have run into another empirical law – in this case, one coined by the late economist Herbert Stein (Stein, 1976): "If something cannot go on forever, it will stop."

Based on this analysis, it appears there is no longer any danger that our single aircraft cost will eventually overtake the total defense budget – in fact, based on this extrapolation, the lines seem to run roughly parallel at least through the prophetic year of 2154. Before we congratulate ourselves on our success, it seems worthwhile to mention that a 4% nominal growth in fighter cost

year over year is still 1.5 times the inflation rate over the same time period. It means fighters are growing more expensive with each generation, and that this growth, if it persists, will continue to vex a Pentagon simultaneously trying to update its tactical and strategic aircraft fleet, its surface ship fleet and its nuclear weapons inventory.

Development and Program Cost

We now turn to Augustine's conclusion that there has been no change in aircraft design and development spans despite the increasing complexity of aircraft design and build over time. Using the same dataset of fighter aircraft, development spans were plotted first by calendar year the aircraft was fielded and second against T100 unit cost.

Based on a RAND database of acquisition milestones (Rothman, 1987), the length of development was defined as the span between a program's initiation and delivery of the first production unit. In this case, the Milestone B date was chosen as the beginning of the official development effort. This is slightly different from Augustine's analysis, which measured development contract award to first flight. First flight was not available from the RAND data, but the first production delivery was chosen as the next best alternative.
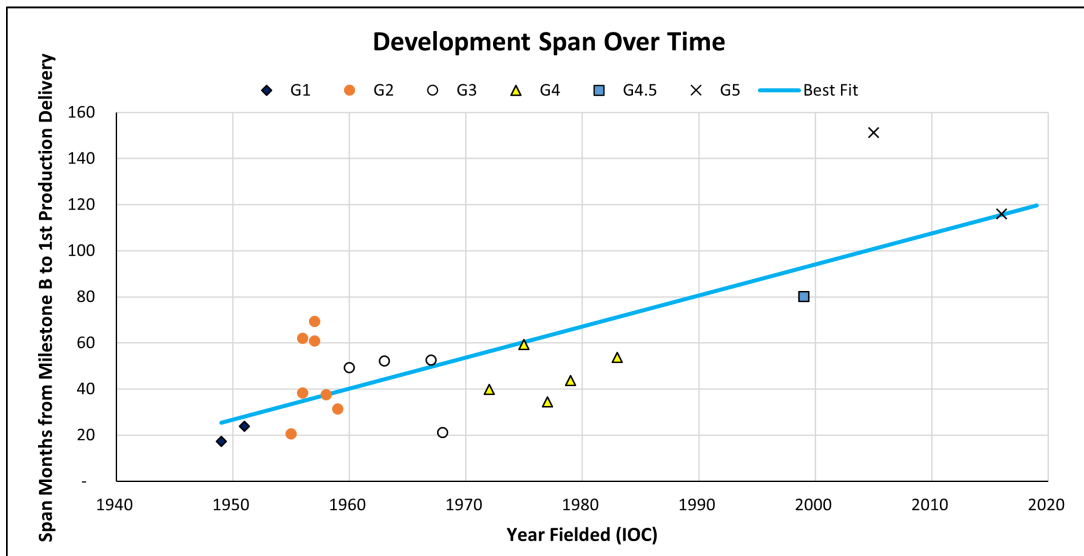

