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Unmanned Ground Vehicle (UGV) Procurement Cost Estimating Methodology

September 2003

**Prepared for the
Deputy Assistant Secretary of the Army for
Cost and Economics (DASA-CE)**

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Executive Summary

This cost research effort was conducted for the Deputy Assistant Secretary of the Army for Cost and Economics (DASA-CE). The objective of this research was to develop improved procurement cost estimating methodologies for unmanned ground vehicles (UGVs).

The research resulted in the development of two principal products: (1) Ground Vehicle Cost and Technical Databases; and (2) UGV Procurement Cost Estimating Methodologies.

Cost and technical data was collected for both unmanned and manned ground vehicles. Technical data collected included various influencing variables identified during the development of our initial analytical hypotheses. We collected cost and technical data for manned ground vehicles in order to analyze better understand the effects of various technologies (e.g., hybrid-electric, diesel, etc.) that are prevalent in manned commercial ground vehicles, but limited in existing UGVs.

Two methodologies were developed for estimating the unit procurement cost of UGVs. The first uses total weight while the second attempts to isolate the effects of both platform and payload weight. Both methodologies account for differences related to various technologies such as wheeled, tracked, gas, diesel, hybrid-electric and electric power. Neither methodology includes a speed variable, which is addressed as a third approach. This third approach identifies differences in speed versus vehicle size. As additional data becomes available, it is our hope to integrate this variable into the cost estimating equations presented in the first two approaches.

Additionally, the cost estimating methodologies were used to estimate two UGV programs: (1) Mobile Detection Assessment and Response System (MDARS) and (2) Future Combat System (FCS).

In conclusion, this research provides two high-level relationships that account for differences in overall size, payload to platform weight

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distributions and technologies such as electric, diesel, hybrid-electric, wheeled and tracked as well as ideas for integrating the potential cost effects associated with vehicle speed.

1.0. Overview

Technomics was contracted by the Deputy Assistant Secretary of the Army for Cost and Economics (DASA-CE) to develop improved methodology for estimating the procurement cost of Unmanned Ground Vehicles (UGVs).

The process by which we conducted the analysis is as follows. First, candidate programs were identified that could be analyzed to provide a better understanding of key cost drivers and their related influences. Concurrently, various hypothetical models were developed. Over the course of the study, these models were re-examined and refined. Subsequently, the data was analyzed and the estimating methodology was developed. A more detailed description of the analytical process is included in Section *1.2 Analytical Process*.

Section *2.0 Analytical Approach* provides details concerning the development of our analytical hypotheses and databases used to conduct the analyses. Section *3.0 Analytical Models and Results* includes two cost estimating methodologies as well as additional ideas regarding the future incorporation of speed per pound as another influencing variable.

Section 4.0 Application discusses the use of the two methodologies to estimate the Mobile Detection and Response System (MDARS) UGV and some of the Future Combat System (FCS) UGV concepts.

1.1. Project Objective

The objective of the project was to develop improved methodology for estimating the unit procurement cost for UGVs.

1.2. Analytical Process

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The analytical process consists of the following steps, many of which are conducted concurrently and revisited during the process:

- Problem definition
- Data collection and normalization
- Key variable identification
- Equation formulation and constraints
- Calculation of constants and exponents

The first and most important step is defining the problem and developing a hypothesis. The primary tool for this step is the use of influence diagrams which help to describe the problem visually. The output of this portion of the process is a hypothetical model described in the form of an influence diagram. This step is critical and helps to focus the data collection effort.

Next, candidate programs are identified and data is collected. Identification of key data and anticipated influences help in determining what questions need to be answered and what normalization techniques need to be implemented.

Sometimes data limitations prevent the implementation of initially developed hypothetical models. In these cases, the hypothetical model must be realigned with higher-level variables for which data are available and that accommodate the effects of multiple, lower-level variables. This spiral development process results in the identification of key, quantifiable variables that can be used to conduct the analyses.

Next, a mathematical equation needs to be formulated. Formulations can be designed to exhibit linear and/or varying non-linear traits. Although it can be argued that most any influence adheres to some type of non-linear relationship, data limitations often force the use of linear, and therefore, sub-optimized models. When data limitations exist (e.g., number of data points is less than required explanatory variables), the next step in the process is to define constraints related to the constants and exponents established in the formulated equation. This should only be done when there is a known, significant

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influencing variable that needs to be accounted for and where there exists credible engineering experience that can be used as a basis for the assumption.

The final step in the process is to solve for the constants and exponents and compare the results to the actual data. The objective is to identify the best combination of values within their established constraints that minimizes the percent error related to the actual data. Our approach uses an optimization technique (Microsoft Excel Solver function) to minimize the average percent error (maximum value of the actual and estimate divided by the minimal value minus 1). This approach evaluates all data points equally on a percentage error basis. The final product of the analytical process is the development of an estimating equation that incorporates key influencing variables and models their influences in a logical fashion. The significance of each variable is tested by analyzing their individual contribution to improving the objective function (i.e., reducing the percent error).

1.3. Products Developed

The research resulted in the development of two principal products: (1) Ground Vehicle Cost and Technical Databases; and (2) UGV Procurement Cost Estimating Methodologies. Both of these products are discussed in detail in the following two sections.

1.3.1. Database

Three databases were developed for conducting this research. The first database includes cost and technical data for UGVs. This database is included in *Appendix A – UGV Cost and Technical Database*. The second database contains cost and technical data collected for Manned Ground Vehicles and is presented in *Appendix B – Manned Ground Vehicle Database*. The third database includes weight and speed data for militarized ground vehicles and is included in *Appendix C – Manned Militarized Ground Vehicle Database*. *Section 2.3 Database Development* provides a more complete description of the database content and sources.

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1.3.2. Estimating Methodology

Two methodologies were developed for estimating the unit procurement cost of UGVs. The first uses total weight while the second attempts to isolate the effects of both platform and payload weight. Both methodologies account for differences related to various technologies such as wheeled, tracked, gas, diesel, hybrid-electric and electric power. Neither methodology includes a speed variable, which is addressed as a third approach. This third approach identifies differences in speed versus vehicle size. With additional technical data, the results of this analysis could be used to enhance the cost estimating methodologies. All approaches were based on our Analytical Hypothesis presented in *Section 2.0 Analytical Approach*. *Section 3.0 Analytical Models* describes the analyses and resulting methodologies in detail.

