Prioritization of Advanced Space Transportation Technologies Utilizing the Abbreviated Technology, Identification, Evaluation, and Selection (ATIES) Methodology for a Reusable Launch Vehicle (RLV)

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ΔV	DELTA V
AATE	ARCHITECTURE ASSESSMENT TOOL
AHP	ANALYTIC HIERARCHIC PROCESS
AIMS	ADVANCED INTEGRATED MODEL SYSTEM
ASDL	AEROSPACE SYSTEMS DESIGN LAB
ASTP	ADVANCED SPACE TRANSPORTATION PROGRAM
ATIES	ABBREVIATED TECHNOLOGY IDENTIFICATION, EVALUATION, AND SELECTION
ATIMS	ASTP TECHNOLOGY INVESTMENT MANAGEMENT SYSTEM
CABAM	COST AND BUSINESS ASSESSMENT MODULE
CASA	CENTER FOR AEROSPACE SYSTEMS ANALYSIS
CA	CONTRIBUTING ANALYSIS
CDF	CUMULATIVE DISTRIBUTION FUNCTION
CER	COST ESTIMATING RELATIONSHIP
CSTS	COMMERCIAL SPACE TRANSPORTATION STUDY
DOE	DESIGN OF EXPERIMENTS
DDT&E	DESIGN, DEVELOPMENT, TESTING, AND EVALUATION
DSM	DESIGN STRUCTURE MATRIX
EC	ENGINEERING CHARACTERISTICS
EMD	ENGINEERING, MANUFACTURING, AND DEVELOPMENT
ERJ	EJECTOR RAMJET
ESJ	EJECTOR SCRAMJET
ETO	EARTH TO ORBIT
FPI	FAST PROBABILITY INTEGRATION
GA	GENETIC ALGORITHM
GEN 3	3RD GENERATION
GLOW	GROSS LIFT-OFF WEIGHT
HSCT	HIGH SPEED CIVIL TRANSPORT
IOC	INITIAL OPERATING CAPABILITY
IPT	INTEGRATED PRODUCT TEAM
IRR	INTERNAL RATE OF RETURN
ISP	SPECIFIC IMPULSE
ISP_BAR	AVERAGE PROPULSIVE ISP WITHOUT LOSSES
ISS	INTERNATIONAL SPACE STATION
IVHM	INTEGRATED VEHICLE HEALTH MONITORING
LCC	LIFE CYCLE COST
LEO	LOW EARTH ORBIT
LRU	LINE REPLACEMENT UNIT
MADAM	MULTIPLE ATTRIBUTE DECISION MAKING
MDO	MULTI-DISCIPLINARY DESIGN OPTIMIZATION
MECO	MAIN ENGINE CUT OFF
MER	MASS ESTIMATING RELATIONSHIP
MM	MORPHOLOGICAL MATRIX
MSFC	MARSHALL SPACE FLIGHT CENTER
MTBF	MEAN TIME BETWEEN FAILURE
MTBR	MEN TIME BETWEEN REPAIR
NAFCOM	NASA-AIR FORCE COST MODEL
NPV	NET-PRESENT-VALUE
NPSS	NUMERICAL PROPULSION SYSTEM SIMULATIONS
OEC	OVERALL EVALUATION CRITERIA
OMS	ORBITAL MANEUVERING SYSTEM
OEC	OVERALL EVALUATION CRITERION
PDF	PROBABILITY DENSITY FUNCTION
PEM	PUGH EVALUATION MATRIX
POST	PROGRAM TO OPTIMIZE SIMULATED TRAJECTORIES

QFD	QUALITY FUNCTION DEPLOYMENT
R&D	RESEARCH AND DEVELOPMENT
RBCC	ROCKET-BASED COMBINED CYCLE
RCS	REACTION CONTROL SYSTEM
RDS	ROBUST DESIGN SIMULATION
RLV	REUSABLE LAUNCH VEHICLE
ROM	ROUGH ORDER OF MAGNITUDE
RSE	RESPONSE SURFACE EQUATION
RSM	RESPONSE SURFACE METHODOLOGY
SSDL	SPACE SYSTEMS DESIGN LAB
SSTO	SINGLE STAGE TO ORBIT
STS	SPACE TRANSPORTATION SYSTEM
T/W	THRUST TO WEIGHT RATIO
TAT	TURN AROUND TIME
TBCC	TURBINE BASED COMBINED CYCLE
TFU	THEORETICAL FIRST UNIT
TCM	TECHNOLOGY COMPATIBILITY MATRIX
TIF	TECHNOLOGY INFLUENCE FACTOR
TIES	TECHNOLOGY IDENTIFICATION, EVALUATION, AND SELECTION
TIM	TECHNOLOGY IMPACT MATRIX
TOPSIS	TECHNIQUE FOR ORDER PREFERENCE BY SIMILARITY TO IDEAL SOLUTION
TPS	THERMAL PROTECTION SYSTEM
TRL	TECHNOLOGY READINESS LEVEL
TSTO	TWO STAGE TO ORBIT
TVC	THRUST VECTOR CONTROL
VIF	VEHICLE INFLUENCE FACTOR
VSLCDE	VIRTUAL STOCHASTIC LIFE CYCLE DESIGN ENVIRONMENT
W&S	WEIGHTS AND SIZING
WS	WEIGHTING SCENARIO

1.0 EXECUTIVE SUMMARY

Any envisioned future with ubiquitous space transportation systems as defined by NASA's Advanced Space Transportation Program (ASTP) will rely on revolutionary improvements in the development and integration of technologies. Given the limitation of financial resources by both the government and industry, strategic decision makers need a method to assist them in the prioritization of advanced space transportation technological investment.

The Technology Identification, Evaluation, and Selection (TIES) methodology is used to leap this gulf of evaluation through a systematic aggregation of decision-making techniques (i.e. Morphological Matrices, Pugh Evaluation Matrices, Multi-Attribute Decision Making, etc.) and sundry probabilistic methods (Response Surface Methodology, Monte Carlo Simulation, Fast Probability Integration, etc.). This study applies an abbreviated version of the original TIES method, referred to ATIES (abbreviated TIES), to a reusable launch vehicle (RLV). The specific system being examined is a single-stage-to-orbit (SSTO) RLV called Hyperion developed by the Space Systems Design Lab (SSDL) in the School of Aerospace Engineering at the Georgia Institute of Technology (Atlanta, GA USA).

For this study a spreadsheet-based model known as the Robust Design Simulation (RDS) model was developed from sophisticated analytical tools used in the conceptual RLV design process and linked to a Monte Carlo model. This RDS model was developed to evaluate the implications of various technology combinations on vehicle output metrics that are eventually aggregated into an Overall Evaluation Criterion (OEC). For the ATIES method, the RDS model was implemented in two fashions: a deterministic, full factorial examination of all feasible technologies combinations and a selected probabilistic examination with all technologies available for use on the vehicle. Three identified technologies out of a potential of ten ranked near the top (in terms of maximizing and affecting the OEC) for both of the above examinations: technologies C (Hot and cooled airframe and integrated primary structures), E (Propulsion IVHM), and H (Improved T/W RBCC engine) with all technologies present in the basket of best concepts. These results are dependent upon the initial, subjective interpretations of technology impact on various vehicle influence factors (VIFs).

The ATIES method is a technique that breaks the bonds of traditional design and analysis and their reliance on the linchpins of historical databases: from past realities towards hypothetical futures, from modeling evolutionary towards modeling revolutionary change.

2.0 INTRODUCTION AND STUDY MOTIVATION

2.1 INTRODUCTION

The National Aeronautics and Space Administration (NASA) is currently funding the Advanced Space Transportation Program (ASTP) to support long-range, basic research to develop advanced space transportation technologies to achieves NASA’s goal of significantly reduced launch costs. Included are programs to develop airframe, propulsion, and long-term space transportation. As NASA defines it, the mission of ASTP is as follows[1]:

> ASTP provides the technological building blocks for earth-to-orbit (ETO) and in-space systems by reducing weight, complexity, and cost while boosting performance over conventional systems. Technologies pursued by ASTP are applicable to systems for the next ten to forty years. ASTP has four initiatives:
>
> 1. Development of new, low-cost technologies;
> 2. Development of advanced, reusable technologies;
> 3. Development of space transfer and upper-stage technologies; and
> 4. Space transportation research.

Some example technologies in this research program include rocket based combined cycle (RBCC) engines, solar thermal propulsion, magnetic levitating sleds, and laser beam propulsion.

Areas of concern for ASTP are technologies for what is termed a 3rd generation (Gen 3) reusable launch vehicle (RLV). These generations define various staggered levels of development for RLVs. The current NASA Shuttle (Space Transportation System or STS) is a first generation RLV. Beyond the second generation RLV of 2010 will be a third generation RLV around 2025 whose stated goal is to reach that plateau where space flight will be as routine as modern air travel. In particular, the specified goals include:

1. Improve the expected safety of launch so that the probability of losing a crew is no worse than 1 in 1,000,000 missions, about the same as today's airliners;
2. Reduce the cost of delivering a pound of payload to low Earth orbit from today's $10,000 down to hundreds of dollars; and
3. Third generation RLV's will require a ground crew of only a couple of people to accomplish a launch, will need only a day to prepare for re-flight, and will fly 2,000 or more times a year.

Development and demonstration of RLV technologies are performed under the NASA Spaceliner 100 program with validation, as required, performed by flight experiments in the NASA Future-X Program. Under management from NASA’s Marshall Space Flight Center (MSFC), the Spaceliner 100 program is examining technologies in five main project areas: Propulsion, Airframe, Launch (avionics, power, crew systems, etc.), Integrated Vehicle Health Management (IVHM), and Operations and Range. Specific technologies include magnetic levitation for ground based launch assist, advanced cryotanks, high temperature integrated structures, advanced fuels, advanced thermal protection systems (TPS), and advanced modular avionics.

A particular initiative being pursued by NASA is the ASTP Technology Investment Management System (ATIMS) whose purpose is to take long-term system goals and defined mission requirements and develop system technology blueprints. In this environment selected vehicle concepts are coupled with promising technologies in a system-engineering environment to assess technology funding and risk through system, safety, and economic models. The modeling aspects of this initiative are part of ASTP's Advanced Integrated Model System (AIMS).

2.2 MOTIVATION

Any envisioned future with ubiquitous space transportation systems as defined by NASA's ASTP will rely on revolutionary improvements in the development and integration of technologies. Given the limitation of financial resources by both the government and industry, strategic decision makers need a method to assist them in the prioritization of advanced space transportation technological investment.

There is a modern emphasis on concurrent engineering with shortened times between research and development (R&D) and the engineering, manufacturing, and development (EMD) phase. With this imperative, new methods have to be developed that are proactive in forecasting the impact of new technologies, even before the maturation of those technologies. Techniques are needed that break the bonds of traditional design and analysis and their reliance on the linchpins of historical databases: from past realities towards hypothetical futures, from modeling evolutionary towards modeling revolutionary change. These evaluation techniques must be quantitative, robust, and applicable to the conceptual design process.

The metrics used to evaluate the impact of these technologies on a system can be composed from various disciplines (i.e. performance, safety, operations, cost, and economics, etc.) representing both a system's technical feasibility and economic viability. These metrics can be included into an Overall Evaluation Criterion (OEC) that serves as proxy for the needs of the customer. The OEC can be decomposed into both qualitative and quantitative measures of fitness. These measures include, but are not limited to, standard system level metrics.

These future conceptual systems can currently be modeled through the full legacy code, multi-modal process utilizing such techniques as Multi-disciplinary Design Optimization (MDO). Lower fidelity representations of this design process (i.e. meta-models) can be coupled with rough order of magnitude (ROM) technological impact scenarios gathered from expert knowledge holders to answer the following question:

> What is the optimal mix of technologies that will maximize the Overall Evaluation Criterion (i.e. feasibility and viability) of a future system?

One can use various technologies, alone and in combination, to implement a conceptual system. Uncertainty, an ever-present character in the design process, can be also be embraced through a probabilistic design environment. The objective is to probabilistically quantify the impact of these technologies on the output metrics of interest from the design process.

The Technology Identification, Evaluation, and Selection (TIES) methodology is used to leap this gulf of evaluation through a systematic aggregation of decision-making techniques (i.e. Morphological Matrices, Pugh Evaluation Matrices, Multi-Attribute Decision Making, etc.) and sundry probabilistic methods (Response Surface Methodology, Monte Carlo Simulation, Fast Probability Integration, etc.). The Aerospace Systems Design Lab (ASDL), in the School of Aerospace Engineering at the Georgia Institute of Technology, pioneered the TIES method[2]. Previous incarnations of the TIES method have been applied by the ASDL to commercial transport aircraft, rotorcraft, and uninhabited combat aerial vehicles[3, 4, 5, 6, 7].

This study applies an abbreviated version of the original TIES method, referred to ATIES (abbreviated TIES), to an alternative transportation system than those mentioned above, namely to reusable launch vehicles (RLVs). The specific system being examined is a single-stage-to-orbit (SSTO) RLV called Hyperion developed by the Space Systems Design Lab (SSDL) in the School of Aerospace Engineering at the Georgia Institute of Technology[8]. Hyperion is a 3rd Generation RLV that uses advanced technologies in such areas as propulsion, structures, and thermal protection systems to achieve breakthroughs in terms of performance, cost, economics, safety, and operational ability for earth-to-orbit (ETO) delivery applications.

3.0 TIES METHODOLOGY

3.1 METHOD OVERVIEW

As defined by the originators of the Technology Identification, Evaluation, and Selection (TIES) methodology[2]:

> The nine step process known as TIES provides the decision maker / designer with the ability to easily assess and balance the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations.

Both formalized techniques of decision-making such as Morphological Matrices (MMs), Pugh Evaluation Matrices (PEMs), and Multi-Attribute Decision Making (MADM) are coupled with various probabilistic methods such as Response Surface Methodology (RSM) and Monte Carlo simulations for use in the TIES process (see Figure 3.1). The ultimate purpose of using the TIES method is to maximize a customer's Overall Evaluation Criterion (OEC) through temporally implementable evaluation processes.

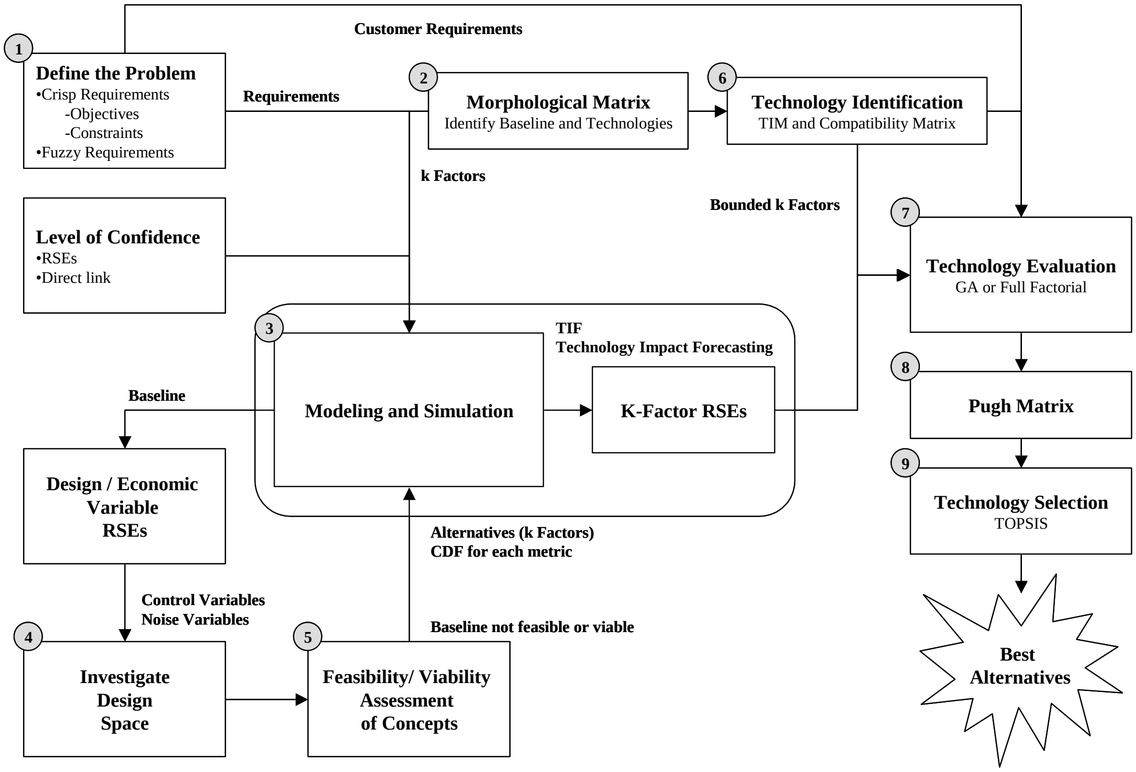


Figure 3.1. Technology Identification, Evaluation, and Selection (TIES) Method

The TIES method encompasses nine steps, namely:

1. Problem definition

   The TIES method begins with an initial problem definition stage. The definition of the problem entails determining the societal wants of a customer. The desires of a customer must be refined and developed into detailed objectives, constraints, and evaluation criteria in terms of both product and process. A management and planning tool such as Qualify Function Deployment (QFD) can be used to quantitatively determine an Overall Evaluation Criterion (OEC) decomposed into economic, engineering, or other quantifiable requirements. Quality Function Deployment (QFD) is a management approach developed by the Japanese and utilized by American industry to use a customer's desires and opinions in the design process to target specific features. QFD can be utilized for rudimentary data mining, establishing a voice of the customer, or to discover strategic opportunities. QFD operates by linking Systems Level Engineering Characteristics (ECs) with Customer Attributes through a relative weighting process achieved through consensus. Arranging various system level concepts and determining the attributes necessary for the optimal system can help in the quantitative assessment of the concepts as to which are best, relative to other concepts.