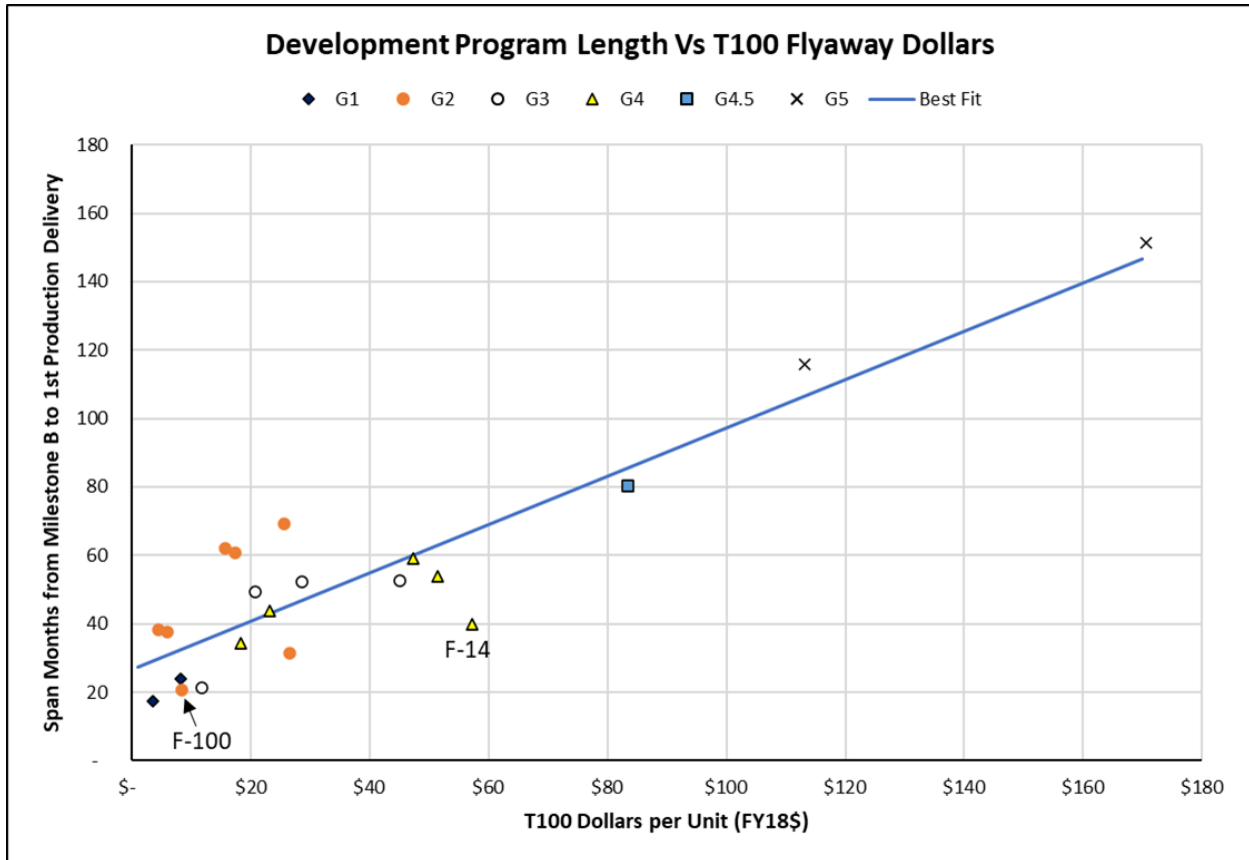*Figure 10. Development Spans Over Time by Fighter Generation*

Figure 11. Development Program Length v. T100 Flyaway Dollars (FY18$) per Unit

Viewing the length of development spans across time, we see the results shown in Figure 10.

Based on the data through the early 1980s, it is easy to see how Augustine came to his conclusion – development spans do not show an especially strong trend across time. But once we introduce later data for F-18E/F, F-22 and F-35A, a different picture emerges. Fighter aircraft fielded after 1990 were in development substantially longer than prior generations.

If we correlate development spans to T100 unit cost, we see the results shown in Figure 11.

Once again, we see a correlation between development spans and flyaway unit costs. It is worth pointing out the two datapoints which are significantly below the trend line: the North American F-100 and the Grumman F-14. Performing a similar analysis, Eskew suggests

that the F-100 and F-14 both benefited from inherited technology from other programs, thus shortening their development spans. The F-100 evolved from the earlier F-86 aircraft, while the F-14 inherited engines and avionics from the cancelled F-111B program (Eskew, 1990).

Examination of the linear best fit line demonstrates a R-square value of 82.2%, suggesting the increase in development span months is positively correlated to T100 flyaway dollars per unit. But once again this fit is highly influenced by the addition of the F-18E/F, F-22 and F-35A data points. Omitting those data points, the R-square drops to 23.9%.