2.0. Analytical Approach

This section begins by addressing deficiencies associated with existing estimating methodologies, then discusses our analytical hypotheses for developing various estimating methodologies, and finally concludes with a detailed discussion of the databases developed for conducting the analyses.

2.1. Deficiency of Current Capability

In our research we concluded that there were no existing high-level cost estimating methodologies for UGVs. Although there appear to be many commercial UGV systems in limited production, the number of militarized UGV systems having completed a formal DoD Acquisition process is none. With such limited data, it is not surprising that there exists a void in this cost area. The approach presented in this report attempts to leverage existing knowledge of manned ground vehicles with that of commercial UGVs to develop a high-level cost estimating approach for militarized UGVs.

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2.2. Analytical Hypotheses

At a high level, cost can be related to the amount of weight associated with (1) movement (i.e., platform weight) and (2) mission (i.e., payload weight). We developed two analytical hypotheses for conducting the analysis. The first identifies key cost drivers related to the vehicle platform while the second focuses on vehicle payload only. For purposes of this report, vehicle platform is defined as the vehicle less payload and payload is defined as any equipment that supports any function other than movement. Both hypotheses were developed using an influence diagramming technique and are described in detail in the following sections.

2.2.1. Platform Hypothesis

All hypotheses and analytical models presented hereafter are described in the form of an influence diagram. An influence diagram can be easily interpreted by the use of the following simple rules.

- 1) Arrows are used to identify influences between two variables.
- 2) Variables connected by an arrow are positively related (i.e., an increase in one results in an increase in the other, a decrease in one results in a decrease in the other) unless noted with a negative sign.
- 3) A negative sign indicates an inverse relationship (i.e., an increase in one results in a decrease in the other and vice versa)

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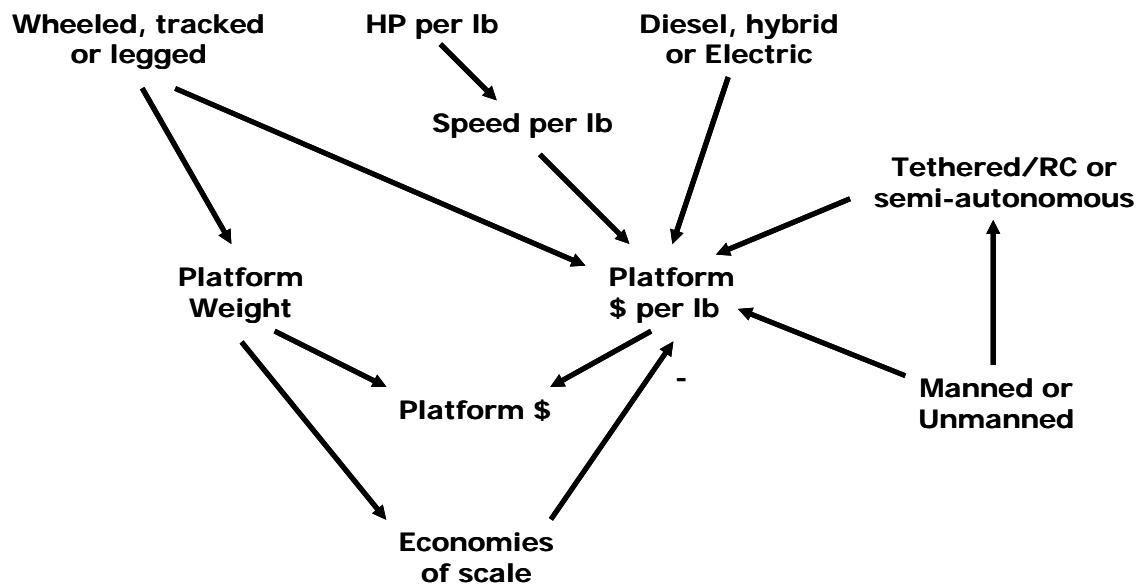


Figure I – Platform Hypothesis – Influence Diagram

The analytical hypothesis shown above, begins with the basic premise that platform cost is a function of both platform weight and platform cost per pound. The diagram also hypothesizes that as platform weight increases, cost per pound decreases due to economies of scale. Platform cost per pound is also influenced by a number of technology related variables, including:

- Horsepower (HP) per pound
 - In general, horsepower costs more per lb than structure.
- Tracked, wheeled or legged
 - Tracked and legged components have been found to cost more per lb than wheeled components.
- Electric, hybrid-electric or diesel
 - Electric and hybrid-electric technologies appear to be more costly per lb than diesel
- Unmanned or manned
 - Unmanned vehicles require some amount of additional electronics for control relative to manned vehicles. An

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increased percentage of electronics weight would result in an increased cost per lb since electronics cost more per lb than structure.

- Tethered/Remote Controlled (RC) or semi-autonomous
 - Unmanned vehicles operating semi-autonomously would require additional electronics and sensors.

2.2.2. Payload Hypothesis

Figure II shows our hypothesis concerning vehicle payload cost. Here again, we show the likelihood of economies of scale where payload cost per lb decreases as payload weight increases.

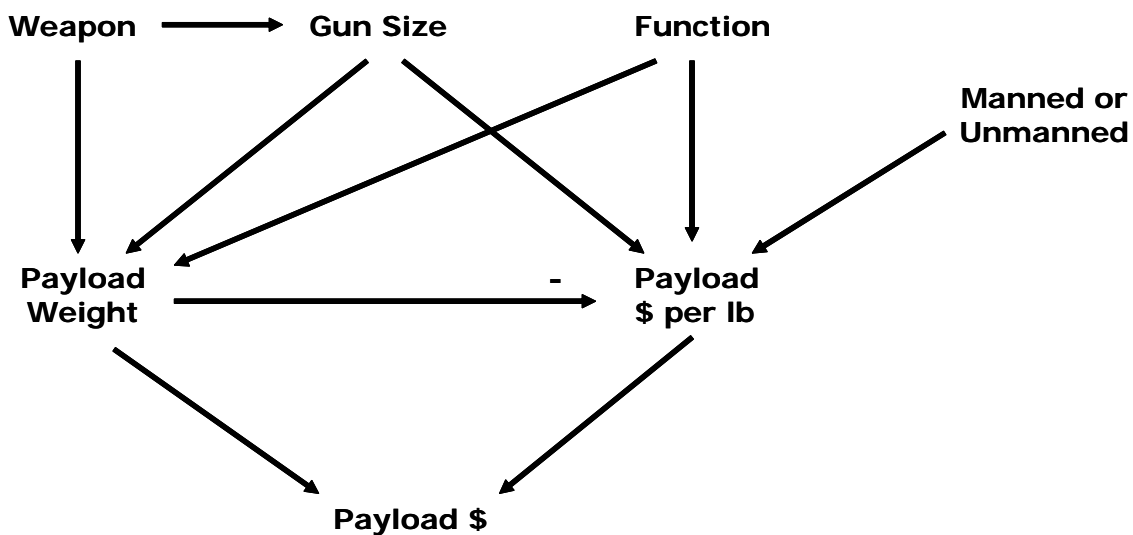


Figure II –Payload Hypothesis – Influence Diagram

Figure II shows that payload cost per lb is also influenced by a number of technology related variables, including:

