AIAA SciTech Forum
6-10 January 2020, Orlando, FL
AIAA Scitech 2020 Forum

10.2514/6.2020-1259

Aircraft Design Weight Methods Comparison and Improvement

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Several existing semi-empirical weight estimation methods that are based on aging fixed-wing aircraft are compared and steps to refine and expand the procedures are proposed. Methods are compared to published and publicly available aircraft weight data. Results of the refined procedures yield more accurate weight estimations for aircraft structure, propulsion and fixed equipment. New procedures are proposed and discussed.

Nomenclature

AAA	=	Advanced Aircraft Analysis
GA	=	General Aviation
GD	=	General Dynamics
USAF	=	United States Air Force
W_{eng}	=	Engine Weight
W_{fuse}	=	Fuselage Weight
W_{gear}	=	Landing Gear Weight
W_{TO}	=	Take-off Weight
W_{wing}	=	Wing Weight

I. Introduction

AIRCRAFT weight estimation and component weight breakdown are critical in aircraft preliminary design. During preliminary design, semi-empirical methods are used to quickly estimate aircraft component weights. Aircraft weight engineers use various semi-empirical weight methods to estimate the aircraft component weights during preliminary design. These equations allow for rapid estimation of the aircraft weight for use in weight & balance calculations before detailed design and structural analysis is performed. Typical methods include the Cessna method,[1] USAF method,[1] General Dynamics method,[1] Torenbeek method[2] and the Vought (Raymer) method[3]. These methods utilize aircraft geometry, performance parameters, statistical aircraft weight data and "fudge factors". The semi-empirical regression formulas used are based on aging aircraft and are only applicable for certain types of aircraft, either general aviation, commercial transport or military fighter aircraft. Therefore, refinement and modernization are needed to enable the use of weight estimation methods for current and future aircraft.

II. Weight Estimation Methods

Based on the aircraft used for regression, various methods are only applicable for certain types of aircraft. Types of aircraft include general aviation, commercial transport, military transport and military fighter/attack aircraft.

A. Cessna Method

The Cessna method is based on methods developed by Cessna Aircraft Company during the 1950s using weight data of Cessna-type general aviation aircraft. This method is typically used for small, relatively low performance aircraft with maximum speeds below 200 kts.

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B. USAF Method

The USAF method is based on methods developed by the United States Air Force. This method is applicable to light and utility type aircraft with performance up to 300 kts.

C. General Dynamics Method

The General Dynamics (GD) method is based on methods developed by General Dynamics. This method is applicable for large commercial transport aircraft, business jets and fighter/attack aircraft.

D. Torenbeek Method

The Torenbeek method is based on methods presented in Ref. 2. Different equations are currently used for general aviation and transport aircraft.

E. Vought Method

The Vought method is based on methods presented in Ref. 3. Different equations are currently used for general aviation, transport aircraft and fighter/attack aircraft.

III. Current Weight Method Comparison

Current weight methods are compared to published data from Ref. 1 and Ref. 4. Weight method calculations are performed using Advanced Aircraft Analysis[5] or AAA. The following problems with current weight methods are observed:

1. Methods are used for broad categories of aircraft and group aircraft together that should not be considered the same category, since different aircraft types also have wide variation between different models.
2. Aircraft weight data and equations do not include the same components. A wing may include fuel tanks and wing/fuselage carry-through structure, but some methods do not account for this.
3. Most publicly available weight data is for older aircraft. Assumed fudge factors for innovation in structural design and materials may be out of date.

A. General Aviation

From Ref. 1, the general aviation category includes homebuilds, single engine propeller GA, twin engine propeller GA, agricultural, turboprops below 12,500 lb, low speed military trainers and small and low speed flying boats and float planes. Weight methods are compared for aircraft representative of different aircraft types. An example aircraft with all weight methods is shown in Table 1.

Table 1. Weight Method Comparison for a Single Engine Propeller GA Aircraft

Component	Cessna 172[1] [lb]	Cessna Method [lb]	USAF Method [lb]	GD Method [lb]	Torenbeek Method [lb]	Vought Method [lb]
Wing	226	214	241	--	222	237
Empennage	57	61	62	--	--	58
Fuselage	353	367	197	--	--	190
Nacelle	27	--	--	--	--	--
Landing Gear	111	101	46	--	133	183
Engine	254	288	--	--	325	462
Air Induction	1	--	--	--	--	--
Fuel System	21	17	46	--	32	149
Propeller Installation	33	--	--	35	35	--
Engine Installation	36	--	--	47	45	--
Avionics	4	--	--	--	132	81
Surface Controls	31	37	132	--	39	28
Electrical System	38	59	164	--	50	201
Anti-icing System	1	--	73	--	10	69
Furnishings	85	87	--	--	107	63

Trends appear when comparing weight methods for aircraft of the general aviation category. Figure 1 presents the comparison of weight methods to estimate the wing weight for GA aircraft. The reported wing weight form a mostly linear trendline for general aviation aircraft, with the equation shown in the figure. All four methods are non-linear. For this set of data, the Cessna method fits well to the reported weight trendline for weights above 1,500 lb. Below 1,500 lb, the Cessna method should not be used. The USAF, Torenbeek and Vought methods are fairly accurate for take-off weights below 2,500 lb. Above 2,500 lb, the USAF, Torenbeek and Vought methods should not be used.

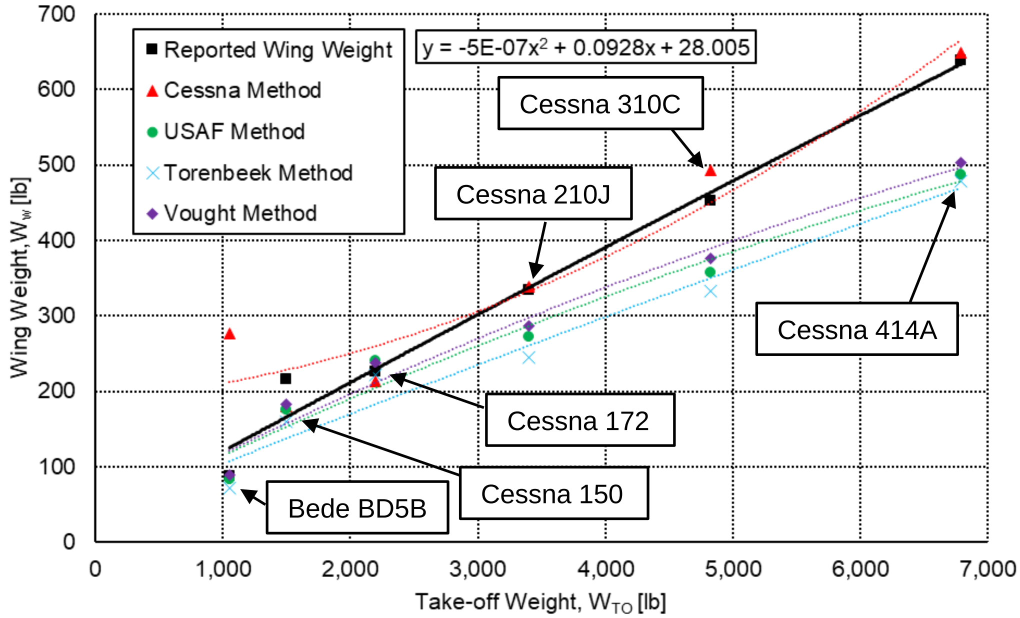

Figure 1. Weight Method Comparison for General Aviation Reported Wing Weight

Figure 2 presents the comparison of weight methods to estimate the fuselage weight for GA aircraft. The reported fuselage weight form a mostly linear trendline for general aviation aircraft, with the equation shown in the figure. The Cessna and USAF methods are non-linear while the Vought method is near linear. The Cessna method should be used with caution while the USAF and Vought methods has a similar trend to the reported fuselage weight. The USAF and Vought methods should not be used on their own.

