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MARVEL – A Modular Vehicle Fleet Simulation Tool

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ABSTRACT

The value of modularity in ground vehicles to the Army and other services has been a topic of much debate for decades. There are instances of successful implementations of modularity in current ground vehicle programs of record. However, these implementations have generally been accomplished through swappable mission equipment rather than large-scale transformation of the vehicle and its core components. Concurrently, the Army Science and Technology (S&T) community has continued to demonstrate the technical feasibility of large-scale, transformative ground vehicle modularity, but the business case of modularity remains elusive. Decision support tools are needed to enable Army leadership to confidently and holistically assess the right balance between modular and mission-specific (conventional) vehicle platforms. This complex problem needs to address numerous considerations, including total lifecycle cost, mission utility, personnel requirements, and fleet adaptability. In this paper we present MARVEL, a modular fleet simulation tool developed to provide decision support when evaluating ground vehicle modularity, and we discuss the tool's application to a US Army TARDEC vehicle demonstrator program. While MARVEL development is ongoing, we present the current set of results available from our models and discuss the lessons learned that can be gleaned from them regarding the holistic value of a modular vehicle fleet.

INTRODUCTION

Modularity in Policy & Guidance

Modularity has long been viewed as a tool to control acquisition and sustainment costs while increasing capability and adaptability of a fielded system. Ground vehicle systems are often used in very different ways to meet a diverse set of missions (tactical resupply, combat, command and control, etc.). No singular vehicle design could meet the capability requirements of many diverse missions while still maintaining realistic levels of SWAP-C (size, weight, power, and cost). At the same time, it would be cost prohibitive to specifically develop, acquire, and maintain a vehicle design that addresses each capability gap. Thus, ground vehicle designers leverage a combination of modular and mission specific vehicle designs as a tool to hit the "sweet spot" between cost, capability, and adaptability.

Defense leadership guidance has been supportive of the smart application of modularity as a solution to technical problems. The DoD Better Buying Power (BBP) 2.0 initiative [1] articulates 5 principles of Modular and Open System Architecture (MOSA), namely: 1) Establish an Enabling Environment, 2) Employ Modular Design, 3) Designate Key Interfaces, 4) Use Open Standards, and 5) Certify

Conformance. The ensuing BBP 3.0 initiative continued the focus on incorporating MOSA into designs:

> *"Implementing MOSA architectures will accelerate and simplify the delivery of advanced capability into systems without replacing entire systems. Incorporating modularity principles should result in systems with highly cohesive, loosely coupled, and severable modules that can be openly competed. This approach would enable both pre-planned and opportunistic technology based upgrades in the areas of technology that are most subject to change. It enables the independent acquisition of systems, subsystems, and components, to include software."[1]*

While the BBP initiative has a large focus on modularity as a cost control measure, other leadership guidance has focused on its ability to promote increased capability and adaptability. Modularity is closely related to the idea of engineering resilient systems. Neches [2] defines an engineered resilient system as "*trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function.*" Modularity may not be the optimal approach to producing resiliency in all cases, but it is clearly a solution worth consideration in many of them.

Condition based maintenance (CBM) has also been an area of focus from defense leadership as a way to control life-cycle logistics costs. The Defense Acquisition Guidebook [3] relates modularity to maintainability as follows:

> *"(Modularity provides the) Packaging of components such that they can be repaired via remove and replace action vs. on-board repair. Care should be taken not to "over modularize" and trade-offs to evaluate replacement, transportation, and repair costs should be accomplished to determine the most cost effective approach."*

Modular approaches to technology development support CBM in that entire systems do not need to be grounded while maintenance occurs. MOSA principles, such as well-defined standards based interfaces and engineering for quick coupling/decoupling of a module to the system support the effective use of CBM.

Modularity in Ground Vehicle Design Practice

Modularity in fielded ground vehicle programs of record has been, for the most part, relegated to modular mission equipment (medical supplies, small weapons, communications equipment, etc.) while the "core" of the vehicle remains untouched (chassis, powertrain, cab, etc.). Modular armor kits could be considered an exception to this. However, the existence of modular armor kits is at least partially attributable to the need to be able to airlift ground vehicle assets which impose weight restrictions on the total vehicle weight versus the need to match capability to mission requirements on demand.