- Mission (Function)
 - A mission requiring sensors (e.g., reconnaissance) would result in higher cost per lb payload than a mission using

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mechanically controlled components (e.g., mechanical arm).

- Weapon System Type (Gun, Sensors, etc.)
 - Payloads incorporating a weapon (e.g., gun) would probably have a lower cost per lb than payloads entirely made of sensors.
- Unmanned or manned
 - Functions performed unmanned would require additional operational electronics compared to those that are human controlled. The same payload performed unmanned should thus have a higher cost per lb.

2.3. Database Development

As part of this project, cost and technical data for various UGVs were collected. Technical data included various influencing variables identified during the development of the two hypotheses discussed previously. Additionally, we collected cost and technical data for manned ground vehicles. The purpose of this effort was to analyze the effects of various technologies (e.g., hybrid-electric, diesel, etc.) that are prevalent in manned commercial ground vehicles, but limited in existing UGVs. Finally, speed and weight data was also collected for manned militarized ground vehicles for use in Approach 3 (Speed per lb Analyses).

2.3.1. UGV Cost and Technical Database

Cost and/or technical data was collected on 100+ unmanned ground vehicles. Data was collected from the Mobile Robot Technology Database, managed by the Space and Naval Warfare Systems Command (SPAWAR), as well as other public sources. Data used in conducting the analyses is included in *Appendix A – Unmanned Cost and Technical Database*. Data contained in the database include:

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- Unit Cost in FY03\$ (represents average cost of ~100 units)
- Vehicle Weight
- Speed
- Various Technology Descriptors
 - Wheeled, Tracked or Legged
 - Electric or Diesel

Appendix D – UGV Cost Research Databases is a Compact Disk containing all data collected during the research effort.

2.3.2. Manned Commercial Ground Vehicle Database

Data was also collected on manned ground vehicles in order to analyze cost impacts associated with various technologies (e.g., electric, diesel, hybrid-electric, etc.) being considered for future militarized UGVs. Data collected on manned ground vehicles is included in *Appendix B – Manned Commercial Ground Vehicle Database*.

2.3.3. Manned Militarized Ground Vehicle Database

The weight and speed data collected for militarized manned ground vehicles for use in Approach 3 (Speed per lb Analyses) are presented later in this report. Data collected on Militarized Manned Ground Vehicles is included in *Appendix C –Manned Militarized Ground Vehicle Database*.

3.0. Analytical Models and Results

This section identifies limitations associated with currently available UGV data and describes how we utilized manned ground vehicle data to account for various technologies being proposed for future UGVs. Next, two analytical models are presented that estimate UGV unit procurement cost. Neither methodology includes a speed variable, which is addressed as a third approach. This third approach analyzes differences in ground vehicle speed relative to a norm. As additional data becomes available, it is our hope to integrate this cost influencing variable into the cost estimating equations presented in the first two approaches.

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3.1. Data Limitations and Challenges

The UGV Cost and Technical Database represents electric powered vehicles. Future UGVs (e.g., FCS) will include technologies (e.g., diesel powered and/or hybrid-electric drive) not represented in the current unmanned systems/data. In order to account for these different technologies, we used manned commercial ground vehicle data to identify similar systems with single characteristic differences (e.g., traditional gas powered versus hybrid-electric drive) and then analyzed the data to determine cost per lb differences specific to the different technologies. Figure III provides an example of this analysis where we compared hybrid-electric drive to traditional gas powered vehicles. Both the Honda Civic Hybrid Electric Vehicle (HEV) and Toyota Prius Hybrid Electric Vehicle appear to be 1.21 times more costly per lb than their comparable gas powered alternatives.

Vehicle	Cost \$ (MSRP)	Curb Weight (lbs)	Cost per lb	Max	Avg	Min
Honda Civic HEV	19,550	2,731	7.2	1.25	1.21	1.18
Honda Civic Sedan DX	13,995	2,449	5.7			
Honda Civic Sedan LX	15,449	2,537	6.1			
Toyota Prius	20,450	2,765	7.4	1.23	1.21	1.19
Toyota Corrola LE	15,165	2,524	6.0			
Toyota Camry LE	19,455	3,142	6.2			

Figure III –Hybrid Electric Cost per lb Impacts

The above process was performed for various technologies of interest using the Ground Vehicle Database. The results of the analyses are shown below in Figure IV.

From	To	Cost per lb Impact
Wheeled	Tracked	1.21
Gas	Diesel	1.03
Gas	Hybrid	1.21
Gas	Electric	1.55

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Figure IV –Technology Cost per lb Impacts

3.2. Approach 1 (Total Weight)

Approach 1 estimates unit cost as a function of total weight and considers cost differences related to key technologies such as wheeled, tracked, electric powered, diesel powered and hybrid-electric drive. Commercial manned vehicle data was used to develop adjustments for diesel and hybrid-electric drive technologies versus electric. Figure V describes Approach 1 in the form of an influence diagram.