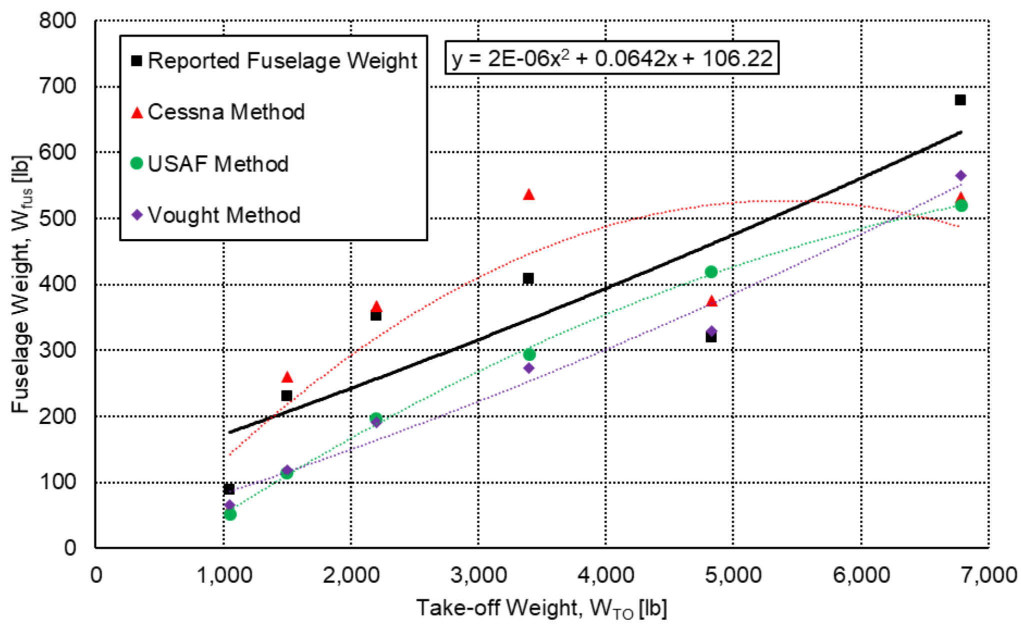

Figure 2. Weight Method Comparison for General Aviation Reported Fuselage Weight

Figure 3 presents the comparison of weight methods to estimate the engine weight for GA aircraft. The reported engine weight is near linear for general aviation aircraft, with the equation shown in the figure. All methods are non-linear and are less accurate the higher the take-off weight is. The Cessna and USAF methods appear accurate up to 3,500 lb and should be used with caution at higher take-off weights. The Vought method should not be used for this category.

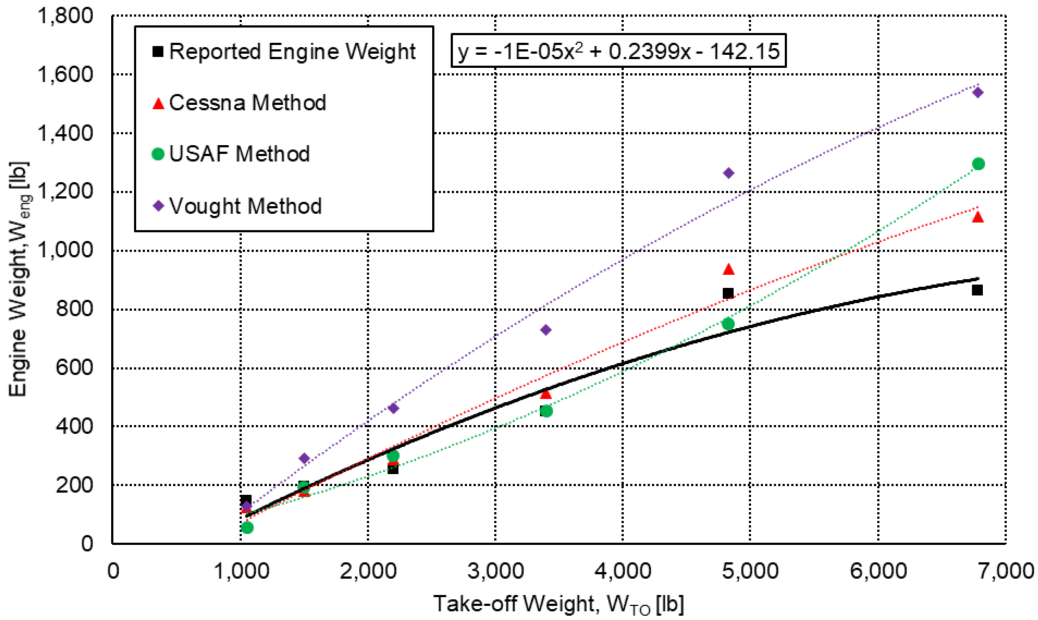

Figure 3. Weight Method Comparison for General Aviation Reported Engine Weight

Figure 4 presents the comparison of weight methods to estimate the landing gear weight for GA aircraft. The reported landing gear weight is non-linear for general aviation aircraft, with the equation shown in the figure. The Cessna method is linear and is close to the reported weight. The Torenbeek method has a similar trend to the reported weight, but is greater on average. The USAF and Vought methods are near linear and are less accurate for higher take-off weights. The USAF and Vought methods may be dropped, so the average between methods is more accurate.