2. Baseline and alternatives concepts identification

   Once the parameters of the OEC are established there is the challenge of determining the various candidate systems to be examined. These systems have to be decomposed into the various characteristics they possess. A Morphological Matrix can be used as an ordered method that arranges the various attributed of a system. Table 3.1 depicts an example Morphological Matrix (MM) for a hypothetical Titan lander interplanetary spacecraft with the circled characteristics the determinants of a particular, single concept. This concept requires a certain set of technologies. Any other combination of alternatives would subsequently require another set of new, infused technologies.

Table 3.1. Example Morphological Matrix for a Titan Lander Interplanetary Spacecraft

	Alternatives		
Characteristics	1	2	3
Main Cruise Stage Propulsion	Solar Electric	[✓ Chemical rocket]	Solar Thermal
Main Communications	[✓ X band]	Orbiter link	S band
Main Power	Solar	[✓ Nuclear]	Chemical Batteries
Main Landing System	Airbags	Rocket thrusters	[✓ Glider]

3. Modeling and simulation

   Modeling helps to determine the properties of a technically feasible design. In the conceptual design stage, modeling can include use of monolithic synthesis / sizing codes or integrated disciplines in a multi-disciplinary environment. These models are representations of the real world based on processes in terms of physics, human operations, financials, etc.

4. Design space exploration

   Once the ability is developed to model these systems, a baseline concept can be identified as the initial starting point for design space investigation. This baseline can be developed from high fidelity analytical tools. The initial characteristics of this concept will be coupled with constraints associated with the design process. Examples of these constraints include ranges for the technical and non-technical parameters in the design process (i.e. ISP, component weights, costs, etc.). Meta-models, or representations of these detailed models, can be employed for situations where computation and monetary expense are to be minimized[9, 10, 11]. Three main probabilistic methods can be used to identify feasible and viable alternatives. These include:

   a. Linkage of an actual simulation code with a Monte Carlo simulation.

      This method is the most accurate but is the most computationally intense, requiring ten thousand simulations for reasonable approximations.

   b. Creation of a meta-model and linkage to a Monte Carlo model

      This method approximates the actual, detailed analytical tools with a lower fidelity models or a Response Surface Equation (RSE).

   c. Fast Probability Integration (FPI)

      This method uses the full analytical tool set but using fewer code executions than the first method.

   The resultant outputs from these methods are cumulative probability distributions or frequency probability distributions rather than deterministic values for each output metric.

5. Determination of system feasibility/viability; probability of success

   Probabilistic evaluation of systems can be used to determine various confidence levels associated with the output metrics of interest. If manipulation of feasible input variables, optimization, constraint relaxation, and maximum of the impact from baseline technologies have not enabled high probabilities of success, than the alternative is to infuse new technologies[2]. The impact of these new technologies can be assessed through qualitative impact factors known as “k” factors. These k factors change specific disciplinary metrics known as Vehicle Influence Factors (VIFs). These VIFs include component weights, costs, and reliabilities that are used in analysis tools or meta-models to determine both technical and non-technical output metrics. These k factors mimic the discontinuities in benefits and/or penalties associated with the infusion of new technologies[2]. The values of these k factors can originate from consultation with experts in the field, physics-based modeling, or literature reviews. These impact values of these k factors can be probabilistic in nature.

6. Technology identification

The infusion of new technologies first requires the identification of those technologies, their compatibility with each other, their quantitative impact, and the Technology Readiness Level (TRL) of each technology. The Morphological Matrix can be used to determine possible technology candidates. The subsequent stages encompass the following:

a. Technology Compatibility Matrix (TCM)

This method is used to determine the physical compatibility between various combinations of technologies and subsequently the number of alternative scenarios to examine (the combinatorial problem). Figure 3.2 shows the compatibility matrix for a High Speed Civil Transport (HSCT) as developed by the ASDL at the Georgia Institute of Technology[2]. The indicator “1” in the symmetric matrix designates a compatible combination whereas a “0” designates an incompatible combination.

Compatibility Matrix **(1: compatible, 0: incompatible)**										Aircraft Morphing		
		Composite Wing	Composite Fuselage	Circulation Control	HLFC	Environmental Engines	Flight Deck Systems	Propulsion Materials	Integrally, Stiffened Aluminum Airframe Structures (wing)	Smart Wing Structures (Active Aeroelastic Control)	Active Flow Control	Acoustic Control
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
	Composite Wing	1	1	1	0	1	1	1	0	0	0	0
	Composite Fuselage		1	1	1	1	1	1	1	1	1	1
	Circulation Control			1	1	1	1	1	1	1	1	1
	HLFC				1	1	1	1	0	0	0	1
	Environmental Engines					1	1	1	1	1	1	0
	Flight Deck Systems						1	1	1	0	1	1
	Propulsion Materials			Symmetric Matrix				1	0	1	1	1
	Integrally, Stiffened Aluminum Airframe Structures (wing)								1	0	1	1
Aircraft Morphing	Smart Wing Structures (Active Aeroelastic Control)									1	1	1
	Active Flow Control										1	1
	Acoustic Control											1

Figure 3.2. HSCT Technology Compatibility Matrix (TCM)[2]

b. Technology Impact Matrix (TIM)

Impact estimates of potential, infused technologies are quantitatively developed in the TIM. These impacts, the k factors, can be probabilistic since each possesses uncertainty. In the TIM, the impact of each technology is associated with technical and non-technical k factors creating a matrix of impact for each technology. The HSCT TIM, as developed by the ASDL, (shown in Figure 3.3) displays the "vectorization" of impact of both benefits and penalties[2].

									Aircraft Morphing		
	Composite Wing	Composite Fuselage	Circulation Control	HLFC	Environmental Engines	Flight Deck Systems	Propulsion Materials	Integrally, Stiffened Aluminum Airframe Structures (wing)	Smart Wing Structures (Active Aeroelastic Control)	Active Flow Control	Acoustic Control
Technical K_Factor Vector	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Wing Weight	-20%			+5%				-10%	-5%	+2%	
Fuselage Weight		-25%				-15%					
Engine Weight				+1%	+40%		-10%				+5%
Electrical Weight			+5%	+1%		+2%	+5%		+5%	+2%	+2%
Avionics Weight				+5%		+2%	+5%		+2%	+5%	+2%
Surface Controls Weight			-5%						+5%	+5%	
Hydraulics Weight			-5%						+5%		
Noise Suppression					-10%		-1%				-10%
Subsonic Drag	-2%	-2%		-10%						-5%	
Supersonic Drag	-2%	-2%		-15%						-5%	
Subsonic Fuel Flow			+1%	+1%	-2%		-4%				+1%
Supersonic Fuel Flow				+1%	-2%		-4%				
Maximum Lift Coefficient			+15%								
O&S	+2%	+2%	+2%	+2%	+2%		+2%	-2%	+2%	+2%	+1%
RDT&E	+4%	+4%	+2%	+2%	+4%	+2%	+4%		+5%	+5%	+5%
Production costs	+8%	+8%	+3%	+5%	+2%	+1%	+3%	-3%	-3%	-3%	-3%

Figure 3.3. HSCT Technology Impact Matrix (TIM)[2]

7. Technology evaluation

   The feasible combinations of technological impacts on system design parameters (as determined from the TCM and TIM) can be evaluated using the modeling capability developed earlier to maximize the OEC. However, given the combinatorial nature of the problem (i.e. up to 2^n combinations where n is the number of technologies, with all technologies being compatible with each other) and the need to generate cumulative or frequency distributions for each combination, the computational expense can become mammoth in proportion. Alternatives, such as Genetic Algorithm (GA) searches or fractional factorial Design of Experiments (DOE) arrays can be useful in determining relatively satisfying, if not optimum, solutions.

8. Population of Pugh Evaluation Matrix (PEM)

   The PEM (see Table 3.2) is a method where various concept alternatives can be evaluated with row vectors for each alternative specifying the population of output metrics (deterministic or probabilistic).

Table 3.2. Example Pugh Evaluation Matrix (PEM)

	Metric 1	Metric 2	…..	Metric X
Alternative 1	#	#	…..	#
Alternative 2	#	#	…..	#
Alternative 3	#	#	…..	#
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
Alternative 2^n	#	#	…..	#

9. Technology selection

A formulation of Multi-Attribute Decision Making (MADM) known as Technique For Order Preference By Similarity To Ideal Solution (TOPSIS) can be used to order the alternatives in the PEM in terms of those that maximize the OEC. The OEC consists of a combination of each type of output metric from the PEM. Various relative weighting scenarios can be used, resulting in slightly different OECs and possible differing optimum technological solutions for each type of OEC. The TOPSIS method includes the following sequence of activities:

a. Formation of a decision matrix from the PEM.

b. Non-dimensionalization by the Euclidean norm of the metric vector (metric columns of PEM).

c. Establishment of positive (maximum metric value of benefit and minimum value of cost) and negative ideal solutions (compliment of positive).

d. Determination of distance of each alternative from positive and negative ideal.

e. Final ranking of alternatives ranked from best to worst with optional evaluation of the robustness of the best alternatives.

3.2 ABBREVIATED TIES (ATIES) IMPLEMENTATION

For this examination the TIES methodology described in the previous section was applied to the evaluation of Hyperion, a 3rd Generation (Gen 3) RLV. A modified implementation of the above TIES method, labeled as Abbreviated Technology Identification, Evaluation, and Selection (ATIES) was applied for this study. Several modifications are inherent in the ATIES method over the original ASDL-inspired TIES method. As the name suggests, the main feature of ATIES is the much simpler nature of the process. In ATIES, more focus is given towards evaluation and selection rather than identification.

ATIES is more application focused and subsequently less concern is placed on some of the initial TIES steps including problem definition, usage of Morphological Matrices (MM), Ishikawa diagrams, and initial system feasibility/ viability determination. An overarching assumption for Gen 3 RLVs is that without these new technologies (i.e. RBCC propulsion) the system is basically incapable of being created as envisioned. Thus the actual determination of the feasibility/ viability for a Gen 3 RLV like Hyperion without technology infusion would be extravagant and not value additive. In addition, systems like Hyperion are already defined in terms of technologies needed for their creation. This study focuses in the impact of those technology alternatives, deterministic and probabilistic; to find the optimal mix of technologies that maximize the OEC. The ATIES method consists of six major parts, most of them similar to the main TIES method discussed earlier (see Figure 3.4). The parts include:

A. Baseline concept determination

B. Technology identification

C. Technology compatibility

D. Technology impact

E. Technology evaluation

F. Technology selection

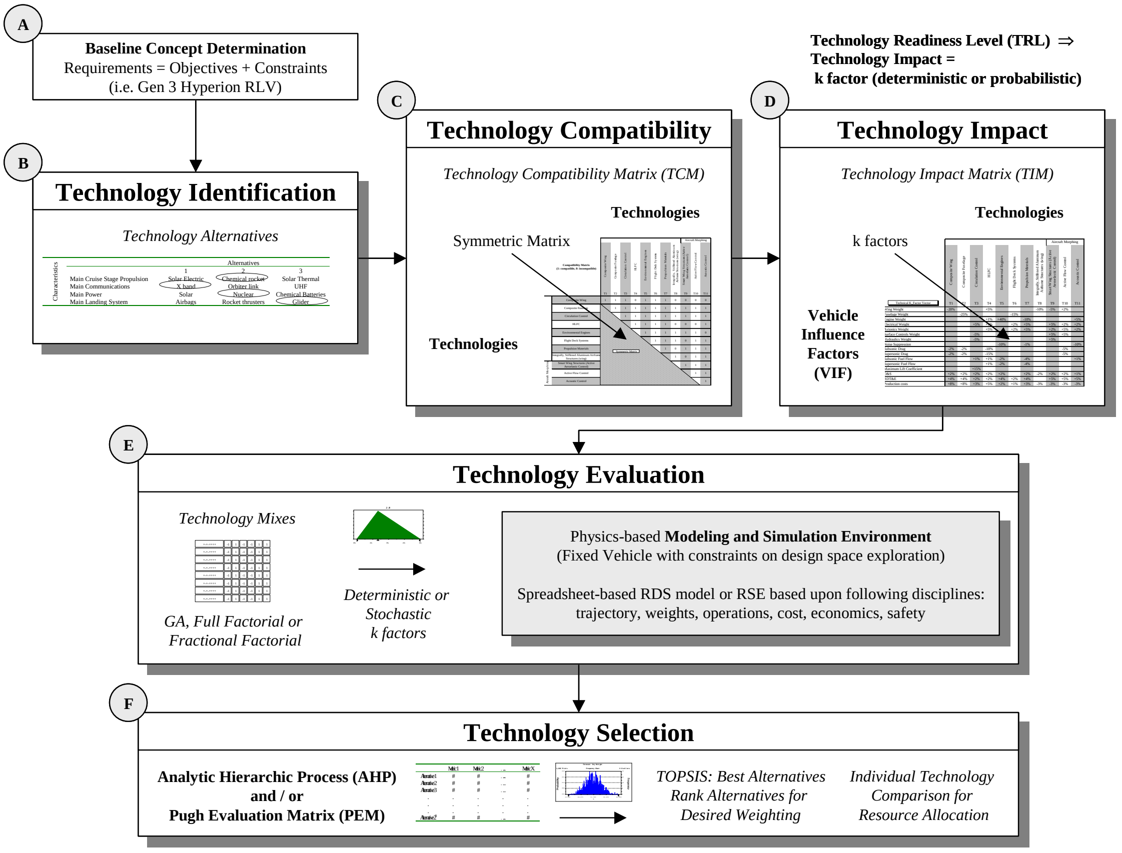


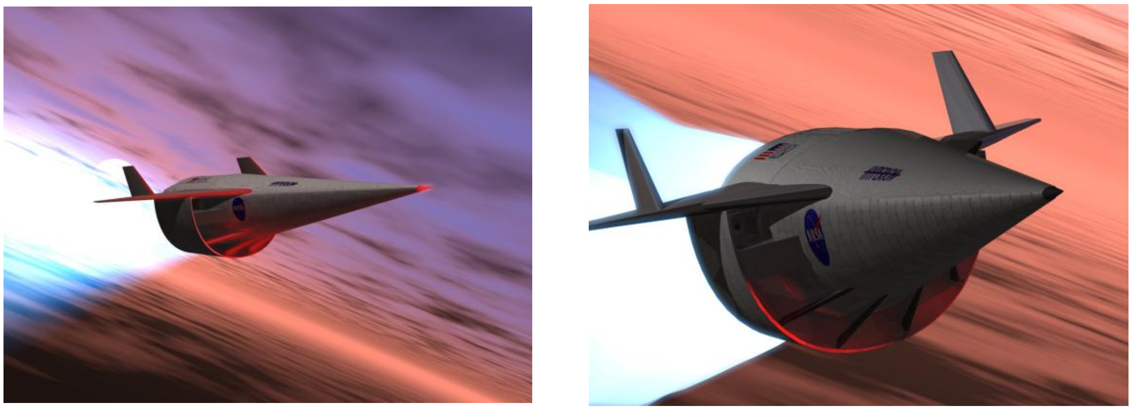
Figure 3.4. Abbreviated Technology Identification, Evaluation, and Selection (ATIES) Method