One form of modularity is often characterized as a "family of vehicles (FOV)," such as the Patria Armored Modular Vehicle and the GDLS produced Stryker. FOV approaches to modularity often result in variety of chasses due to the drastically different weight requirements imposed by heavier technologies such as a large armament [4]. Further, these types of systems, once configured, cannot be readily reconfigured for an alternative purpose. The primary enabler of modularity is the commonality of the hull structure that is capable of accommodating a variety of chassis and mission "modules."

Another successful form of modularity in military practice has been the use of load handling systems (LHS). The LHS allows an operator to load, secure and unload compatible payload modules in minutes using a large hook and hydraulic lifting system. The Palletized Load System (PLS) [5] fielded by the US Army and the Logistics Vehicle System Replacement (LVSR) [6] fielded by the Marines, both from Oshkosh, utilize the LHS to increase mission utility and limit the amount of time an operator exposed to threats during resupply missions.

An example of a failed modular vehicle system is the ambitious "Armored Family of Vehicles" (AFV) program from the 1980s. Originally thirty-nine combat vehicles on three chassis were planned. Cost studies suggested that "*the total costs shown for the Development, Production, Fielding, and Sustainment of the AFV Family of Vehicles (Heavy, Medium, Light, Wheeled, and Trailer groups) provide a very adequate baseline for the quantification of Life Cycle Cost savings*" and predicted cost savings in the range of 15-30% [7]. Conflicting information emerged, however, as a later study found that the AFV fleet would be more expensive in theater, primarily attributed to an overall greater fleet weight. The lessons learned from another study from Science Applications International Corporation (SAIC) regarding the Future Combat Systems (FCS) program to family of infantry carrier vehicles are very similar. SAIC concluded that "*The FCS requirements are very challenging (C130 drive off ready to fight) which makes packaging efficiency and weight optimization even more critical*" [8]. The FCS program was eventually cancelled for budgetary reasons.

PROBLEM STATEMENT

The breadth of both successful and unsuccessful endeavors in ground vehicles does not present a clear direction for future ground vehicle modularity. Further, while DoD leadership may support modularity in principle, at the level of a ground combat vehicle it is clearly a complex issue that entails a large number of variables. Ultimately, the vision of modularity as explored in FCS and other advanced programs fails because it is difficult to establish the complete business case. The effect of modularity on the entire fleet must be considered with careful consideration of the performance and lifecycle cost implications.

The Modular Fleet Simulation Tool (MARVEL) is the result of work done under the US Army TARDEC Automotive Research Center by the University of Michigan Department of Mechanical Engineering. The goal of MARVEL is to provide a decision support tool to holistically assess the costs and benefits of operating a conventional versus modular fleet of vehicles to execute a common set of missions. MARVEL keeps track of vehicle and module levels in the inventory over time, history of vehicles and modules going into maintenance and assembly, history of vehicles executing the set of missions, total number of vehicles and modules used throughout the mission. The outputs of MARVEL can be used to assess positive and negative effects of modularity and various tradeoffs with regards to 1) Adaptability, 2) Maintainability, 3) Manufacturing cost, 4) Fuel economy, 5) Personnel requirements. Considerations that are currently out of scope but are envisioned future enhancements include the effects of modularity on 1) System testing, and 2) System disposal.

A fundamental assumption in tackling the analysis of conventional versus modular platform challenge is that for any given *specific* mission, a conventional vehicle (engineered for the specific mission) will outperform the modular vehicle in terms of cost. This cost difference can qualitatively be attributed to how a modular platform is generally engineered to support more than a single specific mission, and needs to be designed to accommodate the worst case constraints. Also, extra design work is required to build modularity into interfaces. A modular fleet, however, increases adaptability and may be capable of accomplishing a set of missions with fewer total vehicles compared to a fleet of conventional vehicles. Thus, while any individual mission can be better accomplished with a conventional vehicle, it is possible that a modular fleet can outperform a conventional fleet over a set of missions. MARVEL is a tool to help assess if such is the case given model inputs.

MARVEL has been applied in this manner in support of a US ARMY TARDEC ground vehicle demonstrator program. This program is an effort by TARDEC to inform requirements for a possible future program of record capable of replacing many of the Army's current medium and heavy tactical vehicle platforms. The program is currently in engineering development and provided an excellent, realistic test case to apply MARVEL.

