Estimating Missile Guidance and Control Development Cost: An Important Advance

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1.0 Introduction

This paper describes a cost research effort that developed new, important alternative cost estimating methodologies for estimating Tactical Missile Guidance and Control (G&C) Development Engineering (DE). These new methodologies are Cost Estimating Relationships (CERs) that are an alternative approach to commonly used cost factors (e.g., factor of prototype manufacturing or recurring cost).

The objective of the research effort was to develop CERs as a functional relationship between G&C DE effort <u>during Engineering and Manufacturing Development (EMD)</u> and one or more independent variables applicable to development engineering for EMD programs. The variability associated with pre-EMD development engineering was thought to be too great to include in the scope of the analysis.

The research leveraged existing cost, technical and schedule databases. The DOD Contractor Cost Data Reporting (CCDR) System (the cost segment of Cost and Software Data Reporting System (CSDR)) was used extensively in order to isolate nonrecurring engineering cost and hours. DOD Service cost centers and missile procurement commands were contacted to support cost and technical data requirements.

It is emphasized that raw Contractor Cost Data Report (CCDR) cost records (i.e., both the underlying Cost Data Summary Report (CDSR) and Functional Cost-Hour Report (FCHR)) were used in the analysis in order to more fully understand the detail and subtleties of the historical development engineering cost data. Analysis of the functional cost-hour (FCHR) data, resulted in analysis at quite low levels of cost detail. Additionally, cost reporting for several programs was incomplete for various reasons, and cost records from various sources were used to supplement CDSR and FCHR contract cost reporting records.

2.0 Ground Rules and Assumptions

G&C DE data was identified and mapped using DOD MILSTD-881standard WBS for missiles. Development Engineering was defined as the following functional cost elements as specified in the DOD Contractor Cost Data Reporting (CCDR) System:

- Non-recurring Engineering (Labor, Material, OH), excluding G&A, Fee
- Portion of Non-recurring Material that can be identified as Development Engineering
    - Non-recurring Purchased Equipment and Non-recurring Other Costs Not Shown Elsewhere (often used for subcontracted efforts)

One additional element of the definition of Development Engineering being analyzed is that the database includes DE cost for only one prime contractor development effort. To clarify, the database includes DE cost for a single prime contractor and any additional associate or major subcontractors related to the G&C DE effort. The database excludes any DE cost that may be associated with “follower” contractors. However, it should be noted that “follower” cost during EMD is primarily related to technology transfer efforts and does not typically include development engineering efforts – those efforts normally being performed by an associate contractor or major subcontractor.

Author's note: The following sections of this paper have several Tables and Figures that have been edited and/or formatted to obscure data that could be interpreted as FOUO and/or contractor proprietary data. System names and scales on several data and/or statistical graphs have been removed; and some cost and technical values on several tables have been obscured or removed.

3.0 Data

Our research initially identified 22 tactical missile system programs and, related to these programs, 38 total tactical missile system variants were evaluated for inclusion in the analysis. Strategic/nuclear missiles and munitions were excluded from the analysis. Several additional criteria were established to evaluate missile variants for inclusion in the analysis:

- Since Unit 1000 cost was thought to be an important independent variable (i.e., cost driver), we required missile variants to have production actual cost history in order to develop Unit 1000 cost; or, must have reliable estimate of Unit 1000 cost. This excluded approximately ten programs that either never entered or have yet to enter production.
- The missile variant must be an original "all-up" G&C development program, or a modification for which Unit 1000 production cost can be developed.
    - This excludes most G&C evolutionary variants, except where original, new guidance system variants are developed. For example, some missile programs, especially cruise missile programs, developed multiple but completely different guidance systems.
    - This also constrains and simplifies the analysis; but also means reliance on "older" data
- Contractor Guidance and Control System Development Engineering cost must be understood in context of Total Development cost, e.g., using SAR or Budget Justification

The research identified 22 missile programs and 38 missile variants that were evaluated; and identified 21 of the 38 variants for exclusion from the analysis.

After filtering programs for data sufficiency and for evolutionary variants, data for the 17 remaining system variants were analyzed in detail in order to establish Development Engineering cost data point values (i.e., dependent variable values). Cost data from Contract Data Summary Reports (CDSR; DD Form 1921) and Functional Cost-Hour Reports (FCHR; DD Form 1921-1) were used to establish the DE cost data values. Table 1 below identifies the mission and guidance type for the 17 missile variants that were analyzed.

System	Mission	Guidance Type
1	Air-to-air	RF
2	Strike	INS/GPS
3	Precision artillery	Semi-active Laser
4	Strike	INS/GPS
5	Anti-ship	RF
6	Defense suppression	RF
7	Anti-armor	Semi-active Laser
8	Strike	RF
9	Strike	INS/GPS; IR
10	Anti-tank, anti-armor	IR
11	Strike	INS/GPS
12	Strike	EO
13	Strike	IR
14	Air-defense	RF
15	Air-defense	RF
16	Air-to-air	IR
17	Air-defense	IR

Table 1 - Missile Guidance System List

4.0 Data Analysis

After identifying the 17 target Missile G&C Development Programs, development engineering cost data was collected, organized and normalized. Details and results related to the Missile G&C DE data collection process are discussed further below.

4.1 Data Collection

Total development cost for each program was first examined in order to understand development cost context, but also insure that all development engineering cost was included. CDSR and FCHR cost records were reviewed to identify those that comprise total development cost and compared with development cost reported in the SAR. In this manner data record gaps were identified and various data sources were contacted in order to cover data gaps. Summaries of contract costs that make up EMD (and LRIP if included) cost for each program were then prepared.

Relevant cost records that were analyzed included all records that were characterized as reporting development cost (including EMD/FSD/FSED and prior phases), plus early production contracts such as LRIP and Pilot Production. In some cases it was evident that early production contracts contributed to development engineering efforts. This was especially true in cases where early production was funded with RDT&E funding.

Once relevant contracts, contract tasks, contract cost records and contract costs were compiled, related FCHR records were researched to identify EMD program Guidance & Control Development Engineering cost, including the following functional cost elements within the CCDR cost reporting framework:

1. Non-recurring Engineering, including labor, material, overhead and ODC cost.
2. Non-recurring Purchased Equipment (PE) cost
3. Non-recurring Other Cost Not Shown Elsewhere (OCNSE)

Cost records were also inspected to insure consistency with MILSTD881 definitions of Guidance and Control, and occasionally adjustments to reported cost were required to either exclude cost unrelated to G&C or include cost that was reported but assigned to WBS elements other than G&C.

Once relevant contracts were identified and understood, and the relationship between individual program cost reports was understood, program development engineering cost was compiled using FCHR records. In some cases FCHR records were not available or did not report for all G&C elements. In those instances, CDSR and, occasionally, CPR data was used to estimate development engineering cost. Those cases were documented.

Summaries of non-recurring engineering, purchased equipment and OCNSE for each program were documented and a brief explanation of the makeup of each DE cost data value was developed. Costs for guidance and control were segregated when possible; however, no analysis was performed on either guidance or control separately.

The research concluded that analysis of guidance or control cost separately would not be likely to produce estimating methodologies with sufficiently low error metrics. This is thought to be due to significant common functionality between guidance and control, for example, processing, software, etc.; and the fact that assignment and reporting of cost between guidance and control lacks consistency between hardware contractors. This is often due to ambiguity of G&C functionality for some hardware elements, such as inertial systems, autopilots, GPS systems, and signal/data processors.

Finally, program schedule information was documented for each system, including schedule metrics, relevant inflation indices and inflation normalized data values for each DE data point. DE cost was normalized to FY17 dollars using Service-provided inflation indices.

A number of data challenges were encountered among the reported data. See Table 2.

- Cost reporting on several of the programs did not segregate guidance and control cost from one another, necessitating G&C cost to be analyzed in a combined fashion.
- In two cases there was no Control System WBS identified.
- Several other programs exhibited incomplete reporting of functional cost for all G&C elements. In those instances, a study by SAIC (Tactical Missile Development Cost, SAIC, May 1987, York, James L., Richard B. Collins II, et al) was used to augment CDSR/FCHR records.
- In a few cases, development programs exhibited quite small non-recurring engineering cost in EMD, and at the same time, large non-recurring engineering cost in LRIP. Thus, a ground rule was established to include the analysis pf LRIP non-recurring engineering and include those costs in DE. Without this ground rule, several programs' DE values would be evident as outliers.

It is also important to note that Government in-house development engineering efforts play a role in total G&C development engineering. The extent of this role can vary, but nonetheless it is a factor that should be considered for completeness. Unfortunately, cost data for government in-house efforts was not readily available to support the analysis.

System Variant	SAIC Study	G&C Cost	Guidance Cost Available	Control Cost Available	LRIP G&C N-R Design Engr.
1			X	Not reported on FCHR	No N-R
2		X	X	X	Med N-R
3		X	X	X	No N-R
4		X	G&C combined		Small N-R
5	X	X	X	X	Large N-R
6	X	X	X	X	Small N-R
7		X		G&C combined	No N-R
8			X		Small N-R
9		X	X	X	Large N-R
10		X	X	X	No N-R
11		X	X	X	No N-R
12	X	X	X	X	Small N-R
13		X	X	X	Large N-R
14		X	G&C Combined		No N-R
15		X	X	X	Large N-R
16			X	No Control WBS	Small N-R
17	X		X	No Control WBS	No N-R

Table 2 – Data Challenges

4.2 Statistical Analysis

Prior to developing the Missile G&C DE CERs, initial hypotheses were developed to identify potential cost driver variables. These potential cost driver variables are shown below in Figure 1.