It could be argued that that F-22 and F-35 represent peculiar circumstances. For example, the F-22 program, caught in the post-Cold War drawdown of defense spending, was rephased four times with additional time added to the

development program. In addition, it had design challenges surrounding stealth, integration of its avionics suites, and a new propulsion system. That does not explain, however, the longer span time associated with the F-18E/F, which had incremental improvements with minimal stealth, avionics systems mostly taken from its predecessor, and a derivative aircraft design (Younossi, 2005). Based on the experience of inherited technologies like the F-100 and F-14, one might expect it to be like fourth generation aircraft spans, and possibly even below them.

That development span times have increased since the 1980's is recognized by DoD leadership. In his 2013 implementation memo for the Better Buying Power initiative, Undersecretary of Defense (AT&L) Frank Kendall stated, "On average programs are taking about one year longer to complete development than they did 20 years ago, but the root causes of longer program cycle times are not obvious, and the data includes wide variations" (Kendall, 2013, Riposo, 2014). In short, then, Augustine's contention that "[t]he duration of the design and build phase of aircraft development programs has remained virtually unchanged for 40 years" must be considered challenged by the most recent program data.

Conclusions

For the moment, we will take Augustine's humorous "laws" and treat them as literal assertions of truth. We can summarize the laws into a series of propositions, and post conclusions against each, as follows:

Proposition 1: The price of tactical military aircraft is increasing at a factor of four every ten years, i.e., 15 percent per annum, and in time will overtake the United States defense budget and eventually its gross national product.

Conclusion: Taken literally, this proposition is clearly false. An analysis of military fighter unit cost incorporating the most recent vehicles

shows a slower rate of increase than observed for previous generation fighters. Extrapolated into the future, those costs will not overtake either the defense budget or the gross national product. Having said that, the observed year-over-year increase of 4% per year excluding inflation drives increasingly expensive fighter aircraft (and lower quantities) over time – which was Augustine's point.

Proposition 2: This increase in unit cost cannot be explained by improvements in technical parameters (maneuverability, speed, weight, et al.) and are seemingly inherent characteristics of these systems.

Conclusion: This conclusion does not seem to be supported by analysis. The strong relationship between the TASC metrics of aircraft performance and unit cost for first through fourth generation fighters suggests that the increase in unit cost *is* correlated to the technical performance of the aircraft.

Proposition 3: Aircraft design and development spans have not increased over time despite advances in technology and design complexity.

Conclusion: This proposition was supported by the data through the early 1980's. However, military fighter aircraft fielded after 1990 *do* show an increase in aircraft design and development spans, a trend which has been recognized by DoD leadership. This change is an unwelcome development, since it represents a lengthening of the "time to market" for warfighters to make new capabilities available for the battlefield.

So why do Augustine's laws still have lasting appeal? Because most reader – recognizing that Augustine's tongue is firmly planted in cheek – recognize his laws should not be read literally but appreciated for the greater truth they represent. It is no question that military fighter unit costs are increasing at rates higher than inflation and that those rates have compounded significantly over time: fifth generation fighters are almost ten

times the cost of their first-generation predecessors. And this has profound implications for the sixth generation of fighter aircraft, which have already begun their initial DoD studies. For if history holds true, we can expect this next generation of aircraft will likely cross the $200 million per unit threshold.

Or they may not. The slowing of cost growth from the early 1980s when Augustine performed his original analysis gives some hope that the trend might be reduced further, or even reversed. It is possible that the Digital Revolution in design and manufacturing might offer a route to make this happen, as recently suggested by Dr. Will Roper, the former Undersecretary of the Air Force for Acquisition, Technology and Logistics. (Trimble, 2019.) At the same time, cost analysts must recognize such a happy event would be a strong break from the past seventy years of history. The feasibility of doing just that, however, is beyond the scope of this paper, and a subject for another time.