4.0 CASE STUDY: ATIES IMPLEMENTATION ON A 3rd GENERATION RLV

4.1 STEP A: BASELINE CONCEPT DETERMINATION

4.1.1 BASELINE CONCEPT: HYPERION SSTO RBCC RLV`

The future concept being examined in the study is the Gen 3 reusable launch vehicle (RLV) named Hyperion as developed by the Space Systems Design Lab (SSDL) at the Georgia Institute of Technology (see Figures 4.1, 4.2, and 4.3).



a. Ramjet Ascent **b. Scramjet Ascent**

c. On-Orbit Operations **d. Flyback**

Figure 4.1. Hyperion Visual Flight Modes

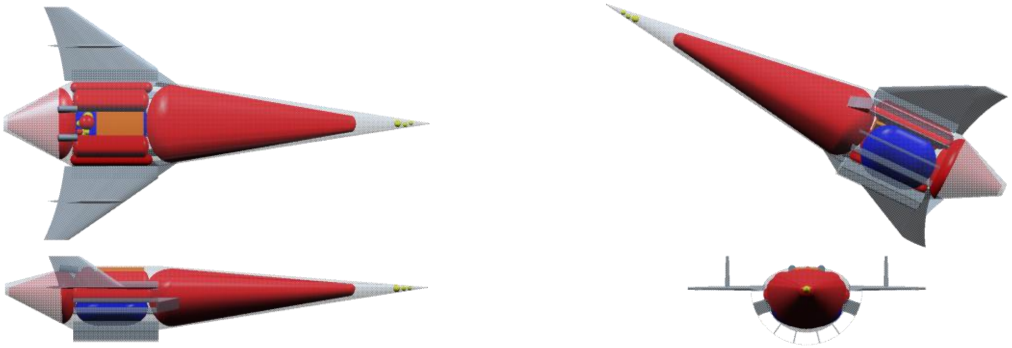
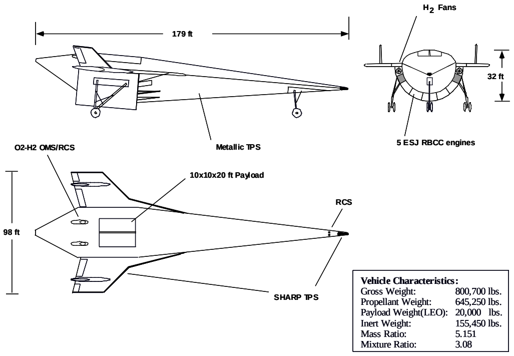


Figure 4.2. Hyperion CAD/Packaging Model



Vehicle Characteristics:	
Gross Weight:	800,700 lbs.
Propellant Weight:	645,250 lbs.
Payload Weight(LEO):	20,000 lbs.
Inert Weight:	155,450 lbs.
Mass Ratio:	5.151
Mixture Ratio:	3.08

Vehicle:

payload = 20 klb to 100 nmi orbit @ 28.5°
dry weight = 155.5 klb
gross weight = 800.7 klb

Propulsion:

5 Ejector Scramjet (ESJ) RBCC engines
Isp @ sea level static = 360 sec. (LOX/LH2)
I* = 471 sec. (for baseline trajectory)
thrust@sea level static = 96.1 klb/ea. (vehicle T/W=0.6)
engine installed T/We = 28.8

Vehicle Technologies:

Mach 10 capable ejector scramjet engines
integral graphite/PEEK tanks (w/liners)
titanium-aluminide/Si-C hot structure (wings, etc.)
SHARP/Metallic/TABI TPS
cryogenic O2/H2 OMS/RCS
BITE/BIT in key components
electro-mechanical surface actuators

Trajectory/Operational Modes:

ejector mode to Mach 2.5
ramjet mode to Mach 5.5 (const.q = 2000 psf)
scramjet mode to Mach 10
built-in RBCC rocket mode to orbit (Isp = 455 s vac)
horizontal landing
5 minute loiter capability with H2 fans

Notes and Issues:

- fully autonomous (no pilots), up to 6 passengers can ride in module in cargo bay
- metallic TPS on windward fuselage, simplifies installation & maintenance
- ESJ RBCC engine builds on historical development; eliminates fan hardware and storage problems

Figure 4.3. Hyperion Concept Summary[8]

Highlights of a typical Hyperion vehicle concept include:

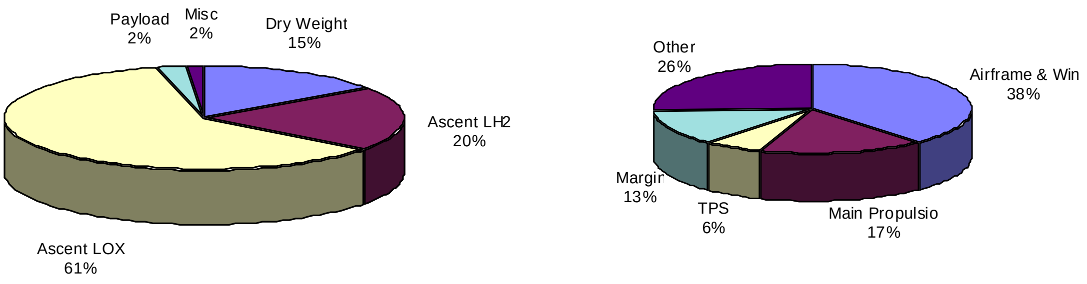
- Initial operational capability (IOC) in 2010, full by year 2012, program termination in 2027
- Market Includes modified CSTS Cargo & Passengers only
- Target Orbit: 100 nmi circular x 28.5 deg
- MECO at 50 X 100 nmi, OMS burn to 100 nmi circular

- Payload: 20,000 lbs LEO (~11,000 lbs ISS from KSC)
- Maximum airbreathing Mach number: 10
- 9.0° Conical forebody angle
- Maximum Dynamic Pressure: 2000 psf
- Dry Weight Margin: 15%
- Vehicle takeoff T/W: 0.6, installed RBCC T/W (SLS): 28.8
- Rocket Mode ISP: 455 sec.

Sample weight and cost data for a typical Hyperion concept are presented in Tables 4.1 and Figures 4.4, 4.5, and 4.6.

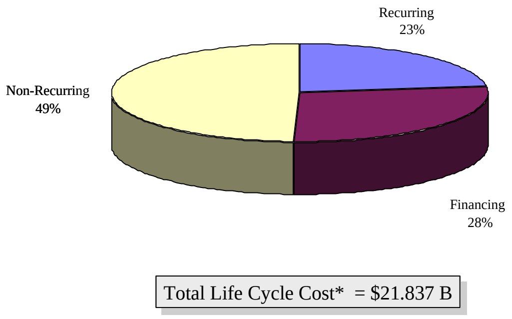
Table 4.1. Typical Hyperion Concept Weight Breakdown[8]

Name	Weight (lbs)
Wing and Tail Group	19,200
Body Group (including tanks)	28,150
Thermal Protection	7,600
Main Propulsion	20,750
OMS/RCS Propulsion	2,500
Subsystems and Other Dry Weights	28,950
Dry Weight Margin (15%)	16,100
Dry Weight	123,250
Payload	20,000
Other Inert Weights (residuals, etc.)	12,200
Insertion Weight	155,450
Ascent Propellants	645,250
Gross Lift-off Weight (GLOW)	800,700



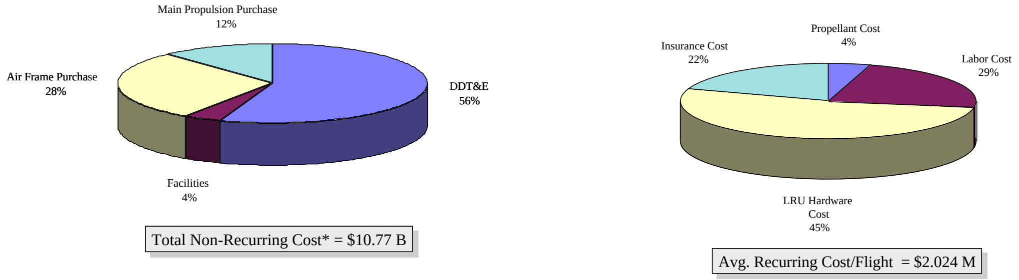
a.) Gross Weight Breakdown **b.) Dry Weight Breakdown**

Figure 4.4. Typical Hyperion Concept Weight Breakdown[8]



*Prior to government contributions

Figure 4.5. Typical Hyperion Concept Total Life Cycle Cost (LCC)[8]



*Prior to government contributions

b.) Total Non-Recurring Cost **c.) Average Recurring Cost Per Flight**

Figure 4.6. Typical Hyperion Concept Non-Recurring and Recurring Cost[8]

4.2 STEP B: TECHNOLOGY IDENTIFICATION

This author did not develop any detailed technology identification process but utilized a technology alternative list developed by NASA for the Spaceliner 100 and ATIMS programs. Proposed technology areas (based on NASA groupings) for the recent Spaceliner 100 initiative included: Airframe, Integrated Vehicle Health Monitoring (IVHM), Range, Propulsion, Operations, and TPS (see Table 4.2).

Table 4.2. Selected Spaceliner 100 Technologies

Technology Subgroup	Specific Technologies
Airframe	Safe structures design technologies
	Advanced materials, fabrication, manufacturing, and assembly
	Aerodynamic / aerothermic tools for rapid design
	Integrated airframe design environment
	RLV crew interface technology
	Nonlinear airframe dynamic for flight control
	Advanced cryotank structures
	Structurally integrated sensors and avionics
	Hot and cooled airframe and integrated primary structures
	Aerodynamic performance and control through drag modification
	Advanced aerodynamic airframe design and databasing
IVHM	Advanced avionics IVHM
	Power IVHM with autonomous controls
	Advanced ground IVHM
	IVHM systems engineering and integration testbeds
	Advanced structure IVHM
	Propulsion IVHM
Range	Advanced checkout and control systems
	Intelligent instrumentation and inspection systems
	On-site, on-demand production and transfer of cryogenics
	Advanced umbilical
	Advanced payload system technology
Propulsion	Maglev development
	Hydrocarbon TSTO RBCC
	Numerical propulsion systems simulations (NPSS) for space transportation propulsion
	SSTO hydrogen RBCC
	Long, life high T/W hydrocarbon rocket
	Long life, light weight propulsion materials and structures
	Information rich test instrumentation
	Pulsed detonation engine rocket
	TSTO hydrocarbon TBCC
	Airbreathing pulsed detonation engine combined cycle
	SSTO TBCC aiurbreather
	High performance hydrocarbon fuels
	Long life, high T/W hydrogen rocket
	Propulsion life prediction
	High (better than densified) hydrogen
	Green operable RCS
	Integrated propulsion management system
Operations	Advanced range decision models
	Advanced weather instrumentation and systems
	Space based range
	Single, integrated spaceport range system
TPS	Sharp body TPS
	Adaptive, intelligent TPS IVHM
	Quickly change-out TPS
	Highly reusable TPS
	Advanced TPS inspection
	TPS life cycle design tools

In the interest of project time and scope, the above basket of technologies was significantly abbreviated for use in the present proof-of-concept ATIES process. These technologies were chosen irrespective of the specific RLV concept to be examined (i.e. TSTO or SSTO). Technologies from these subsets were selected through consultation with Dr. John R. Olds, Director and Assistant Professor, Space Systems Design Lab (SSDL), School of Aerospace Engineering, Georgia Institute of Technology and head of SpaceWorks Engineering, Inc. (see Table 4.3).

Table 4.3. Down-Selected Spaceliner 100 Technologies Used in Study

No.	Technology Code	Technology Item
1	A	Aerodynamic/aero-thermodynamic tools for rapid design
2	B	Advanced cryotank structures
3	C	Hot and cooled airframe and integrated primary structures
4	D	Advanced ground IVHM
5	E	Propulsion IVHM
6	F	On-site, on-demand production and transfer of cryogenics
7	G	Maglev development
8	H	Improved T/W RBCC engine
9*	I	Long life, high T/W hydrogen rocket
10	J	Sharp body TPS
11	K	Highly reusable TPS

Note: * Technology not applicable to Hyperion RLV concept given presence of technology 8

4.3 STEP C: TECHNOLOGY COMPATIBILITY

Once an adequate basket of technologies was established, the compatibilities between them had to be determined. Once again, through consultation with Dr. John R. Olds, compatibilities were determined between the 11 down-selected technologies (See Figure 4.7). Subsequent to the decision to down select to 11 technologies, it was realized that of the technologies selected all but one are compatible with each other. The technologies of “Improved T/W RBCC engine” (technology code H) and “Long life, high T/W hydrogen rocket” were not applicable at the same time and thus for the Hyperion (RBCC engine based) RDS model technology I was not used in this analysis.

Compatibility Matrix (1: compatible, 0: incompatible) Input Technologies Below	No.	Aerodynamic/aerothermodynamic tools for rapid design A 1	Advanced cyrotank structures B 2	Hot and cooled airframe and integrated primary structures C 3	Advanced ground IVHM D 4	Propulsion IVHM E 5	On-site, on-demand production and transfer of cryogenics F 6	Maglev development G 7	Improved T/W RBCC engine H 8	Long life, high T/W hydrogen rocket I 9	Sharp body TPS J 10	Highly reusable TPS K 11
Aerodynamic/aerothermodynamic tools for rapid design	A	1	1	1	1	1	1	1	1	1	1	1
Advanced cyrotank structures	B		1	1	1	1	1	1	1	1	1	1
Hot and cooled airframe and integrated primary structures	C			1	1	1	1	1	1	1	1	1
Advanced ground IVHM	D				1	1	1	1	1	1	1	1
Propulsion IVHM	E					1	1	1	1	1	1	1
On-site, on-demand production and transfer of cryogenics	F						1	1	1	1	1	1
Maglev development	G							1	1	1	1	1
Improved T/W RBCC engine	H								1	0	1	1
Long life, high T/W hydrogen rocket	I									1	1	1
Sharp body TPS	J										1	1
Highly reusable TPS	K											1

Figure 4.7. RDS Model Technology Compatibility Matrix (TCM)

4.4 STEP D: TECHNOLOGY IMPACT

The impact of each technology is determined by the value of the k factor. The k factor is generally a non-dimensional numerical value representing the impact of a technology on a value such as cost or weight. These k factors can be either deterministic of probabilistic. The impact of these k factors are translated in the modeling process to certain Vehicle Influence Factors (VIFs). A VIF can be either technical (i.e. engine T/W) or non-technical (i.e. debt loan rate). There is a compounded effect of multiple k factors when they affect the same VIF. In other words, the addition of each technology through k factors can affect multiple VIFs and similarly each VIF can be influenced by multiple k factors. For the 10 feasible technologies (A-H, J, K) of the Hyperion RLV, both deterministic and probabilistic k factor impacts of each technology were determined through consultation with Dr. John R. Olds.

Tables 4.4 through 4.8 display the impact of all the selected technologies on the VIFs. The k factors shown as “Base@100%” are the base k factor values that are used for a deterministic study. The k factors can be above or below this base value in a probabilistic analysis. Probabilistic k factor values are used as triangular distributions with a minimum, most likely (the Base@100% value), and maximum value. The tables also show the Vehicle Influence Factors (VIFs) and their associated nomenclature (i.e. P.1 for ISP_bar). None of the technologies selected for this cases study impacted all the VIFs. Table 4.9 shows the effects on the VIFs due to compounded technology effects. The values in the table represent the possible range of the VIFs for any and all technology combinations. The various technologies examined in this study only influenced what are termed "technical" VIFs. The "non-technical" VIFs, which consist of governmental financial incentives and economic influences and are discussed in Section 4.5.2 remain fixed.