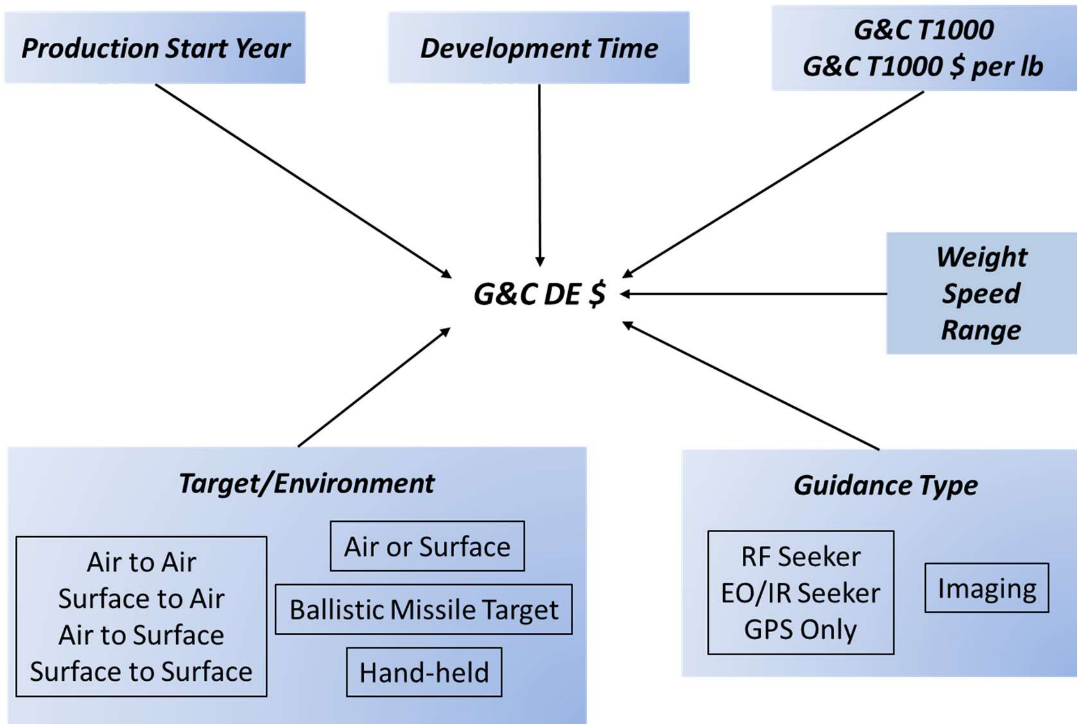


Figure 1 – Potential Missile G&C DE Influences

Primary cost driver influences were considered to be Missile Development Time and G&C T1000 Unit Cost. Other variables that were analyzed included technical and programmatic characteristics including:

- Weight, speed and range
- Target type and launch environment
- Guidance type
- Production start year (i.e., Prod Start Year – 1971)
- G&C T1000 Unit Cost and G&C T1000 cost per pound

Production start year, G&C T1000 unit cost and G&C T1000 cost per pound were employed as proxy variables to account for complexity, technology advancement, and development and manufacturing process changes. The analysis found both target type and guidance type to be critical for understanding the factors that influence the amount of development engineering effort required during EMD.

The process of hypothesizing influences and performing some initial analysis helped to identify the data to be collected within a Missile G&C Technical Database. Table 3 displays the final Missile G&C Technical Database used for developing the various CERs.

Program	Weight, G&C (lbs)	Max Range (nmi)	Range per lb (Missile)	Range per lb (G&C)	Speed per lb (Missile)	Speed per lb (G&C)	Air-Launched	Handheld	Air to Air Target	Air to Surface Target	Surface to Air Target	Surface to Surface Target	Ballistic Missile Target	Air Target	Ground Target	Ship Target	Fixed Target	Imaging Guidance	RF Seeker (Air)	RF Seeker (Surface)	RF Seeker	IR/EO Seeker	GPS Only
System A	120	40.1	0.12	0.33	12.8	37	✓		✓					✓					✓		✓		
System B	503	161.6	0.06	0.32	1.8	10						✓					✓						✓
System C	35	8.6	0.06	0.25								✓			✓							✓	
System D	30	37.8	0.06	1.26	2.6	52						✓					✓						✓
System E	193	69.5	0.09	0.36	4.9	20	✓			✓						✓	✓			✓	✓		
System F	142	75.0	0.05	0.53	0.5	5	✓			✓						✓	✓			✓	✓		
System G	32	4.3	0.04	0.13	13.2	44	✓			✓					✓							✓	
System H	32	5.6	0.05	0.18	12.9	44	✓			✓					✓			✓		✓	✓		
System I	100	199.8	0.08	2.00	0.4	9	✓			✓					✓		✓	✓				✓	
System J	7	1.3	0.05	0.19				✓				✓			✓			✓				✓	
System K	76	70.2	0.07	0.93			✓			✓							✓						✓
System L	120	25.2	0.05	0.21	1.7	7	✓			✓					✓			✓				✓	
System M	140	25.2	0.05	0.18	2.1	7	✓			✓					✓			✓				✓	
System N	340	53.5	0.03	0.16	1.7	10					✓			✓					✓		✓		
System O	200	93.0	0.13	0.47	7.9	28					✓		✓	✓					✓		✓		
System P	30	19.1	0.10	0.64	12.0	75	✓		✓					✓				✓				✓	
System Q	14	4.3	0.20	0.31	93.3	147		✓			✓			✓								✓	

Table 3 – Missile G&C Technical Database for Conducting Analyses

Missile G&C T1000 Unit Cost estimates were developed for each program in order to use T1000 Unit Cost as an independent variable. Contractor Cost Data Report (CCDR) cost data was analyzed and relevant G&C cost data was identified, organized, normalized and analyzed in order to develop G&C cost improvement curves (i.e., non-rate-adjusted) for each program.

In some cases, the data and analyses were fairly straightforward. In other cases, the process was more complicated, requiring judgment and/or estimation. For example, judgment was used to exclude the unit cost of later production lot costs of the example program (below), which were influenced by competition. This was done to develop a more realistic cost improvement curve T1000 estimate. Inclusion of the last two data points would clearly skew the estimate of T1000 (from regression of the data) to be below a more accurate estimate. Figure 2 depicts the G&C T1000 analysis example.

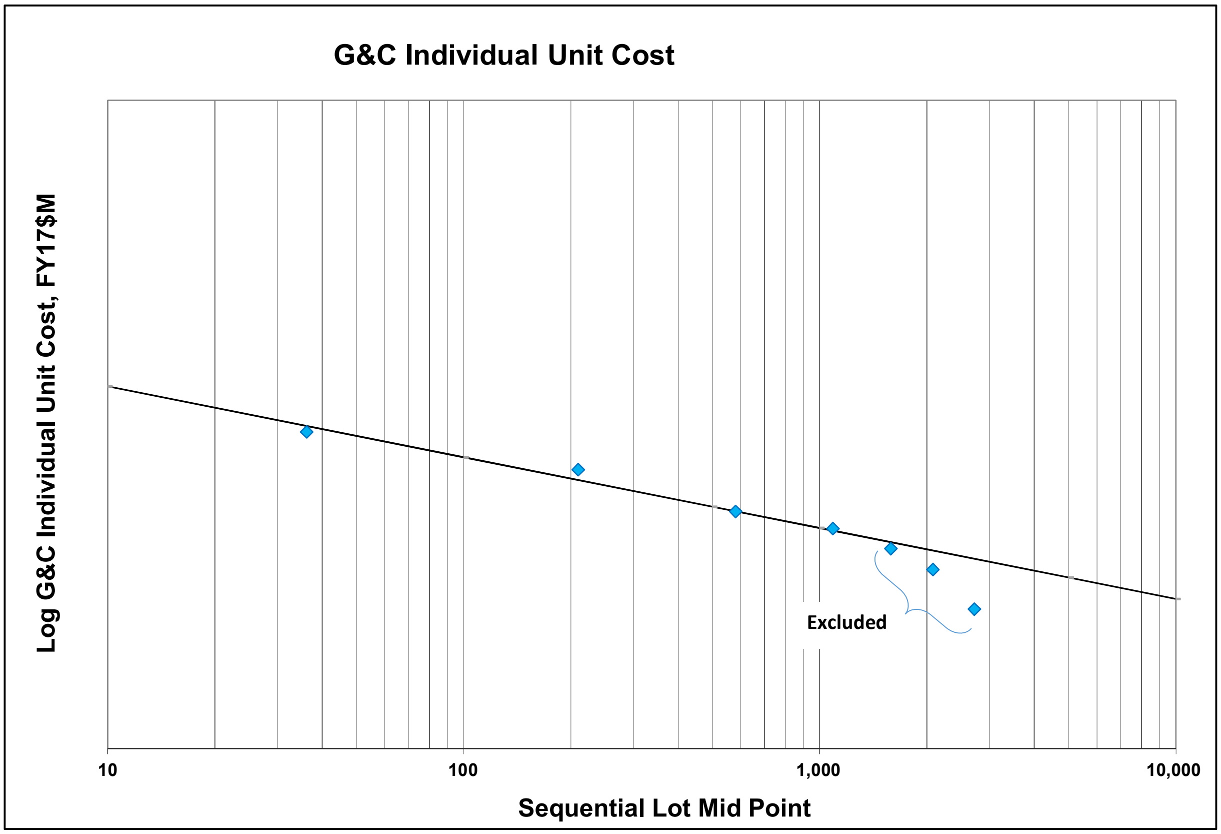


Figure 2 – Example G&C T1000 Analysis

The initial data analysis conducted a number of investigations in order to better understand the data and the relationship between G&C DE (the dependent variable) and the various independent variables. These activities included:

- Identify cost drivers (i.e., significant independent variables) and test their significance
- Identify data point subgroups and data trends
- Identify data anomalies
- Test data correlation
- Identify data gaps

In addition, both single-variable and multi-variable equation forms were hypothesized and analyzed.