It seems appropriate to close with a word of warning: this analysis – and Augustine's own – hinge on the validity of extrapolating historical data into the future. One cannot do better than Mark Twain to outline the risks of doing so:

> In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself two hundred and forty-two miles. That is an average of a trifle over one mile and a third per year. Therefore, any calm person, who is not blind or idiotic, can see that in the Old Oölitic Silurian Period, just a million years ago next November, the Lower Mississippi River was upward of one million three hundred thousand miles long, and stuck out over the Gulf of Mexico like a fishing rod. And by the same token any person can see that seven hundred and forty-two years from now the Lower Mississippi will be only a mile and three-quarters long, and Cairo and New Orleans will have joined their streets together and be plodding comfortably along under a single mayor and a mutual board of aldermen. There is something fascinating about science. One gets such a wholesale return of conjecture out of such a trifling investment of fact. (Quoted in Huff, 1954.)

Appendix – Commercial Jetliner Aircraft

Augustine's assertion that cost growth of highly complex systems is an inherent characteristic of those systems applies – as he indicated himself – to the commercial world as well as defense systems. In his book, Augustine graphs the cost of commercial airliners and produces a similar growth trend as tactical aircraft (Augustine, 1983).

To verify Augustine's claim, a similar cost database for commercial airliners was assembled. The data was limited to commercial passenger jets, both wide body
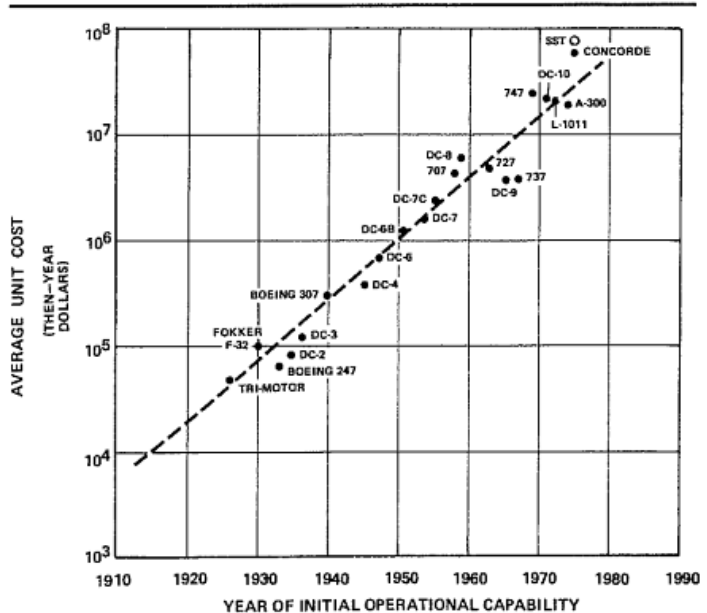
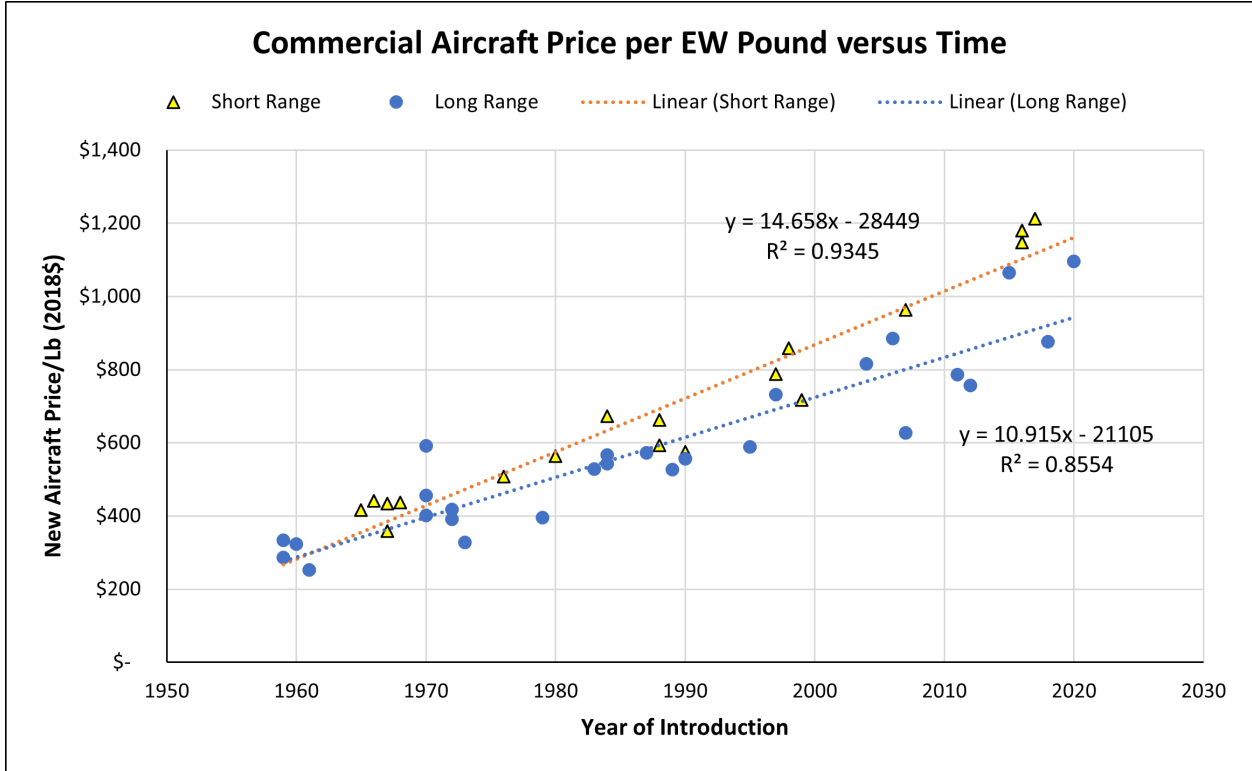*Figure 12. Reprinted with Permission of Norman Augustine*

