MARS SCENARIO-BASED VISIONING: LOGISITICAL OPTIMIZATION OF TRANSPORTATION ARCHITECTURES

GEORGIA INSTITUTE OF TECHNOLOGY

Contributors:
Ashraf Charania
Kris Cowart
Brad St. Germain
Tadashi Sakai
Roberto Salinas
Kirk Sorensen
Jeffrey Tooley
Shannan Wilson

Advisor:
Dr. John R. Olds
Assistant Professor, School of Aerospace Engineering
Director, Space Systems Design Lab (SSDL)
Georgia Institute of Technology

ABSTRACT

The purpose of this conceptual design investigation is to examine transportation forecasts for future human missions to Mars. Scenario-Based Visioning is used to generate possible future demand projections. These scenarios are then coupled with availability, cost, and capacity parameters for indigenously designed Mars Transfer Vehicles (solar electric, nuclear thermal, and chemical propulsion types) and Earth-to-Orbit launch vehicles (current, future, and indigenous) to provide a cost-conscious dual-phase launch manifest to meet such future demand. A simulator named M-SAT (Mars Scenario Analysis Tool) is developed using this method. This simulation is used to examine three specific transportation scenarios to Mars: a limited "flags and footprints" mission, a more ambitious scientific expedition similar to an expanded version of the Design Reference Mission from NASA, and a long-term colonization scenario. Initial results from the simulation indicate that chemical propulsion systems might be the architecture of choice for all three scenarios. With this mind, "what if" analyses were performed which indicated that if nuclear production costs were reduced by 30% for the colonization scenario, then the nuclear architecture would have a lower life cycle cost than the chemical. Results indicate that the most cost-effective solution to the Mars transportation problem is to plan for segmented development, this involves development of one vehicle at one opportunity and derivatives of that vehicle at subsequent opportunities.

NOMENCLATURE

ΔV	velocity increment
AHP	Analytic Hierarchical Process
CER	cost estimating relationship
CHEM	chemical
DDT&E	design, development, testing, & evaluation
DRM	design reference mission
DSM	Design Structure Matrix
EELV	evolved expendable launch vehicle
ETO	earth-to-orbit
GA	genetic algorithm
HEO	highly elliptical orbit
HLLV	heavy lift launch vehicle
HRST	highly reusable space transportation
IMLEO	initial mass in low earth orbit
Isp	specific impulse, s
LCC	life cycle cost
LEO	low Earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MER	mass estimating relationship
MR	mass ratio, inbound and outbound
M-SAT	Mars Scenario Analysis Tool
MT	metric ton
MTV	Mars transfer vehicle
NTR	nuclear thermal rocket
SBV	scenario based visioning
SEP	solar electric propulsion
TFU	theoretical first unit
TMI	trans-Mars injection
T/W	thrust-to-weight

I. INTRODUCTION TO THE STUDY

Current thinking on Mars seems limited in examining the links between the depth of available transportation vehicles with a breadth of future scenarios. Analyses such as NASA's Design Reference Mission (DRM) or the Mars Direct Mission can only be used as starting points. In trying to send the initial human mission to Mars, these concepts have not appropriated a long-term philosophy. These visions cannot adequately deal with the inherent problems of transportation systems that are to be used repeatedly in the next millenium. These designs avoid examining the possible synergies between how often a society demands to go to Mars and the transportation methods available to implement that demand.

The inquiry presented here looks into the bimodal shipping arrangement inherent in the Mars transportation market: from Earth-to-orbit (ETO) and from Earth orbit to Mars. A conceptual design method is created that can integrate all aspects of the space transportation infrastructure for going to Mars. Planning space transportation systems for the future in the conceptual design phase requires a method to evaluate how each envisioned future changes the final design. In each imagined future it should be possible to see how cargo requirements actually change the development cycle of the transportation system itself. Specifically, how does cargo demanded affect the payload capability of the "truck" that will be developed to transport that cargo.

II. PROBLEM APPROACH

A new design approach to address the deficiency defined above is based on Mars Scenario-Based Visioning (SBV). SBV is a philosophy that tries to define the future according to various drivers. In essence, visions of the future help drive one to obtain specific scenarios. A process is developed that can utilize these envisioned scenarios, along with availability projections of future launch vehicles and Mars transfer vehicles (MTVs), to determine the cost-conscious combination of such vehicles to meet that scenario requirement.

Large cargo delivery to another planet such as Mars is a problem of transportation logistics. Previous studies indicate that more than 40% of the total cost associated with going to Mars stems from the Earth-to-orbit and TMI phases, with the rest of the cost coming from habitation, operations, and a small percentage for Earth return. This study focuses only on the one-way transportation problem to Mars, specifically up to trans-Mars injection (TMI). The payload at TMI must contain its own equipment for orbit capturing at Mars and for all post-TMI transportation, therefore the costs calculated in this study are only for the transportation segment to TMI.

The timeframe examined in this study spans from 2011 to 2031. Since optimum orbital alignment does not occur for 2.1 years between Mars and Earth the cargo is sent only in those ten launch opportunity years between 2011 and 2031 (2011, 2013/4, 2016, 2018, 2020, 2022, 2024, 2026, 2028, and 2030/1).

With all of these assumptions in mind a process is designed to simulate and optimize a bimodal transportation system to Mars (see Figure 1). At the center of the figure is a new simulation tool called M-SAT (Mars Scenario Analysis Tool), specifically designed for this study. M-SAT is a spreadsheet-based simulation that utilizes inputs of scenario forecasting, ETO vehicle databases, and MTV databases. Internally M-SAT contains modules to calculate the following: vehicle flight rate combinations, vehicle transportation costs, and in-space operations costs. Attached to these modules is a contracted genetic algorithm optimization routine that selects the optimum combination of ETO vehicles and MTVs per year to reduce overall life cycle cost (LCC) of the transportation system.

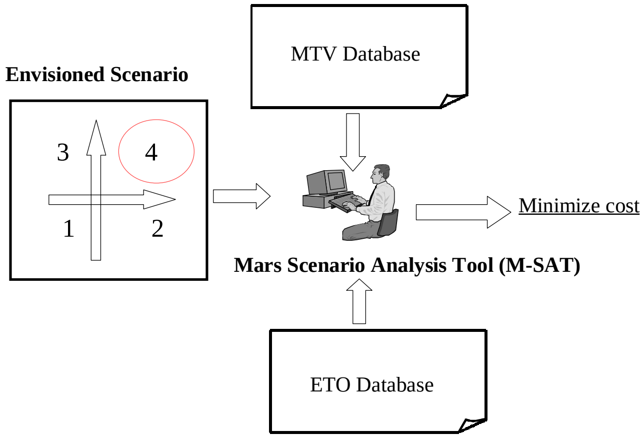


Figure 1: Process Overview Visualized

II.1 Scenario Visioning and Populating the Input Databases

Mission scenarios and available vehicles are what defines the future of Mars transportation systems, therefore these are the inputs to the M-SAT simulation. Envisioning these scenarios and populating the databases is then the first step towards creating a valuable simulation tool.

II.1.1 Scenario Definition and Visioning

The foundation of Scenario-Based Visioning as applied in this examination can be seen in Figure 2. The horizontal axis represents increasing social and political will of going to Mars and the vertical represents reduced transportation costs. In a scenario where the social and political will is low one can imagine a future in which only robotic exploratory missions would be developed. In a future where social and political will for going to Mars is high, and yet high space transportation costs exist, only a limited one-time manned mission might be advanced, called "Flags and Footprints." In another vision of the future where these particular costs have been reduced, missions might increase to point near or slightly above those envisaged by NASA in the Design Reference Mission (DRM). Colonization may be a likely future if both the collective will to go to Mars increases and transportation costs decrease.

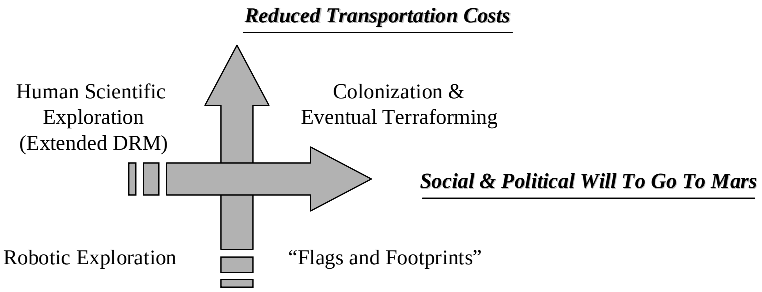


Figure 2: Scenario-Based Visionsing for Going to Mars

Payload requirements in metric tons for each Mars launch opportunity (approximately every 2.1 years) are assigned for each scenario (see Figure 3). The payload requirement per year parameter reflects the fact that for each scenario a certain TMI payload would be demanded. This requirement is essentially a proxy for the societal demand to go to Mars during that year. These payload requirements are the inputs to the simulation from the scenarios.