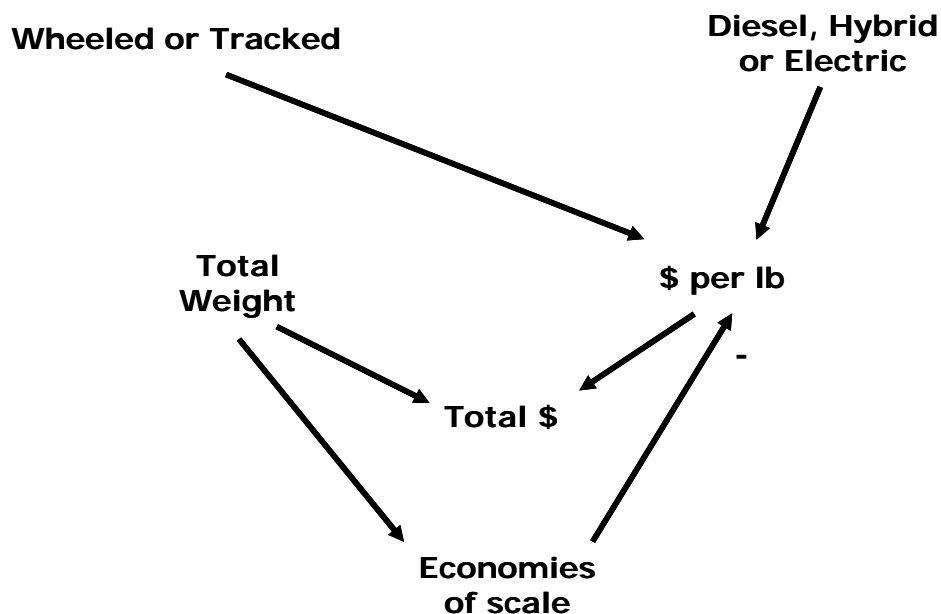


Figure V –Approach 1 Influence Diagram

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Figure VI shows that as weight increases the cost per lb decreases due to economies of scale as described in Figure V.

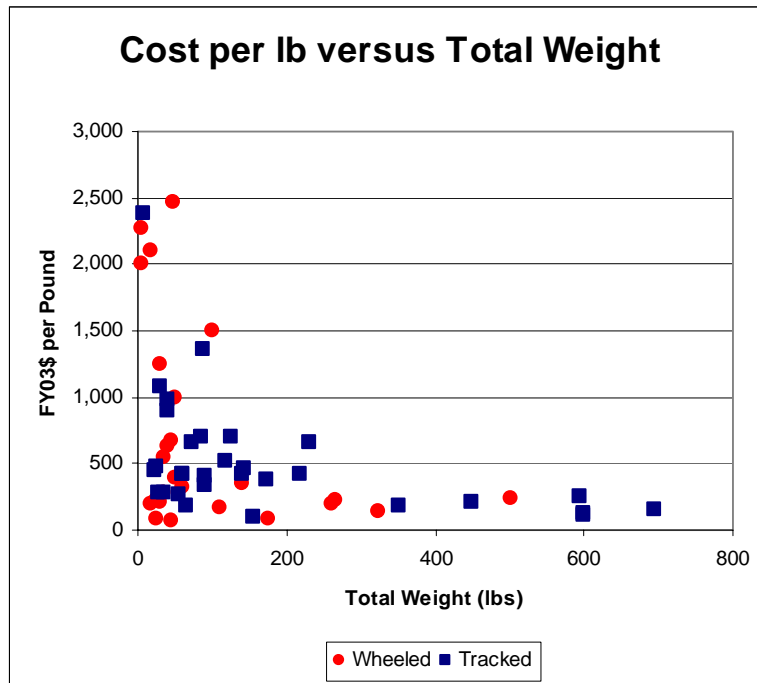


Figure VI – UGV Cost per lb versus Total Weight

Analysis of the data resulted in the development of Equation 1, where unit cost represents the average unit cost of ~ 100 units.

Equation 1 – Approach 1 Estimating Equation

$$\text{Unit Cost FY03\$} = 2,582 * \text{Total Weight (lbs)}^{0.577} * e^{(\text{Tracked} * 0.048)} * e^{(\text{Diesel} * -0.18)} * e^{(\text{Hybrid} * -0.10)}$$

The analysis produced the following key findings:

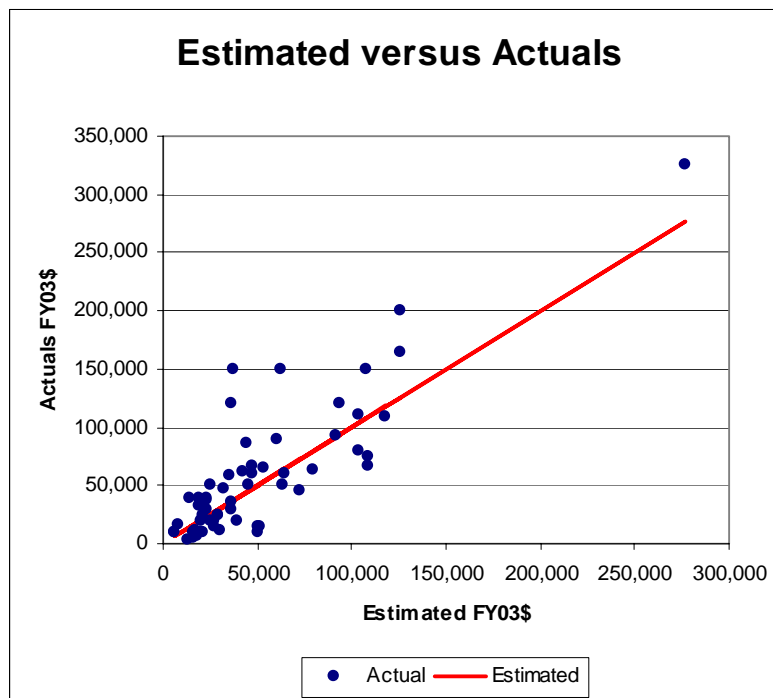
- Significant economies of scale found for cost versus total weight

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- Tracked found to be 5% more costly per lb than wheeled (would expect impact to be greater if payload weight were excluded or modeled separately)
- Equation 1 is based on data for electric UGVs but includes adjustment terms for diesel and hybrid-electric technology derived through analysis of manned commercial ground vehicle data as discussed in Section 3.1. Since the technology factors shown in Figure IV are representative of manned commercial ground vehicles whose cost can be characterized as 100 percent platform and zero percent payload, it was necessary to normalize the factors for application to UGVs whose cost covers both platform and payload. We assumed that UGV cost is 50 percent payload and therefore, the factors shown in Figure IV should be reduced by 50 percent.

Figure VII shows the estimated values versus the actual values for the data analyzed.