Figure 13. Commercial Aircraft Price per Empty Weight Pound Over Time

and narrow. Lee (1990) was the primary source for cost data for jetliners introduced before 1995. T100 unit cost is not available and even if it were, it would be of doubtful utility. Commercial aircraft prices are frequently delinked to actual costs. Manufacturers routinely offer early units at prices below cost, hoping to establish their product in the market and recover losses later in the product life cycle once the model is safely established in the marketplace. Instead, Lee reported the listed aircraft price at the time of introduction. Lee's values, reported in constant year 1995 dollars, were escalated to CY2018 dollars using the U.S. GDP implicit price deflator (Federal Reserve, 2019). For aircraft introduced after 1995, the cost data was supplemented by press releases of published prices and other sources (Airliner.net, 2013, Airbus, 2018a, Boeing 2019) normalized to CY2018 dollars. The final database was comprised of 46 aircraft models, the most recent being the Boeing 737 MAX.

It is useful to segregate the jetliner dataset between long range (>4000 nautical miles) and short range (<4000 nautical miles). Examples of short-range jetliners include the Airbus A220 and A320, the Boeing 717, 727 and 737, the Douglas DC-9 and the McDonnell Douglas MD-80. Example of long-range jetliners include the Airbus A300, A310, A330, A350 and A380; the Boeing 707, 720, 747, 767, 777 and 787; the McDonnell Douglas DC-10 and MD-11, and the Lockheed L-1011.

A view of the CY2018 dollars per pound against the year of introduction shows a sizeable increase over the 1960-2019 time period, as shown in Figure 13.

The annualized growth in constant year dollars is 2.4% per year for short-range aircraft and 2.0% per year for long-range aircraft. This is approximately half of the annualized growth in military fighter aircraft.

The taxonomy of commercial aircraft generations is much more poorly defined than its military equivalent, and there is no agreement among

sources. Table 7 summarizes changes in commercial jetliner design in safety features, engine performance, and materials usage (Airbus, undated, Airliners.net, 2007, Hiken, 2018). From this table, approximately four or five generations of aircraft designs can be identified, each more technologically advanced than the other. While this evolution is perhaps not as radical as its military equivalent – these aircraft examples operate at subsonic speeds, none carry weapons, and all are highly visible on radar – nonetheless it seems reasonable to suppose that the higher costs of commercial transport are also tied to higher levels of technical performance.