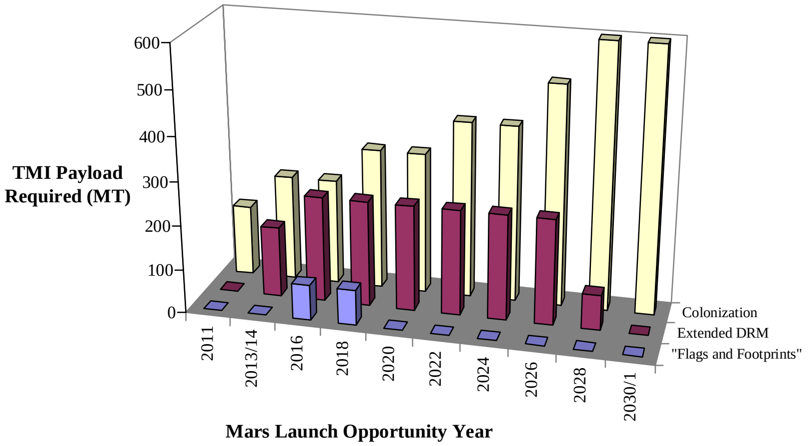


Figure 3: TMI Payload Forecasts for Three "Envisoned" Mars Scenarios

II.1.2 Populating Input Databases

The M-SAT simulation consists of two input databases: one for the ETO vehicles and one for the MTVs. Similar to the scenario definitions, the vehicles used in the databases can define a future scenario. Any vehicles deemed important to a Mars transportation system can be input into the database. Each database contains inputs that describe the vehicle type, availability, reusability, payload capacity, weight, and cost.

Each of the inputs has a different effect on the scenario envisioned. For instance, vehicle type indicates to the simulator whether certain vehicles are derivatives of one another. This is useful in obtaining learning curve effects from production of similar vehicles. Both availability and payload capacity are input for each opportunity to simulate possible performance upgrades and operational improvements in a vehicle, which can be significant over a twenty-year period. Reusability is important to the MTV database because a reusable vehicle will be able to repeat its mission at the next opportunity with only marginal refurbishment. The ETO and MTV databases contain a maximum of eight and three vehicles, respectively. The databases are populated with both existing designs and conceptual designs. The conceptual designs used for the databases are in-house designs.

Creating these in-house designs requires the use of very intensive design processes optimizing for minimum cost. Detailed designs are necessary because specific values are needed in order to estimate the input parameters to the database. An example of this is occurs in vehicle cost estimation, which involves relationships that are dependent on the particular weight of vehicle components. These next two sections will chronicle the designs and design processes in the databases and introduce information that is useful for deciding on the input parameters in each database. These designs are not meant to be a result of this study, designing them is merely part of the process of generating the inputs.

II.1.2.1 Earth-to-Orbit Vehicle Database Definition

The task of the ETO transportation designs is to populate a database of vehicles to be used as inputs to the M-SAT simulation. In order to fully explore the possibilities for ETO transportation, an array of vehicles spanning a wide payload spectrum is needed. By compiling this spectrum the question of what is the “best” way of launching a Mars transfer vehicle can be answered with more confidence. These ETO designs use existing, interim, and future designs to meet the demands of exploring low cost options for a variety of payloads to low Earth orbit or LEO (400 km x 400 km).

The purpose of the database for the ETO team is two-fold. First, it is intended to serve as a test for the trial runs of the scenario vision; second, it is intended for future users who do not have their own vehicle designs. The beauty of the database lies in the fact that it is easily amendable. If a new design is created, it can be placed in the database and accessed as an ETO transportation option. Introduced below are possible launch vehicle candidates come from existing, interim, and future vehicles that can launch more than 10 MT to LEO (see Figure 4).

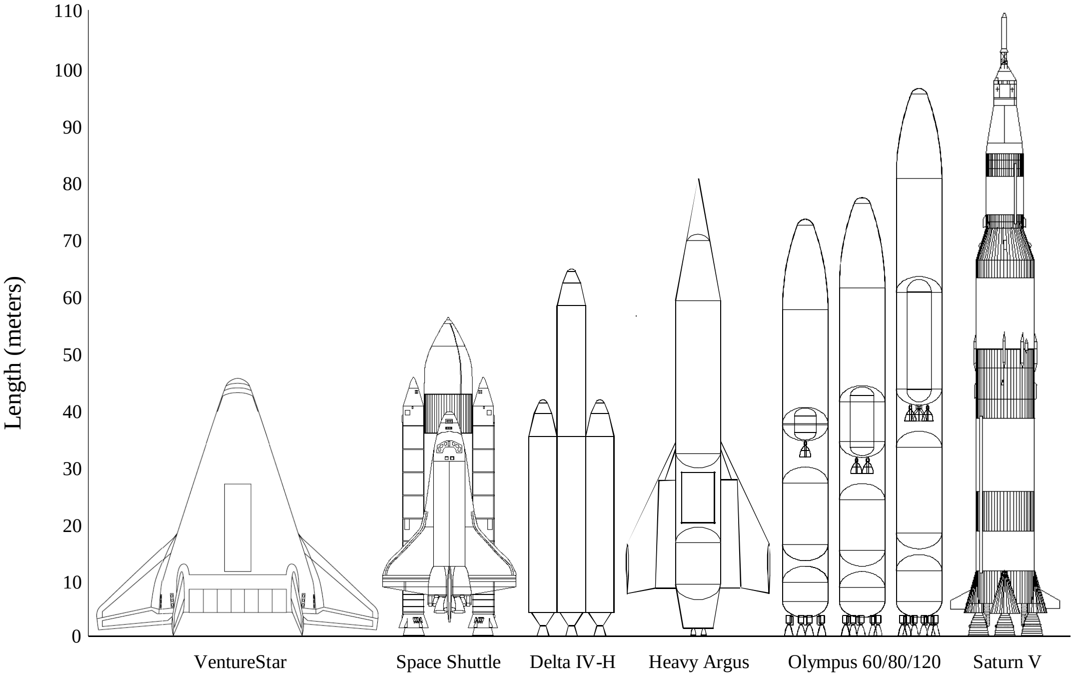


Figure 4: Selected Earth-to-Orbit Vehicle Comparison

- **Existing Vehicles**

The Proton is a standard Russian heavy-lifter, having been used to launch all Russian space station components for the last thirty years. Proton is a four-stage vehicle fueled by hypergolic propellants. Its advantages include flight heritage, relatively low cost, and a surprisingly modern operations scenario. Drawbacks include toxic propellants, high-latitude (lower performance) launch sites, and heavy airframe design.

The latest member of the Ariane family was originally designed to loft the Hermes spaceplane into LEO, and hence retains a significant lift capability. Ariane 5 is a liquid oxygen (LOX) / liquid hydrogen (LH2) core vehicle with solid strap-ons. Among its advantages are a modern design and near-equatorial launch site.

It should be noted that existing vehicles can lift a maximum of 15 MT to LEO, hence more powerful vehicles must be considered. It should also be noted that the Space Shuttle was omitted from the list due to high operations cost and an uncertain future in the timeframe projected.

- **Vehicles Under Development**

The Heavy Lift Variant Evolved Expendable Launch Vehicle (EELV) program seeks to upgrade existing Delta and Atlas vehicles to handle projected commercial and military launch needs in the next decade. The Delta IV and Atlas V will each have a heavy-lift variant capable of lifting around 20 MT to LEO (to replace the Titan IV). The EELV program is in an advanced state of development and these vehicles should enter service in 2001. The EELV variants of Delta and Atlas have superior operational, manufacturing, and performance capabilities and are an excellent candidate for the database.

Lockheed Martin's VentureStar program seeks to drastically lower the cost of ETO transportation through the development of a single-stage-to-orbit, fully-reusable launch vehicle. Projected to be available in 2005, VentureStar is another excellent candidate for the database due to its highly efficient, low-cost, rapid turnaround operations.