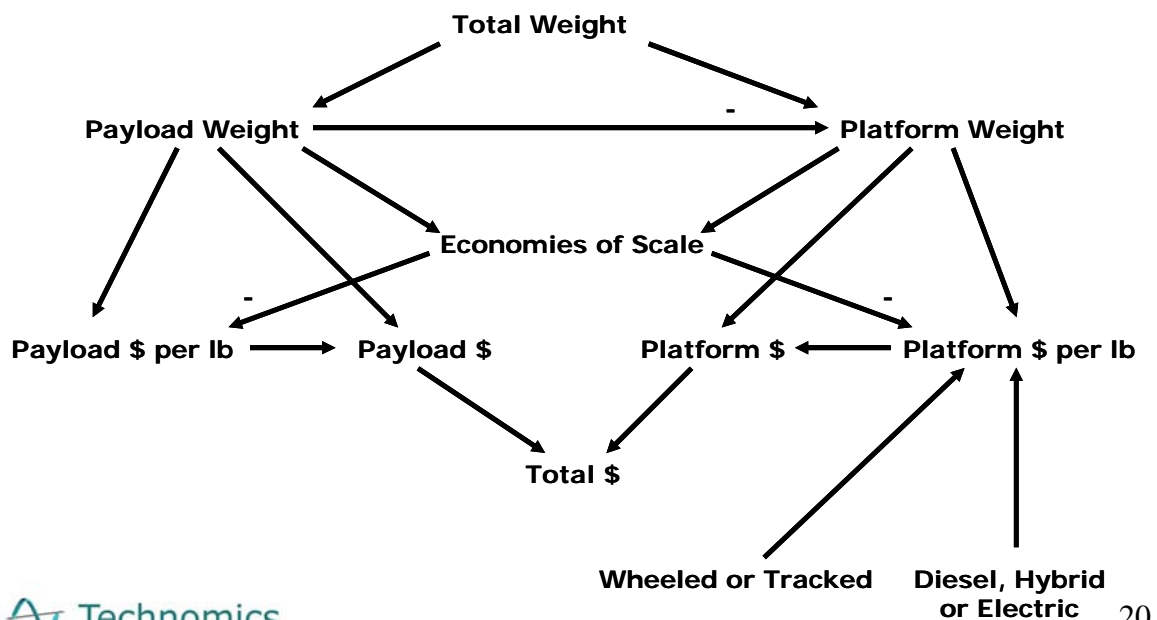
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Figure VII – Approach 1 – Estimated versus Actuals

3.3. Approach 2 (Platform and Payload Weight)

Approach 1, which is based on total vehicle weight, is prone to error for estimating UGV designs that have either high or low payload content. Approach 2 improves upon Approach 1, by using both payload and platform weight vice total weight. Figure VIII shows Approach 2 in the form of an influence diagram.



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UGV Procurement Cost Estimating Methodology

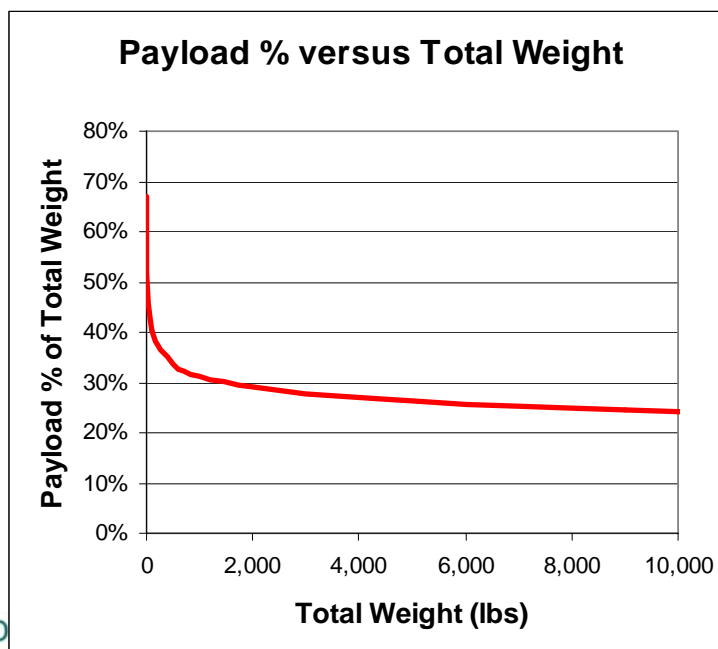
Figure VIII – Approach 2 Influence Diagram

Since we are limited by insufficient payload weight data, Approach 2 develops a platform and payload cost component by assuming a common payload percentage relationship based on total weight. Based on very small vehicles having high payload capacities of ~ 50% (measured as percentage of total weight) and larger vehicles (e.g., MDARS-E and FCS) having payload objectives of ~25%, we developed Equation 2 to estimate the average payload weight associated with the UGV data.

Equation 2 – Payload Weight Estimating Equation

$$\text{Payload Weight (lbs)} = 0.67 * \text{Total Weight}^{0.89}$$

Figure IX shows the results of Equation 2 graphically in the form of payload percentage of total weight versus total weight. As total weight increases, the percentage of weight associated with payload decreases.



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Figure IX – Payload % versus Total Weight

Analysis of the data resulted in the development of Equation 3, where unit cost represents the average unit cost of ~ 100 units.

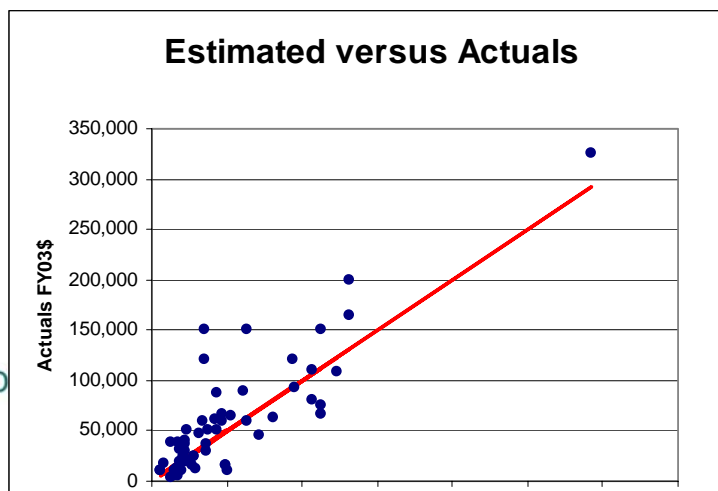
Equation 3 – Approach 2 Estimating Equation

$$\text{Unit Cost FY03\$} = 967 * \text{Platform Weight (lbs)}^{0.657} * e^{(\text{Tracked} * 0.159)} * e^{(\text{Diesel} * -0.39)} * e^{(\text{Hybrid} * -0.22)} + 2,495 * \text{Payload Weight (lbs)}^{0.583}$$

The analysis produced the following key findings:

- Significant economies of scale were found for both Platform and Payload cost versus weight
- Tracked found to be 17% more costly per lb than wheeled (results are consistent with manned commercial vehicle analysis)
- Equation 3 is based on data for electric UGVs but includes adjustment terms for diesel and hybrid-electric technology derived through analysis of manned commercial ground vehicle data as discussed in Section 3.1.