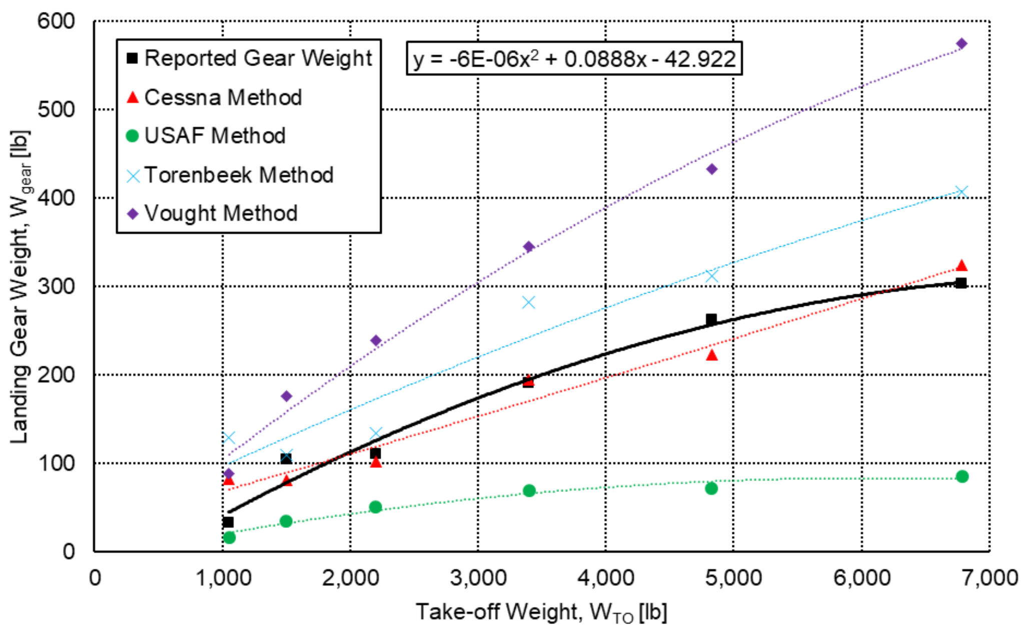

Figure 4. Weight Method Comparison for General Aviation Reported Landing Gear Weight

B. Commercial Transport

The commercial transport category includes business jets, turboprops above 12,500 lb, jet transports, large and highspeed flying boats and float planes and commercial supersonic cruise aircraft per Ref. 1. Weight methods are compared for aircraft representative of different aircraft types. An example commercial transport aircraft with all methods is shown in Table 2.

Table 2. Weight Method Comparison for a Commercial Transport Aircraft

Component	Cessna 550[1] [lb]	Cessna Method [lb]	USAF Method [lb]	GD Method [lb]	Torenbeek Method [lb]	Vought Method [lb]
Wing	1,288	--	--	611	1,271	1,108
Empennage	295	--	--	284	327	221
Fuselage	1,069	--	--	737	1,049	2,135
Nacelle/Air Induction	246	--	--	299	311	419
Nose Gear	87	--	--	104	88	90
Main Gear	378	--	--	450	370	376
Engine	1,100	--	--	--	1,152	--
Fuel System	189	--	--	62	432	317
Propulsion System	105	--	--	71	194	32
Avionics/Electronics	400	--	--	236	505	515
Surface Controls	203	--	--	439	287	392
Hydraulic System	96	--	--	--	162	97
Electrical System	340	--	--	630	471	356
AirCo/Pressurization/ Icing System	362	--	--	281	330	147
Furnishings	800	--	--	730	909	106

Trends appear when comparing weight methods for aircraft of the commercial transport category. Figure 5 presents the comparison of weight methods to estimate the wing weight of commercial transport aircraft. The reported wing weight is linear, with the equation shown in the figure. The Torenbeek and Vought methods are near-linear and follow the reported wing weight well. Both methods could be adjusted slightly to better fit the reported wing weight. The GD method is linear and is less accurate for higher take-off weights. The GD method should be reconsidered for this category of aircraft.

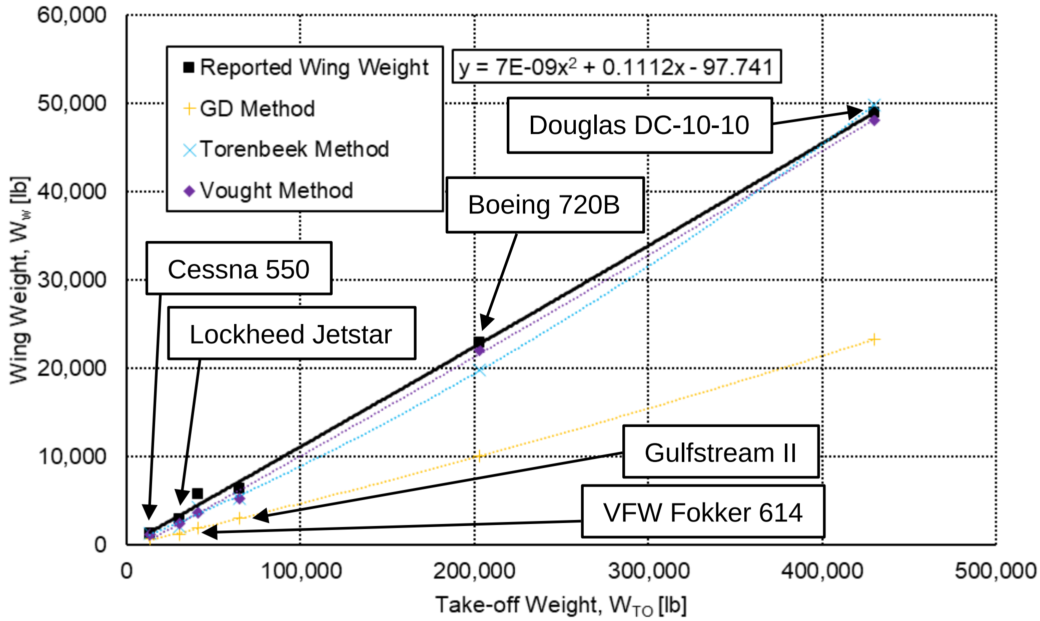

Figure 5. Weight Method Comparison for Commercial Transport Reported Wing Weight

Figure 6 presents the comparison of weight methods to estimate the fuselage weight of commercial transport aircraft. The reported fuselage weight is near-linear, with the equation shown in the figure. All three methods are near-linear and are more accurate at lower take-off weight. As the take-off weight increases, the methods are less accurate. The GD method should be reconsidered while the Torenbeek and Vought methods may be used up to 200,000 lb.