During the analysis, potential data anomalies and gaps were identified, resulting in verification activities related to the development engineering cost data, technical data and G&C T1000 data. This process resulted in data corrections where needed and additional data collection where deemed beneficial.

One of the first steps of the analytical process was to assess the historical Missile G&C DE cost in relation to key potential cost drivers. Figure 3 below shows the relationship between Development Time (months) and Missile G&C DE cost.

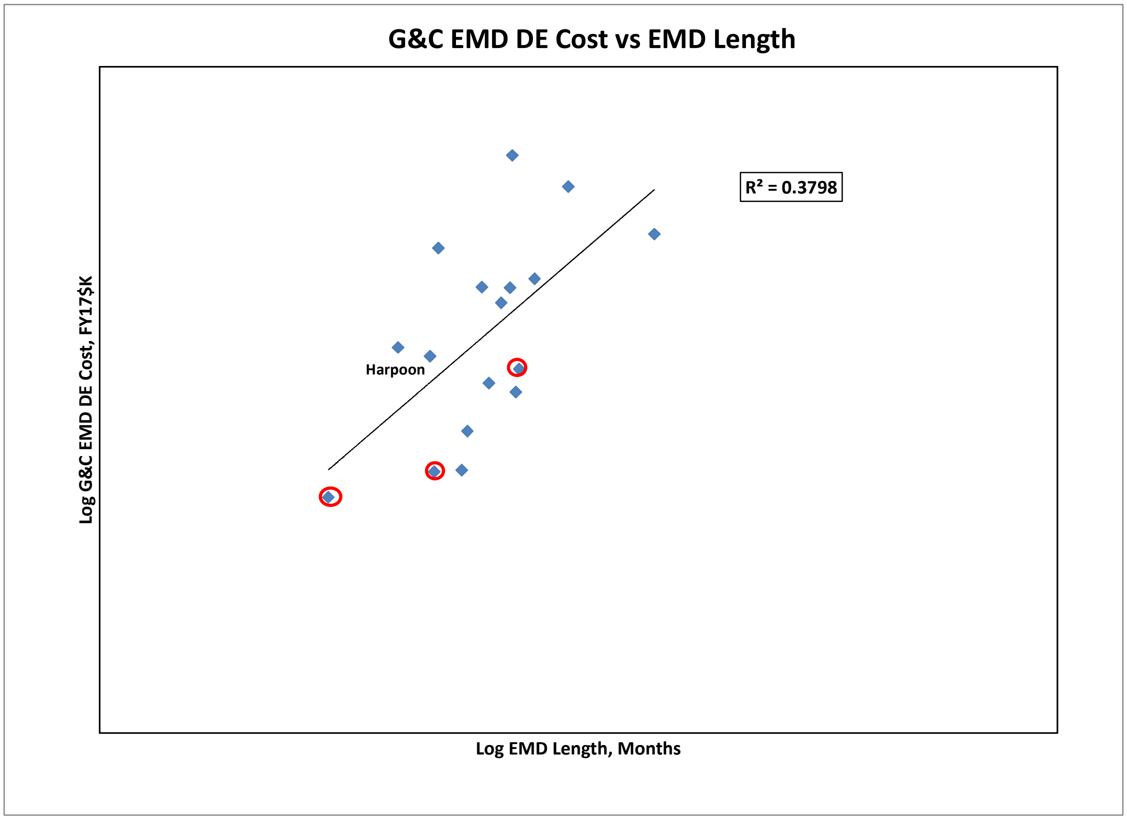


Figure 3 – Missile G&C DE FY17$K vs Development Time (months)

Observations from the above analysis include:

- Correlation with just Development Time has no clear outliers, although some data points may certainly be potential outliers
- There appears to be correlation between dependent and independent variable; however, dispersion is high with just the single independent variable
- Development Time appears to be a significant cost driver; however, this variable is typically seen as being within the responsibility of the technical and program management communities to specify. Thus an independent estimate of this variable is desirable but may not be available.
- This correlation seems to show a clear subgrouping of GPS/INS guidance systems, indicated by the data points circled in red.

Figure 4 shows the relationship between Missile G&C T1000 and Missile G&C DE Effort.

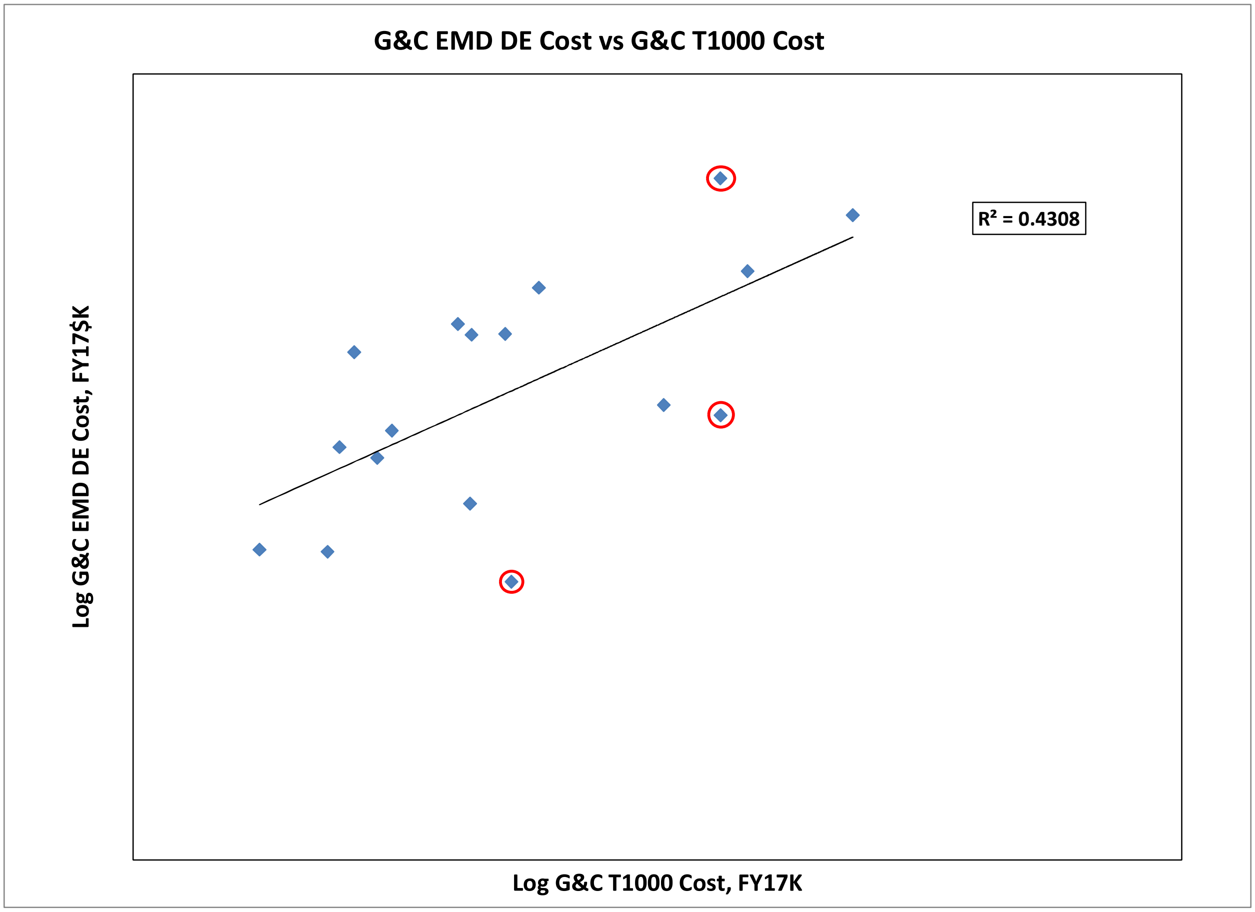


Figure 4 – Missile G&C DE FY17$K vs Missile G&C T1000 FY17$K

When correlating G&C Development Engineering with Missile G&C T1000 unit cost, it appears some correlation is indicated, however, the correlation also identifies possible outliers or data anomalies (those identifies with red circles).

Figure 5 depicts the relationship between Missile G&C DE and Missile G&C T1000 $-per-pound. The logic in using T1000 $-per-lb. is that it represents complexity normalized to size. For example, radar cost has been shown to be well correlated with density since the cost per pound has been shown to increase as platform size and weight decrease. Thus, radar cost per pound for ships and surface vehicles is clearly lower than that for aircraft; and, radar cost per pound for larger, heavier aircraft is generally less than that for smaller, lighter aircraft (e.g., fighter aircraft).

Figure 5 indicates the potential for correlation, but also exhibits high dispersion. Indeed, all three of the potential key cost drivers (i.e., Development Time, G&C T1000, G&C T100 $-per-lb.) appear "similar" in their correlation with G&C development engineering effort. "Similar" is used in the sense of moderate correlation with significant dispersion, but typical for a traditional development effort related CER.