- **Conceptual Vehicles**

Heavy Argus is a second-generation reusable launch vehicle designed at the Space Systems Design Lab at the Georgia Institute of Technology, projected to take advantage of advanced technologies that are too immature to be included on VentureStar. Heavy Argus is a 40 MT variant of this vehicle that was originally designed to launch Space Solar Power components. The vehicle is highly reusable, and is projected to be available in or around 2010.

It is clear that none of these vehicles has an ETO capability greater than 40 MT. Hence, as part of this analysis, a Heavy Lift Launch Vehicle (HLLV) design was undertaken and designated Olympus. The philosophy behind the design approach was to look at technology alternatives besides those used on Shuttle or Saturn-V. The Olympus vehicles were designed for 60, 80, and 120 MT payload capabilities.

Design tools used for Olympus included APAS (Aerodynamic Preliminary Analysis System) for aerodynamic analysis, POST (Program to Optimize Simulated Trajectories) for trajectory optimization, MS Excel for weights and sizing, SDRC I-DEAS for visualization, and NAFCOM (NASA Air-Force Cost Model) based cost-estimating relationships (CERs) for weight based costing. These tools were used in conjunction with concurrent engineering philosophies such as Quality Function Deployment and Analytical Hierarchical Processing (AHP). The flow of information between these tools in the Design Structure Matrix (DSM) illustrates the iterative process needed for design convergence (see Figure 5). Each dot represents the passage of information, when information is fed backwards iterations are required. An automated script was constructed as an interface with POST, allowing extremely rapid iterations between the spreadsheet-based weights analysis and the sophisticated trajectory optimization of POST. This allowed optimization of the staging ΔV for minimum dry weight (low cost) for all three vehicles.

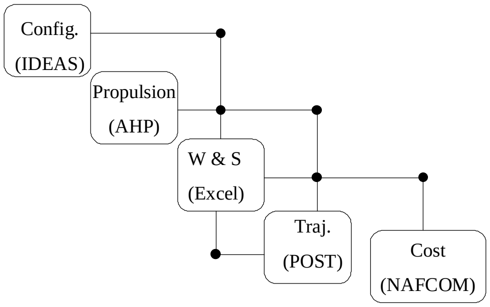


Figure 5: Heavy Lift Launch Vehicle Design Strucuture Matrix (DSM)

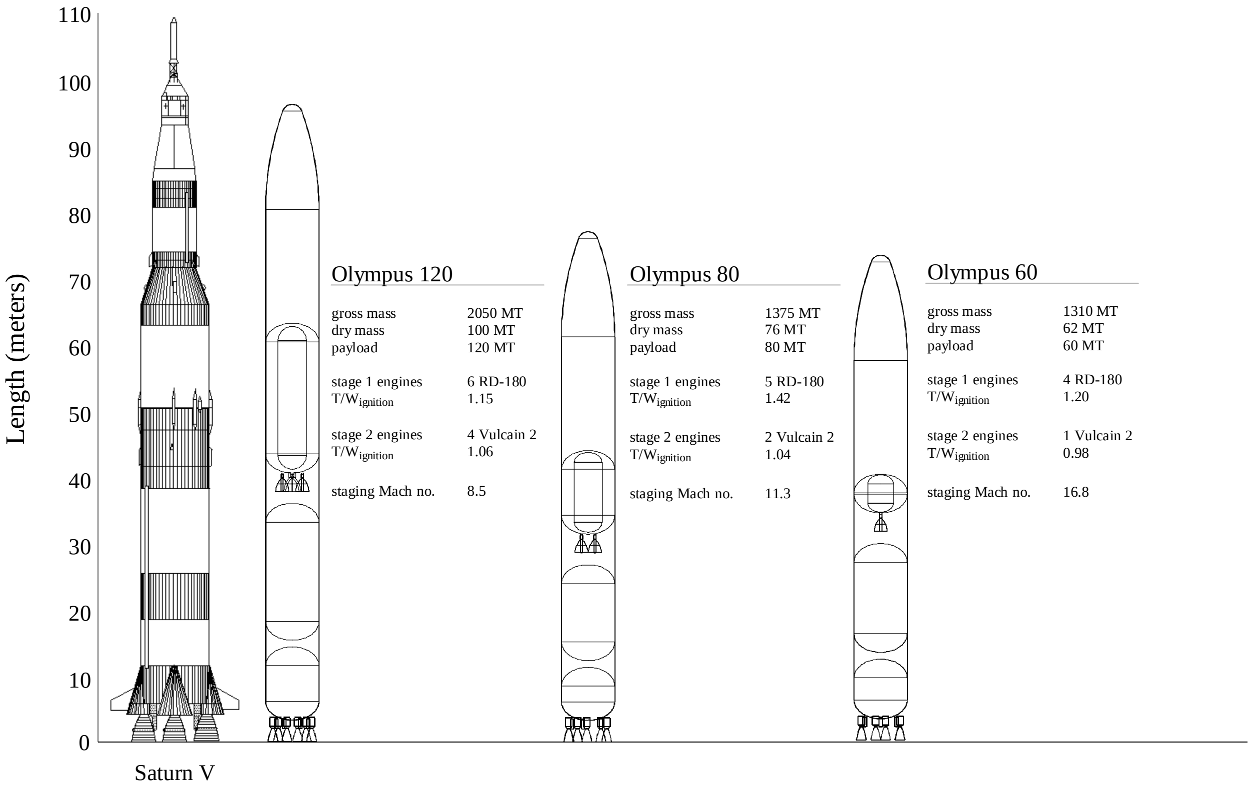


Figure 6: Comparison of In-House Heavy Lift Launch Vehicle Designs

After implementing this process the three designs seen in Figure 6 were obtained. The booster stage utilizes RD-180 engines burning kerosene and liquid oxygen with an upper stage that utilizes LH2/LOX Vulcain 2 engines. These engines were chosen based on cost, specific impulse, thrust, and possibilities for international cooperation.

Another improvement to the Olympus design was to take advantage of new technologies in large, cryogenic, lightweight composite tanks, and structures. The upper-stage tanks also have an innovative design feature called “tank within a tank” wherein the LOX tank is housed inside the LH2 tank. These advanced materials are used for nearly every structural system on the vehicle, and significantly reduce the vehicle's mass compared to older launch vehicles.

Operationally, the Olympus incorporates efficient strategies recently developed for the EELV and VentureStar programs. By designing for operations at the outset, design features that might interfere with an operational strategy can be avoided (such as solid strap-on boosters or parallel staging). The first and second stages are carefully mated at the horizontal integration facility located adjacent to the launch pad. Once raised by the rail mounted strong back the payload is then raised and attached at the launch site (see Figure 7).

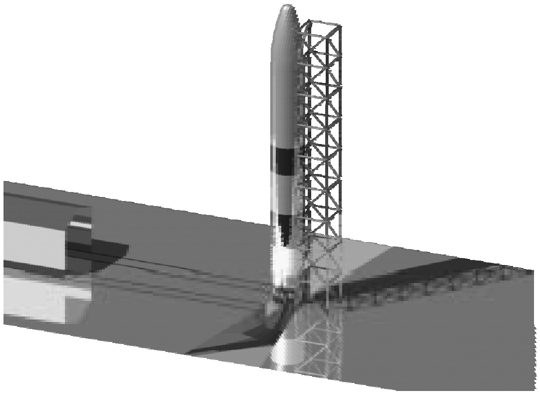


Figure 7: Operational Image of Olympus Heavy Lift Launch Vehicle

II.1.2.2 Mars Transfer Vehicle Database Definition

The purpose of the MTV database was to create a population of vehicles that could fully test the capabilities of the Mars Scenario Analysis Tool (M-SAT) and as reference database for future users. This database was populated by three unique MTVs each having a different propulsion system. The three propulsion systems examined are nuclear thermal rocket (NTR) propulsion, solar electric propulsion (SEP), and LOX/LH2 chemical propulsion. These vehicles were designed to provide new low cost options for Mars missions. Each class of vehicles has five sub-designs, one for each different payload class. The payload classes available in the database are 40MT, 80MT, and 160MT. The MTVs are designed only to perform up to TMI.