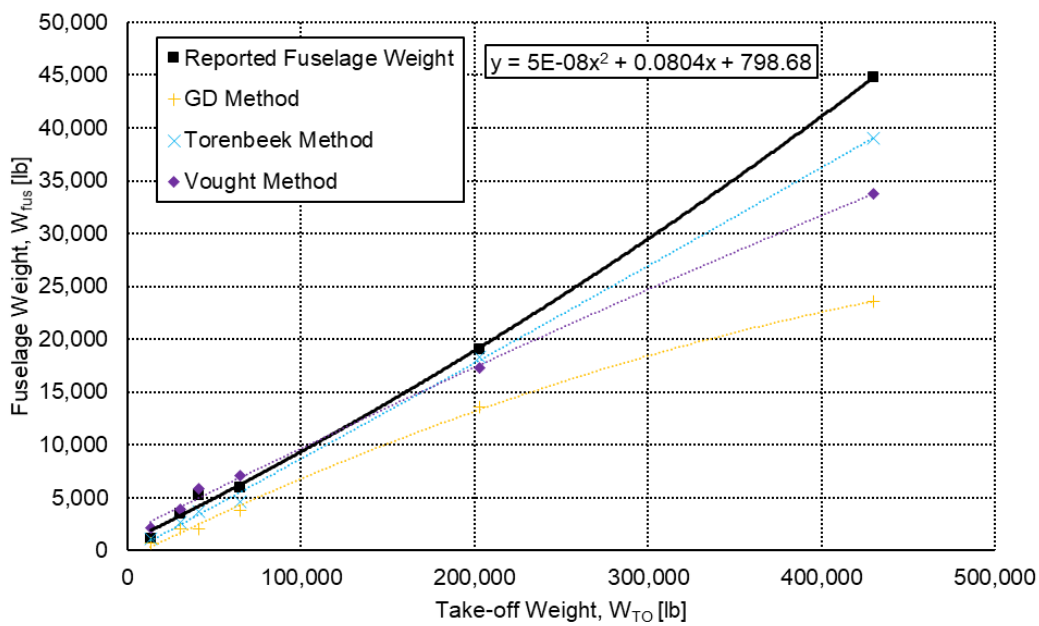

Figure 6. Weight Method Comparison for Commercial Transport Reported Fuselage Weight

Figure 7 presents the comparison of weight methods to estimate the engine weight of commercial transport aircraft. Both the reported engine weight and the Torenbeek method are non-linear. The reported engine weight trendline equation is shown in the figure. The Torenbeek method may be used up to 200,000 lb.

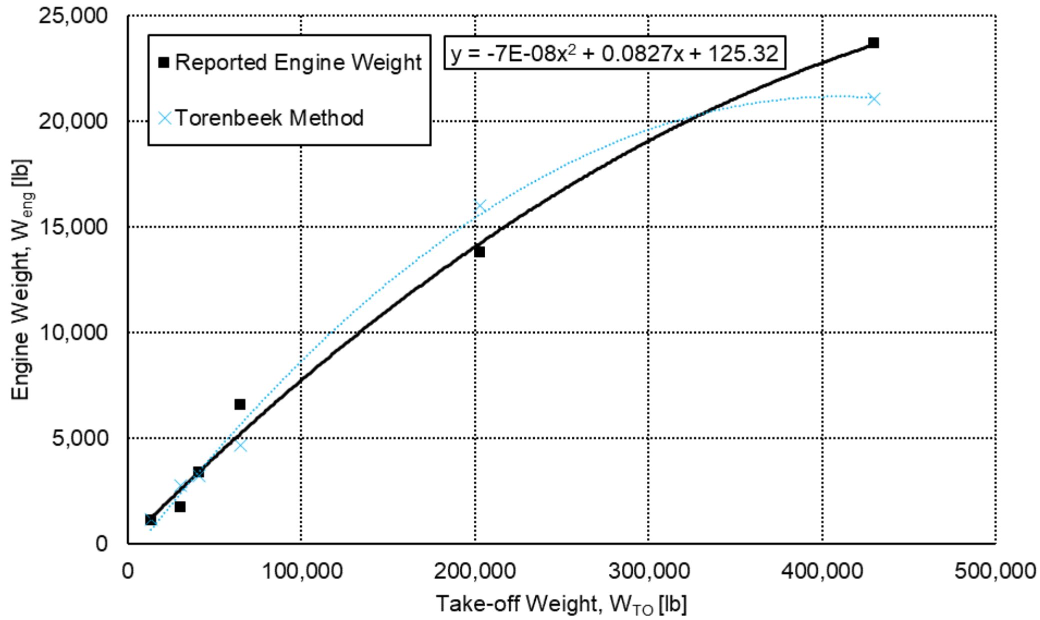

Figure 7. Weight Method Comparison for Commercial Transport Reported Engine Weight

Figure 8 presents the comparison of weight methods to estimate the landing gear weight of commercial transport aircraft. The reported landing gear weight is non-linear, with the equation shown in the figure. All three methods are non-linear and fit the reported weight with varying degrees of accuracy. The Torenbeek method is accurate up to 20,000 lb and the GD and Vought methods are accurate at low weights, mainly for business jet aircraft. At take-off weights higher than 200,000 lb, the three methods should be averaged together.

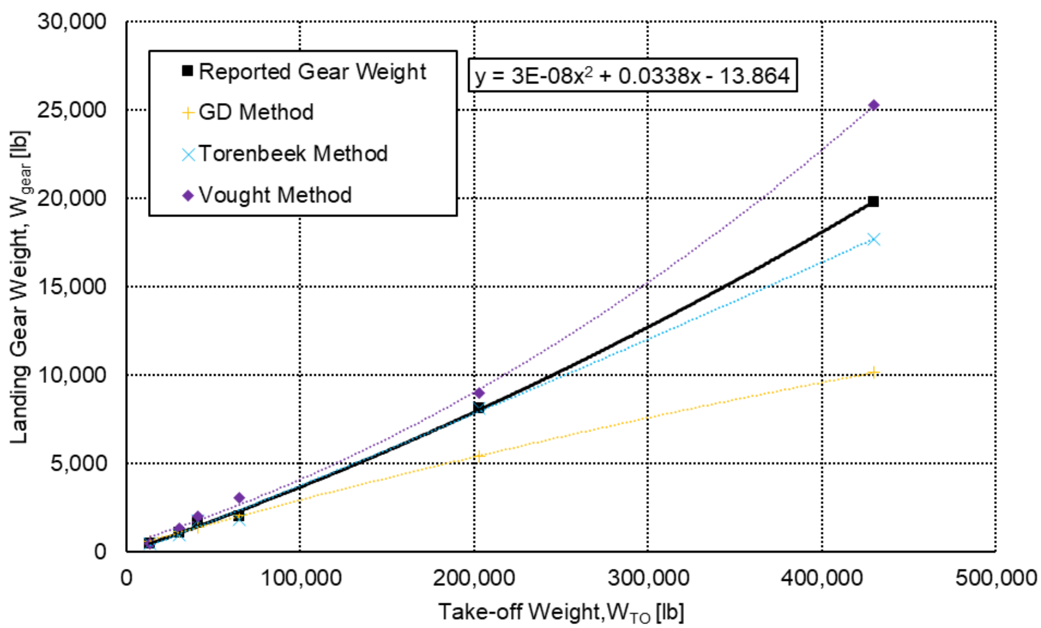

Figure 8. Weight Method Comparison for Commercial Transport Reported Landing Gear Weight

Figure 9 presents the comparison of weight methods to estimate the furnishing weight of commercial aircraft. The reported furnishing weight trendline is near linear and fits the data well, with the equation shown in the figure. All three weight methods are non-linear and under estimate the furnishing weight.