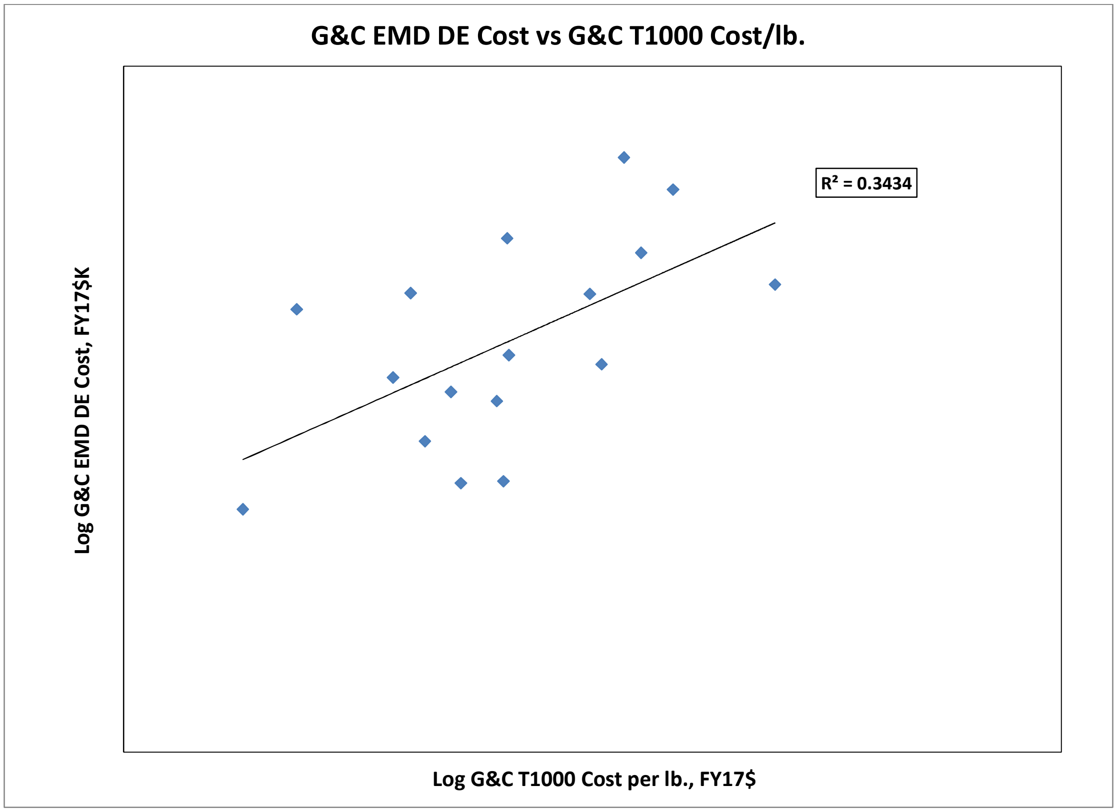


Figure 5 – Missile G&C DE FY17$K vs Missile G&C T1000 $ per lb.

These initial findings resulted in substantial effort being focused on identifying logical reasons why some programs might be more complex (i.e., requiring more development engineering effort) than others. This led to the identification and tagging of numerous technical characteristics for each program. These technical characteristics seemed to be of critical importance in discriminating complexity. They included those shown below in Table 4; and are primarily related to target type and guidance type.

Launch Type	Environment to Target	Target	Guidance
Air-Launched	Air to Air Target	Ballistic Missile Target	RF Seeker
Handheld	Air to Surface Target	Air Target	IR/EO Seeker
	Surface to Air Target	Ground Target	GPS Only
	Surface to Surface Target	Ship Target	Imaging Guidance
		Fixed Target	

Table 4 – Missile G&C Characteristics List

After associating, categorizing and comparing development engineering effort in relation to the technical characteristic tagging listed above, there appeared to be significant correlation. Figure 6 depicts the organized scaling (from low to high) of development engineering effort related to the characteristics as complexity and cost increases. In general, guidance type complexity increases from GPS to IR/EO to RF; and imaging functionality also adds additional complexity. For target type, complexity increases from surface to air targets.

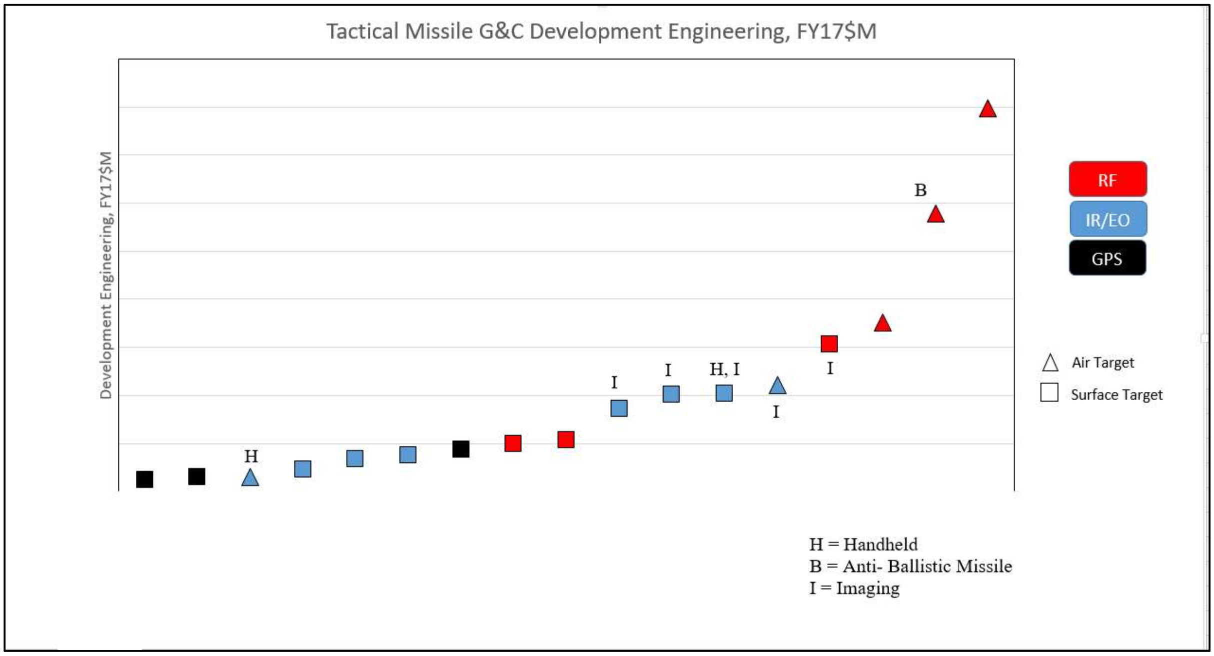


Figure 6 – Missile G&C DE Effort by Guidance and Target Types, V1

Figure 6 also shows the identification of hand-held launchers, which implies a decreased complexity compared to others in the same mission category. Figure 7 provides another view of the development engineering effort in relation to guidance and target type complexities.

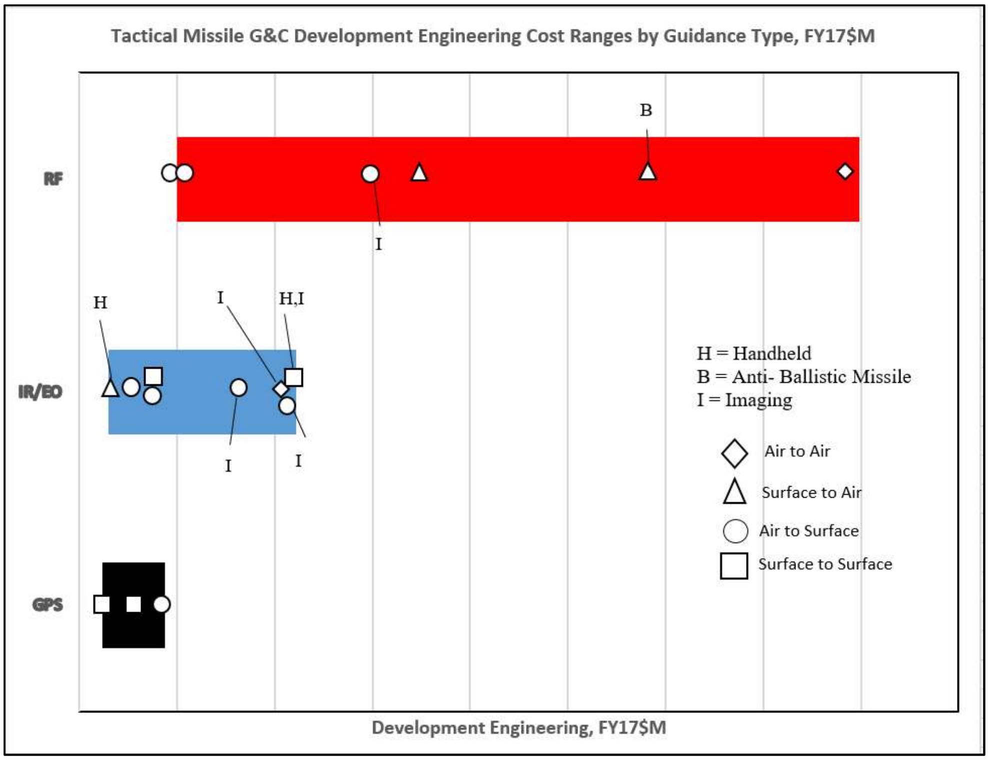


Figure 7 – Missile G&C DE Effort by Guidance and Target Types, V2

Additionally, Figure 8 provides an alternative third view of the same information relating development engineering effort to guidance and target type information.