It should be noted that MARVEL takes a future-forward approach to ground vehicle modularity assuming it is "lego-like." MARVEL does not assess technical feasibility of modularity; instead, MARVEL assumes technical feasibility is known *a priori* and acknowledges that the currently modeled level of modularity has not been executed by any known program of record to date. This is not to say that the model makes unrealistic assumptions about the amount of modular component swapping that can be attempted and in what environments. Large maintenance activities (such as swapping of one powertrain system for another) can only be done in maintenance depots in the field or may even be required to be accomplished in the continental United States during an equipment reset, depending on user defined parameters. Realistic disassembly, maintenance, and assembly times are used based on information from technical manuals of comparable programs of record. Thus, while the simulation presented does not map exactly to any existing program of record or ground vehicle demonstrator in the Army, it is sufficiently grounded in reality to provide insight to decision makers on the value of a modular vehicle platform to be developed in the coming decade.

MODELING APPROACH

Modeling and Simulation Framework

The overall modeling frame work is presented in Figure 1. The individual elements and dataflow are described in subsequent sections. The MARVEL framework is unique because it utilizes the inputs and outputs of several different simulation tools that have been developed for various purposes. MARVEL also conducts a Monte Carlo (MC) simulation of the entire fleet over the duration of the set of missions, which in our case example demonstrator program case was a year. Lastly, MARVEL is an expansion of initial work, the details of which are presented in [9].

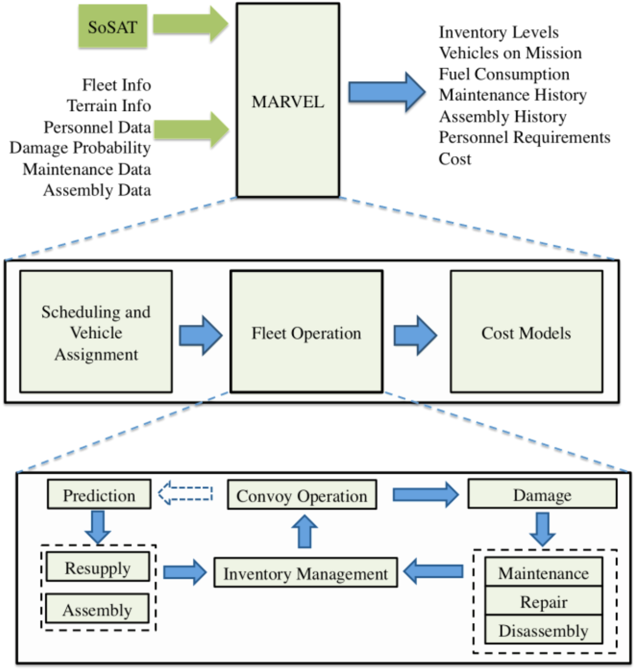


Figure 1. MARVEL Modeling Framework

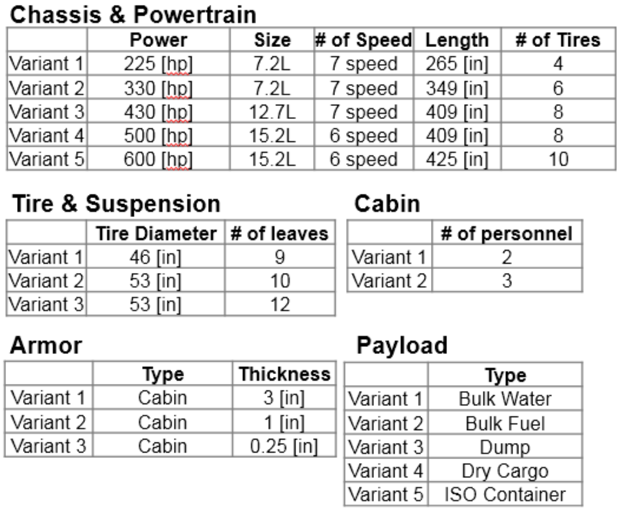
Fleet Scheduling and Randomization

MARVEL begins with input obtained from the System of Systems Analysis Toolset (SoSAT) [10] simulation of the Army Training and Doctrine Command (TRADOC) Multi-Level Scenario (MLS) 2.0. Both MARVEL and SoSAT are discrete event simulation tools. SoSAT has wide use throughout the DoD and is very effective at simulating sustainment throughout a complex logistics network (such as an Army theater of operation). Each "node" (e.g., base camp) in the logistics network generates demand for various classes of supply over time. The SOSAT model of MLS 2.0 scenario is applied to the Combined Arms Support Command (CASCOM) OPLOG Planner 8.0 tool to predict supply demand data.