Year	Safety	Engines	Materials
	First commercial jetliner enters service in 1952.		
1950s	Dials and gauges in the cockpit with early auto-flight systems.	Turbojet engines	Metallic airframes
1960s	More elaborate auto-pilot and auto-throttle systems	Turbofan engines introduced.	
1970s		First generation of high bypass turbofan engines.	First introduction of composite materials in select applications
1980s	Electronic cockpit displays, improved navigation performance and Terrain Avoidance Systems		Composites usage approximately 1-5% by weight
1990s	Fly-by-wire technology, enabled flight envelope protection		Composites usage approximately 15% by weight on new models
2000s		Next generation of high bypass turbofan engines.	
2010s			Composites usage 30-50% by weight on new models

Table 7. Technology Advances in Commercial Aircraft Over Time

References

Airbus. (2018a). Airbus 2018 Price List Press Release, 15 January 2018. Retrieved from https://www.airbus.com/newsroom/press-releases/en/2018/01/airbus-2018-price-list-press-release.html.

Airbus. (2018b). Family Figures Farnborough 2018 Edition. Retrieved from https://www.google.com/search?ei=aDxcXemXNoqWsQWWrZmIDg&q=airbus+family+figures+2018+farnborough&oq=airbus+family+figures+2018+farnbor&gs_l=psy-ab.1.0.33i160.1315.8586..10933...0.2..5.799.9802.0j4j10j4j4j2......0....1..gws-wiz.......0i71j0i67j0i131j0j0i22i30j33i22i29i30j33i299.TM1ds6K9qiQ.

Airbus. (Undated.) Technology's Contribution to Aviation Safety. Retrieved from https://accidentstats.airbus.com/statistics/generations-of-jet.

Airliners.net. (2007.) Airliner generations. Retrieved from https://www.airliners.net/forum/viewtopic.php?t=461777.

Airliners.net. (2013). Historical List Prices: Boeing And Airbus. Retrieved from https://www.airliners.net/forum/viewtopic.php?t=561643.

Aitoro, Jill. (October 25, 2016). "30 Years: A Norm Augustine Retrospective." Retrieved from https://www.defensenews.com/30th-annivesary/2016/10/25/30-years-a-norm-augustine-retrospective/.

Augustine, Norman R. (Spring 1979). "Augustine's Laws and Major System Development Programs." *Defense Systems Management Review, 2* (2), 50-76.

Augustine, Norman R. (1983). *Augustine's Laws and Major System Development Programs.* Reston, VA: American Institute of Aeronautics and Astronautics.

Boeing Company. (2019). About Boeing Commercial Airplanes. Retrieved from https://www.boeing.com/company/about-bca/.

Budget of the United States Government, FY2019. (2019a). Table 3.1, Outlays by Superfunction and Function, 1940-2023. Retrieved from https://www.govinfo.gov/content/pkg/BUDGET-2019-TAB/pdf/BUDGET-2019-TAB.pdf.

Budget of the United States Government, FY2019. (2019b). Table 10.1. Gross Domestic Product and Deflators used in the Historical Tables: 1940-2023. Retrieved from https://www.govinfo.gov/content/pkg/BUDGET-2019-TAB/pdf/BUDGET-2019-TAB.pdf.

Bureau of Labor Statistics (2019). BLS CPI Inflation Calculator. Retrieved from https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=10000&year1=191301&year2=201906.

Department of Defense. (2012a). *Department of Defense Fiscal Year (FY) 2013 President's Budget Submission February 2012. Navy, Justification Book Volume 1, Aircraft Procurement, Navy, Budget Activity 1-4*. Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2013.aspx.

Department of Defense. (2012b). *Selected Acquisition Report: F/A-18E/F Super Hornet Aircraft (F/A-18E/F)*. Washington, D.C.: Defense Acquisition Management Information Retrieval. Retrieved from https://www.globalsecurity.org/military/library/budget/fy2012/sar/f-a-18e-f_december_2012_sar.pdf

Department of Defense. (2013). *Department of Defense Fiscal Year (FY) 2014 President's Budget Submission April 2013. Navy, Justification Book Volume 1 of 4, Aircraft Procurement, Navy, Budget Activity 1-4*. Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2014.aspx.

Department of Defense. (2014). *Department of Defense Fiscal Year (FY) 2015 President's Budget Submission March 2014. Navy, Justification Book Volume 1, Aircraft Procurement, Navy, Budget Activity 1-4*. Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2015.aspx.