Figure X shows the estimated values versus the actual values for the data analyzed.



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Figure X – Approach 2 Estimated versus Actuals

Figures XI and XII show Equation 3 cost per lb projections for a wheeled/electric UGV.

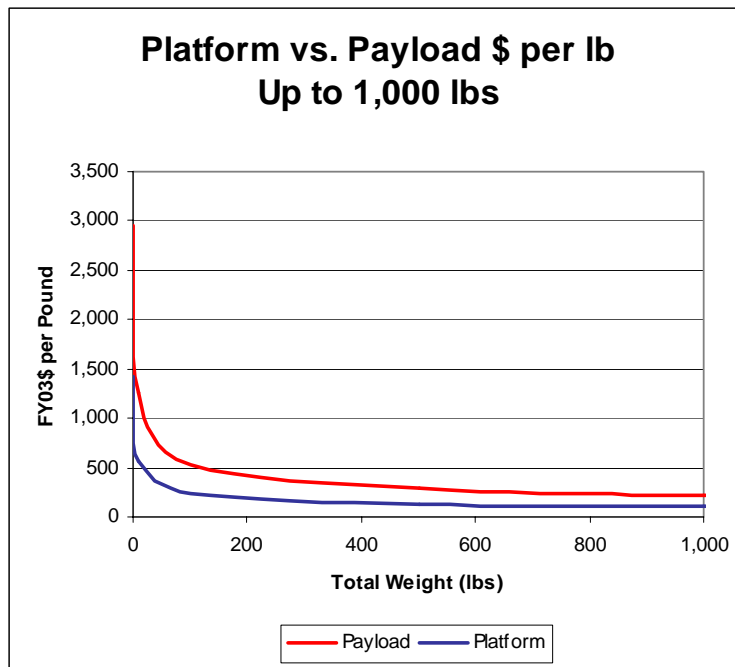
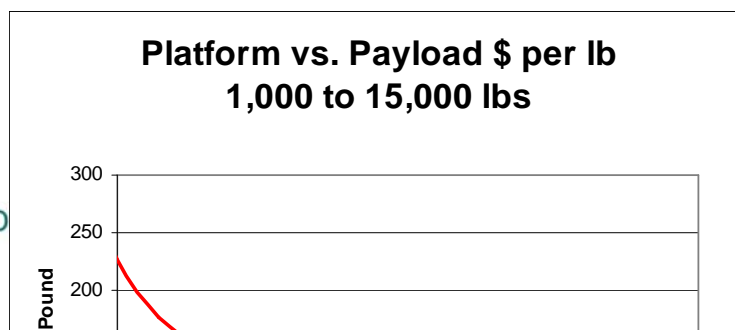


Figure XI – Platform versus Payload \$ per lb (up to 1,000 lbs)



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Figure XII – Platform versus Payload \$ per lb (1,000 to 15,000 lbs)

3.4. Approach 3 (Speed per lb Analysis)

Approach 3 explores speed and its potential value as a cost influencing variable. The hypothesis is that faster than average vehicles (for a given size) cost more per lb. For example, race cars are much more expensive than family cars but weigh about the same. Also, the Marine Corps Advanced Amphibious Assault Vehicle (AAAV) is projected to have a water speed of ~ 30 mph, much faster than previously produced amphibious vehicles (~ 8 mph) and unit cost per lb estimates are much higher than historical combat vehicle actual costs.

Implementation of Approach 3 requires some knowledge of the average speed for various vehicles of different sizes. By comparing a vehicle's speed to the average speed for a vehicle of similar size, we can then determine if any cost influence exists. Figure XIII shows our approach for developing a speed per lb relationship, where speed per lb is modeled as a function of total weight, form of movement (e.g., wheeled, tracked or legged), type of power (e.g., diesel, hybrid-electric or electric), whether it is unmanned or manned, whether or

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not it is militarized and finally, whether or not it is designed for combat (expressed as gun size).

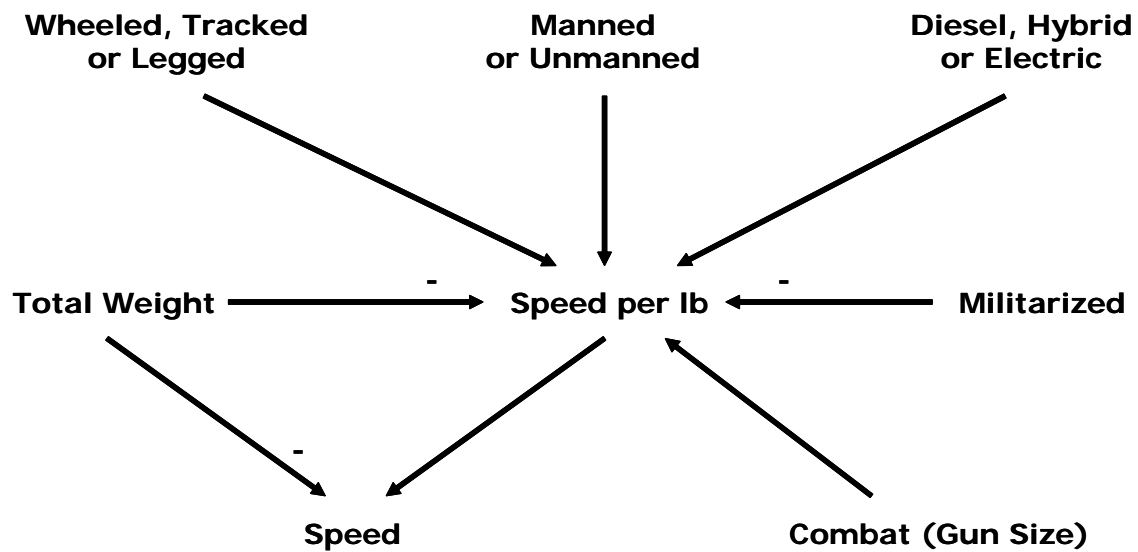
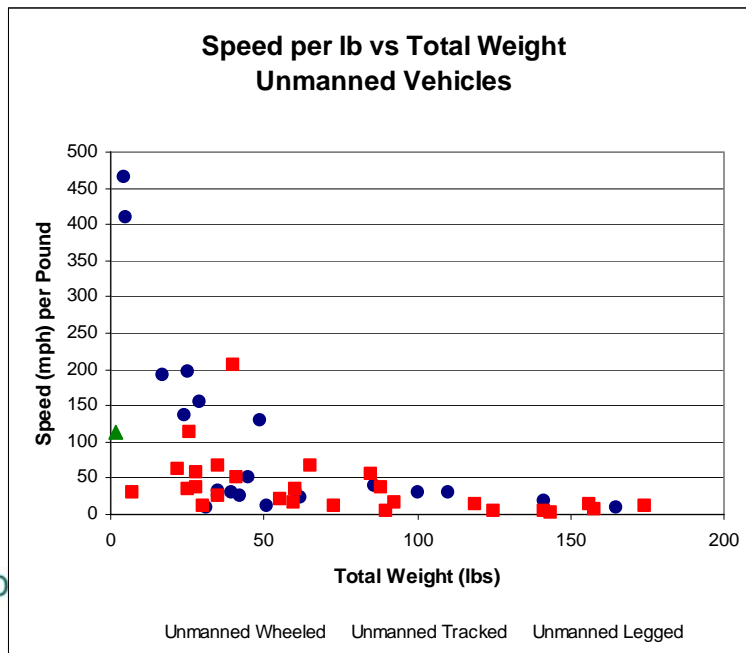