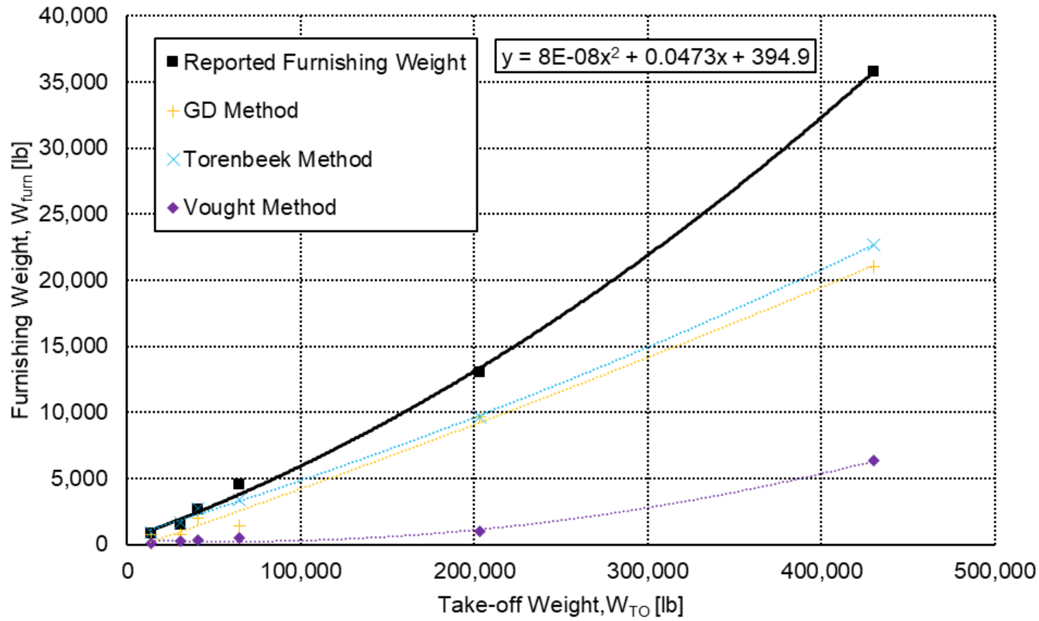

Figure 9. Weight Method Comparison for Commercial Transport Reported Furnishing Weight

C. Military Patrol, Bomber and Transport

From Ref. 1, this category includes military patrol, military bombers, military transport and supersonic patrol, bombers and transport aircraft. Methods used for commercial transport aircraft are used for military patrol, bomber and transport aircraft with appropriate substitutions made for structural loading and the V-n diagram. Therefore, the statements made in the previous section hold with this category. Due to more innovation occurring for this category, less regard for structural weight optimization and a wider variation in structural layout, weight methods may have a higher percentage error for this category. An example aircraft with all weight methods is shown in Table 3.

Table 3. Weight Method Comparison for a Military Transport Aircraft

Component	Lockheed C-130H[1] [lb]	Cessna Method [lb]	USAF Method [lb]	GD Method [lb]	Torenbeek Method [lb]	Vought Method [lb]
Wing	13,950	--	--	6,699	13,944	12,622
Empennage	3,480	--	--	2,353	1,127	2,744
Fuselage	14,695	--	--	4,329	--	15,903
Nacelle	2,756	--	--	--	2,570	3,297
Nose Gear	730	--	--	602	1,841	697
Main Gear	4,579	--	--	3,700	5,524	7,063
Engine	13,746	10,098	--	--	11,076	11,071
Fuel System	3,105	--	--	806	1,303	1,697
Propeller Installation	in engine	--	--	3,306	3,306	--
Propulsion System	in engine	--	--	1,507	2,543	218
Avionics/Electronics	3,582	--	--	2,007	1,160	2,358
Surface Controls	1,673	--	--	2,749	--	1,383
Hydraulic System	664	--	--	--	1,085	305
Electrical System	2,459	--	--	1,963	--	646

Table 3. Continued

Component	Lockheed C-130H[1] [lb]	Cessna Method [lb]	USAF Method [lb]	GD Method [lb]	Torenbeek Method [lb]	Vought Method [lb]
APU	651	--	--	--	620	660
Oxygen System	231	--	--	172	145	--
AirCo/Pressurization/Icing System	2,481	--	--	2,825	--	2,089
Furnishings	4,472	--	--	3,668	--	1,901
Operating items	532	--	--	--	2,334	--

D. Fighter and Attack

The fighter and attack category include high speed military trainers, fighter aircraft and supersonic fighter aircraft. Carrier-based fighters are also included with fudge factors for folding wings and landing gear for carrier landing. Due to more innovation occurring for this category, less regard for structural weight optimization and a wider difference in structural layout, weight methods may have a higher percentage error for this category. Trends appear when comparing weight methods for wing weight of the fighter and attack category, as seen in Figure 10. The reported wing weight trendline is non-linear, with the equation shown in the figure. The GD method has a similar trend to the reported wing weight while the Vought method forms a linear trendline. Both methods should be reconsidered.

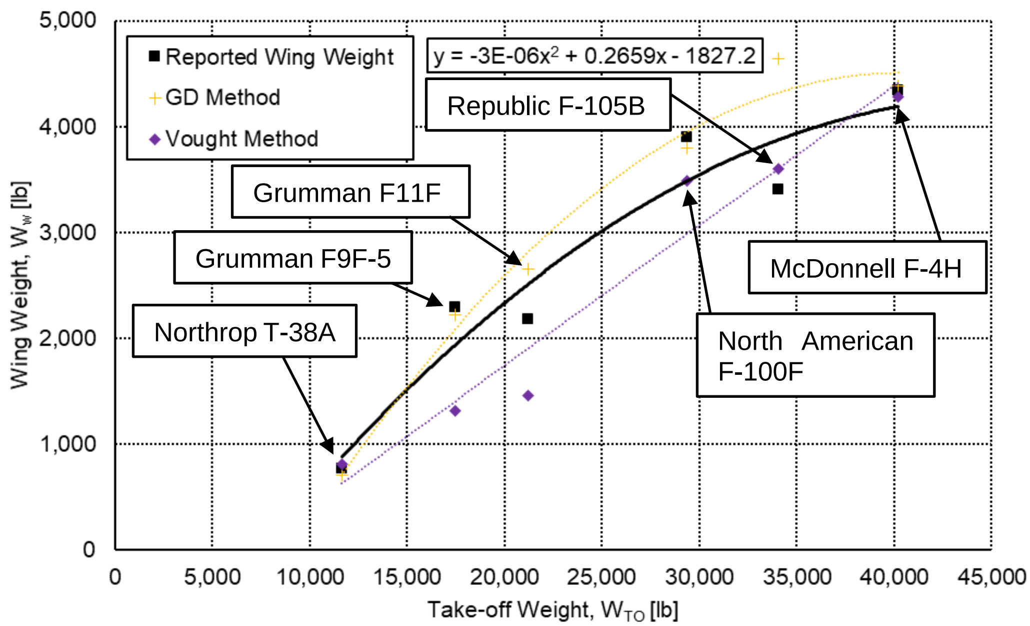

Figure 10. Weight Method Comparison for Fighter and Attack Reported Wing Weight

Figure 11 presents the comparison of weight methods to estimate the fuselage weight of fighter and attack aircraft. The reported fuselage weight trend is non-linear and does not fit with the data, with the equation shown in the figure. The GD and Vought methods should not be used due to the inaccuracies on an aircraft to aircraft basis. Neither method has an apparent trend as the take-off weight increases.