All MTV designs are optimized for lowest initial mass in low Earth orbit (IMLEO). Trajectory analysis is done depending on the type of trajectory flown (high or low thrust). Depending on the trajectory the size of the engines can be determined and in turn the mass of the vehicle components. Propulsion analysis and mass estimation were done in spreadsheets. Since these vehicles have never been built, inherent uncertainties exist in the mass-estimating relationships. Therefore, triangular uncertainty distributions are placed on the mass estimators to obtain 90% confidence level mass statements through the use of Monte Carlo simulations.

- **NTR MTV Design**

The NTR MTV is a relatively simple design because its only function is to provide the TMI burn. The MTV uses only one NTR to provide the required thrust. The NTR uses liquid hydrogen that is stored in a foam insulated propellant tank. The NTR was designed with a chamber pressure of 1.0 x 107 Pa and a characteristic velocity of 5500 m/s. The vehicle was sized to be able to provide 4,198 m/s of ΔV. This corresponds to the ΔV requirement to go from a 400km circular Earth orbit to a Mars injection orbit in the year 2022. This is one of the largest ΔV requirements as is seen in Figure 8.

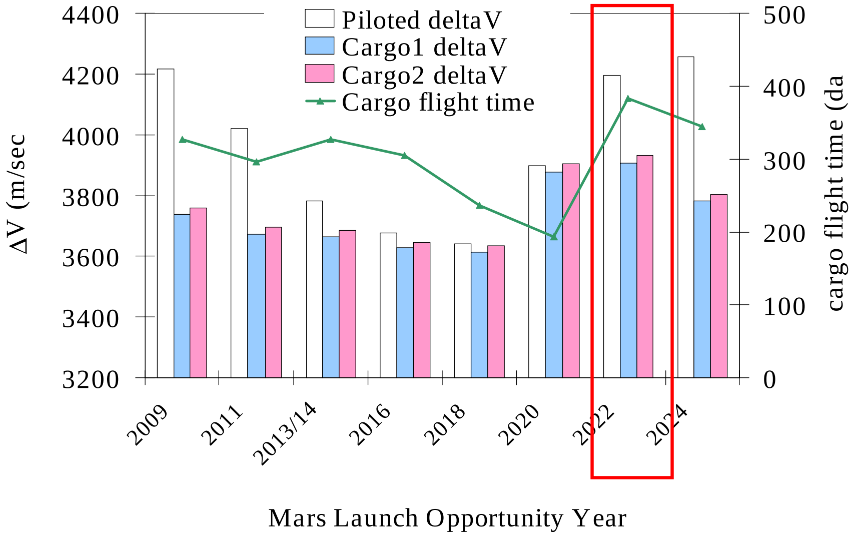


Figure 8: Required ΔV for TMI and Associated Flight Time (Based on DRM Flights)

The mass breakdown for the 80 MT NTR MTV based on the trajectory analysis above is shown in Table 1.

Table 1: Mass Breakdown for 80MT NTR MTV (90% Confidence Values)

No.	Item	Mass (kg)
1.0	LH2 Tank Structure	6,690
2.0	LH2 Tank Insulation	1,640
3.0	Other Structure	2,150
4.0	NTR Nozzle	630
5.0	Nuclear Reactor & Systems	3,310
6.0	Subsystems	5,420
	MTV Dry Mass	19,840
7.0	Payload	80,000
	Mars Arrival Mass	99,840
8.0	TMI Prop Req'd	61,600
9.0	Phase 1 Prop losses	1,910
	Initial Mass in LEO	163,350

The choice of the expansion ratio of the nozzles was an optimization problem. The larger the expansion ratio the higher the specific impulse of the engine, which decreases the amount of propellant used, but increases the nozzle weight. The optimal expansion ratio for minimum IMLEO was found to be 180 (specific impulse = 935 s). After the expansion ratio was determined the remaining engine properties were calculated. The • V of 4,198 m/s plus the additional 3.5% for losses was then used to determine the mass ratio (MR) of the vehicle. This mass ratio (MR) was used to determine the amount of propellant needed by the vehicle. The propellant losses assumed in the weight breakdown structure consisted of boiloff (1.6% of total propellant, sized for 1 month of losses), reserves (1.0% of total propellant), and residuals propellant (0.5% of total propellant). Figure 9 shows a size comparison of the various NTR designs.

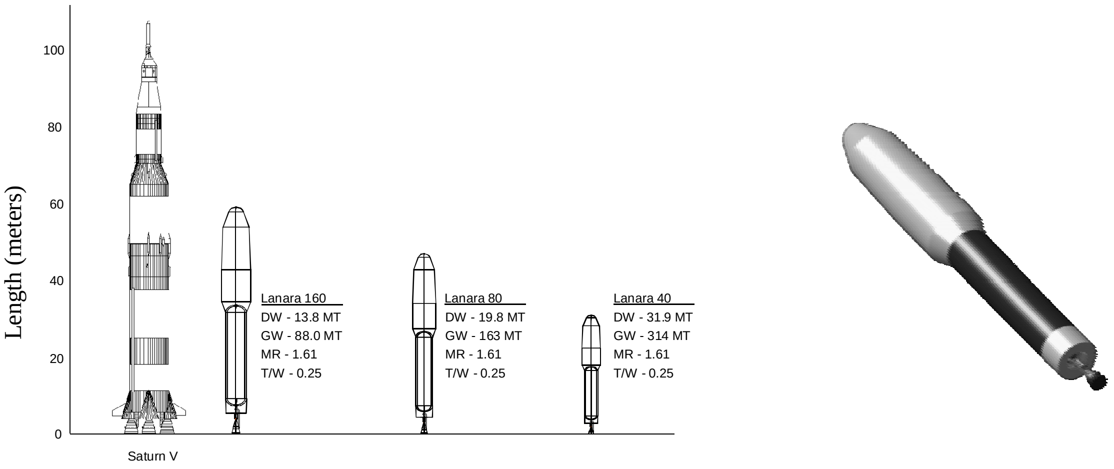
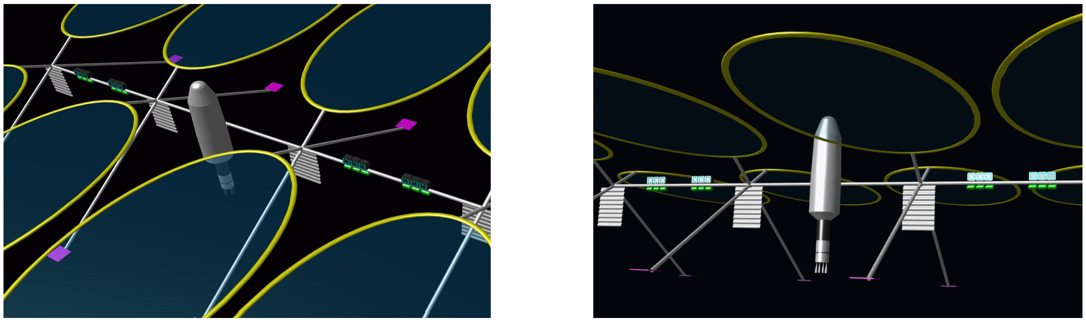


Figure 9: NTR Comparison

- SEP MTV Design

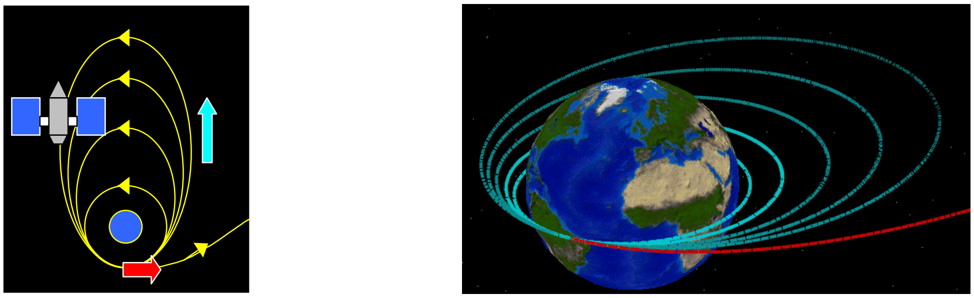
The second Mars transportation system evaluated was a Solar Electric Propulsion (SEP) design (see Figure 10). This architecture uses a SEP orbit transfer vehicle to transport the Mars-bound payload from a LEO to a Highly Elliptical Orbit (HEO) of 71,000 km x 400 km. For human missions the crew is sent out to the orbiting SEP vehicle using a crew taxi that consists of a crew capsule with an attached chemical propulsion stage. After the crew arrives at the SEP vehicle, they transfer to the MTV bound for Mars and then a small chemical kick-stage sends the payload to Mars. The SEP vehicle then returns to LEO for reuse.