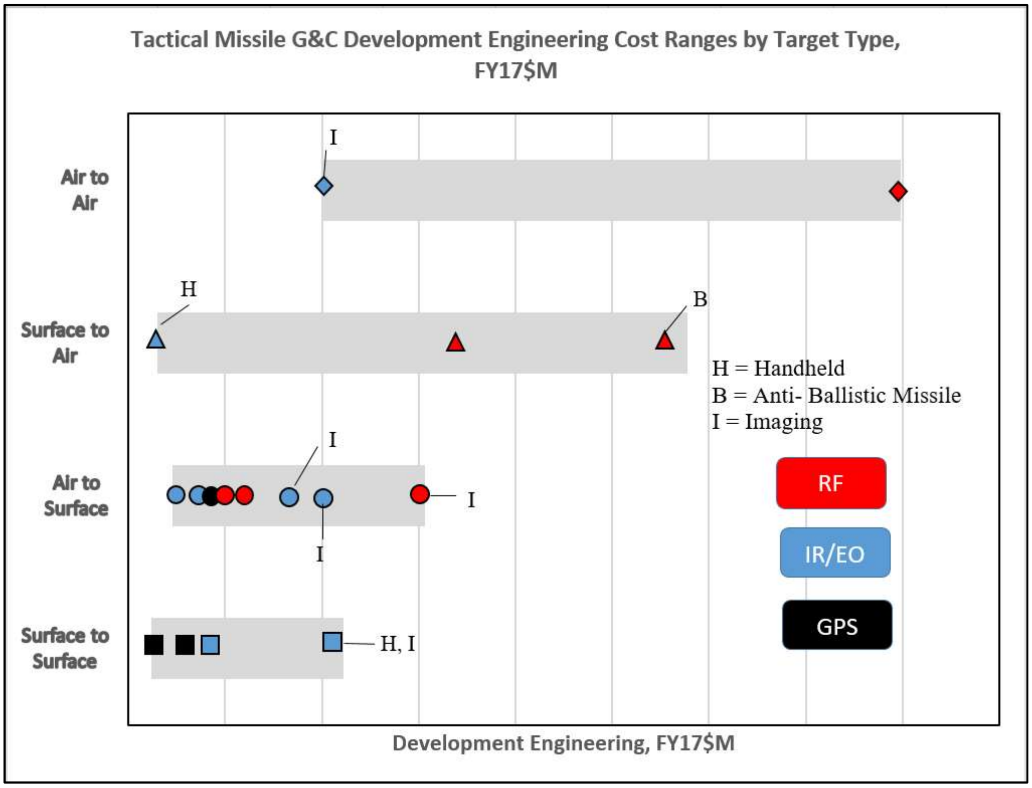


Figure 8 – Missile G&C DE Effort by Guidance and Target Types, V3

The primary purpose of the three database views displayed above is to provide analysts with a first step approach to identify an estimated rough order magnitude (ROM) range of development engineering effort based on the missile's G&C technology and mission.

Figures 6, 7 and 8 which characterize the Development Engineering cost database suggest the database itself can be used as an estimating tool in many circumstances; potentially for analogy estimating, double checking estimates and informing the estimating process in general.

5.0 CER Results

Table 5 relates, or matches, actual historical G&C DE cost with missile G&C characteristics, with target/launch environment being grouped with other G&C characteristics. Table 5 also depicts associated statistical metrics including number of data points, population average, median and range; and additionally, two error metrics. With respect to error calculations, Table 5 shows the median and average percent error**.** Note that there are a number of characteristic groupings where the number of observations is minimal (i.e., 1 or 2).

Program	Hand-held	Imaging Guidance	Ballistic Missile Target	Surface, No Imaging	Surface, Imaging	Air, Hand-held	Air, Not Hand-held	Surface to Surface, No Imaging	Surface to Surface, Imaging	Air to Surface, No Imaging	Air to Surface, Imaging	Surface to Air, Hand-held	Surface to Air, Not Hand-held	Air to Air	GPS Only	EO/IR Seeker, No Imaging	EO/IR Seeker, Imaging	RF Seeker, Surface	RF Seeker, Air
SYSTEM A				$				$							$				
SYSTEM B				$				$							$				
SYSTEM C	Y					$						$				$			
SYSTEM D		Y			$						$						$		
SYSTEM E				$						$						$			
SYSTEM F				$				$								$			
SYSTEM G				$						$					$				
SYSTEM H				$						$								$	
SYSTEM I				$						$								$	
SYSTEM J		Y			$						$						$		
SYSTEM K		Y					$$							$$			$$		
SYSTEM L		Y			$$						$$						$$		
SYSTEM M	Y	Y			$$				$$								$$		
SYSTEM N		Y			$$						$$								$$
SYSTEM O							$$						$$						$$
SYSTEM P			Y				$$						$$						$$
SYSTEM Q							$$							$$					$$
Min				$	$		$$	$		$	$		$$	$$	$	$	$	$	$$
Median				$	$$		$$	$		$	$		$$	$$	$	$	$$	$	$$
Average				$	$	$	$$	$	$$	$	$	$	$$	$$	$	$	$	$	$$
Max				$	$$		$$	$		$	$$		$$	$$	$	$	$$	$	$$
n	2	6	1	7	5	1	4	3	1	4	4	1	2	2	3	3	5	2	4
Median Percent Error				29%	14%		38%	43%		12%	26%		26%	92%	56%	23%	17%	5%	40%
Average Percent Error				62%	77%		58%	57%		16%	88%		26%	92%	68%	43%	66%	5%	40%

$$: < $100M $$$: > $100M

Table 5 – Missile G&C DE FY17$M Results by Combined Characteristic Groupings

The analysis next combined the key cost drivers discussed previously (i.e., from Figure 3 - 5) with the guidance and target type characteristics shown above. Since the number of data points within certain characteristic subgroups was limited, the analysis required tradeoffs between how many and which variables to include, with the tradeoffs being determined by the significance of individual variables.

After testing a large number of combinations of variables, several CERs were identified as having sufficient statistical significance and value-added, for use in estimating Missile G&C DE. These CERs leverage the characteristics shown in Table 5, represented by dummy variables; and by using one or more of the following cost drivers to "scale" estimates, i.e., as a function of a continuous variable.

- Development Time (Months)
- Missile G&C T1000 (FY17$) and Missile G&C T1000 FY17$ per lb.
- Production Start Year

Two groups of CERs were developed. One group includes the use of development schedule as an independent variable, while the second group excludes this variable. Within each group of CERs, multiple cost database scenarios were analyzed. In addition to the full database being analyzed, additional scenarios were analyzed for each CER group and those are discussed further below.

The CERs detailed below were developed with the objective of minimizing percent estimating error. The intent was to avoid using the OLS regression error that "favors" data points with large observation values. Instead an iterative optimization tool was used to minimize percent error. Table 6 provides a summary view of the form of the CER results and comparison of coefficient results, where:

$$\text{G\&C DE FY17\$K} = a \bullet \text{EXP}^{((\text{Prod Start Year - 1971}) \bullet b)} \bullet \text{Scaler}^{c} \bullet d^{\text{Characteristic = 1/0}}$$

Scalers = Dev Time, G&C T1000 FY17$K and G&C T1000 FY17$ per lb.

Characteristics = Target and Guidance Type

	1 - No Dev Time	2 - No Dev Time *	3 - No Dev Time **	4 - Dev Time plus	5 - Dev Time plus *	6 - Dev Time plus **
Intercept	A	B	C	D	E	F
Production Start Year - 1971	-0.029	-0.029	-0.029			
Dev Time (months)				1.30	1.26	1.60
G&C T1000 FY17$K						
G&C T1000 FY17$ per lb	0.36	0.42	0.34			
Hand-held	0.48	0.38				
Air Target		1.51				
Surface Target						
Air to Air Target	2.78			2.54		
Surface to Air Target	1.34					
Air to Surface Target			1.33			
Surface to Surface Target						
Ballistic Missile Target	3.40	3.50		1.91	2.31	
Imaging Guidance	2.34	2.67	2.20	2.38	2.79	2.35
RF Seeker	1.81	1.37		3.28	2.77	3.157
EO/IR Seeker						
GPS Only						
Median Absolute Deviation of % Errors	39%	21%	17%	25%	13%	11%
Mean Absolute Deviation of % Errors	40%	32%	28%	26%	18%	19%

* Exclude Outlier

** Only includes Surface Target G&C Systems

Table 6 – Missile G&C DE CER Summary Results

Each of the CERs is depicted and discussed individually below. CER equations use the abbreviations depicted on Table 7 in place of independent variable names.

MISSILE CHARACTERISTICS	ABREVIATION	
G&C DE (Total) FY17$K	G&C	
Production Start Year - 1971	Year	Scalers
Development Time (months)	DevTime	Scalers
G&C T1000 UC FY17$K	FY17$K	Scalers
G&C T1000 UC FY17$K per lb.	Cost_lb	Scalers
Air Target	AT	Target Type
Surface Target	ST	Target Type
Ballistic Missile Target	BMT	Target Type
Air-to-Air Target	AAT	Launch/Target Type
Surface-to-Air Target	SAT	Launch/Target Type
Air-to-Surface Target	AST	Launch/Target Type
Surface-to-Surface Target	SST	Launch/Target Type
RF Seeker	RF	Guidance Type
EO/IR Seeker	IREO	Guidance Type
GPS Only	GPS	Guidance Type
Imaging Guidance	IG	Other
Hand-held	HH	Other

Table 7 - Variable Reference Table

As indicated earlier, substantial effort was expended identifying those variables that are significant cost drivers for missile G&C development engineering. Independent variables were categorized into groups of variables shown in Table 7, those being Scaler (i.e., continuous) variables and additional discreet (i.e., dummy) variable groups, those being Target Type, Launch/Target Type, Guidance Type and Others. This was accomplished due to the fact that the Target Type group and Launch/Target Type group are not entirely independent of one another; and also to identify baseline variables for each group.