The SoSAT model and MLS 2.0 scenario both include FOUO data. As MARVEL is a public-domain effort, a loose coupling of the simulation tools was applied. MARVEL uses the SOSAT time phased supply demand requirements, which translate into logistics vehicle lift requirements, as inputs. These lift requirements are then randomly scheduled across a 3-day time horizon to be transported by a convoy of vehicles. In addition, the lift requirements are further randomized in terms of terrain traveled (primary road, secondary road, cross-country) and threat level faced (low, medium, high). The reasoning for additional randomization of the SoSAT-derived lift requirements is to test the postulate that modular vehicles will show greater adaptability (and thus, lower total cost) when mission demand unpredictability and heterogeneity increases.

Modular Vehicle Decomposition

Figure 2 displays the module types, variants, and relevant parameters that make up the modular fleet in the current MARVEL scenario. There are theoretically 450 unique combinations of modules, but some combinations are eliminated prior to simulation because of module incompatability (for example, combinations including a heavy 3" thick armor with a weak 225 HP engine would not be utilized). The conventional fleet that is utilized for the study is presented in Figure 3. It should be noted that there are many more medium and heavy tactical vehicle variants currently in use by the Army, and this is a simplification of the real environment.



Chassis & Powertrain

	Power	Size	# of Speed	Length	# of Tires
Variant 1	225 [hp]	7.2L	7 speed	265 [in]	4
Variant 2	330 [hp]	7.2L	7 speed	349 [in]	6
Variant 3	430 [hp]	12.7L	7 speed	409 [in]	8
Variant 4	500 [hp]	15.2L	6 speed	409 [in]	8
Variant 5	600 [hp]	15.2L	6 speed	425 [in]	10

Tire & Suspension

	Tire Diameter	# of leaves
Variant 1	46 [in]	9
Variant 2	53 [in]	10
Variant 3	53 [in]	12

Cabin

	# of personnel
Variant 1	2
Variant 2	3

Armor

	Type	Thickness
Variant 1	Cabin	3 [in]
Variant 2	Cabin	1 [in]
Variant 3	Cabin	0.25 [in]

Payload

	Type
Variant 1	Bulk Water
Variant 2	Bulk Fuel
Variant 3	Dump
Variant 4	Dry Cargo
Variant 5	ISO Container

Figure 2. Modules and Variants Simulated

Conventional Fleet

Platform	Variant	Function
FMTV	M1094A1	Dump
FMTV	M1157	Dump
Heavy Dump	M917	Dump
HEMMTT	M1120A4	Water
HEMMTT	M978A4	Fuel
FMTV	M1078A1P2	Dry Cargo
FMTV	M1083	Dry Cargo
HEMMTT	M977	Dry Cargo
FMTV	M1085A1P2	ISO Container
FMTV	M1148A1P2 LHS	ISO Container
HEMMTT	M1120A4 LHS	ISO Container
PLS	M1075A1	ISO Container

Figure 3. Conventional Vehicles Simulated

Fuel Economy Estimation and Vehicle Allocation

Both conventional and modular vehicles are allocated to missions to optimize fuel economy subject to constraints on the vehicles performance in different terrains and against different threat levels. AMESim [11] is used to estimate fuel economy on different terrains for both conventional and modular vehicles. Due to the large number of vehicle variants, variability of the load on a vehicle and the time required to execute AMESim analysis on different terrains for all vehicles, a surrogate model is used to estimate fuel economy for each (conventional and modular) vehicle in each terrain in a reasonable amount of computing time. Separate surrogate models are created for 5 types of powertrains in the modular fleet and 12 types of conventional vehicles using the fuel consumption data generated by AMESim. These surrogate models utilize the observed effect that for any powertrain, there is a strong linear relationship between the fuel economy estimated by AMESim and the gross weight of the vehicle.

Demand Prediction & Resupply

A demand prediction function is used to predict the demand needed throughout the simulation in terms of vehicles (conventional fleet) and modules (modular fleet). Both fleets of vehicles can undergo damage during the simulation. Damage occurs to parts and modules stochastically based on the threat level of the mission as well as the condition (operating hours, terrain) of the part or module. In the conventional fleet, damage can result in a need for spare parts (such as destroying a tire) or the need to completely scrap the vehicle (such as destroying the powertrain). In the modular case, all modules can be replaced if damaged.