The impact of all these technologies was constrained by ranges on the k factors. Tables 4.10 through 4.12 display the range of impacts the k factors were allowed to have on various VIFs. Any technology or combination of technologies was not allowed to have an impact greater than that listed in these tables. The purpose of this constraint mechanism is to disallow the subjective technology impact assessments (TCMs, TIMs) to override basic physical principles inherent in the RDS model. Constraints are placed on the extent of the design solutions created in the RDS model, avoiding infeasible design solutions. A "toggle" option is available in the ATIES model to allow or disallow this constraint mechanism.

Table 4.4. Deterministic / Probabilistic Impacts of Technologies on Vehicle Influence Factors (1)

No.	Vehicle Influence Factor (VIF)	Technology A Aerodynamic/aerothermodynamic tools for rapid design			Technology B Advanced cyrotank structures		
		k factor Values			k factor Values		
		Min.	Most Likely	Max.	Min.	Most Likely	Max.
P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%
P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%
P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%
P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%
W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%
W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%
W.3	Propellant Tank Weight	0%	0%	0%	-30%	-10%	-5%
W.4	TPS Weight	0%	0%	0%	0%	0%	0%
W.5	Engine T/W	0%	0%	0%	0%	0%	0%
W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%
W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%
W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%
W.9	Fuel Density	0%	0%	0%	0%	0%	0%
W.10	Payload Weight	0%	0%	0%	0%	0%	0%
C.1	Facilities Cost	0%	0%	0%	0%	0%	0%
C.2	Airframe DDT&E Cost	-10%	-2%	0%	0%	3%	5%
C.3	Engine DDT&E Cost	0%	0%	0%	0%	0%	0%
C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	3%	5%
C.5	Engine Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%
C.6	Vehicle Recurring Cost / Flight	0%	0%	0%	0%	0%	0%
M.1	Ground Turnaround Time	0%	0%	0%	0%	0%	0%
M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%
M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%
R.1	Overall Vehicle Reliability (MTBF)	0%	0%	0%	0%	0%	0%

Table 4.5. Deterministic / Probabilistic Impacts of Technologies on Vehicle Influence Factors (2)

No.	Vehicle Influence Factor (VIF)	Technology C Hot and cooled airframe and integrated primary structures			Technology D Advanced ground IVHM		
		k factor Values			k factor Values		
		Min.	Most Likely	Max.	Min.	Most Likely	Max.
P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%
P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%
P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%
P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%
W.1	Wing and Tail Weight	-15%	-10%	-5%	0%	0%	0%
W.2	Fuselage Weight	-15%	-10%	-5%	0%	0%	0%
W.3	Propellant Tank Weight	-5%	-2%	0%	0%	0%	0%
W.4	TPS Weight	-20%	-10%	-5%	0%	0%	0%
W.5	Engine T/W	0%	0%	0%	0%	0%	0%
W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%
W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%
W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%
W.9	Fuel Density	0%	0%	0%	0%	0%	0%
W.10	Payload Weight	0%	0%	0%	0%	0%	0%
C.1	Facilities Cost	0%	0%	0%	2%	4%	6%
C.2	Airframe DDT&E Cost	0%	2%	5%	0%	0%	0%
C.3	Engine DDT&E Cost	0%	0%	0%	0%	0%	0%
C.4	Airframe Procurement Cost (Manufacturing)	0%	2%	5%	0%	0%	0%
C.5	Engine Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%
C.6	Vehicle Recurring Cost / Flight	0%	0%	0%	-15%	-10%	-5%
M.1	Ground Turnaround Time	0%	0%	0%	-25%	-15%	-10%
M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%
M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%
R.1	Overall Vehicle Reliability (MTBF)	0%	0%	0%	1%	3%	10%

Table 4.6. Deterministic / Probabilistic Impacts of Technologies on Vehicle Influence Factors (3)

No.	Vehicle Influence Factor (VIF)	Technology E Propulsion IVHM			Technology F On-site, on-demand production and transfer of cryogenics		
		k factor Values			k factor Values		
		Min.	Most Likely	Max.	Min.	Most Likely	Max.
P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%
P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%
P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%
P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%
W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%
W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%
W.3	Propellant Tank Weight	0%	0%	0%	0%	0%	0%
W.4	TPS Weight	0%	0%	0%	0%	0%	0%
W.5	Engine T/W	0%	0%	0%	0%	0%	0%
W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%
W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%
W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%
W.9	Fuel Density	0%	0%	0%	0%	0%	0%
W.10	Payload Weight	0%	0%	0%	0%	0%	0%
C.1	Facilities Cost	0%	0%	0%	0%	0%	0%
C.2	Airframe DDT&E Cost	0%	0%	0%	0%	0%	0%
C.3	Engine DDT&E Cost	0%	3%	6%	0%	0%	0%
C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%
C.5	Engine Procurement Cost (Manufacturing)	0%	3%	6%	0%	0%	0%
C.6	Vehicle Recurring Cost / Flight	-15%	-3%	-2%	-10%	-4%	-2%
M.1	Ground Turnaround Time	-15%	-10%	-5%	0%	0%	0%
M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%
M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%
R.1	Overall Vehicle Reliability (MTBF)	1%	5%	20%	0%	0%	0%

Table 4.7. Deterministic / Probabilistic Impacts of Technologies on Vehicle Influence Factors (4)

No.	Vehicle Influence Factor (VIF)	Technology G Maglev development			Technology H Improved T/W RBCC engine		
		k factor Values			k factor Values		
		Min.	Most Likely	Max.	Min.	Most Likely	Max.
P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	5%	8%	15%
P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%
P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%
P.4	Launch Assist ΔV	*	*	*	0%	0%	0%
W.1	Wing and Tail Weight	-15%	-10%	-5%	0%	0%	0%
W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%
W.3	Propellant Tank Weight	0%	0%	0%	0%	0%	0%
W.4	TPS Weight	0%	0%	0%	0%	0%	0%
W.5	Engine T/W	0%	0%	0%	10%	15%	35%
W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%
W.7	Undercarriage Weight	-60%	-50%	-40%	0%	0%	0%
W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%
W.9	Fuel Density	0%	0%	0%	0%	0%	0%
W.10	Payload Weight	0%	0%	0%	0%	0%	0%
C.1	Facilities Cost	100%	200%	500%	0%	0%	0%
C.2	Airframe DDT&E Cost	0%	0%	0%	0%	0%	0%
C.3	Engine DDT&E Cost	0%	0%	0%	2%	3%	5%
C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%
C.5	Engine Procurement Cost (Manufacturing)	0%	0%	0%	0%	2%	4%
C.6	Vehicle Recurring Cost / Flight	2%	4%	10%	0%	0%	0%
M.1	Ground Turnaround Time	0%	4%	10%	0%	0%	0%
M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%
M.3	Engine life (MTBR)	0%	0%	0%	25%	50%	100%
R.1	Overall Vehicle Reliability (MTBF)	-10%	-5%	-2%	3%	5%	8%

Note: * If technology used then translates to Min. (400 m/s), Most (800m/s), Max. (1200 m/s) ΔV

Table 4.8. Deterministic / Probabilistic Impacts of Technologies on Vehicle Influence Factors (5)

No.	Vehicle Influence Factor (VIF)	Technology J Sharp body TPS			Technology K Highly reusable TPS		
		k factor Values			k factor Values		
		Min.	Most Likely	Max.	Min.	Most Likely	Max.
P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%
P.2	Drag Losses During Ascent	-10%	-3%	0%	0%	0%	0%
P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%
P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%
W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%
W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%
W.3	Propellant Tank Weight	0%	0%	0%	0%	0%	0%
W.4	TPS Weight	0%	2%	6%	-5%	-2%	0%
W.5	Engine T/W	0%	0%	0%	0%	0%	0%
W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%
W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%
W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%
W.9	Fuel Density	0%	0%	0%	0%	0%	0%
W.10	Payload Weight	0%	0%	0%	0%	0%	0%
C.1	Facilities Cost	0%	0%	0%	0%	0%	0%
C.2	Airframe DDT&E Cost	0%	1%	5%	0%	1%	3%
C.3	Engine DDT&E Cost	0%	0%	0%	0%	0%	0%
C.4	Airframe Procurement Cost (Manufacturing)	0%	1%	3%	0%	1%	3%
C.5	Engine Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%
C.6	Vehicle Recurring Cost / Flight	0%	0%	0%	-8%	-5%	-2%
M.1	Ground Turnaround Time	0%	0%	0%	-15%	-10%	-5%
M.2	Airframe Life (MTBR)	0%	0%	0%	10%	20%	30%
M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%
R.1	Overall Vehicle Reliability (MTBF)	0%	0%	0%	0%	0%	0%

Table 4.9. Maximum VIF Effects Due to Compounded Technology Effects:

Performance, Weight, Cost, Operations, and Reliability

	No.	Vehicle Influence Factor (VIF)	Minimum	Most Likely	Maximum
1	P.1	ISP_bar (average propulsive ISP w/o losses)	5%	8%	15%
2	P.2	Drag Losses During Ascent	-10%	-3%	0%
3	P.3	TVC Losses During Ascent	0%	0%	0%
4	P.4	Launch Assist ΔV*	40000%	80000%	120000%
5	W.1	Wing and Tail Weight	-30%	-20%	-10%
6	W.2	Fuselage Weight	-15%	-10%	-5%
7	W.3	Propellant Tank Weight	-35%	-12%	-5%
8	W.4	TPS Weight	-25%	-10%	1%
9	W.5	Engine T/W	30%	40%	85%
10	W.6	Subsystem Weight	0%	0%	0%
11	W.7	Undercarriage Weight	-60%	-50%	-40%
12	W.8	Oxidizer Density	0%	0%	0%
13	W.9	Fuel Density	0%	0%	0%
14	W.10	Payload Weight	0%	0%	0%
15	C.1	Facilities Cost	102%	204%	506%
16	C.2	Airframe DDT&E Cost	-10%	5%	18%
17	C.3	Engine DDT&E Cost	4%	9%	16%
18	C.4	Airframe Procurement Cost (Manufacturing)	0%	7%	16%
19	C.5	Engine Procurement Cost (Manufacturing)	0%	7%	14%
20	C.6	Vehicle Recurring Cost / Flight	-46%	-18%	-1%
21	M.1	Ground Turnaround Time	-55%	-31%	-10%
22	M.2	Airframe Life (MTBR)	10%	20%	30%
23	M.3	Engine life (MTBR)	50%	100%	200%
24	R.1	Overall Vehicle Reliability (MTBF)	-4%	10%	40%

Note: * if technology used, then % translates to m/s, i.e. 40000% = 400 m/s ΔV

Table 4.10. Non-Technical VIF Ranges: Government Financial Incentive Programs

No.	Vehicle Influence Factor (VIF)	Worst	Base@100%	Best
G.1	Facilities Offset Percentage	0%	100%	100%
G.2	DDT&E Offset Percentage	0%	25%	100%
G.3	Debt Loan Rate	5.0%	7.5%	15.0%
G.4	Tax Holiday Program Duration [years]	0	0	5
G.5	Government Cargo Flights per Year [flights / year]	10	50	300

Table 4.11. Non-Technical VIF Ranges: Economics

No.	Vehicle Influence Factor (VIF)	Worst	Base@100%	Best
E.1	Required Commercial Internal Rate of Return (IRR)	10%	25%	30%
E.2	Commercial Market Growth Factor	0%	30%	100%

Table 4.12. Technical VIF Ranges: Performance, Weight, Cost, Operations, and Reliability

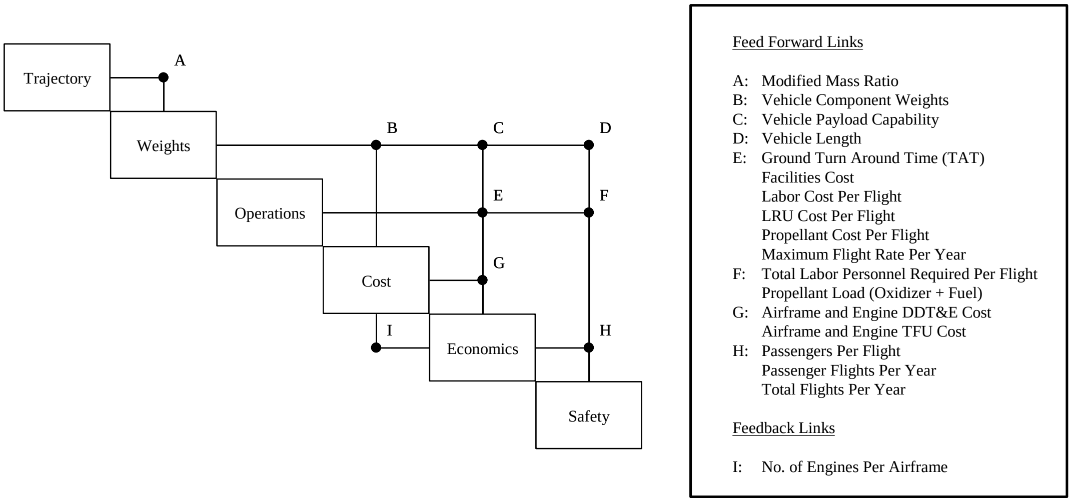
	No.	Vehicle Influence Factor (VIF)	Worst	Base@100%	Best
1	P.1	ISP_bar (average propulsive ISP w/o losses)	95%	100%	105%
2	P.2	Drag Losses During Ascent	115%	100%	90%
3	P.3	TVC Losses During Ascent	115.0%	100.0%	90.0%
4	P.4	Launch Assist ΔV [m/s]	0.0	0.0	1,500.0
5	W.1	Wing and Tail Weight	125%	100%	80%
6	W.2	Fuselage Weight	125%	100%	80%
7	W.3	Propellant Tank Weight	125%	100%	80%
8	W.4	TPS Weight	125%	100%	80%
9	W.5	Engine T/W	80%	100%	125%
10	W.6	Subsystem Weight	125%	100%	80%
11	W.7	Undercarriage Weight	125%	100%	80%
12	W.8	Oxidizer Density	150%	100%	75%
13	W.9	Fuel Density	150%	100%	75%
14	W.10	Payload Weight [lbs]	15,000	20,000	40,000
15	C.1	Facilities Cost	200%	100%	0%
16	C.2	Airframe DDT&E Cost	200%	100%	0%
17	C.3	Engine DDT&E Cost	200%	100%	0%
18	C.4	Airframe Procurement Cost (Manufacturing)	200%	100%	0%
19	C.5	Engine Procurement Cost (Manufacturing)	200%	100%	0%
20	C.6	Vehicle Recurring Cost / Flight	200%	100%	50%
21	M.1	Ground Turnaround Time	10%	100%	200%
22	M.2	Airframe Life (MTBR) [no. of flights]	100	1,000	10,000
23	M.3	Engine life (MTBR) [no. of flights]	100	500	10,000
24	R.1	Overall Vehicle Reliability (MTBF) [no. of flights]	500	10,000	10,000,000

4.5 STEP E: TECHNOLOGY EVALUATION

For this study a spreadsheet-based RDS model for the baseline concept, the Hyperion RLV, was developed from sophisticated analytical tools. This meta-model was developed so as to evaluate the implications of various technology combinations on vehicle output metrics and eventually the Overall Evaluation Criterion (OEC). This meta-model simulated the typical RLV design process used by the SSDL and the ATIES methodology through the inclusion of a TCM, TIM, and PEM. This model is referred to as a Robust Design Simulation (RDS) model due to the probabilistic nature of this conceptual-level model to determine feasible system concepts given design objectives and constraints.

4.5.1 RDS MODEL DESIGN

As shown in Figure 4.8, a methodology employed to derive the various functional relationships within the RDS model was a Design Structure Matrix (DSM). In this methodology a structured relationship is derived of inputs and outputs operating over functional blocks or Contributing Analysis (CAs) of an engineering system (i.e. trajectory, weights, cost, etc.). A DSM is a tool that can be used for visualization of the functional relationships between sub-systems. DSMs also employ feedback links to these CAs.