a.) SEP Top Angled View **b.) SEP Side View**

Figure 10: SEP Imagery

For trajectory analysis the following parameters were calculated: total ΔV required to go from LEO to HEO using a low thrust trajectory, the time of flight of that trip, the required low thrust ΔV to go from HEO to LEO, and the required chemical kick ΔV needed to go from the HEO orbit to Mars. The crew taxi uses a high thrust chemical engine to go from LEO to HEO, which shortens the trip time and reduces the radiation exposure to the crew. This high thrust ΔV must also be provided by trajectory calculations. Figure 11 below graphically displays the SEP trajectory.



a.) SEP Spiral Trajectory with Chemical Kick Stage (Top View)

b.) SEP Spiral Trajectory with Chemical Kick Stage (Angled View)

Figure 11: SEP MTV Trajectory

The low thrust ΔV supplied by the trajectory analysis is used to calculate the outgoing mass ratio (MR) for the SEP transfer vehicle, using krypton-fueled ion engines with Isp of 4,000 sec. Specifically, these engines consist of gridded ion thrusters power rated at 500kW with an anticipated lifetime of 12,000 hours.

This MR is used in the weight breakdown statement to calculate the amount of propellant needed for the outbound trip. The inbound MR is used to calculate the inbound propellant needed. The total power needed by the propulsion system is determined by the IMLEO (initial mass in low Earth orbit) of the SEP vehicle. The power to mass ratio used for this determination is 0.025 kW/kg. This power requirement is used to size the inflatable, dense concentrator collectors as well as determine the number of ion engines. Photovoltaic arrays are used in conjunction with the concentrators to harness the necessary solar energy. The remaining items in the SEP vehicle mass breakdown statement were sized using various mass-estimating relationships (MERs) provided by NASA's Mars Orbit Basing and Space Solar Power projects. Table 2 details the mass breakdown structure for the 80 MT SEP.

Table 2: 80 MT SEP MTV Mass Breakdown Statement (90% Confidence Values)

No.	Item	Mass (kg)
1.0	Solar Collectors	14,000
2.0	Body Structure	4,740
3.0	Propulsion	47,670
4.0	Fuel Storage	11,130
5.0	Data Processing	20
6.0	Navigation Sensing/Control	280
7.0	Telecom and Data	80
	Dry Weight	77,920
8.0	Inbound Reserves and Residuals	320
9.0	Outbound Reserves and Residuals	1,250
10.0	Inbound Propellants	6,890
	Elliptical Orbit Departure Mass	86,380
11.0	Payload	80,000
12.0	Chemical Kick Dry Weight	17,550
13.0	Chemical Kick-Stage Propellants	44,630
	Elliptical Orbit Arrival Mass	228,560
14.0	Outbound Propellants	24,100
	IMLEO	252,660

RL-10A4-1 engines are used to power the chemical kick-stage that propels the payload from HEO to Mars. Vulcain 2s were analyzed for the 160 MT and 120 MT payload stages, but this increased the IMLEO of the SEP MTV and the overall weight of the chemical kick-stage propulsion system. RL-10s are also used for the crew taxi’s propulsion system. The simple weight breakdown structure for the kick-stage includes total propellant weight, obtained from the stage's mass ratio, tank weight obtained using MERs developed during the NTR MTV design, and unusable propellant.

The crew taxi was designed using an expendable crew capsule. The taxi consists of the capsule and a detachable propulsion stage that contains of all tanks, fuel and hardware necessary to perform the burn to transfer the crew from LEO to HEO. The crew capsule weight of 6500 kg was taken from NASA's DRM. The rest of the weight breakdown structure was determined using the required ΔV of the stage, along with engine properties and various MERs.

The final vehicle designs obtained from above analysis are shown in Figure 12.

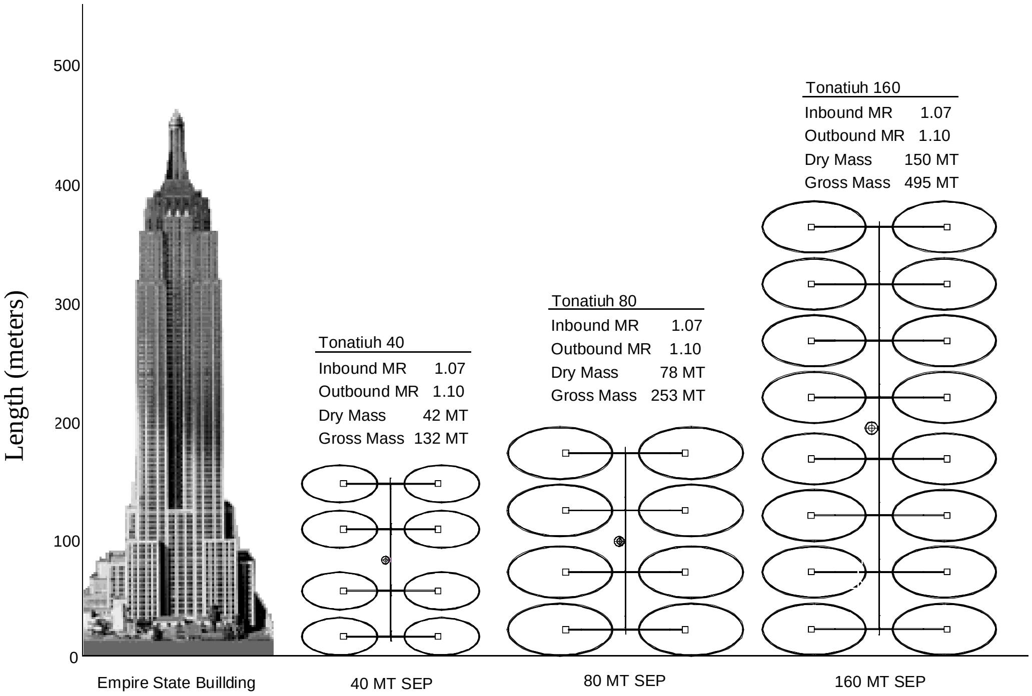


Figure 12: SEP Comparison

- **Chemical MTV Design**

The chemical MTV is designed to perform the same mission as the NTR MTV and similarly designed to provide the same 4,198 m/s of ΔV needed to go from LEO to Mars. The chemical design uses the same mass estimating methods described in the NTR section (see Table 3). The most significant difference between the chemical and NTR design is the propulsion system. The chemical design uses a single LOX/LH2 Vulcain 2 to provide the needed thrust. Since the Vulcain has a much lower Isp than the NTR and because the chemical MTV has to carry LOX, it is much heavy than its NTR counterpart. The final vehicle designs obtained from above analysis are shown in Figure 13.

Table 3: 80MT Chemical MTV Mass Breakdown Statement (90% Confidence Value)

No.	Item	Mass (kg)
1.0	LH2 Tank Structure	2,700
2.0	LH2 Tank Insulation	810
3.0	LOX Tank Structure	1,030
4.0	LOX Tank Insulation	130
5.0	Engine Weight	1,940
6.0	Other Structure	1,480
7.0	Subsystems	5,460
	MTV Dry Mass	13,550
8.0	Payload	80,000
	Mars Arrival Mass	93,550
9.0	Required Propellant	176,360
10.0	Unusable Prop	5,470
	Initial Mass in LEO	275,380