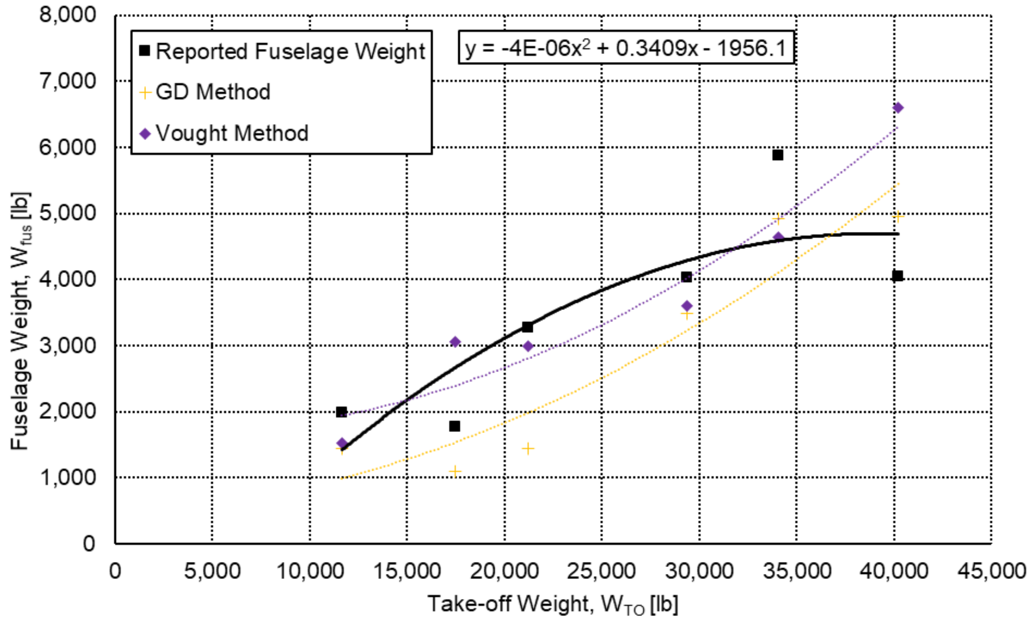

Figure 11. Weight Method Comparison for Fighter and Attack Reported Fuselage Weight

Figure 12 presents the comparison of weight methods to estimate the engine weight of fighter and attack aircraft. The reported engine weight forms a non-linear trendline that fits well with the reported data, with the equation shown in the figure. The Torenbeek method should not be used due to the differences in calculated engine weight.

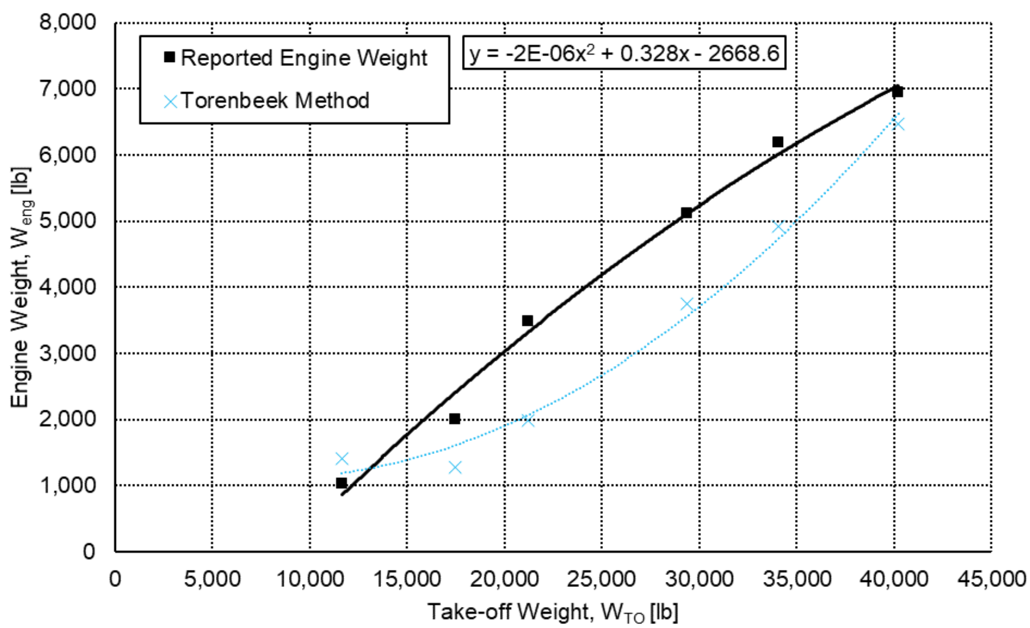

Figure 12. Weight Method Comparison for Fighter and Attack Reported Engine Weight

Figure 13 shows the comparison of weight methods to estimate the landing gear weight of fighter and attack aircraft. The reported landing gear weight forms a non-linear trendline and fits the data marginally well, with the equation shown in the figure. The Torenbeek method is a good estimation of the landing gear weight and may be used. The GD and Vought methods form linear trendlines and should be reconsidered when determining landing gear weight.

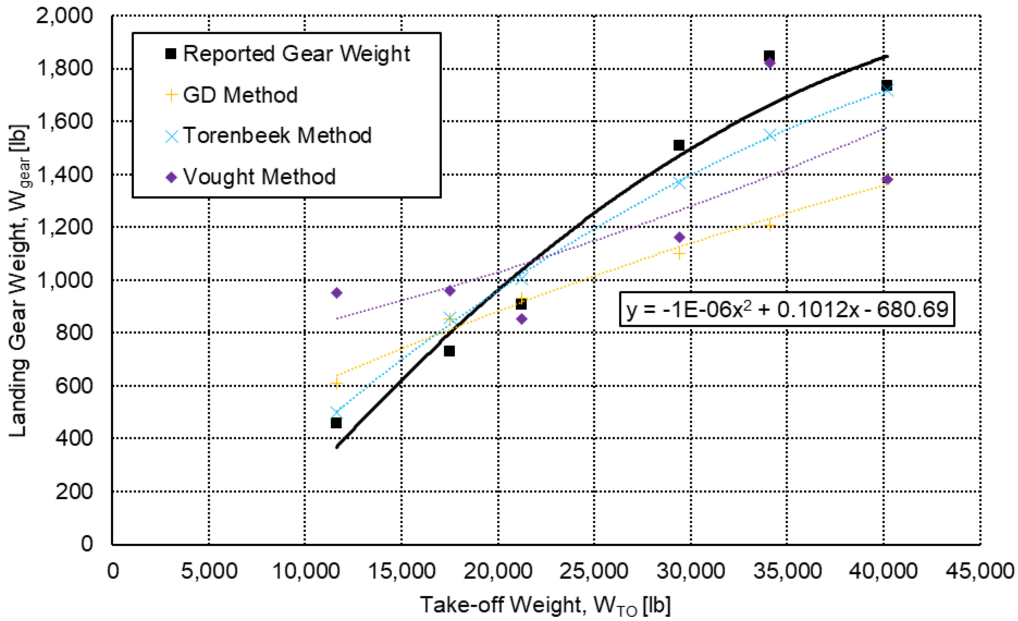

Figure 13. Weight Method Comparison for Fighter and Attack Reported Landing Gear Weight