The resupply model schedules a pre-determined number of resupply events. Each resupply event calls for a calculated number of vehicles, spare parts (conventional fleet) and modules (modular fleet) for the simulation time horizon. Two options are implemented for resupply scheduling: fixed-time resupply and optimally scheduled resupply. Fixed-time option schedules a given number of resupplies for evenly distributed time intervals. The optimal scheduling uses the demand prediction to estimate the inventory volume requirements and determines the schedule to minimize the peak inventory volume requirement.

Two types of inventory management are implemented into MARVEL to allow easy customization: usage based selection and random selection. Usage based selection means the vehicles with the highest amount of hours of use are chosen to send out to execute the mission. This method prevents the situation where the entire sets of available modules and vehicles which are in disrepair. Random selection means that vehicles are selected randomly, regardless of their condition. The random case may be more realistic, as information about module state may not be readily available.

Maintenance and Modular Vehicle Assembly

A preventive maintenance model is utilized based on usage of the vehicles and modules. In the conventional fleet, maintenance is performed on a vehicle as a whole. In the modular fleet, modules are disassembled from a vehicle when maintenance is needed. A maintenance probability is assigned to vehicles and modules based on the ratio of the current usage and a usage threshold. As the usage of vehicles and modules increases, the probability to require maintenance increases.

Figure 4 – Supply chain optimization

During the maintenance a conventional vehicle becomes unavailable for mission until the maintenance is complete. A modular vehicle with a module to be maintained is unavailable while the corresponding module is swapped with a fresh one from the inventory. Then, the modular vehicle is sent back to inventory and the module that needs maintenance becomes unavailable throughout the maintenance process. After the maintenance process, the usage of the vehicle or module is reset to pristine.

MARVEL has two types of modular vehicle assembly models: long-term assembly, and short-term assembly. To reduce sudden large assembly requirements when large numbers of modular vehicles are suddenly needed, the long-term assembly model uses the demand prediction for the whole simulation time horizon to distribute more evenly the assembly burden over time. However, due to discrepancies between the predicted and the real demand, the long-term assembly model alone is not sufficient to meet all the modular vehicle demand. To address this, the short-term assembly model is designed to meet the leftover demand within a shorter time (on the order of hours). When the accuracy of the prediction is low, the load on the short-term assembly is larger. That, in turn results in higher personnel requirements for assembly. Such phenomena can be easily explored and analyzed using MARVEL.

Manufacturing Models

At the end of the simulation, MARVEL post-processes the vehicle and module order information to calculate the associated manufacturing cost. The manufacturing model solves a dynamic programming problem to find the optimal path in the supply chain with minimum final assembly cost. The representation of the supply chain optimization problem is depicted in Figure 4. The dynamic programming approach for the supply chain optimization problem has been presented in [12]. Given some choices for component suppliers, the model generates all possible subassembly options. Then, dynamic programming searches the optimal path that defines the components suppliers and an assembly plan by minimizing the sum of acquisition, delivery and assembly costs.

Personnel Requirements and Other Costs

After simulating the fleet operation for the entire time horizon, MARVEL provides a suite of outputs designed for high-level analysis and fleet design. The outputs include the personnel requirements organized in two groups: personnel in harm's way, and personnel on-base. Using the history of vehicles which executed the needed functions, the required personnel in harm's way is calculated by assigning a certain number of personnel to each vehicle type based on cabin capacity. In addition, maintenance history is post-processed to calculate the maintenance personnel requirement using a given number of personnel per maintenance task assigned. That number varies based on the vehicles and modules maintained. The personnel required for assembly also varies depending on the assembly task, such as the number and types of modules to be assembled. The sum of maintenance and assembly personnel gives the personnel required on the base.

In addition to personnel and the manufacturing cost, MARVEL can estimate the transportation cost using a linear model from [13]. In that model, the vehicles and modules are assumed to be transported to a port near the destination by sea and then ground transportation is used from the port to the base. The model includes the cost of washing and inspection as well as shipping the vehicles and modules back to the US after the mission is complete.

RESULTS

Selected results will be presented and analyzed at the GVSETS conference.

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