Baseline variables for dummy variable groups are important since they do not have to be included as variables in the individual regressions, and this prevents over specification, ensuring degrees of freedom. For example, for the Launch/Target Type group, only three of the four variables need to be included in regressions and the remaining variable is the “baseline” for that group. Additionally, for the Target Type and Launch/Target Type groups, these groups were tested independently. For example, the Air Target variable was not used at the same time as was the Air-to-Air Target variable, again, to insure independence, prevent over specification and maximize degrees of freedom.

Two groups of CERs were developed. One group includes the use of development schedule as an independent variable, while the second group excludes this variable. As indicated earlier, Development Time is clearly a significant cost driver and its inclusion as an independent variable produces the most favorable statistical results.

However, estimates of Development Time are typically the responsibility of the technical and program management communities and these estimates are not only inherently uncertain (i.e., considerable up-side risk) they are also considered to be non-independent (i.e., biased). Thus, CERs excluding Development Time as an independent variable were investigated.

Assuming an estimate of Development Time is available, both groups of CERs can be investigated for use. Furthermore, even if an independent estimate of development schedule is available, it is desirable to apply more than one estimating methodology, and the group of CERs excluding Development Time provides this capability.

Within each group of CERs, multiple cost database scenarios were analyzed. In addition to the full database being analyzed, three additional scenarios were analyzed for each CER group.

1. A cost database that excluded a sizable outlier as a data point. While there were additional data points that were potential outliers, the outlier was also the only missile in its mission category and guidance type. As a result, it was a primary cause of high mean error during the analysis, and error was reduced significantly when it was excluded.
2. A second database excursion focused on those systems that attack surface targets only. Of the seventeen guidance systems in the database, twelve of those have surface target missions. Furthermore, of the remaining five air-target systems, three of these have RF guidance, which typically exhibit cost at the higher end of the cost range. As such, a surface targets only database scenario was a logical excursion from the full database.
3. A third database excursion excluded those data points for the missiles that entered production prior to 1980. Although there were formulations derived from this dataset that had favorable error metrics, none of these were recommended, for a variety of reasons. To summarize, these formulations suffer primarily from logical inconsistencies in coefficients and application limitations, for example, no application for certain mission categories.

Important observations to be considered at this point include:

1. The worst mean error (i.e., 40%) exhibited by the set of CERs is roughly one-half that exhibited by a factor approach (i.e., ~ 100%) based on the full dataset.
2. While the CERs that exclude the use of development schedule may have more (perceived) independence, these CERs have significantly higher error metrics than do the CERs that include Development Time.
3. The independent variable that best represents technology advancement, i.e., Production Start Year, estimates a 3% increase in cost annually, as the cost impact of technology advance. A highlight of this is the fact that it has the same impact (i.e., the same coefficient to three decimal places) in all three formulations in which it is used. Although two of the three formulations use a quite similar database (full database and full database less one

outlier) all three formulations have at least one independent variable that is different. The third database (i.e., surface target set only) is quite different than the other two.

4. While several of the recommended CERs have numerous independent variables, none of these formulations have less than seven degrees of freedom. In other words, these formulations are not necessarily “over-fitting” the data simply by adding independent variables. All of the independent variables are thought to be significant.
5. The Development Engineering database itself can be used as an estimating tool in many circumstances; potentially for analogy estimating, double checking estimates and inform the estimating process in general.

Prior to conducting statistical analysis, cross correlation between independent variables was investigated. A correlation matrix showing correlation between variables is displayed below. While it shows correlations with the dependent variable (a desirable outcome), other correlations between independent variables led to better understanding of variable relationships. No cases of cross correlation that might jeopardize the validity of the resulting CER coefficients were identified.

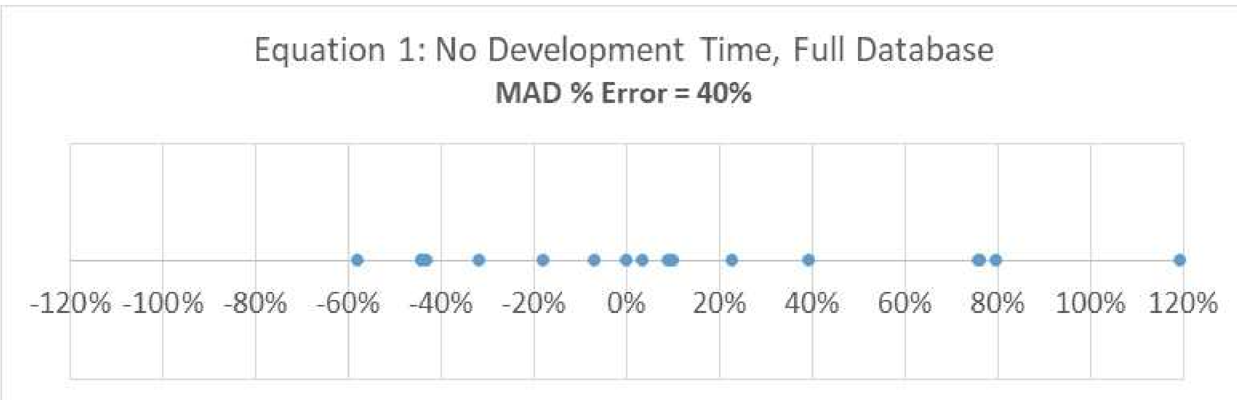
	G&C DE (Total) FY17$K	Prod Start Year - 1971	Dev Time (months)	G&C HW T1000 FY17$K	Weight, G&C (lbs)	G&C T1000 $ per lb	Hand-held	Air to Air Target	Air to Surface Target	Surface to Air Target	Surface to Surface Target	Ballistic Missile Target	Imaging Guidance	RF Seeker	EO/IR Seeker	GPS Only
G&C DE (Total) FY17$K	1.00															
Prod Start Year - 1971	-0.07	1.00														
Dev Time (months)	0.43	-0.01	1.00													
G&C HW T1000 FY17$K	0.68	-0.04	0.37	1.00												
Weight, G&C (lbs)	0.09	0.05	0.06	0.38	1.00											
G&C T1000 $ per lb	0.40	-0.23	0.19	0.27	-0.28	1.00										
Hand-held	-0.13	0.08	0.05	-0.22	-0.33	0.55	1.00									
Air to Air Target	0.54	-0.20	0.09	0.07	-0.14	0.12	-0.13	1.00								
Air to Surface Target	-0.29	0.27	-0.37	-0.22	-0.15	-0.30	-0.34	-0.34	1.00							
Surface to Air Target	0.27	0.11	0.58	0.57	0.22	0.06	0.31	-0.17	-0.44	1.00						
Surface to Surface Target	-0.31	-0.26	-0.15	-0.31	0.09	0.20	0.23	-0.20	-0.52	-0.26	1.00					
Ballistic Missile Target	0.46	-0.28	0.28	0.80	0.15	0.27	-0.09	-0.09	-0.24	0.54	-0.14	1.00				
Imaging Guidance	-0.03	-0.18	-0.09	-0.35	-0.31	0.26	0.11	0.11	0.29	-0.34	-0.12	-0.18	1.00			
RF Seeker	0.63	0.17	0.17	0.76	0.27	0.23	-0.27	0.11	0.04	0.30	-0.41	0.34	-0.29	1.00		
EO/IR Seeker	-0.33	0.19	0.02	-0.53	-0.48	0.02	0.39	0.02	0.06	-0.13	0.03	-0.24	0.54	-0.70	1.00	
GPS Only	-0.35	-0.46	-0.24	-0.26	0.29	-0.31	-0.17	-0.17	-0.13	-0.21	0.47	-0.12	-0.34	-0.34	-0.44	1.00

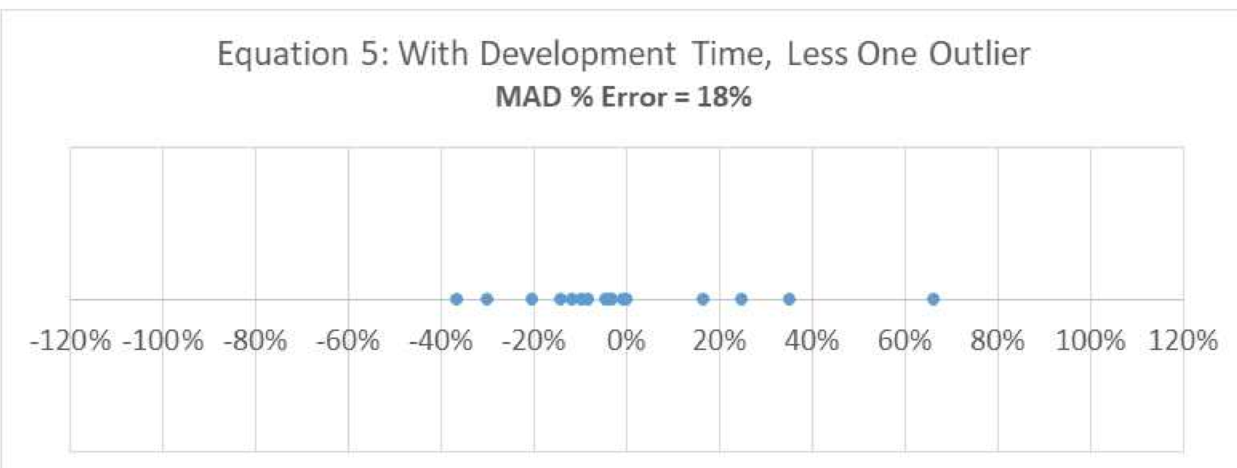
Table 8 – Covariance Matrix

Each CER is presented and discussed below. Where missile/guidance characteristics are indicated as exponents, they take the value of either zero or one depending on whether they apply in any given case. Intercepts are obscured to protect proprietary data. The significance of the characteristic (or “dummy”) variables is indicated by the magnitude of their coefficient. The error terms are the Mean Absolute Deviation (MAD) of % errors produced by 500 iterations of an iterative optimization routine.