Feed Forward Links

A: Modified Mass Ratio
B: Vehicle Component Weights
C: Vehicle Payload Capability
D: Vehicle Length
E: Ground Turn Around Time (TAT)
Facilities Cost
Labor Cost Per Flight
LRU Cost Per Flight
Propellant Cost Per Flight
Maximum Flight Rate Per Year
F: Total Labor Personnel Required Per Flight
Propellant Load (Oxidizer + Fuel)
G: Airframe and Engine DDT&E Cost
Airframe and Engine TFU Cost
H: Passengers Per Flight
Passenger Flights Per Year
Total Flights Per Year

Feedback Links

I: No. of Engines Per Airframe

Figure 4.8. Interior DSM (Disciplinary CAs) for Spreadsheet Based RDS Model

For the RDS model, a DSM was developed with system functional blocks and links to represent relationships between various expert systems / tools. Using these blocks and links; a process was developed to determine various engineering parameters. The upper segment of inputs are feed forwards, whereas the lower segments are feedback loops. It is apparent that there is a set of highly correlated functional feed forward relationships that exist in the center of the DSM. Each CA is representative of a different sheet in the RDS model. This particular DSM is the interior DSM of the RDS model, exclusive of the optimizers used to converge a particular design for an input set of technologies.

This DSM was modeled upon a type of RLV design process used by the Space Systems Design Lab (SSDL) based upon an Integrated Product Team (IPT) approach. Each CA is representative of a higher fidelity tool being employed by the SSDL in their design process (see Appendix A for sample detailed views of each spreadsheet based CA). Table 4.13 lists the computational codes by the SSDL for a typical Hyperion RLV design process while Table 4.14 lists the mapping of the RDS model CA with its counterpart higher fidelity design tool.

Table 4.13. SSDL Computational Codes Used for Conceptual RLV Design

Discipline	Computational Code
Performance	POST
Aerodynamics	APAS
Propulsion	SCCREAM, SCORES
Vehicle Weights	MERS in MS Excel Spreadsheet
Engine Weights	WATES
Solid Modeling	IDEAS
Operations	AATe
Cost and Economics	CABAM

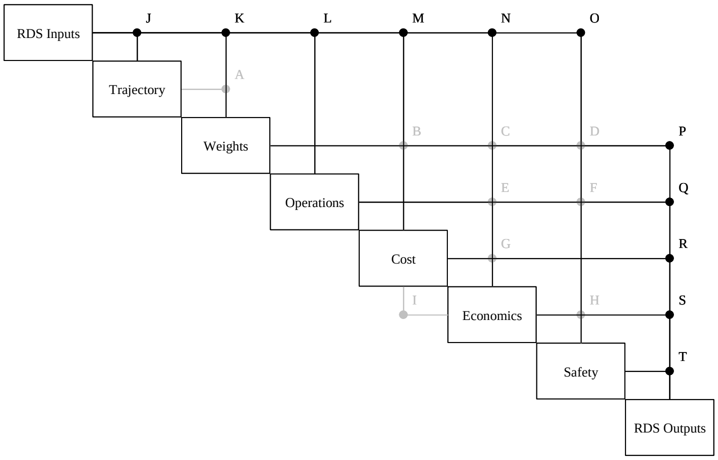
Table 4.14. Detailed Breakdown of RDS Model Contributing Analyses (CAs)

RDS CA	Higher Fidelity Design Tool	RDS Substitution / Usage for Tool
Trajectory	POST (Program to Optimize Simulated Trajectories) ETO trajectory optimization developed by NASA LaRC	Calibrated POST trajectory data for Hyperion SSTO RLV with multipliers for ΔV losses to obtain a new mass ratio
Weights	WATES, W&S Sizer RBCC engine weight, vehicle mass sizer and scaling models developed by SSDL	Use of SSDL W&S spreadsheet with no propulsion discipline; scaling of vehicle length of obtain mass ratio compatible with one obtained from the trajectory CA
Operations	AATe (Architecture Assessment Tool) Ground operations model developed by NASA KSC	Response Surface Equation (RSE) of AATe model based upon four input parameters: Airframe Life (MTBR), Dry Weight, Vehicle Length, and Overall Vehicle Reliability (MTBF), see Appendix B for more details
Cost	NAFCOM (NASA-Air Force Cost Model) Parametric cost model developed by NASA Marshall	Inclusion of Level 1 Cost Estimating Relationships (CERs) from NAFCOM
Economics	CABAM (Cost and Business Analysis Module) RLV economics model developed by SSDL	Use of basic financial sheets, with a regression curve fit of CSTS commercial payload delivery market. Routine for learning curve determination, see Appendix C for details.
Safety	Georgia Tech Safety Model-GT Safety developed by SSDL (Dr. John R. Olds)	Inclusion of complete spreadsheet model using order of magnitude comparisons with Shuttle

For implementation in ATIES each RDS model has to be correlated for a specific concept. Thus another formulation of the RDS model must be created in order to examine a two-stage-to-orbit (TSTO) RLV. This would entail changes in the disciplinary sheets in the RDS model such as trajectory, weights, operations, and cost based on higher-level fidelity tools used in the expanded conceptual design process for an RLV. The RDS model created for this study was specific to the Hyperion SSTO RLV. Still, there exists the possibility of comparing different concepts such as TSTO versus SSTO or all-rocket versus RBCC propulsion using the ATIES method. These alternative concepts may require different disciplinary tools to be included in the RDS model.

4.5.2 INTEGRATION OF RDS MODEL AND ATIES METHOD

The RDS model consists of the set of sheets representing disciplinary models coupled with an input / output (I/O) control sheet. This RDS I/O construct provides an interface between the base, interior RDS DSM with the rest of the RDS model that contains the technologies and the technical and non-technical k factors (see Section 4.4 for more detail on the k factors and RDS inputs / outputs). Figure 4.9 shows the relationship between the interior DSM and the RDS I/O that acts as a global optimizer in the exterior DSM, while Table 4.15 shows the output metrics that result from this exterior DSM.



Feed Forward Links

J: ΔV Flight / Drag / TVC / Isp Modifications
K: Vehicle Length
Payload Capability
LH2 Density
LOX Density
Engine T/W
Component Weights
L: Airframe Life
Facilities Cost
M: Airframe and Engine DDT&E Cost
Airframe and Engine TFU Cost
N: Average Annual Interest Rate
Tax Holiday Program Duration
Commercial Market Growth Factor
Overall Vehicle Reliability
Vehicle Recurring Cost Per Flight
Airframe and Engine DDT&E Cost
Airframe and Engine TFU Cost
Facilities Cost
Operations and Maintenance Cost
Payload Capability
Government Cargo Flights Per Year
Airframe Life
Engine Life
Static Government Cargo Launch price
IRR Goal
O: Overall Vehicle Reliability

RDS Outputs

P: Vehicle Length
Q: Ground Ops Turn Around Time (TAT)
R: DDT&E Cost
S: Iterated NPV for Desired IRR
T: Inverse Safety Metric

Figure 4.9. Exterior DSM (Disciplinary CAs) for Spreadsheet Based RDS Model

Table 4.15. Sample RDS I/O Model Outputs

No.	Output Factor Name	Sample Values	Units
O.1	Gross Weight	554,041	lb
O.2	Dry Weight	85,070	lb
O.3	Fuselage Length	154.0	ft
O.4	DDT&E cost	4,793	USD ($M)
O.5	Recurring cost / flight	1.14	USD ($M) / Flight
O.6	Vehicle Turnaround Time	8.78	days
O.7	Govt. Price / lb (required for IRR)	5,616.6	USD ($) / lb
O.8	Govt. Price / flight (required for IRR)	112.3	USD ($M) / Flight
O.9	NPV (for required IRR)	0	USD ($M)
O.10	NPV (at 25% discount rate)	0	USD ($M)
O.11	Life cycle cost (LCC)	63,406	USD ($M)
O.12	Safety Metric	339,960	# flights between loss of life

The RDS I/O converges the design using two independent scaling variables: one price and one vehicle length parameter. The price is the government cargo price per lb to charge, based on Commercial Space Transportation Study (CSTS) market elasticity curve fits, and is determined for an input internal rate of return (IRR). In addition, the RDS I/O converges the vehicle through manipulation of the vehicle length for an input level of technical vehicle influence factors (VIFs) from the trajectory and weights CAs such as ISP_bar (average propulsive ISP w/o losses), drag losses during ascent, Thrust Vector Control (TVC) losses during ascent, launch assist ΔV, vehicle component weights, and oxidizer / fuel densities.

The convergence process is run through MS Excel Solver that optimizes both vehicle length and government cargo price for an objective function of a net present value (NPV) of zero for the required IRR (see Table 4.16). In particular, instead of using two objective functions, one for price and one for vehicle length, one objective function (for price) is used along with one constraint (for vehicle length). The scaling variable for price is used in the economics spreadsheet of the RDS model. The scaling variable for vehicle length is used in the weights spreadsheet of the RDS model to size a vehicle for a required mass ratio. This process of convergence, meeting the objective function with associated constraints, takes approximately several seconds and various restarts on the part of MS Excel Solver. To converge a single vehicle in this manner could take as little as a few seconds or up to 30 seconds with various MS Excel Solver restarts.

Table 4.16. Sample Design Convergence Criteria for MS Excel Solver

No.	Name	Purpose	Discipline	Value	Units	Comment
D.1	NPV for Req'd IRR	Target For Zero	Economics	0.00	USD ($M)	FY$2018
D.2	Mass Ratio error	Constraint	Weights	0.00		
D.3	Total vehicle length (fuselage length)	Manipulate	Weights	*	ft	
D.4	Static Yearly Launch Price – Govt. Cargo	Manipulate	Economics	*	$/lb	FY$2018

Note: * indicates value being converged by MS Excel Solver for required k factors

At this point the ATIES implementation requires integration of the RDS model with Technology Compatibility Matrices (TCMs) and Technology Impact Matrices (TIMs). Figure 4.10 details the pieces of the ATIES implementation that comprise the complete technology evaluation process. In the complete ATIES process, technologies are identified, their compatibilities examined, deterministic or probabilistic influences determined, non-technical influences identified, and finally the RDS model is executed using MS Excel Solver. At this point in the process a vehicle concept is generated based upon a standard baseline concept (i.e. a 3rd Generation RLV) perturbed (through the RDS model) to accept a selected set of infused technologies (from the TCM and TIM). After many of these simulations, a list of the best combination of technologies can be developed.

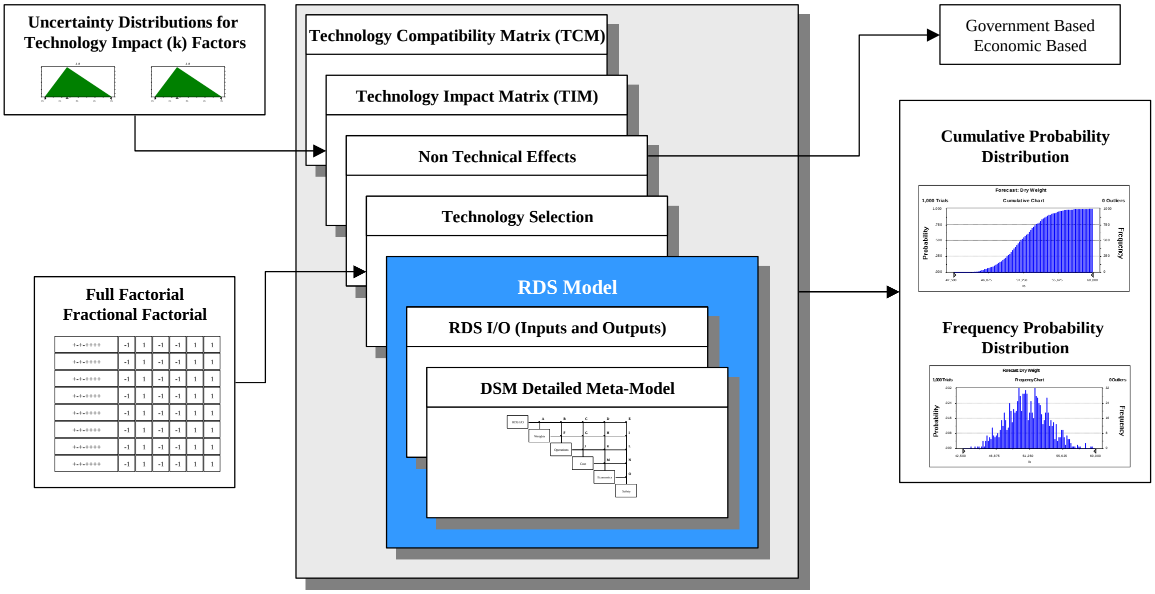


Figure 4.10. Complete ATIES Model Architecture

As described in an earlier section, the design space can be explored in many ways. The method pursued in this study consisted of creation of the RDS model and linkage to a Monte Carlo model (the TIM k factor distributions through the Monte Carlo computer program Crystal Ball). This method approximates the actual, detailed analytical tools that the SSDL uses to design conceptual vehicles with lower fidelity spreadsheets. Many times a Response Surface Equation (RSE) will be used as the meta-model. In this case a “full” spreadsheet-based analogue was used instead of an RSE. This creates problems in that the convergence requirements for the model (between seconds to minutes) made full/fractional factorial deterministic or probabilistic examinations of the design space expensive in terms of time and computational cost. Alternatives not fully implemented in this study include a Response Surface Equation of the entire RDS model. This would reduce the current fidelity of the RDS model (i.e from multiple “full” spreadsheets to RSEs).

For this study non-technical factors were left at pre-selected values. The parameters that influence the RDS model consist of technical and non-technical factors (as seen in Figure 4.11). A detailed examination of sensitivities of the model to non-technical effects, government financial incentives and economic priorities, are a secondary objective of the ATIES method. The ATIES method as detailed in this examination is focused on determining the influence of various technologies on vehicle output metrics rather than an expansive assessment of various programmatic and financial scenarios.

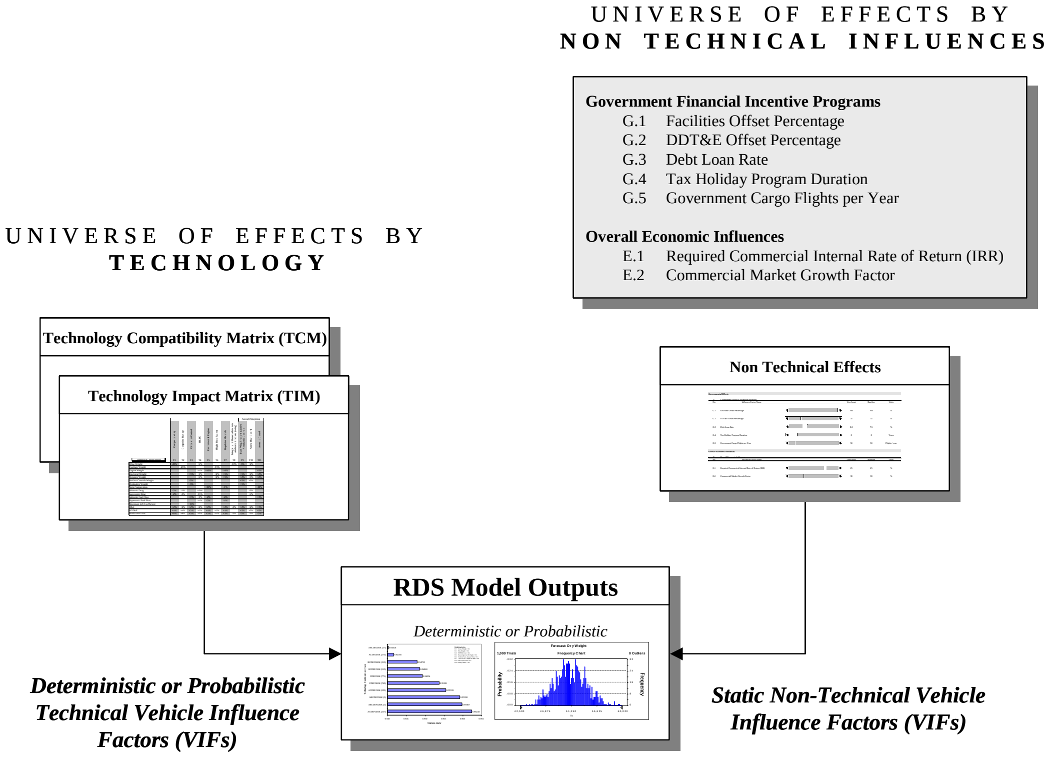


Figure 4.11. Technical and Non-Technical Vehicle Influence Factors (VIFs)

All evaluations in this study maintained constant assumptions as they relate to the non-technical influences, namely the government and economic environment. The static values for these non-technical vehicle influences factors (VIFs) are given in Tables 4.17 and 4.18, divided between government financial incentives and overall economic influences respectively. These influence of these VIFs extend to the cost and economics CAs in the RDS model.