IV. Weight Method Refinement

Initial weight method refinement focuses on the heaviest components of the aircraft. This includes the aircraft structure and engines. Furnishing weight may also be a large component of the empty weight, depending on the type of aircraft. The largest components of the overall weight are chosen, because a percent change in a heavy component has a larger effect on the overall aircraft weight than the same percent change in a lighter component. Table 4 shows the percentage of the largest components compared to the design gross weight. On average these percentages hold for any category. Engines and furnishings may vary by a large amount depending on the category.

Table 4. Aircraft Component Percentage of Gross Weight

Component	Component Weight/Gross Weight
Wing	~10%
Fuselage	~10%
Engine	~5-15%
Landing Gear	~5%
Furnishings	~2-10%

Table 5 presents the accuracy of each method for each component for the GA category. A 'plus' or 'plus-plus' represents a method that fits the data while a 'minus' or 'minus-minus' represents a method that does not fit the data.

Table 5. Accuracy of Methods for General Aviation Aircraft

Component	Cessna Method	USAF Method	Torenbeek Method	Vought Method
Wing	+	-	-	-
Fuselage	--	-	N/A	-
Engine	+	+	N/A	--
Landing Gear	++	--	-	--

Table 6 presents the accuracy of each method for each component for the transport category.

Table 6. Accuracy of Methods for Commercial and Military Transport Aircraft

Component	GD Method	Torenbeek Method	Vought Method
Wing	--	++	++
Fuselage	--	+	+
Engine	N/A	+	N/A
Landing Gear	--	++	+
Furnishings	-	-	--

Table 7 presents the accuracy of each method for each component for the fighter and attack category.

Table 7. Accuracy of Methods for Fighter and Attack Aircraft

Component	GD Method	Torenbeek Method	Vought Method
Wing	-	N/A	--
Fuselage	--	N/A	--
Engine	N/A	--	N/A
Landing Gear	--	++	--

The first step of refinement is to create more than four categories. Weight methods will be created for each new category. The following categories are used for this analysis.

- General Aviation Aircraft
- Regional Propeller Aircraft
- Business Jets
- Jet Transport Aircraft
- Propeller Transport Aircraft
- Air Force Fighter and Attack Aircraft
- Navy Fighter and Attack Aircraft

When the component weight is plotted versus the take-off weight, trendlines appear. For example, Figure 14 through Figure 17 presents the wing weight versus take-off weight for different categories.