For each equation, individual percent error outcome, by system, is depicted on a horizontal scale, about zero percent. Equations with the best and worst mean absolute percent error metrics are shown below.

Equation 5, which has less than one-half the error of Equation 1, naturally has a considerably narrower error band. The data point with the largest positive error (i.e., predicted > actual) associated with Equation 5 is nearly half that of the largest error associated with Equation 1 (66% vs 119%). Similarly, the largest negative error (i.e., actual > predicted) associated with Equation 5 is about two-thirds that of the largest negative error associated with Equation 1 (-37% vs -58%).





CERs that exclude Development Time as an independent variable

Equation 1: Full Database, 2 scalers, 6 characteristics

G&C DE FY17$K = A • EXP $^{(Year \bullet -0.029)}$ • (Cost/lb$^{0.36}$) • (0.48^{HH}) • (2.78^{AAT}) • (1.34^{SAT}) • (3.40^{BMT}) • (2.34^{IG}) • (1.81^{RF})

Mean Absolute Deviation (MAD) % Error = 40%

This CER uses the full database and does not depend on an estimate of development schedule and thus presents the highest error metric. While this equation required estimation of nine coefficients, it has at least seven degrees of freedom (DF) by making use of the full database; and could be thought of having as many as twelve degrees of freedom, depending on definition of DF.

Of note is the fact that one of the coefficients equates to a simple estimating factor since it is based on a single data point. Other than this coefficient, the dummy variable with the most impact is the Air-to-Air Target (AAT) coefficient. The Imaging Guidance (IG) coefficient is nearly as significant as is AAT; while the Hand-held (HH) coefficient reflects the influence of the two HH systems.

Figure 9 displays individual percent error outcomes, for each missile variant, on a horizontal scale, about zero percent.

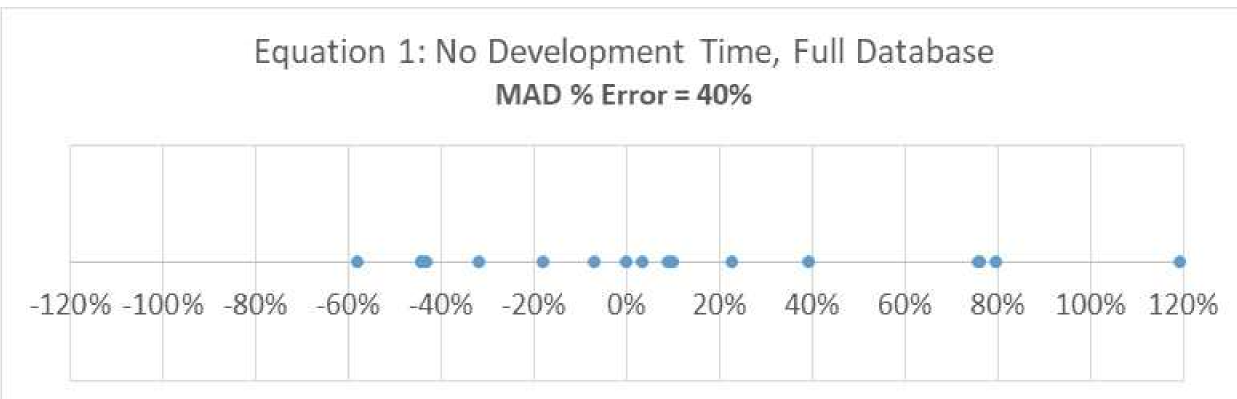


Figure 9 – Missile G&C DE CER 1; FY17$M; Percent Error about Zero

Equation 2: Full Database less one outlier, 2 scalers, 5 characteristics

G&C DE FY17$K = B • EXP $^{(Year \bullet -0.029)}$ • (Cost/lb$^{0.42}$) • (0.38^{HH}) • (3.50^{BMT}) • (1.51^{AT}) • (2.67^{IG}) • (1.37^{RF})

MAD % Error = 32%

Similar to Equation 1, this CER does not depend on an estimate of development schedule. By dropping a single outlier from the database, its influence on the remaining data points is mitigated and the error metric is improved considerably. This CER may be preferred in instances that do not address the mission case represented by the outlier. The BMT and Imaging characteristics have the greatest impact of the dummy variables.

Figure 10 displays individual percent error outcomes, for each missile variant, on a horizontal scale, about zero percent.

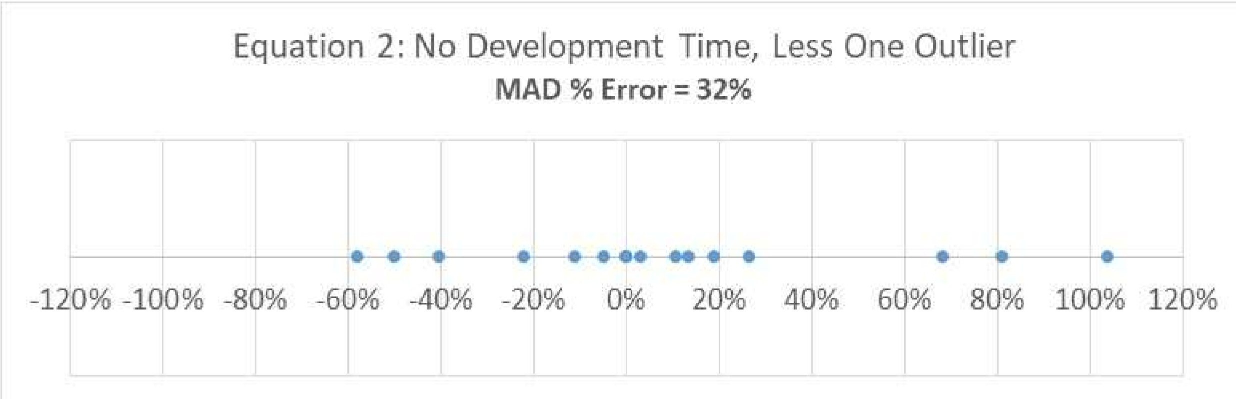


Figure 10 – Missile G&C DE CER 2; FY17$M; Percent Error about Zero

<u>**Equation 3**</u>: Surface Target only Database, 2 scalers, 2 characteristics

G&C DE FY17$K = C • EXP $^{(\text{Year} \cdot -0.029)}$ • (Cost_lb$^{0.34}$) • (1.33^{AST}) • (2.20^{IG})

MAD % Error = 28%

Again, this CER does not depend on an estimate of development schedule. By analyzing only the surface target data set, the error metric is improved due to considerably reduced variation in the data set due to the exclusion of the airborne target data points and several RF data points – these having generally high estimating errors.

Figure 11 displays individual percent error outcomes, for each missile variant, on a horizontal scale, about zero percent.

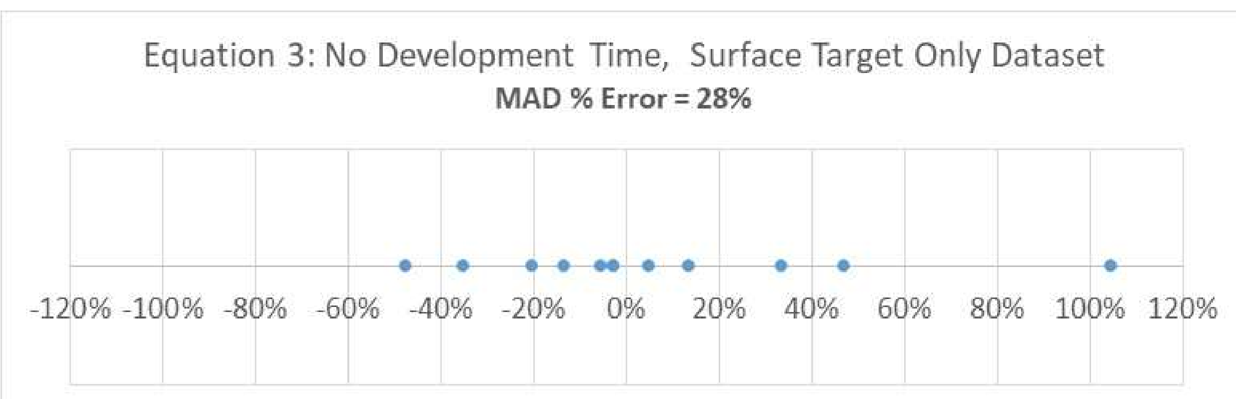


Figure 11 – Missile G&C DE CER 3; FY17$K; Percent Error about Zero

CERs that include Development Time as an independent variable

Equation 4: Full Database, 1 scaler, 4 characteristics

G&C FY17$K = D • (DevTime$^{1.296}$) • (2.541^{AAT}) • (1.914^{BMT}) • (2.378^{IG}) • (3.283^{RF})

MAD % Error = 26%

This equation uses an estimate of EMD Development Time (in months) and the impact and significance of this variable can be understood by noting the magnitude of the coefficient (i.e., an exponent exceeding the value of one), and an Average Absolute % Error approximately equal to that of the best CER from the group that excludes the use of development schedule as a variable.