DePuy, William E., Jr., Moyer, Rosemarie, Palmer, Paul R., Jr., McKinney, Bruce J., Kreisel, George R., Balut, Stephen J., McNichols, Gerald R. (1983). *U.S. Military Aircraft Cost Handbook*. Falls Church, VA: Management Consulting & Research, Inc.

Eskew, Henry L. (2000). "Aircraft Cost Growth and Development Program Length: Some Augustinian Propositions Revisited." *Acquisition Review Quarterly*, Summer 2000, 209-220.

Federal Reserve Bank of St. Louis. (2019). Federal Reserve Economic Data (FRED), Gross Domestic Product: Implicit Price Deflator. Retrieved from https://fred.stlouisfed.org/series/GDPDEF.

Franck, Raymond E., Jr. (1992). *Performance Choices in Post-Cold War Weapon Systems*. Maxwell Air Force Base, AL: Air University Press.

General Accounting Office. (2019). *F-35 Joint Strike Fighter: Action Needed to Improve Reliability and Prepare for Modernization Efforts*. GAO-19-341. Retrieved from https://www.gao.gov/products/GAO-19-341.

Hess, R.W., Romanoff, H. P. (1987). *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions.* R-3255-AF. Santa Monica, CA: RAND.

Hildebrandt, Gregory G., Sze, Man-bing. (1986). *Accounting for the Cost of Tactical Aircraft.* RAND N-2420-PA&E. Santa Monica, California: RAND Corporation.

Hiken, Alen. (2018). *The Evolution of the Composite Fuselage: A Manufacturing Perspective*. Retrieved from https://www.intechopen.com/online-first/the-evolution-of-the-composite-fuselage-a-manufacturing-perspective.

Huff, Darrell. (1954). *How to Lie with Statistics.* New York, NY: W. W. Norton and Company.

Johnstone, Brent M. (2017). Do Production Rates Really Matter? *Proceedings of the 2017 ICEAA Professional Development and Training Workshop*, Portland, Oregon. Retrieved from https://www.iceaaonline.com/pdx17papers/#DA03

Kendall, Frank. (2013, April 24). *Implementation Directive for Better Buying Power 2.0*. [Memorandum]. Retrieved from https://www.dau.edu/policy/PolicyDocuments/the564BBP%202.0%20Implementation%20Directive%2024%20April%202013.pdf.

Lee, Joosung Joseph. (2000). *Historical and Future Trends in Aircraft Performance, Cost and Emissions* (Unpublished Master's thesis). Massachusetts Institute of Technology: Cambridge, MA. Retrieved from https://dspace.mit.edu/handle/1721.1/8825.

Lockheed Martin. (2019, September 1). *F-35 Lightning II Program Status and Fast Facts*. Retrieved from https://www.f35.com/assets/uploads/documents/FG18-24036_009_F35FastFacts9_2019.pdf.

Resetar, Susan A., Rogers, J. Curt, Hess, Ronald W. (1991). *Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology*. R-4016-AF. Santa Monica, CA: RAND Corporation.

Riposo, Jessie, McKernan, Megan, Duran, Chelsea Kailioi. (2014). *Prolonged Cycle Times and Schedule Growth in Defense Acquisition: A Literature Review*. RR-455. Santa Monica, CA: RAND Corporation.

Rothman, M. B. (1987). *Aerospace Weapon System Acquisition Milestones: A Data Base*. N-2599-ACQ. Santa Monica, CA: RAND Corporation.

Stein, Herbert. (1976). "A Symposium on the 40th Anniversary of the Joint Economic Committee, Hearings Before the Joint Economic Committee, Congress of the United States, Ninety-Ninth Congress, First Session; Panel Discussion: The Macroeconomics of Growth, Full Employment, and Price Stability". Retrieved from https://babel.hathitrust.org/cgi/pt?id=umn.319510030778307&view=1up&seq=270.

The Analytic Sciences Corporation. (1980). *The TASCFORM-AIR Model: A Technique for Assessing Comparative Force Modernization in Tactical Aviation, Vol. I: Methodology Development*. TR-1334-3. Reading, MA: The Analytic Sciences Corporation.