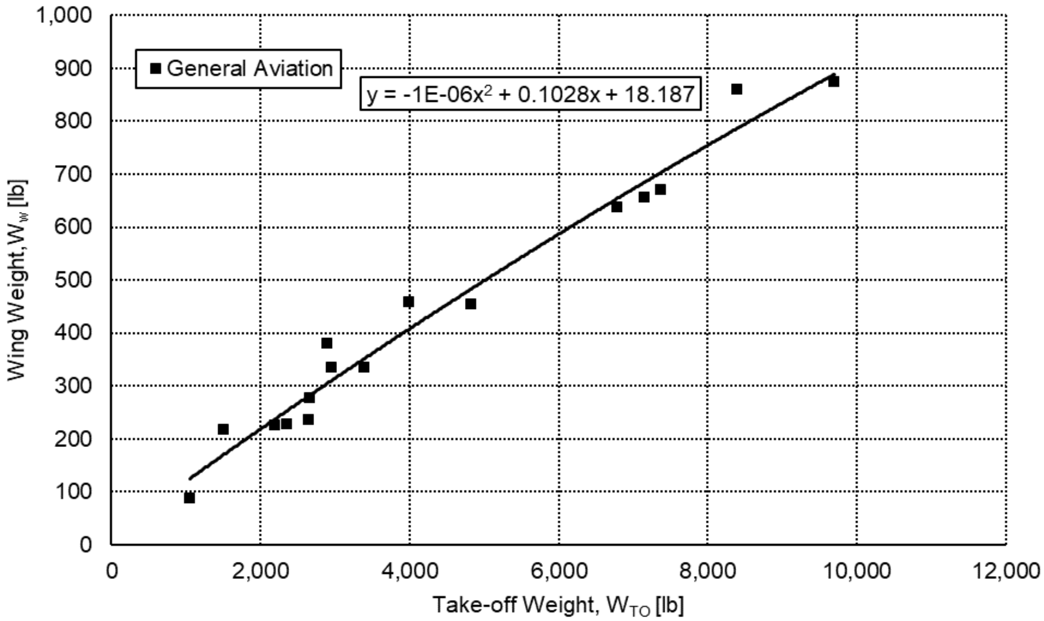

Figure 14. General Aviation Wing Weight Trendline

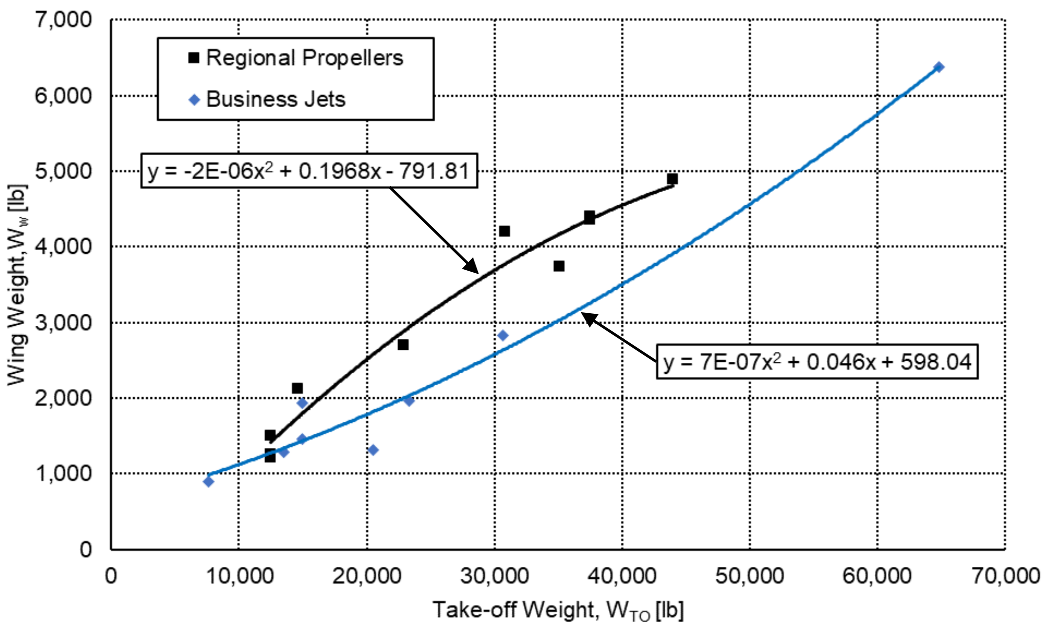

Figure 15. Business Jets and Regional Propeller Aircraft Wing Weight Trendlines

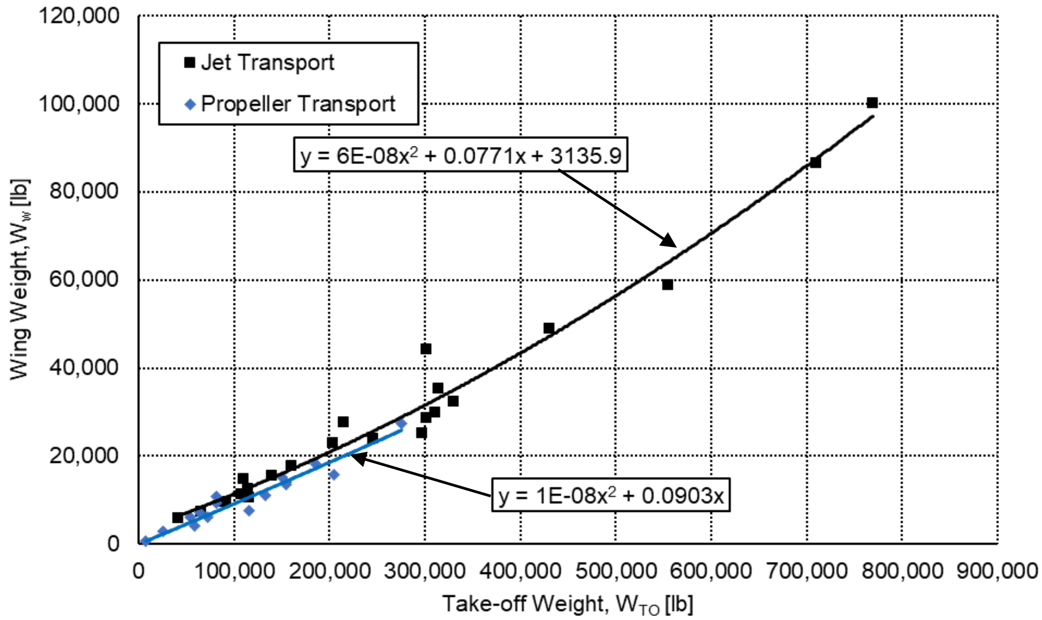

Figure 16. **Jet and Propeller Transport Wing Weight Trendlines**

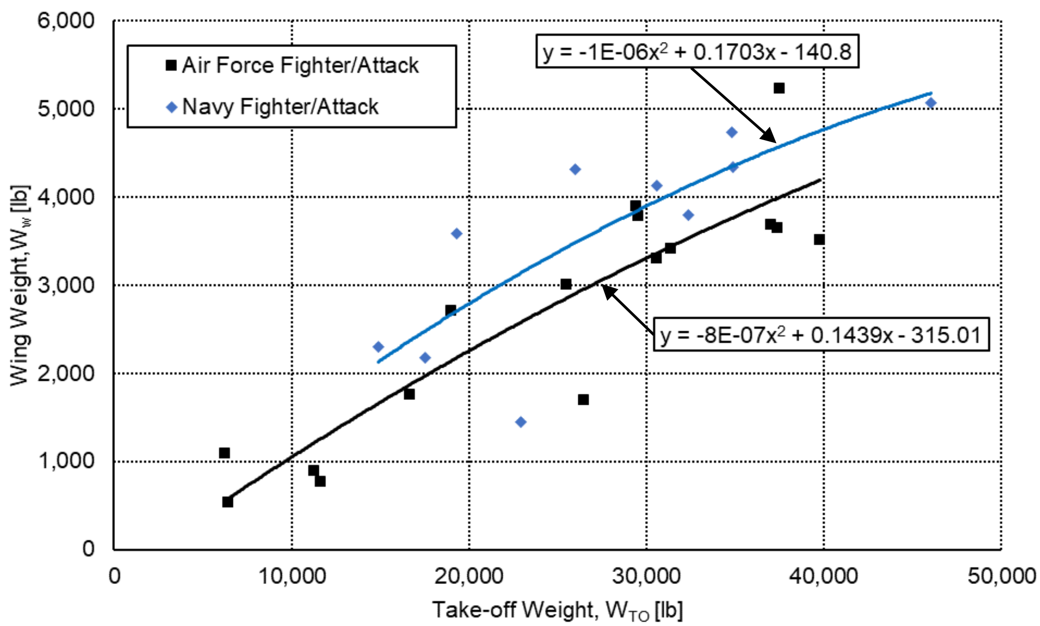

Figure 17. **Air Force and Navy Fighter/Attack Aircraft Wing Weight Trendlines**

The equations for the wing weight trendlines is as follows:

- General Aviation: $W_w = -1.35E^{-6} \cdot W_{TO}{}^2 + 0.103 \cdot W_{TO} + 18.2$
- Regional Propeller Aircraft: $W_w = -1.58E^{-6} \cdot W_{TO}{}^2 + 0.197 \cdot W_{TO} - 792$
- Business Jets: $W_w = 6.67E^{-7} \cdot W_{TO}{}^2 + 0.046 \cdot W_{TO} + 598$

- Jet Transport: $W_w = 5.87E^{-8} \cdot W_{TO}{}^2 + 0.077 \cdot W_{TO} + 3136$
- Propeller Transport: $W_w = 1.27E^{-8} \cdot W_{TO}{}^2 + 0.090 \cdot W_{TO}$
- Air Force Fighter and Attack Aircraft: $W_w = -1.19E^{-6} \cdot W_{TO}{}^2 + 0.170 \cdot W_{TO} - 141$
- Navy Fighter and Attack Aircraft: $W_w = -7.70E^{-7} \cdot W_{TO}{}^2 + 0.144 \cdot W_{TO} - 315$

Comparing the difference between the calculated wing weight and actual wing weight to the take-off weight, the above equations result in wing weights that are closer to the actual wing weight than the multiple existing methods listed in Section II. Using these simple equations in conjunction with other methods, a more accurate estimation of the wing weight can be reached.

V. Future Work

Future work includes the following:

- Generate fuselage weight trendline equations for all categories
- Generate engine weight trendline equations for all categories
- Generate landing gear weight trendline equations for all categories
- Generate furnishing weight trendline equations for commercial transport categories
- Expand the weight trendlines to include more aircraft

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