Table 4.17. Government Financial Incentive Program Influence Assumptions

No.	Influence Factor Name	User Input	Baseline	Units
G.1	Facilities Offset Percentage	100	100	%
G.2	DDT&E Offset Percentage	25	25	%
G.3	Debt Loan Rate	8	7.5	%
G.4	Tax Holiday Program Duration	0	0	Years
G.5	Government Cargo Flights per Year	50	50	Flights / year

Table 4.18. Overall Economic Influence Assumptions

No.	Influence Factor Name	User Input	Baseline	Units
E.1	Required Commercial Internal Rate of Return (IRR)	25	25	%
E.2	Commercial Market Growth Factor	30	30	%

For the ATIES method, the RDS model was implemented for two sets of examinations:

1. A deterministic, full factorial examination of all feasible technologies combinations (referred to as the deterministic technology case)

   With an "n" number of technologies, this translates to 2^n possible combinations of technologies. This study examined 10 feasible technologies for the Hyperion RLV. This yields 2^{10} or 1024 possible technology combinations. The computational expense for all these evaluations consisted of 8 to 9 hours of processing time on a 550 MHz Pentium III PC computer running MS Excel 2000 on a Windows 98 platform with 128 MB of RAM.

2. A selected probabilistic examination with all technologies available for use (referred to as the nominal or probabilistic technology case)

   Monte Carlo simulations were run on the RDS model with the MS Excel add-in package Crystal Ball. Similar to the above case, the computational expense for this simulation consisted of 6 to 7 hours of processing time utilizing 1000 Monte Carlo simulations on a 550 MHz Pentium III PC computer running MS Excel 2000 on a Windows 98 platform with 128 MB of RAM.

4.6 STEP F: TECHNOLOGY SELECTION

In order to evaluate the impact of a particular combination of technologies, an Overall Evaluation Criterion (OEC) was developed. This OEC is based upon an aggregation of several output metrics of interest given a certain governmental and economic environment. The OEC is based upon a mathematical formulation consisting of the summation of the normalized values of each output metric multiplied by a numerical weighting. The weighting for each metric acts a quantitative proxy for the qualitative importance of the output metric relative to all other metrics. This weighting is subjectively based and different scenario types can be established.

The development of the weighting scenarios seen in Table 4.19 was a qualitative process. The method of formulating quantitative weightings was based on the assumption of three main types of criteria for program importance. These types include:

1. Technical merits (gross weight, dry weight)
2. Cost merits (DDT&E cost, recurring cost / flight, government price / lb, and life cycle cost)
3. Operational merits (vehicle turn-around-time and safety metric)

The metrics are designated with their numerical identifier in the RDS model. Some of the metrics are not used in the evaluation and selection process since they are intermediaries for the RDS model. These include the fuselage length, which is less of a metric than an intermediary technical parameter being manipulated by MS Excel Solver in the convergence process for a vehicle in the RDS model. A similar situation exists for the net-present value (NPV) parameter. For this study the discount rate used in the economic model (25%) was equal to the input IRR required and thus the output metrics O.9 and O.10 are equal to each other, namely both are equal to zero. The RDS model will converge the vehicle in the design process for input non-technical vehicle influence factors (such as required IRR, in this case 25%) and the performance impact of selected combinations of technologies (such as ISP and ΔV losses on trajectory). MS Excel Solver is used in the RDS model to converge the vehicle using the parameters of vehicle length (photographic scaling) and government price / lb required (for a required IRR, determined from overall economic vehicle influence factors). An overall goal is to minimize all metrics of interest except safety.

Table 4.19. Weighting Scenarios (WS) for OECs Based Upon Various Output Factors*

No.	Output Factor Name (goal)	Weighting Scenarios (WS)										
		1	2	3	4	5	6	7	8	9	10	11
O.1	Gross Weight (minimize)	0.1	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0
O.2	Dry Weight (minimize)	0.3	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.0
O.3	Fuselage Length**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O.4	DDT&E cost (minimize)	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.0
O.5	Recurring cost / flight (minimize)	0.1	0.1	0.1	0.2	0.1	0.3	0.1	0.1	0.1	0.2	0.0
O.6	Vehicle Turnaround Time (minimize)	0.1	0.1	0.1	0.0	0.0	0.1	0.3	0.1	0.1	0.1	0.0
O.7	Govt. Price / lb (required for IRR) (minimize)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.5
O.8	Govt. Price / flight (required for IRR)**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O.9	NPV (for required IRR)**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O.10	NPV (at 25% discount rate)**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O.11	Life cycle cost (LCC) (minimize)	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.3	0.1	0.0
O.12	Safety Metric (maximize)	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.5
	Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Note: * WS 10 is the baseline case, ** Not included in OEC because outputs are convergence parameters

The weighting scenarios (WSs) for the Overall Evaluation Criterion (OEC) are distinguished as follows:

- WS 1: The focus of this weighting scenario is to examine the influence of one technical and one non-technical metric: with the technical metric being given the highest importance. In this case, this would be dry weight and life cycle cost (LCC). All other metrics are given equivalent weighting.

- WS 2: The focus of this weighting scenario, similar to Scenario 1, is to examine the influence of one technical and one non-technical metric. In this WS, the technical metric is gross weight. Given the debate between minimum vehicle gross weight and minimum vehicle dry weight advocates, it was determined that an interesting comparison could be developed using the first two WSs.

- WS 3: In this weighting scenario both technical metrics for WS 1 and WS 2, gross weight and dry weight, were given equal weighting along with LCC. All three were ranked slightly higher in importance than the rest of the metrics.

- WS 4: This weighting scenario focused on considering both the non-recurring and recurring cost portions of the program, with both being given equal weighting with gross and dry weights.
- WS 5: This weighting scenario placed its emphasis on safety as the main priority over all other metrics.
- WS 6: The emphasis for this weighting scenario was on prioritizing recurring cost per flight. This might possibly occur for those programs that where recurring costs supersede non-recurring costs in terms of program importance (i.e. where government contribution is expected only in the DDT&E phase).
- WS 7: In this weighting scenario vehicle turn-around-time (TAT) was the set as the main high-level goal.
- WS 8: In this weighing scenario the government price per flight (for the required IRR) was taken as the primary metric of importance.
- WS 9: This weighting scenario made cost, both DDT&E and overall LCC, as the main metrics of importance.
- WS 10: This weighting scenario was taken as the baseline scenario since it presented all metrics relatively equally with slightly heavier emphasis dry weight, DDT&E cost, and recurring cost per flight. These represented the author's preference as to important metrics.
- WS 11: This weighting scenario was an extreme case in which only two equally weighted metrics were used, namely price and safety.

4.6.1 DETERMINISTIC TECHNOLOGY SELECTION

A full factorial search of the impact of all feasible technology combinations was performed using the ATIES method and RDS model. A Pugh Evaluation Matrix (PEM) was created for each technology set combination. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was then applied to order the cases according to the various weighting scenarios. The Overall Evaluation Criterion (OEC) is shown below (w_i's are weighting factors):

$$\begin{aligned}\mathrm{OEC} = {} & w_1 \frac{\text{Gross Weight}}{\text{Gross Weight}_{BL}} + w_2 \frac{\text{Dry Weight}}{\text{Dry Weight}_{BL}} + w_3 \frac{\text{DDT \& E Cost}}{\text{DDT \& E Cost}_{BL}} + w_4 \frac{\text{Recurring Cost / Flight}}{\text{Recurring Cost / Flight}_{BL}} + \\ & w_5 \frac{\text{Vehicle Turn Around Time}}{\text{Vehicle Turn Around Time}_{BL}} + w_6 \frac{\text{Govt. Price/ lb}}{\text{Govt. Price/ lb}_{BL}} + w_7 \frac{\text{Life Cycle Cost}}{\text{Life Cycle Cost}_{BL}} + w_8 \frac{\text{Safety Metric}}{\text{Safety Metric}_{BL}}\end{aligned} \tag{1}$$

The baseline values used in the determination of the OEC are values at the "Base@100%" or nominal setting. Thus the baseline gross weight is the vehicle weight with no application of technologies. The top technology combinations that maximize the OEC were determined for particular weighting scenarios (WSs). Figure 4.12 shows the OEC for the top technology combinations for the baseline-weighting scenario (WS 10). Similar charts for all weighting scenarios are given in Appendix E. The letter combinations represent the technology combinations that yielded that particular OEC with the number in parentheses representing the set number out of the 2^{10} (1,024) possible combinations. For weighting scenario 10, the best combination used all technologies but technology B (advanced cryotank structures). The second best combination used all 10 possible technologies. Of the top 10 combinations (as determined by OEC score) shown in Figure 4.12, all contained 8 or more of the 10 possible technologies that could have been used.

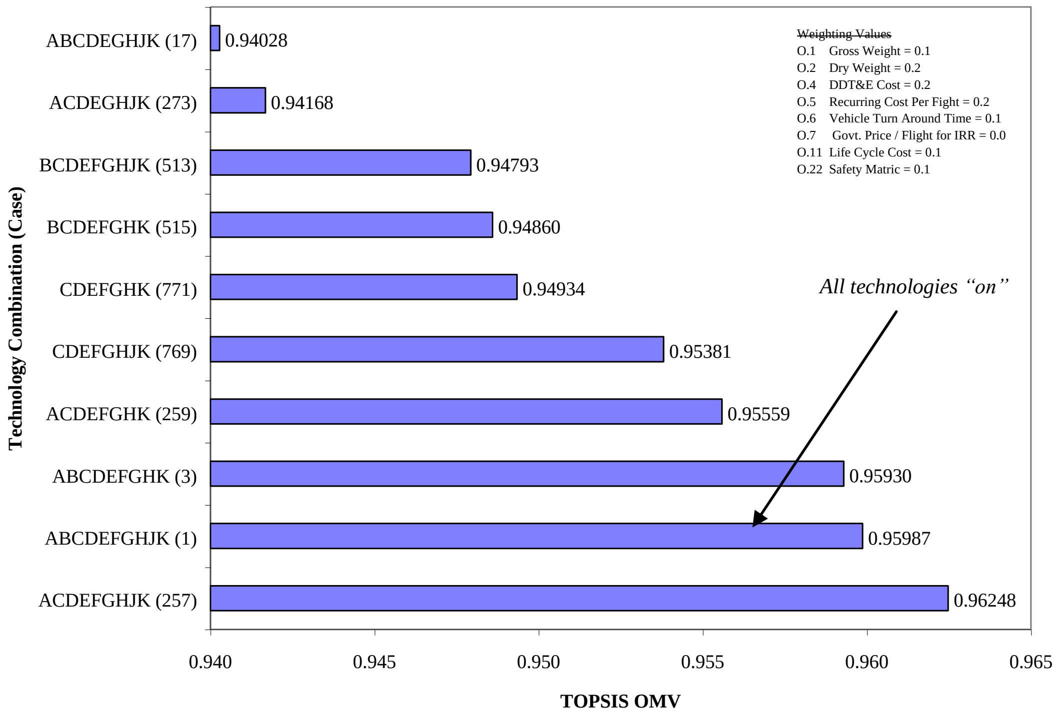


Figure 4.12. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 10 (Baseline)

The top 25 resulting technology combinations for each weighting scenario are then used to evaluate the best set of technologies. Table 4.20 displays those top 25 combinations using the TOPSIS order preference method. Each numeric value in the table is representative of a particular technology combination from the full factorial search. The specific technology combination subsets of the 1,024 cases that appear at least once in the top 25 for any of the 11 weighting scenarios are listed in Table 10.1 in Appendix E. That table lists the combinations for all of the cases listed in Table 4.20.

Table 4.20. TOPSIS Deterministic Cases for Various OEC Weighting Scenarios (WS)*

Rank	Weighting Scenario (WS)										
Best = 1	1	2	3	4	5	6	7	8	9	10	11
1	1	257	257	257	1	257	257	257	257	257	260
2	257	1	1	1	257	1	1	259	259	1	276
3	3	3	3	3	513	259	3	273	273	3	258
4	17	273	273	769	3	3	259	3	3	259	274
5	273	769	769	259	17	769	273	275	275	769	259
6	769	17	17	513	769	771	769	1	1	771	275
7	19	513	19	515	2	515	17	771	19	515	257
8	513	19	513	771	273	513	771	19	771	513	273
9	515	785	259	273	515	273	19	769	769	273	4
10	785	515	515	17	514	17	275	17	17	17	20
11	259	259	785	2	529	275	515	787	787	19	772
12	529	529	771	19	19	19	513	785	785	275	2
13	531	771	529	258	258	785	785	515	515	785	788
14	771	531	275	785	785	787	787	513	513	529	18
15	275	275	531	4	4	529	531	531	531	787	3
16	787	787	787	289	770	531	529	529	529	531	770
17	2	2	2	33	531	385	385	258	258	2	19
18	258	258	258	770	259	129	129	260	260	258	786
19	4	770	4	275	516	289	401	4	4	4	771
20	514	514	770	529	771	387	145	2	2	289	1
21	770	4	514	514	18	33	387	770	274	33	787
22	18	18	18	35	275	131	131	274	289	770	17
23	33	33	33	531	530	35	403	772	770	35	769
24	516	289	516	801	274	291	897	289	772	514	785
25	289	274	289	516	787	801	147	291	291	260	516

Note: * WS 10 is the baseline case

Examination of these top 25 cases for each WS reveals that a certain set of technologies always seem important regardless of the weighting scenario. Table 4.21 shows the number of times technology combinations appear in the top 25 cases for all 11 weighting sceneries; in other words the ranking of all technologies in Table 4.20. Examination of these results indicates that 44 different technology combinations appear in Table 4.20. Of these candidate combinations, 21 combinations appear 8 times or more and 11 combinations appear in all 11 weighting scenarios (see Table 4.21). There then appears to be a large gap between these "high appearance" technology combinations and a group of "low appearance" combinations that appear 6 times or less in the top 25 cases for all OEC weighting scenarios.

Table 4.21. Technology Combinations in Top 25 for all 11 Weighting Scenarios

Number of Times in Top 25 for All 11 WSs	11	10	9	8	7	6	5	4	3	2	1
Technology Combination Set From Full Factorial Search	1	513	2	289		33	18	260	35	129	20
	3	515	4			514	274		291	131	145
	17	529	258				516		772	385	147
	19	531	770							387	401
	257	787								801	403
	259										530
	273										786
	275										788
	769										897
	771										
	785										

21 "high appearance" combinations

The actual technologies in each of the 21 "high appearance" combinations are displayed in Table 4.22. Technologies C (Hot and cooled airframe and integrated primary structures), D (Advanced ground IVHM), E (Propulsion IVHM), G (Maglev development), H (Improved T/W RBCC engine), and K (Highly reusable TPS) are in almost all of the combinations. In addition, all of the technologies appear at least in half of the top 21 technology cases. Thus regardless of the WS, about 6 technologies consistently show up in the top 25 technology combinations that maximize the OEC. Additionally, all of the technologies are used in more than a majority of the top cases. This would indicate two dimensions of preference, one for these top 6 technologies and another preference to use all of the technologies.