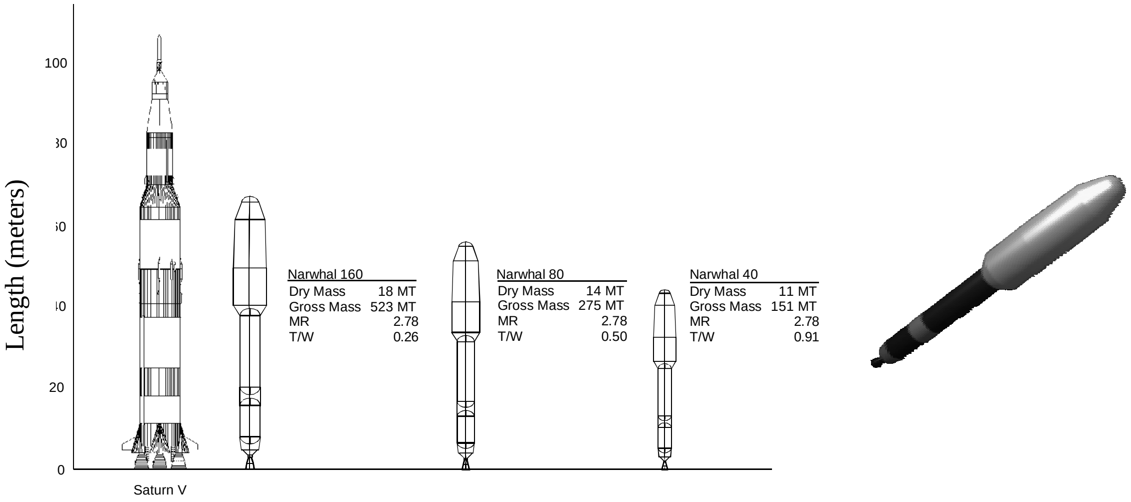


Figure 13: 80 MT Chemical MTV Size Comparison

- **MTV Summary**

Each MTV has its specific attributes and limitations. The nuclear MTV is very efficient, but there are environmental concerns associated with it. A SEP MTV would constitute a large technological advance in that area but would provide an exciting new form of space transportation. The chemical MTV uses very near term technology but uses the least efficient propulsion system and therefore is the most massive. Figure 14 shows IMLEO comparisons for five different payload class MTVs.

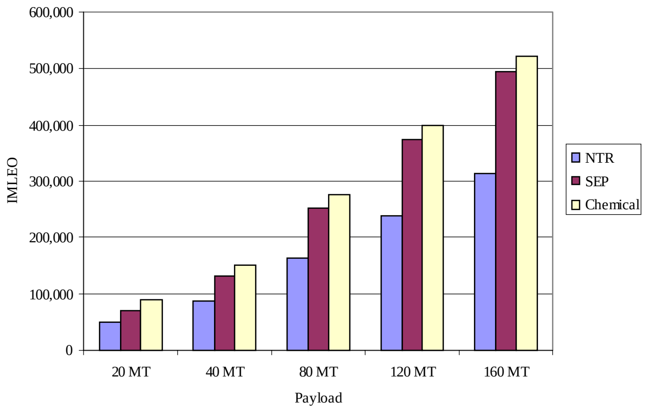


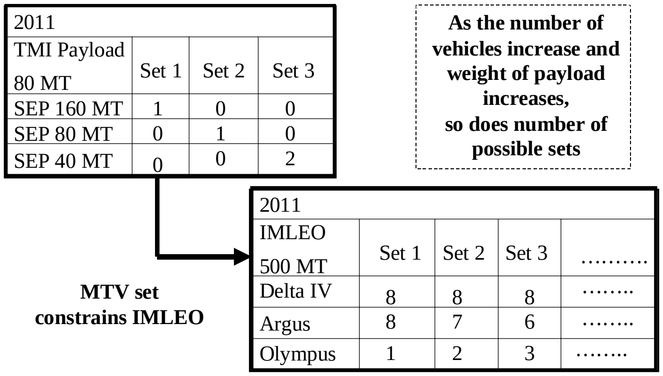
Figure 14: IMLEO versus Payload at TMI for Three Propulsion Arhcitectures (NTR, SEP and Chemical)

II.2 Modules

Now that the inputs have been established in terms of the vehicles and scenarios, the modules in the M-SAT simulation will be discussed. The modules are defined as algorithms that represent the analysis of the space transportation system. The three modules are the vehicle flight rate set generating module, the costing module, and the in-space operations module. The modules are referenced to the inputs in the database and are also cross-referenced to each other.

II.2.1 Vehicle Flight Rate Set Generation Module

The purpose of vehicle flight rate set generation is to reduce the size of the problem. Vehicle flight rate sets are defined as possible combinations of vehicles that can meet the payload constraints. Two example sets are shown in Figure 15.



2011			
TMI Payload 80 MT	Set 1	Set 2	Set 3
SEP 160 MT	1	0	0
SEP 80 MT	0	1	0
SEP 40 MT	0	0	2

As the number of vehicles increase and weight of payload increases, so does number of possible sets

2011				
IMLEO 500 MT	Set 1	Set 2	Set 3	………
Delta IV	8	8	8	……..
Argus	8	7	6	……..
Olympus	1	2	3	……..

MTV set constrains IMLEO

Figure 15: Example of Vehicle Flight Rate Set Generation

As can be seen from the figure for a given year and a given payload requirement there are only a finite number of vehicles flight rate combinations that deliver the required payload. The module calculates sets first for the MTVs dependent on the TMI payload from the scenario in that year. These sets are usually small since there can only be three MTVs in the database. The ETO vehicle set is dependent on IMLEO of the MTVs, this number is usually high and their can be up to eight ETO vehicles, therefore ETO flight rate sets can be in the tens of thousands for large problems. For problems of this size set generation can take up to an hour. In order to generate the ETO sets one must know IMLEO, but this number changes if a different MTV set is chosen. ETO sets are therefore generated for a range of IMLEO, where the range is based on ranges of MTV IMLEO for each year.

Once the vehicle flight rate sets have been generated they become variables that can be changed in M-SAT. Changing these variables will result in different total LCC of the transportation system.

II.2.2 In-Space Operations Module

To determine the cost and weight penalties of assembly in LEO a module called in-space operations was developed. The cost outputs from this module are based on several factors including number of robots used and number of space platforms (dependent on the number of robots), each of those having fixed and variable costs. A general schematic of a typical in-space operations scenario is given in Figure 16.

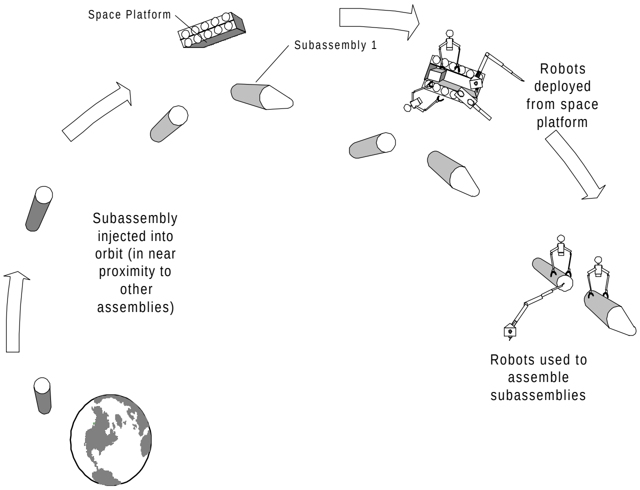


Figure 16. In-Space Assembly of MTV Pieces

The cost of in-space assembly is heavily dependent on the total number of ETO flights. A simple relationship exists between in-space operational complexity and the number of ETO flights. This relationship is the number of assemblies is equal to the number of ETO flights minus one. If there are less than five ETO flights autonomous docking is used for in-space assembly. Robots are used exclusively if there are more than five ETO flights.

The in-space operations module has the capability to use several different types of robots. Each robot is mission specific and designed, developed, tested and evaluated before the beginning of each mission. This non-recurring cost is dispersed evenly over 5 years prior to the initial launch. Learning curves are added into the simulation for the development of the robots.

Space platforms for the robots are also modeled. These space platforms are small "robot space stations" of ten metric tons with lifespans of six years. The robots can keep necessary tools, power, and communication systems on board these platforms. The number of space platforms needed is determined by the total number of robots to be in orbit during assembly. Each can sustain only twenty robots at any given time.

II.2.3 Cost Module

Costs are determined separately for the ETO and MTV transportation segments. Recurring and non-recurring costs are calculated for each MTV. Selected ETO launch vehicles are sunk cost programs whereas others are developed exclusively for these scenarios.

The non-recurring and recurring costs of each type of MTV are determined through the use of cost-estimating relationships or specific costs. The NTR, SEP, and chemical MTV architectures each have varying non-recurring costs (as seen in Table 4 for the 40, 80 and 160 MT payload class vehicles). The non-recurring cost of the NTR is the highest of the three, while SEP has the highest recurring cost. This is due to the fact that the SEP is an architecture made up of many small components.