Figure XIII – Approach 3 (Speed per lb Analysis) Influence Diagram

Figure XIV shows that, in general, smaller unmanned ground vehicles are faster per lb than larger vehicles.



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We developed two speed per lb estimating equations based on the model presented in Figure XIII. Equation 4, shown below, estimates the speed per lb for an electric powered UGV while Equation 5 estimates the speed per lb for a manned ground vehicle.

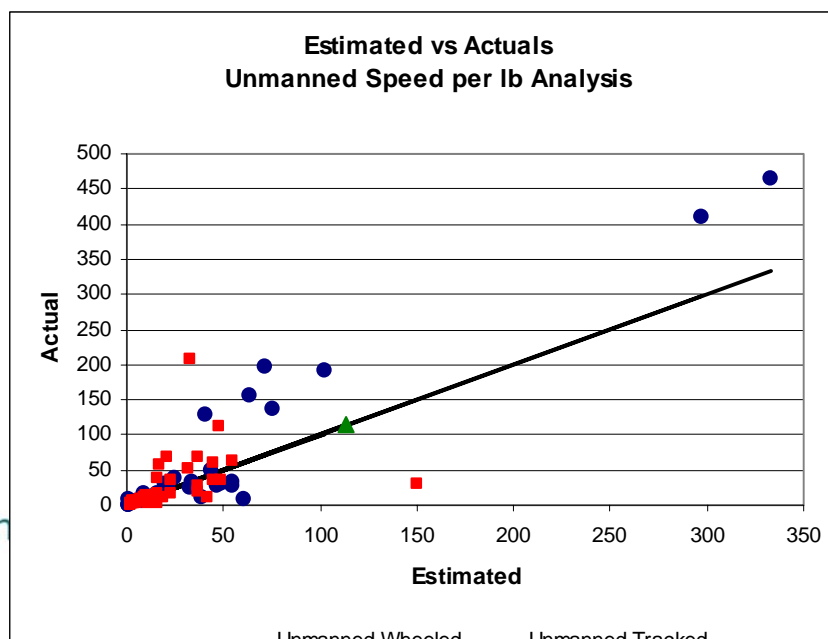
Equation 4 – Approach 3 Estimating Equation for Unmanned

$$\text{Speed (mph) per lb} = 1,217 * \text{Total Weight}^{-0.875} * e^{(\text{Tracked} * -0.392) * e^{(\text{Legged} * -2.02)}}$$

The analysis produced the following key findings:

- As total weight increases, speed per lb decreases
- Tracked found to be ~30% slower than wheeled vehicles
- Legged found to be significantly slower than wheeled vehicles (~85%)

Figure XVII shows the estimated versus actual values using Equation 4.



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Figure XVII –Unmanned Speed per lb Estimated vs. Actuals

Analysis of the manned ground vehicle data resulted in the development of Equation 5 shown below.

Equation 5 – Approach 3 Estimating Equation - Manned

$$\text{Speed (mph) per lb} = 97,697 * \text{Total Weight}^{-1.037} * e^{(\text{Tracked} * -0.408)} * e^{(\text{Gas} * 0.50)} * e^{(\text{Diesel} * 0.50)} * e^{(\text{Hybrid} * 0.30)} * e^{(\text{Militarized} * -0.696)} * e^{(\text{Gun Size mm} * 0.0013)}$$

The analysis produced the following key findings:

- As total weight increases, speed per lb decreases significantly
- Tracked found to be ~30% slower than wheeled vehicles
- Gas and Diesel powered vehicles found to be ~60% faster than electric
- Electric-hybrid vehicles found to be ~35% faster than electric
- Militarized vehicles found to be ~50% slower
- As gun size increases, vehicles appear to be faster. For example, a tank with a 152 mm gun would first be projected to be 50% slower than a commercial vehicle of similar size. However, since it is designed for close combat (increasing its speed requirements), it would be estimated to be ~20% faster ($e^{(1.52 * 0.0013)} = 1.22$). The overall effect would be a speed per lb estimate that is ~40% slower than a comparable sized commercial vehicle possessing the same type of movement design (i.e., tracked).

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Figure XVIII shows the estimated versus actual values using Equation 5.