Table 4.22. Actual Technologies for the 21 "High Appearance" Combinations

Case	Technologies (1 = Inclusion, -1 = Exclusion)										
	A	B	C	D	E	F	G	H	I*	J	K
No. of 1	12	10	21	21	20	13	21	21	0	12	17
No. of -1	9	11	0	0	1	8	0	0	21	9	4
1	1	1	1	1	1	1	1	1	-1	1	1
2	1	1	1	1	1	1	1	1	-1	1	-1
3	1	1	1	1	1	1	1	1	-1	-1	1
4	1	1	1	1	1	1	1	1	-1	-1	-1
17	1	1	1	1	1	-1	1	1	-1	1	1
19	1	1	1	1	1	-1	1	1	-1	-1	1
257	1	-1	1	1	1	1	1	1	-1	1	1
258	1	-1	1	1	1	1	1	1	-1	1	-1
259	1	-1	1	1	1	1	1	1	-1	-1	1
273	1	-1	1	1	1	-1	1	1	-1	1	1
275	1	-1	1	1	1	-1	1	1	-1	-1	1
289	1	-1	1	1	-1	1	1	1	-1	1	1
513	-1	1	1	1	1	1	1	1	-1	1	1
515	-1	1	1	1	1	1	1	1	-1	-1	1
529	-1	1	1	1	1	-1	1	1	-1	1	1
531	-1	1	1	1	1	-1	1	1	-1	-1	1
769	-1	-1	1	1	1	1	1	1	-1	1	1
770	-1	-1	1	1	1	1	1	1	-1	1	-1
771	-1	-1	1	1	1	1	1	1	-1	-1	1
785	-1	-1	1	1	1	-1	1	1	-1	1	1
787	-1	-1	1	1	1	-1	1	1	-1	-1	1

Note: Technology I (Long life, high T/W hydrogen rocket) not used for Hyperion RLV

4.6.2 PROBABILISTIC TECHNOLOGY SELECTION

A probabilistic examination was conducted as to the impact of having all 10 technologies on the Hyperion RLV. Using the Monte Carlo MS Excel add-in Crystal Ball, 1000 simulations were performed with triangular probability distributions on the impact of each technology on various k factors (see Section 4.4). Appendix F contains the forecast statistics, percentiles, frequency, and cumulative distributions for all output metrics that contribute to the OEC for this nominal case of all technologies being applied to the vehicle. Table 4.23 and Figure 4.13 respectively list and chart the sensitivity of all these technologies on metrics that contribute to the OEC. A current artifact of the ATIES modeling process involves the determination of sensitivities from the Monte Carlo simulation. Sensitivities consist of the relationship between the technical k factor of a technology and the output metrics that make up the OEC. The sensitivities listed here and in the proceeding appendices are absolute sensitivities without regard to sign. They are used to show only the magnitude of the sensitivity of each technology on the inputs to the OEC.

Table 4.23. Absolute Sensitivity of All Technologies on OEC Input Metrics

Tech.	Dry Weight	Gross Weight	Fuselage Length*	DDT&E cost	Recurring cost / flight	Vehicle Turnaround Time	Govt. Price / lb (required for IRR)	Life cycle cost (LCC)	Safety Metric
A				0.5			0.4	0.4	
B	0.2	0.2	0.2	0.3	0.1		0.4	0.4	0.2
C	0.3			0.6	0.2		0.5	0.6	0.3
D					0.4	0.7		0.1	
E				0.2	0.6	0.4	0.1	0.2	
F		0.1	0.1	0.1	0.4		0.1	0.1	
G		0.1	0.1	0.3	0.4	0.5	0.4	0.2	
H	1.0	1.0	1.0	0.7	0.1	0.1	0.8	0.8	1.0
J	0.2	0.2	0.2	0.3	0.1	0.1	0.4	0.3	0.2
K		0.1	0.1	0.2	0.4	0.4	0.2	0.2	

Note: * Not an OEC input metric but included for reference

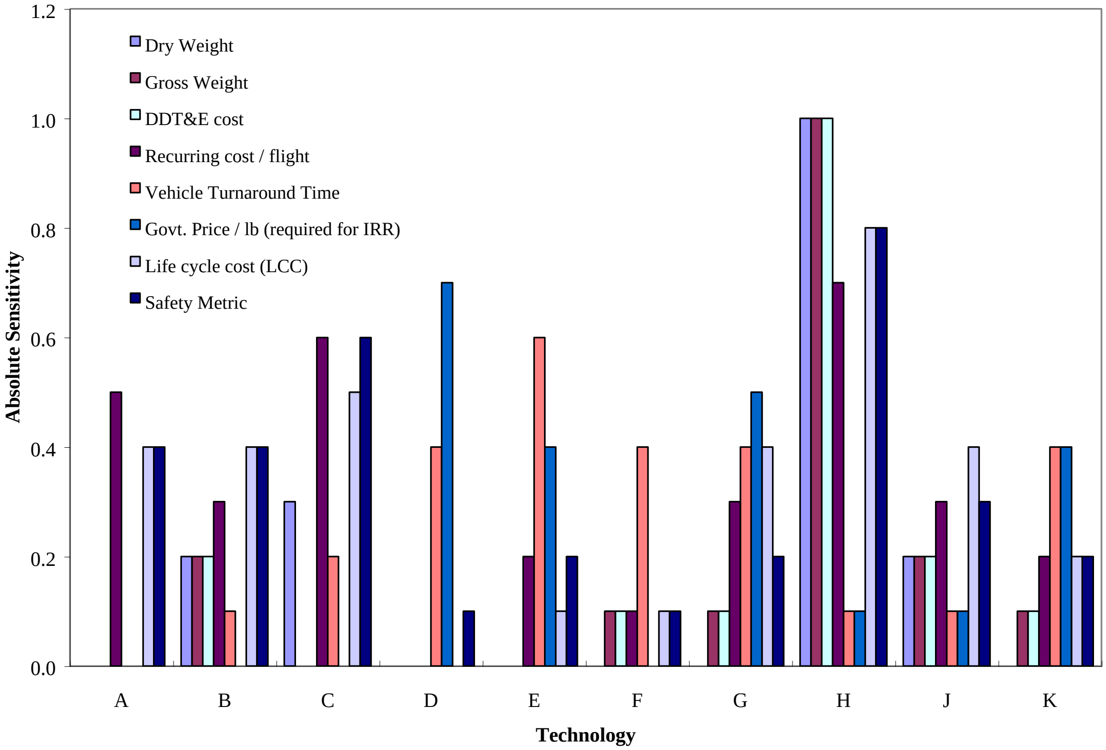


Figure 4.13. Graphical Sensitivity of Each Technology on OEC Input Metrics

Examination of the above data indicates the technology H (Improved T/W RBCC engine) has a very high sensitivity upon the output metrics. The TIM of this technology indicates that the benefits of this technology occur in performance (i.e. ISP), engine life, and safety with the only drawback being increased engine DDT&E cost. All other technologies seem to yield positive sensitivities for all output metrics. Almost all technologies affect prices and costs but only a few affect safety.

The sensitivities for the probabilistic technology impacts were coupled to the OEC and various weighting scenarios. Table 4.24, shows the most influential technologies and their average impact on the OEC. The top 3 technologies (C, E, and H) were part of the top 6 most influential technologies identified deterministically in the previous section. From the full factorial, deterministic examination of all possible technology combinations, and the probabilistic examination of the one case of all technologies being used, only three identified technologies rank near the top (in terms of maximizing and affecting the OEC) for both methods for the given TCM and TIM, namely technologies C, E, and H. Additionally, all technologies have some impact on the OEC since no technology had an average impact on the OEC of less than 4%. Once again this suggest two levels of impact in terms of the technologies used: one for a top tier of technologies (C, E, and H) and another that includes all technologies.

Table 4.24. Absolute Impact of Technologies for Various OEC Weighting Scenarios

Tech.	Weighting Scenario (WS)										Avg. Impact	Avg. Impact
No.	1	2	3	4	5	6	7	8	9	10	%	Rank
A	7%	7%	7%	7%	6%	6%	7%	9%	10%	7%	7%	8
B	9%	9%	9%	9%	7%	7%	7%	9%	9%	8%	8%	5
C	12%	13%	13%	13%	11%	11%	10%	14%	14%	12%	12%	3
D	7%	7%	7%	5%	7%	10%	13%	7%	7%	8%	8%	7
E	12%	12%	12%	12%	18%	15%	14%	11%	11%	13%	13%	2
F	4%	4%	4%	5%	4%	6%	3%	3%	3%	5%	4%	10
G	8%	9%	8%	7%	10%	10%	12%	10%	9%	9%	9%	4
H	27%	26%	27%	26%	25%	17%	16%	22%	21%	21%	23%	1
J	8%	8%	8%	8%	8%	7%	6%	9%	9%	8%	8%	6
K	6%	6%	6%	6%	3%	10%	11%	7%	8%	8%	7%	9

5.0 CONCLUDING REMARKS

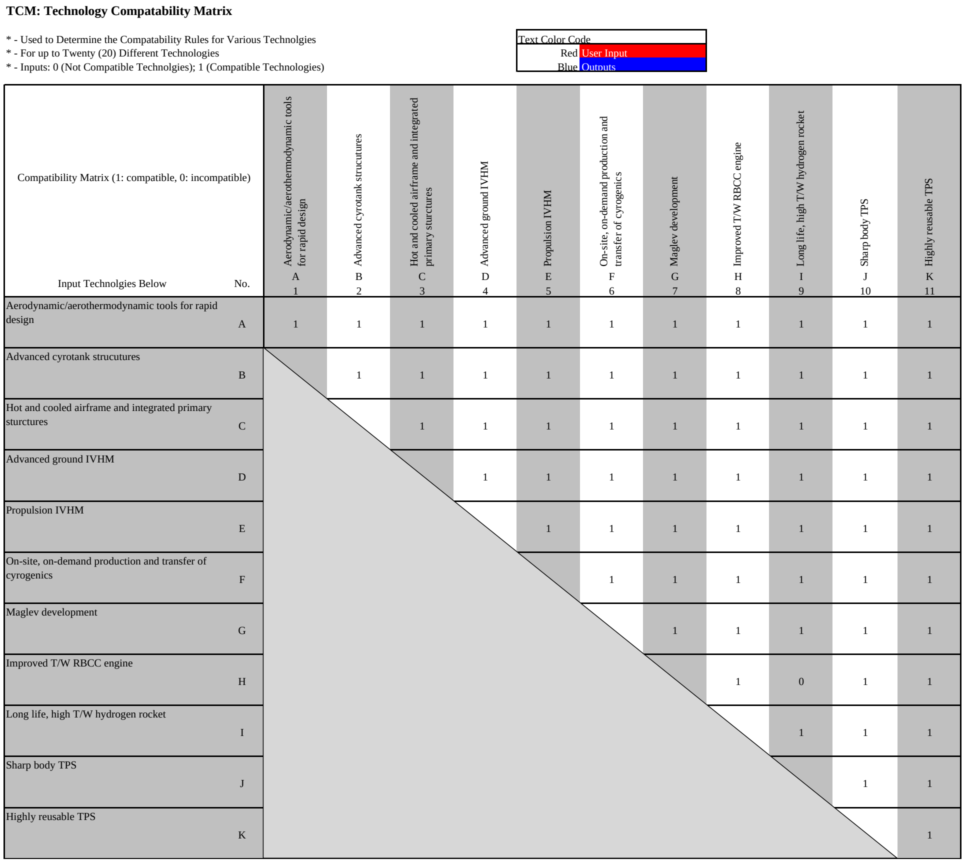
The Abbreviated Technology, Identification, Evaluation, and Selection (ATIES) methodology can be applied to aid the strategic decision maker in prioritization of advanced space transportation technologies. The original TIES method, as developed by the Aerospace Systems Design Lab (ASDL) in the School of Aerospace Engineering at the Georgia Institute of Technology, was applied both deterministically and probabilistically to in an RDS model that was a proxy for a representative reusable launch vehicles (RLVs)

The results in the study are based upon the qualitative inputs to the Technology Impact Matrix (TIM) and are dependent upon the initial, subjective interpretations of technology impact on various vehicle influence factors (VIFs). Thus any reasonable results from the method stem from reasonable inputs into the TIM. With these caveats in mind, two levels of technology preference were identified. Three technologies were the most influential in terms of maximizing the Overall Evaluation Criterion (OEC), namely Technology C (Hot and cooled airframe and integrated primary structures), Technology E: (Propulsion IVHM), and Technology H (Improved T/W RBCC engine). Additionally, examination of the top technology combinations for various weighting scenarios reveals that all ten technologies should be included in the vehicle to maximize the OEC.

Future work could include a probabilistic examination to determine the sensitivity of the top “impactful” technologies in isolation from each other, in essence a resource allocation investigation evaluating individual technology impacts. The top technologies could be determined through the full factorial deterministic evaluation. Monte Carlo simulations could then be run on the RDS model for each top technology. In addition, a single Response Surface Equation (RSE) could be generated as a proxy for the “full” spreadsheet based RDS model. With an RSE, the current computational cost for probabilistic examination of the design space could be mitigated.

Additional work could examine more probabilistic technology combinations for different concepts such as an all-rocket based RLV (versus the RBCC-based Hyperion RLV examined in this study). The template of the ATIES methods described here can be used to envelope RDS models of different transportation concepts in order to probabilistically examine the impact of various technology combinations on output metrics of interest. With this added capability, the methodology could be expanded to the Internet and allow decisions makers globally to examine the impact of their own technologies on such space transportation systems.

6.0 APPENDIX A: RDS MODEL SHEET OVERVIEW



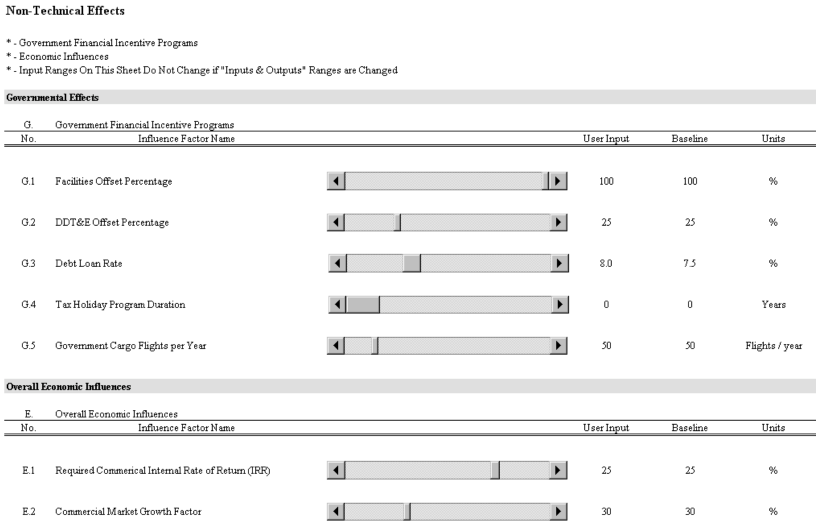
TCM: Technology Compatability Matrix

* - Used to Determine the Compatability Rules for Various Technolgies
* - For up to Twenty (20) Different Technologies
* - Inputs: 0 (Not Compatible Technolgies); 1 (Compatible Technologies)

Text Color Code	
Red	User Input
Blue	Outputs

Compatibility Matrix (1: compatible, 0: incompatible) Input Technolgies Below	No.	Aerodynamic/aerothermodynamic tools for rapid design A 1	Advanced cyrotank strucutures B 2	Hot and cooled airframe and integrated primary sturctures C 3	Advanced ground IVHM D 4	Propulsion IVHM E 5	On-site, on-demand production and transfer of cyrogenics F 6	Maglev development G 7	Improved T/W RBCC engine H 8	Long life, high T/W hydrogen rocket I 9	Sharp body TPS J 10	Highly reusable TPS K 11
Aerodynamic/aerothermodynamic tools for rapid design	A	1	1	1	1	1	1	1	1	1	1	1
Advanced cyrotank strucutures	B		1	1	1	1	1	1	1	1	1	1
Hot and cooled airframe and integrated primary sturctures	C			1	1	1	1	1	1	1	1	1
Advanced ground IVHM	D				1	1	1	1	1	1	1	1
Propulsion IVHM	E					1	1	1	1	1	1	1
On-site, on-demand production and transfer of cyrogenics	F						1	1	1	1	1	1
Maglev development	G							1	1	1	1	1
Improved T/W RBCC engine	H								1	0	1	1
Long life, high T/W hydrogen rocket	I									1	1	1
Sharp body TPS	J										1	1
Highly reusable TPS	K											1

Figure 6.1 Sample Sheet from RDS Model: TCM



Non-Technical Effects

* - Government Financial Incentive Programs
* - Economic Influences
* - Input Ranges On This Sheet Do Not Change if "Inputs & Outputs" Ranges are Changed