Table 4: Non-Recurring and Recurring Costs of MTV Architectures for Various Payload Classes (1999$M)

Architecture Type	Payload Capability – Class		
	40 MT	80 MT	160 MT
NTR			
Non-Recurring Cost	$4,291 M	$4,547 M	$5,059 M
Recurring Cost	$829 M	$1,441 M	$2,662 M
SEP			
Non-Recurring Cost	$1,892 M	$2,236 M	$2,911 M
Recurring Cost	$1,368 M	$2,261 M	$4,175 M
CHEM			
Non-Recurring Cost	$1,231 M	$1,323 M	$1,472 M
Recurring Cost	$273 M	$281 M	$293 M

The ETO launch vehicle cost analysis is handled in two ways. For those launch vehicles whose design, development, testing, and evaluation (DDT&E) costs are sunk or already accounted for, such as the VentureStar or Ariane 5, only a constant recurring price per flight is charged to the MTV launch customer. For those vehicles which are developed just to handle these Mars payload missions, such as a new heavy lift launch vehicle (Olympus), the costs for those vehicle developments as well as the recurring cost per flight is included in the transportation cost (see Table 5).

Table 5: Non-Recurring and Recurring Costs of ETO Vehicle Architectures for Various Payload Classes (1999$M)

Architecture Type	Payload Capability - Class		
	60 MT	80 MT	120 MT
Olympus			
Non-Recurring Cost	$2,464 M	$2,813 M	$3,483 M
Recurring Cost	$507 M	$577 M	$713 M

The cost module of the M-SAT simulation accepts the DDT&E (non-recurring) and TFU (theoretical first unit) costs of each transportation vehicle, MTV or ETO. These costs are taken in conjunction with the flight rates of each of the transportation architectures to determine the life cycle transportation costs. Learning curves are included for the DDT&E and TFU costs. The DDT&E is applied starting five years before the construction of the first unit with the DDT&E amount spread out evenly over those five years. A DDT&E learning curve of 85% and a TFU leaning curve of 90% are included in the analysis. The cost module has built-in logic which instructs the module to build the lowest payload class vehicle first if multiple payload class vehicles are built in the same year. With this logic the learning curve effect is applied to the larger payload class vehicle, which is the vehicle with the larger DDT&E cost. With these learning curve effects the cost module is robust enough to handle multiple architectures.

II.3 Optimization Process

Now that the inputs and modules have been introduced the problem statement is redefined in terms of the newly designated parameters. This statement is, ”For a given scenario and database find the minimum total life cycle cost by changing the vehicle flight rates of the MTVs and ETO vehicles.” In order to find the minimum cost, an optimizer must be incorporated with the databases.

The decision of which type of optimizer to use is facilitated by characterizing the design space. Independent variables in the design space are the vehicle flight rate sets. Because the flight rate sets are determined for each opportunity and for both MTV and ETO vehicles there are twenty independent variables. The design space of the problem is not a continuous function because it is undefined when vehicle flight rat set guesses are not integers. Total LCC is the objective function. The problem is also multi-modal, containing more than one local minimum for the objective function. Finally, the size of the space is defined as possible values of each of the twenty independent variables multiplied by each other. Therefore if there is an average of 8 MTV sets and 6,000 ETO sets for a given scenario the total number of possible combinations is approximately 1×10^{50}. The first two characteristics of the problem lead one to choose a stochastic optimizer. The large number of possible flight rate combinations makes a random grid search unreasonable so a 'smart' stochastic search must be done. The stochastic optimizer chosen for this problem is a spreadsheet based contracted genetic algorithm (GA) program. GAs incorporate the idea of survival of the fittest and use binary digits to represent the 'genes' of the independent variables. There are of course problems with GA, the main problem being that GAs do not necessarily generate the optimal solution, but usually approach a near optimal solution.

A schematic of the genetic algorithm integrated with the entire process is shown in Figure 17. Once the database, scenario, and flight rate sets have been created the program is initiated. The inputs to the GA are the upper and lower bounds of each design variable and the value of the objective function, namely total LCC. The optimization begins by first initializing a random 'generation' of independent variables. A generation consists of a specific number (50-100) number of candidate designs. This generation is evaluated and the cost is returned into the optimizer and three 'biological' processes performed. The first is replication of good designs. Next is crossover, where 'parents' are combined to diversify the next 'generation'. Lastly, random mutation occurs, which adds diversity to the design pool.. These new 'fitter' variables are placed back into the simulation and then the process continues. A fourth process called restart is sometimes implemented if the generation becomes inbred. The optimization is stopped when the desired number of iterations is complete, however there is no mathematical proof that the optimized answer has been obtained.

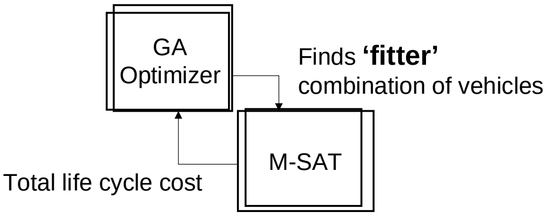


Figure 17: Genetic Algorithm Optimizing for Minimum Cost

III. RESULTS

III.1 Scenario Forecasts

Each of the three mission scenarios is designed to test and evaluate different aspects of the simulation. "Flags and Footprints", which represents a simple exploratory mission to Mars was used as a test case of the simulation's accuracy. This simple scenario was chosen because the optimal answer could be ascertained without running the simulation. For the "Flags and Footprints" mission, all eight launch vehicles slots were used. They were Heavy Argus, the Proton M, EELV, Ariane 5, the Venture Star, and three classes of the Olympus HLLV. The inclusion of all the vehicles gave the simulator the full range of launch vehicle choices needed to determine if it was functioning correctly. This scenario, as well as the others, were each run using three MTV propulsion types. These sets were all SEP, all NTR and all chemical transfer vehicles.

The second scenario analyzed was a DRM based exploratory mission. For this mission, the choice being tested was whether to use HLLVs to place the MTVs in orbit. Ideally, every launch vehicle choice would have been included in this scenario. However, because of the large amounts of tonnage that needed to be placed in orbit, the number of ETO sets generated using all available launch vehicles was too large to allow efficient analysis of the problem. For this reason, the Ariane 5 and the Proton M were not included in the ETO sets. However, the flight rates of the remaining non-HLLVs in the database were increased to allow the simulation the choice of being able to launch the entire payload without using a HLLV.

The third scenario, colonization, was used to determine the characteristics of the simulation's HLLV selection. For this scenario, all three Olympus class vehicles, along with the VentureStar, were included in the ETO sets. The VentureStar's flight rates were limited to two per year. These two flight rates were to allow for the insertion of small amounts of payload left over after the Heavy Lift launches. The main goal of this concept was to determine which classes of HLLVs would be built first and how the payload would be divided between the various classes of Heavy Lifts.

III.2 Results

Each of the results are representative of the simulators ability to evaluate different scenarios and depend greatly on the assumptions made for each simulation. The total number of GA iterations for each case is 10,000 with three restarts. This dependence on the initial assumptions of the launch vehicles and MTVs make these results applicable only to the specific cases discussed here. The main result of this simulation is the optimization process itself. A potential user should be excited about the possibility of placing their own launch and transfer vehicles, with their own assumptions, into the simulation and generating results valid for their particular interests.

The first scenario analyzed was "Flags and Footprints", taking one hour to run through the process. For this scenario it was expected that existing launch vehicles would be used to launch the MTVs. The simulation arrived at the same solution. For the chemical MTV scenario, a total of 13 Heavy Argus, 2 EELVs, and one Proton M were used to launch the payload. This solution approached the optimal, but did not find the true minimum. The true minimum cost would be achieved by having an additional Heavy Argus flight, therefore utilizing all of the vehicle's available flights. This solution is the cheapest because Argus is the cheapest launch vehicle available. The main reason the simulation did not find the exact optimal solution was because these solutions did not yield a guaranteed minimum. However, the simulation does show an important tread, namely no HLLVs were built. This trend is the same for each MTV case. The results for the other MTVs architectures were also as expected. For each type of MTV, the 80MT vehicle was launched in each of the two years.

The DRM-based exploration scenario was analyzed to determine if it was cheaper to build a HLLV for this mission, taking three hours to run though the process. The results of the analysis show that it is more economical to use existing smaller vehicles to complete this mission. The NTR scenario was the only one were no HLLVs were selected. The other two scenarios selected a few HLLVs but showed the general trend of using the smaller vehicles. Given enough optimization time, it is believed these scenarios would converge on a solution containing no HLLVs. Trends were also noticeable for the specific MTV classes chosen. For the NTR and SEP MTVs, the predominate choice was the 80MT class, the chemical MTV predominantly chose the 160MT class. This consistency of choosing the same payload class of MTV for each specific vehicle type was expected because of cost benefits associated with repeatedly producing the same class of vehicle.