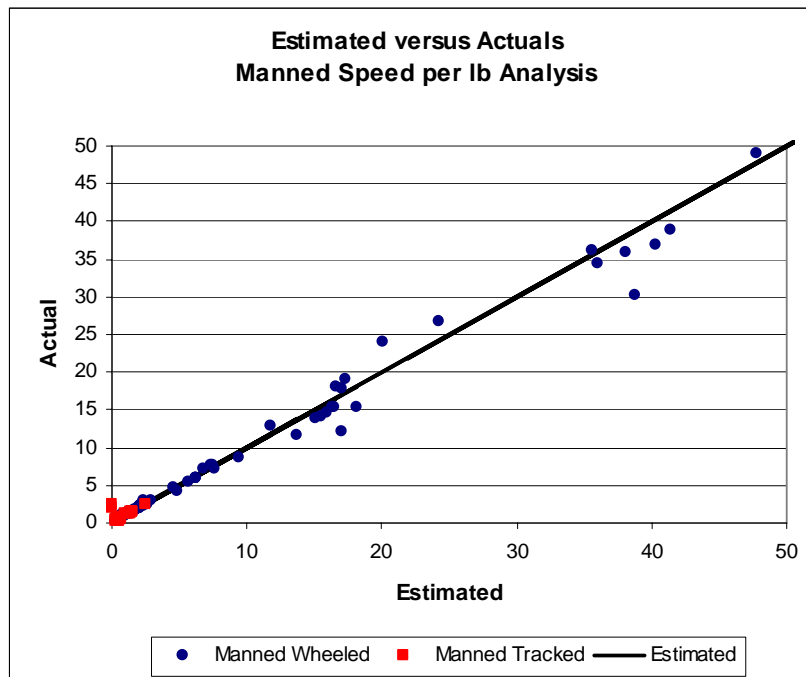


Figure XVIII –Manned Speed per lb Estimated vs. Actuals

By analyzing the estimated versus actual plots, it is clear that the manned ground vehicle speed per lb estimating equation more accurately predicts the actual data than the unmanned equation. This was expected and is the reason why we would like to leverage this speed per lb variability associated with UGVs by relating it to differences in cost.

At this time, we cannot integrate these findings into the previously presented cost estimating equations. We first need more payload weight data. If payload weights were known for enough systems in the database, speed per lb could possibly be integrated into the cost estimating equations. Payload weight is required since any cost per lb

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adjustments, as a result of a vehicle being slower or faster than average for a given size, would need to be applied to the platform portion of the system only (not the payload).

4.0. Application

This section applies the developed cost estimating equations to two key UGV programs: (1) Mobile Detection Assessment and Response System (MDARS) and (2) Future Combat System (FCS).

4.1. MDARS

The Mobile Detection Assessment and Response System (MDARS) is a joint Army-Navy development effort to provide an automated intrusion detection and inventory assessment capability for use in Department of Defense (DoD) warehouses and storage sites. The program is managed by the Office of Program Manager - Physical Security Equipment at Ft. Belvoir, VA. Overall technical direction for the program is provided by the Space and Naval Warfare Systems Center, San Diego (SSC San Diego). The MDARS goal is to provide multiple mobile platforms that perform random patrols within assigned areas of warehouses and storage sites.

The current SSC unit cost estimate (Goal) for MDARS-E (Mobile Detection Assessment Response System – Exterior) is \$187,500, where unit cost represents the average cost of ~ 100 units in FY03\$.

Vehicle characteristics:

- Wheeled, Diesel Vehicle
- Platform Weight (vehicle w/o electronics) = 1,803 lbs
- Payload Weight (vehicle electronics incl. batteries) = 842 lbs

Our equations produce unit cost estimates of:

- Approach 1 = \$203,528
- Approach 2 = \$216,695

4.2. FCS

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For FCS, we used the Approach 2 cost estimating equation to provide a unit cost range for two possible FCS UGV concepts, a ~1,500 lb UGV and a larger ~10,000 lb UGV. The two ranges of estimates are shown in the circled areas on Figure XIX. With additional information, the cost estimating equations presented in this report could be used to provide more specific unit cost estimates for all FCS UGV concepts.

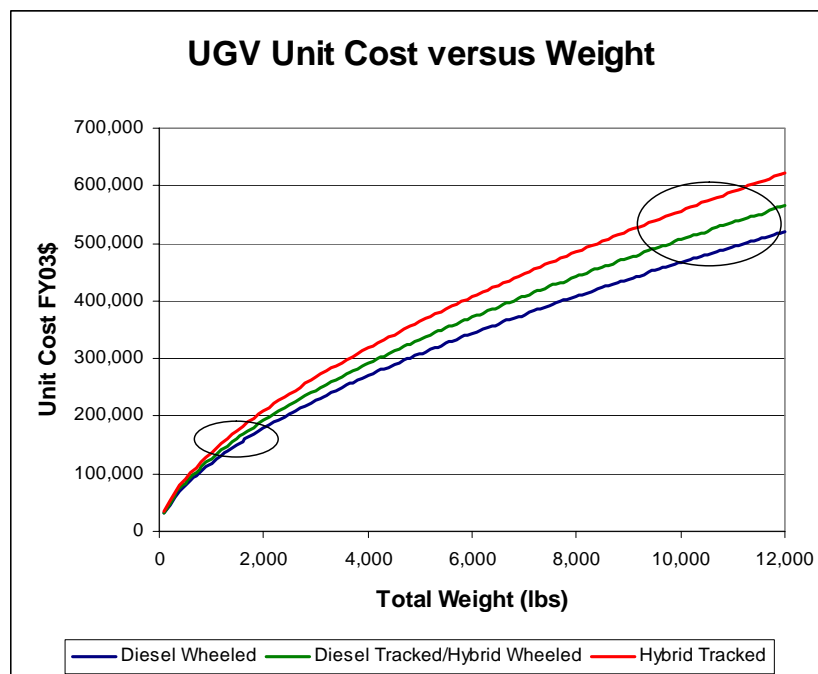


Figure XIX – UGV Unit Cost versus Weight – FCS Application

5.0. Conclusion

In conclusion, the cost estimating equations developed and presented in this report show that, at a high-level, general relationships exist between unit cost and weight. Additionally, Approach 1 accounts for cost differences related to electric, diesel and hybrid-electric technologies as well as wheeled and tracked technologies. Approach 2 provides a cost estimating equation capable of providing sensitivity analysis regarding platform versus payload weight distributions.

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Finally, Approach 3 shows that speed per lb differences can be determined. In the future, we hope to collect sufficient data to estimate the cost impacts of this characteristic.

Continued research in this area should focus on collecting specific payload weight and definition data. With actual payload weight data, Approach 2 could be improved. If payloads could be categorized by function and cost differences determined, the Approach 2 estimating equation could be further enhanced. If actual payload weight were known, we could attempt to integrate Approach 3 with Approach 2.