Furthermore, using Development Time in the equation allows use of only one scaler variable instead of two, and only four dummy variables instead of six (as in Equation 1). By reducing the number of independent variables, this improves the degrees of freedom and thereby the mean % error (assuming the reduced variable set explains the underlying variation as well as does the original variable set).

Of further note is the fact that the coefficients for the dummy variables all approximate or exceed a factor of two – an indication of significance.

Figure 12 displays individual percent error outcomes, for each missile variant, on a horizontal scale, about zero percent.

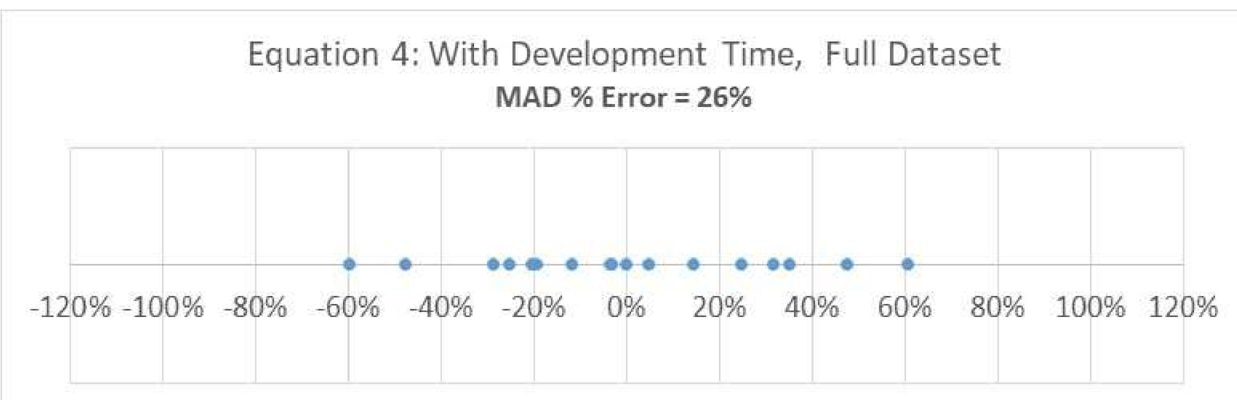


Figure 12 – Missile G&C DE CER 4; FY17$M; Percent Error about Zero

Equation 5: Full Database less one outlier, 1 scaler, 3 characteristics

G&C FY17$K = E • (DevTime$^{1.264}$) • (2.308^{BMT}) • (2.787^{IG}) • (2.771^{RF})

MAD % Error = 18%

Once again, dropping a single outlier from the data set improves mean error considerably. Another result is that the influence of the remaining dummy variables increases and the influence of DevTime remains approximately the same.

Figure 13 displays individual percent error outcomes, for each missile variant, on a horizontal scale, about zero percent. As before, exclusion of the outlier data point decreases dispersion significantly.

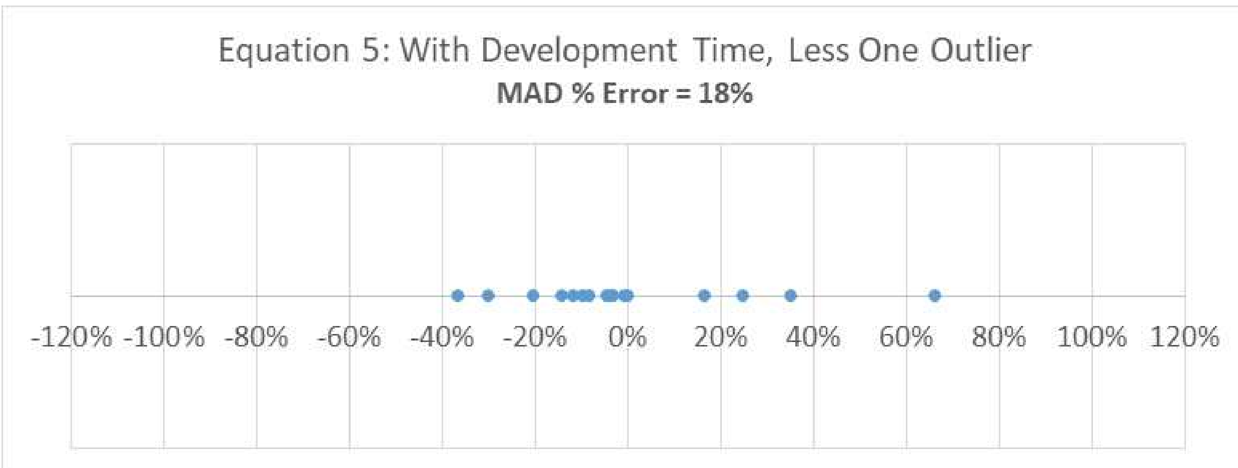


Figure 13 – Missile G&C DE CER 5; FY17$M; Percent Error about Zero

Equation 6: Surface Target only Database, 1 scaler, 2 characteristics

G&C DE FY17$K = F • (DevTime$^{1.598}$) • (2.35^{IG}) • (3.157^{RF})

MAD % Error = 19%

This CER applies to the surface-target-only data set. By using a data set with only surface target related data points, the BMT dummy variable is removed and the DevTime variable takes on more importance as does the RF dummy variable.

Note that Equation 6 has an error metric approximately the same as that of Equation 5. This may imply the mean percent error of Equation 5 and 6 is a lower limit for the data set, at least with the independent variables being tested. Potentially, the data set itself could be improved in some manner - either in terms of accuracy (i.e., of data points) or by additional data points. However, it is difficult to imagine what additional independent variables might explain sufficient variation, that is, to reduce error enough to compensate for the increase in error due to additional variable(s) (i.e., loss of DF).

Figure 14 displays percent error outcomes and dispersion of this data set is similar to that of CER #5.

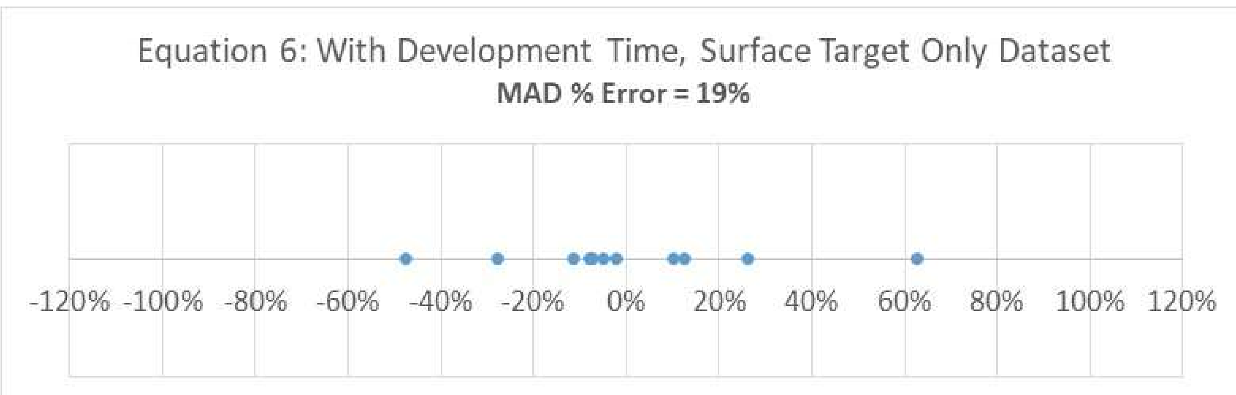


Figure 14 – Missile G&C DE CER 6; FY17$M; Percent Error about Zero

6.0 Summary of Findings

The research described in this paper produced a rigorously constructed development engineering cost database and a set of G&C EMD DE CERs that were developed through an intensive analytical process.

The database is a quite large, normalized cost database (i.e., seventeen missile G&C variants) of missile G&C development engineering for missile programs that have completed EMD and produced significant quantities of fielded missiles. The database is, in and of itself, a significant estimating tool.

The CERs have increased the ability to estimate tactical missile G&C EMD development engineering cost with substantially greater confidence than current methodology.

The database and CERs increase the ability to estimate G&C EMD DE in a variety of ways.

1. The database views and database itself allow a user to establish a rough order of magnitude (ROM) estimate range based on G&C Technology and Mission
2. The tabulated cost database results organized by characteristic groupings (Table 5) allow a user to better understand specific statistics, cost uncertainties and database drawbacks related to the system being estimated (e.g., relatable observations, etc.)
3. The CERs improve G&C EMD DE estimating error substantially over a straight cost factor approach. Using the G&C EMD DE cost database as a benchmark, the CERs improve mean percent estimating error from approximately 100% to a worst case of approximately 40%, and best case 18% -- a significant improvement over simple cost factors.
    a. Use of a development schedule variable can improve estimating error significantly, although this approach relies on a schedule estimate that is inherently uncertain as well as potentially biased by a program advocate responsible for specifying the estimated development time. The independence issue, and by inference the uncertainty issue to some extent, is mitigated if an independent schedule estimate is available.
    b. If development time is an available input then the relevant CER result can be compared with the no-development-time CER to assess differences and possibly assess schedule. If a suitable development time input is not available, then a CER that employs G&C T1000 cost per lb. as a scaler independent variable is available for use.