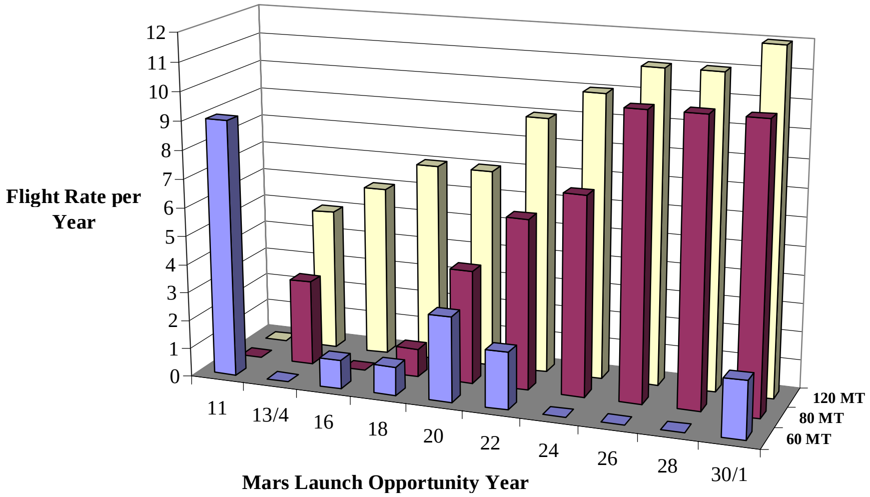


Figure 18: HLLV ETO Traffic Rate for Colonization Scenario of Chemical MTV

The final scenario analyzed was colonization (see Figure 18), taking two hours to ruin through the process. The objective of this scenario was to determine the optimal use of the HLLVs. For each MTV scenario the first HLLV produced was the 60MT version. In the first year of each scenario only 60MT HLLVs were launched. In following years the cost reduction obtained from the learning associated with building the 60MT HLLVs allowed larger vehicles to be built at less cost. As the scenarios proceeded further the trend was to build the larger 120 MT HLLVs. In almost every year the two allowable VentureStar flights were used to transport excess payload that could not be easily integrated with the HLLV flights chosen for that year. Similar trends were noticed with the MTVs. In the first years of the scenarios, the smaller MTVs were chosen. As time progressed, the larger vehicles gave the optimum price for lowest total LCC. This is referred to as segmented development. This makes intuitive sense for a long-term scenario. Segmented development requires one to think long term and develop a vehicle with possible derivatives in mind during the conceptual design phase, developing a family of vehicles rather than just one.

The final cost for each scenario is shown below in Table 6. As can be seen, the chemical MTV was the optimal solution for each case. This result is greatly influenced by the cost assumptions made for chemical vehicle.

Table 6: Scenario Total Costs

MTV Type	Flags & Footprints	DRM Reference	Colonization
Chemical	$3.7 B	$ 19.5 B	$ 59.8 B
Nuclear	$ 6.9 B	$ 30.5 B	$ 69.4 B
Solar Electric	$ 6.5 B	$ 36.0 B	$ 83.9 B

To show the flexibility of M-SAT to various assumptions made by the individual, several cost trade studies were analyzed to see what effect MTV costs would have on the results shown above. These trade studies were coined "what if" studies. They show how M-SAT can be tailored for each individual's vehicle design and cost assumptions. For the extended DRM mission, the question was asked, "What if the NTR MTV costs were reduced by 50%?". The answer is the total cost for the NTR DRM mission would be reduced to $19.4B. Secondly, it was asked, "What if the SEP MTV costs were reduced by 70%?." The answer given by M-SAT was a cost of $19.2B. These same trades were also performed on the colonization mission. For the NTR MTV a cost reduction of 30% yields a new total mission price of $58B. A SEP MTV cost reduction of 55% gives a total colonization mission cost of $59.3B. These results, which are summarized in the Table 7, show that the simulation is inherently non-biased toward any particular vehicle manifest.

Table 7: "What If" Study Results To Beat Chemical MTV

Architecture	Reduction %	Scenario	Cost
NTR	50%	DRM Extended	$ 19.4 B
SEP	70%	DRM Extended	$ 19.2 B
NTR	30%	Colonization	$ 58.0 B
SEP	55%	Colonization	$ 59.3 B

IV. CONCLUSIONS

This study developed the M-SAT simulation that can take launch vehicles, MTVs, and payload demand for a twenty-year period to give the user the optimum manifest of launch vehicles and MTVs for the most cost-conscious solution. Interesting patterns can be seen as far as the development of MTVs or heavy lift launch vehicles for particular scenarios. The simulation is an amalgamation of various modules: ETO launch vehicle's, MTVs, in-space ops model, a cost module, and an optimizer. The power of the simulation lies in the directions it indicates for future transportation architecture developments. One can add substitute vehicles to the database or examine already existing fleets. The simulation is a new tool that can be used to examine the dual phase transportation problem, from Earth-to-orbit and then from Earth orbit to Mars

V. FUTURE STUDIES

Most of the elements of future work involve improving the M-SAT simulation, which can be expanded in both capability and the types of architectures examined. Increasing the speed and ease of use will expand the capabilities of the simulation. The most readily available means of increasing the speed is to reevaluate the logic planning within the code. Improving the vehicle set generation module may also increase speed. Another specific example of possible expansion is in the operations module. Our thinking is to develop a more robust system that can handle different types of assemblies such as combinations of astronauts and the existing robotic assembly. Another concept under study is to create a web-based interface where the user can input the type of scenario they would like to explore and then one hour later results would be e-mailed for review.

VI. OUTREACH

Outreach was accomplished by trying to bring this problem to the attention of the entire School of Aerospace Engineering at Georgia Institute of Technology. Incentives were given for introductory aerospace students in the School to attend the final presentation. Many of the introductory students did attend and were rewarded with an interesting glimpse into what may await them in their future deign careers. In addition, a web presence was developed that not only describes the work performed in this study and eventually allows one to obtain the M-SAT simulation. An overarching philosophy in this study was to allow users to examine their own scenarios within the confines of the simulation. By allowing the general community to obtain the simulation, the communal result will allow both greater access and improvement in the simulation (see http://atlas.cad.gatech.edu/~ksorensen/msbv.html).

VII. ACKNOWEDLGEMENTS

The authors would like to extend their most sincere appreciation to the many students of the Space Systems Design Lab (SSDL) at the Georgia Institute of Technology. Gratitude goes out to Irene Budianto, David Way, Laura Ledsinger, David McCormick, John Bradford, Rebecca Cutri-Kohart, and Tara Poston for their invaluable encouragement and assistance throughout this process of exploration and discovery. We would like to thank the School of Aerospace Engineering at the Georgia Institute of Technology as a whole for their help in providing the support required for such an endeavor. Special consideration is given to Dr. John R. Olds, without whose invaluable experience and guidance this project would not have taken place.

VIII. REFERENCES

Drake, Bret, Ed., *Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*, Exploration Office Advanced Development Office, June 1998.

Frisbee, Robert H. and Hoffman, Nathan J., *Electric Propulsion Options for Mars Cargo Missions*, AIAA Paper AIAA 96-3173, Presented at the 32nd AIAA/SAE/ASEE Joint Propulsion Conference, Lake Buena Vista, FL, July 1-3, 1996.

International Space Industry Report. July 6, 1998, Vol. 2, No. 11. Washington, D.C.

Isakowitz, Steven J., *International Reference Guide to Space Launch Systems*, 2nd Edition, Washington D.C., AIAA, 1995.

Kirchmyer , Hank. Personnel correspondence. NASA / Marshall Space Flight Center.

Kos, Larry. *The Human Mars Mission: Transportation Assessment*. NASA / Marshall Space Flight Center.

Kos, Larry. *Interplanetary Reference Mission Design Handbook*. NASA / Marshall Space Flight Center.

Paschall, Robert K., *Nuclear Thermal Propulsion Engine Cost Trade Studies*, American Institute of Physics, 1993

Phillips, Allan. Personnel correspondence. NASA / Marshall Space Flight Center

Vanderplaats, Garret N., *Numerical Optimization Techniques for Engineering Design*, 2nd Edition, Vanderplaats Research & Development, Colorado Springs, 1998.