Trimble, Stephen. (2019, September 23). NGAD Program Redirected to Promote Digital Industrial Revolution. *Aviation Week and Space Technology*. Retrieved from https://aviationweek.com/combat-aircraft/ngad-program-redirected-promote-digital-industrial-revolution.

United States Air Force. (2010). *United States Air Force FY2011 Budget Estimates, Aircraft Procurement, Air Force Volume I*. Retrieved from https://www.saffm.hq.af.mil/FM-Resources/Budget/Air-Force-Presidents-Budget-FY11/.

United States Air Force (2015, September 23). F-22 Raptor Fact Sheet. Retrieved from https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104506/f-22-raptor/.

United States Navy. (1999). *Department of the Navy, Fiscal Year (FY) 2000/2001 Biennial Budget Estimates, Justification of Estimates, February 1999. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2000.aspx.

United States Navy. (2000). *Department of the Navy, Fiscal Year (FY) 2001 Budget Estimates, Justification of Estimates, February 2000. Aircraft Procurement, Navy, Volume I: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2001.aspx.

United States Navy. (2001). *Department of the Navy, Fiscal Year (FY) 2002 Amended Budget Submission, Justification of Estimates, June 2001. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4*. Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2002.aspx.

United States Navy. (2002). *Department of the Navy, Fiscal Year (FY) 2003 Budget Estimates, Justification of Estimates, February 2002. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4*. Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2003.aspx.

United States Navy. (2003). *Department of the Navy, Fiscal Year (FY) 2004/2005 Biennial Budget Estimates, Justification of Estimates, February 2003. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2004.aspx.

United States Navy. (2004). *Department of the Navy, Fiscal Year (FY) 2005 Budget Estimates, Justification of Estimates, February 2004. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2005.aspx.

United States Navy. (2005). *Department of the Navy, Fiscal Year (FY) 2006/FY2007 Budget Estimates, Justification of Estimates, February 2005. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2006.aspx.

United States Navy. (2006). *Department of the Navy, Fiscal Year (FY) 2007 Budget Estimates Submission, Justification of Estimates, February 2006. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2007.aspx.

United States Navy. (2007). *Department of the Navy, Fiscal Year (FY) 2008/2009 Budget Estimates, Justification of Estimates, February 2007. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2008.aspx.

United States Navy. (2008). *Department of the Navy, Fiscal Year (FY) 2009 Budget Estimates, Justification of Estimates, February 2008. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2009.aspx.

United States Navy. (2009). *Department of the Navy, Fiscal Year (FY) 2010 Budget Estimates, Justification of Estimates, May 2009. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2010.aspx.

United States Navy. (2010). *Department of the Navy, Fiscal Year (FY) 2011 Budget Estimates, Justification of Estimates, February 2010. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2011.aspx.

United States Navy. (2011). *Department of the Navy, Fiscal Year (FY) 2012 Budget Estimates, Justification of Estimates, February 2011. Aircraft Procurement, Navy, Volume 1: Budget Activities 1-4.* Retrieved from https://www.secnav.navy.mil/fmc/fmb/Pages/Fiscal-Year-2012.aspx.

Yoon, Joe. (June 27, 2004). "Fighter Generations." Aerospaceweb. Retrieved from http://www.aerospaceweb.org/question/history/q0182.shtml.

Younossi, Obaid, Kennedy, Michael, Graser, John C. (2001). *Military Aircraft Costs: The Effects of Advanced Materials and Manufacturing Processes*. MR-1370. Santa Monica, CA: RAND Corporation.

Younossi, Obaid, Stem, David E., Lorell, Mark H., Lussier, Frances M. (2005). *Lessons Learned from the F/A-22 and F/A-18E/f Development Programs*. MG-276. Santa Monica, CA: RAND Corporation.

Brent Johnstone *is a Lockheed Martin Fellow and production air vehicle cost estimator at Lockheed Martin Aeronautics Company in Fort Worth, Texas. He has 34 years' experience in the military aircraft industry, including 31 years as a cost estimator. He has worked on the F-16 program and has been most recently the lead Production Operations cost estimator for the F-35 program. He has a Master of Science from Texas A&M University and a Bachelor of Arts from the University of Texas at Austin.*

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