Governmental Effects

G. Government Financial Incentive Programs

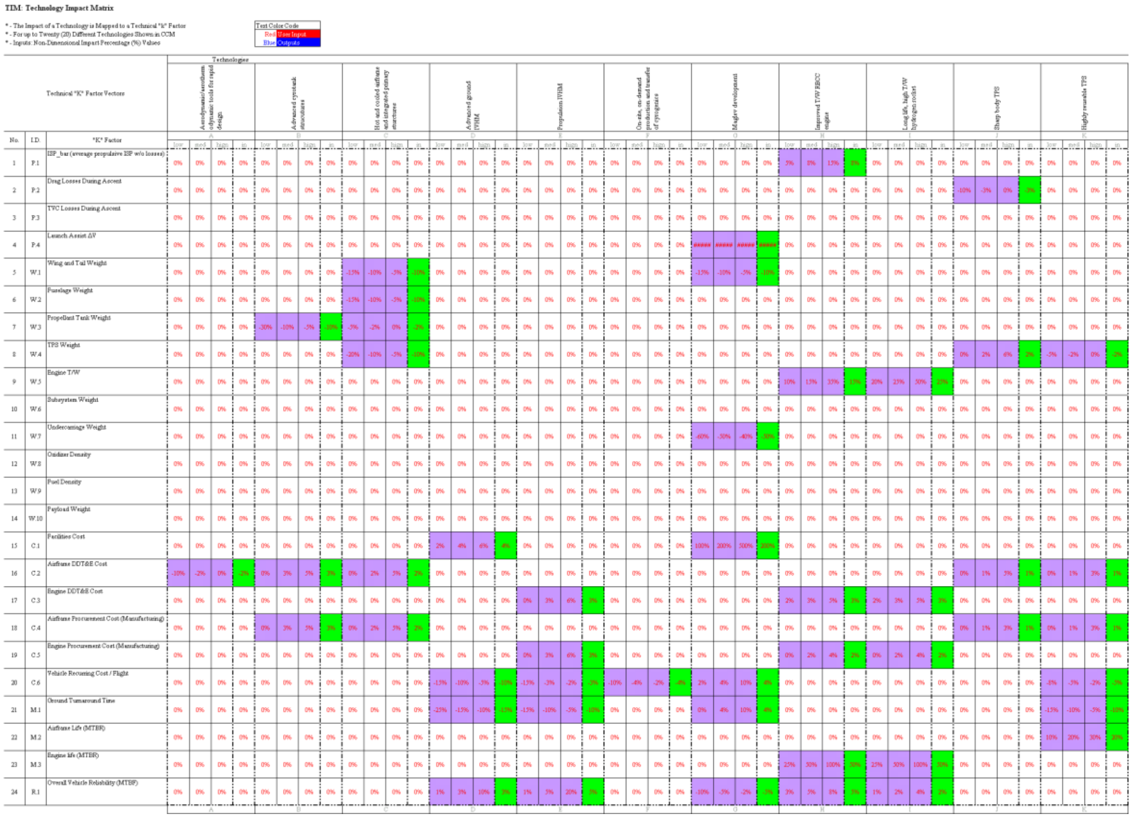
No.	Influence Factor Name	User Input	Baseline	Units
G.1	Facilities Offset Percentage	100	100	%
G.2	DDT&E Offset Percentage	25	25	%
G.3	Debt Loan Rate	8.0	7.5	%
G.4	Tax Holiday Program Duration	0	0	Years
G.5	Government Cargo Flights per Year	50	50	Flights / year

Overall Economic Influences

E. Overall Economic Influences

No.	Influence Factor Name	User Input	Baseline	Units
E.1	Required Commerical Internal Rate of Return (IRR)	25	25	%
E.2	Commercial Market Growth Factor	30	30	%

Figure 6.2. Sample Sheet from RDS Model: Non-Technical Factor Manipulation



TIM: Technology Impact Matrix

- * - The Impact of a Technology is Mapped to a Technical "k" Factor
- * - For up to Twenty (20) Different Technologies Shown in CCM
- * - Inputs: Non-Dimensional Impact Percentage (%) Values

Text Color Code	
Red	User Input
Blue	Outputs

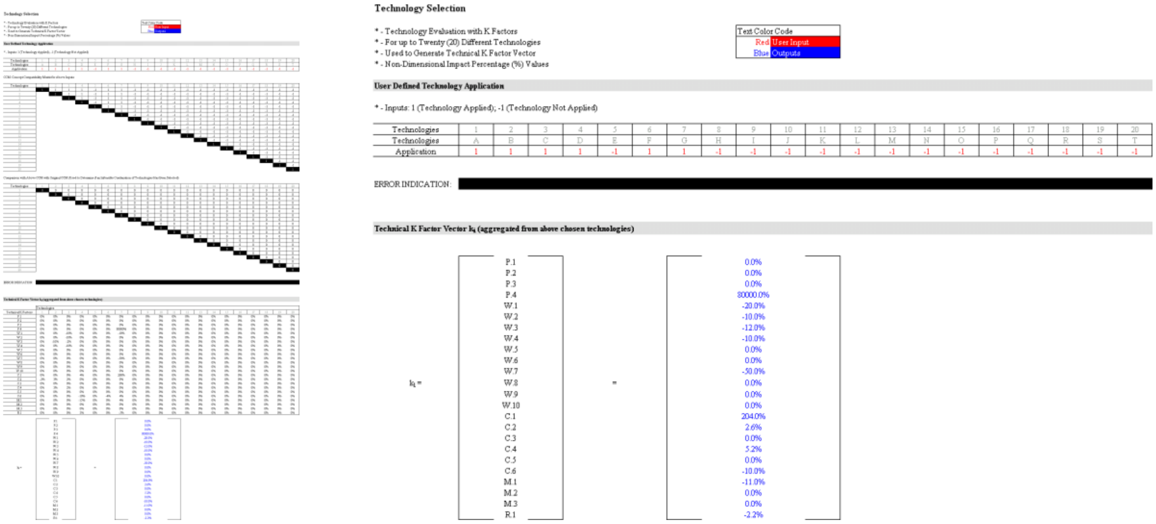
Technical "K" Factor Vectors – Technologies

No.	I.D.	"K" Factor	Aerodynamic/aerothermodynamic tools for rapid design				Advanced cryotank structures				Hot and cooled airframe and integrated primary structures				Advanced ground IVHM			
			A				B				C				D			
			low	med	high	in	low	med	high	in	low	med	high	in	low	med	high	in
1	P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2	P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3	P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4	P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
5	W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%	0%	0%	-15%	-10%	-5%	-10%	0%	0%	0%	0%
6	W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%	0%	0%	-15%	-10%	-5%	-10%	0%	0%	0%	0%
7	W.3	Propellant Tank Weight	0%	0%	0%	0%	-30%	-10%	-5%	-10%	-5%	-2%	0%	-2%	0%	0%	0%	0%
8	W.4	TPS Weight	0%	0%	0%	0%	0%	0%	0%	0%	-20%	-10%	-5%	-10%	0%	0%	0%	0%
9	W.5	Engine T/W	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10	W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11	W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12	W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
13	W.9	Fuel Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
14	W.10	Payload Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
15	C.1	Facilities Cost	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	4%	6%	4%
16	C.2	Airframe DDT&E Cost	-10%	-2%	0%	-2%	0%	3%	5%	3%	0%	2%	5%	2%	0%	0%	0%	0%
17	C.3	Engine DDT&E Cost	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18	C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	3%	5%	3%	0%	2%	5%	2%	0%	0%	0%	0%
19	C.5	Engine Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
20	C.6	Vehicle Recurring Cost / Flight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-15%	-10%	-5%	-10%
21	M.1	Ground Turnaround Time	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-25%	-15%	-10%	-15%
22	M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
23	M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24	R.1	Overall Vehicle Reliability (MTBF)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%	10%	3%

No.	I.D.	"K" Factor	Propulsion IVHM				On-site, on-demand production and transfer of cryogenics				Maglev development				Improved T/W RBCC engine			
			E				F				G				H			
			low	med	high	in	low	med	high	in	low	med	high	in	low	med	high	in
1	P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	5%	8%	15%	8%
2	P.2	Drag Losses During Ascent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3	P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4	P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%	0%	0%	#####	#####	#####	#####	0%	0%	0%	0%
5	W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%	0%	0%	-15%	-10%	-5%	-10%	0%	0%	0%	0%
6	W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7	W.3	Propellant Tank Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
8	W.4	TPS Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9	W.5	Engine T/W	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	10%	15%	35%	15%
10	W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11	W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%	0%	0%	-60%	-50%	-40%	-50%	0%	0%	0%	0%
12	W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
13	W.9	Fuel Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
14	W.10	Payload Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
15	C.1	Facilities Cost	0%	0%	0%	0%	0%	0%	0%	0%	100%	200%	500%	200%	0%	0%	0%	0%
16	C.2	Airframe DDT&E Cost	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
17	C.3	Engine DDT&E Cost	0%	3%	6%	3%	0%	0%	0%	0%	0%	0%	0%	0%	2%	3%	5%	3%
18	C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
19	C.5	Engine Procurement Cost (Manufacturing)	0%	3%	6%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	4%	2%
20	C.6	Vehicle Recurring Cost / Flight	-15%	-3%	-2%	-3%	-10%	-4%	-2%	-4%	2%	4%	10%	4%	0%	0%	0%	0%
21	M.1	Ground Turnaround Time	-15%	-10%	-5%	-10%	0%	0%	0%	0%	0%	4%	10%	4%	0%	0%	0%	0%
22	M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
23	M.3	Engine life (MTBR)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	50%	100%	50%
24	R.1	Overall Vehicle Reliability (MTBF)	1%	5%	20%	5%	0%	0%	0%	0%	-10%	-5%	-2%	-5%	3%	5%	8%	5%

No.	I.D.	"K" Factor	Long life, high T/W hydrogen rocket				Sharp body TPS				Highly reusable TPS			
			I				J				K			
			low	med	high	in	low	med	high	in	low	med	high	in
1	P.1	ISP_bar (average propulsive ISP w/o losses)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2	P.2	Drag Losses During Ascent	0%	0%	0%	0%	-10%	-3%	0%	-3%	0%	0%	0%	0%
3	P.3	TVC Losses During Ascent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4	P.4	Launch Assist ΔV	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
5	W.1	Wing and Tail Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6	W.2	Fuselage Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7	W.3	Propellant Tank Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
8	W.4	TPS Weight	0%	0%	0%	0%	0%	2%	6%	2%	-5%	-2%	0%	-2%
9	W.5	Engine T/W	20%	25%	50%	25%	0%	0%	0%	0%	0%	0%	0%	0%
10	W.6	Subsystem Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11	W.7	Undercarriage Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12	W.8	Oxidizer Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
13	W.9	Fuel Density	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
14	W.10	Payload Weight	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
15	C.1	Facilities Cost	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
16	C.2	Airframe DDT&E Cost	0%	0%	0%	0%	0%	1%	5%	1%	0%	1%	3%	1%
17	C.3	Engine DDT&E Cost	2%	3%	5%	3%	0%	0%	0%	0%	0%	0%	0%	0%
18	C.4	Airframe Procurement Cost (Manufacturing)	0%	0%	0%	0%	0%	1%	3%	1%	0%	1%	3%	1%
19	C.5	Engine Procurement Cost (Manufacturing)	0%	2%	4%	2%	0%	0%	0%	0%	0%	0%	0%	0%
20	C.6	Vehicle Recurring Cost / Flight	0%	0%	0%	0%	0%	0%	0%	0%	-8%	-5%	-2%	-5%
21	M.1	Ground Turnaround Time	0%	0%	0%	0%	0%	0%	0%	0%	-15%	-10%	-5%	-10%
22	M.2	Airframe Life (MTBR)	0%	0%	0%	0%	0%	0%	0%	0%	10%	20%	30%	20%
23	M.3	Engine life (MTBR)	25%	50%	100%	50%	0%	0%	0%	0%	0%	0%	0%	0%
24	R.1	Overall Vehicle Reliability (MTBF)	1%	2%	4%	2%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 6.3. Sample Sheet from RDS Model: TIM with Probabilistic k factor Distributions



Technology Selection

- * - Technology Evaluation with K Factors
- * - For up to Twenty (20) Different Technologies
- * - Used to Generate Technical K Factor Vector
- * - Non-Dimensional Impact Percentage (%) Values

Text Color Code	
Red	User Input
Blue	Outputs

User Defined Technology Application

* - Inputs: 1 (Technology Applied); -1 (Technology Not Applied)

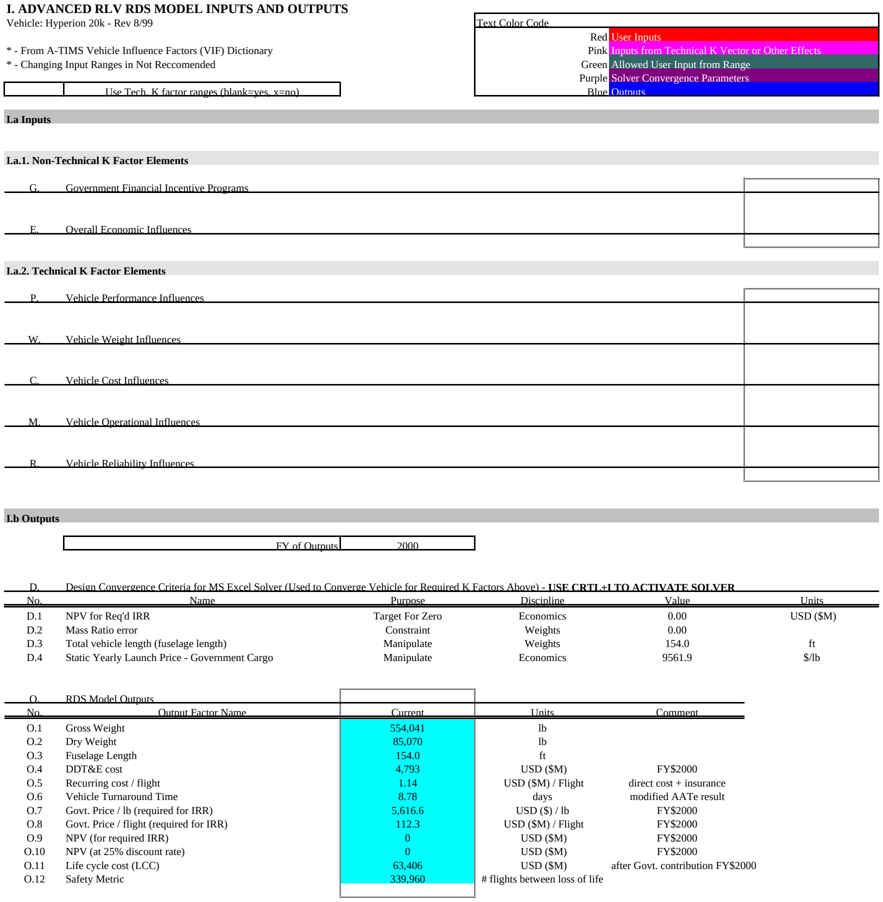
Technologies	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Application	1	1	1	1	-1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

ERROR INDICATION:

Technical K Factor Vector k_t (aggregated from above chosen technologies)

$$k_t = \begin{bmatrix} P.1 \\ P.2 \\ P.3 \\ P.4 \\ W.1 \\ W.2 \\ W.3 \\ W.4 \\ W.5 \\ W.6 \\ W.7 \\ W.8 \\ W.9 \\ W.10 \\ C.1 \\ C.2 \\ C.3 \\ C.4 \\ C.5 \\ C.6 \\ M.1 \\ M.2 \\ M.3 \\ R.1 \end{bmatrix} = \begin{bmatrix} 0.0\% \\ 0.0\% \\ 0.0\% \\ 80000.0\% \\ -20.0\% \\ -10.0\% \\ -12.0\% \\ -10.0\% \\ 0.0\% \\ 0.0\% \\ -50.0\% \\ 0.0\% \\ 0.0\% \\ 0.0\% \\ 204.0\% \\ 2.6\% \\ 0.0\% \\ 5.2\% \\ 0.0\% \\ -10.0\% \\ -11.0\% \\ 0.0\% \\ 0.0\% \\ -2.2\% \end{bmatrix}$$

Figure 6.4. Sample Sheet from RDS Model: Technology Selection (Used for Evaluation in Model)



I. ADVANCED RLV RDS MODEL INPUTS AND OUTPUTS
Vehicle: Hyperion 20k - Rev 8/99

* - From A-TIMS Vehicle Influence Factors (VIF) Dictionary
* - Changing Input Ranges in Not Reccomended

Use Tech. K factor ranges (blank=yes, x=no)

Text Color Code	
Red	User Inputs
Pink	Inputs from Technical K Vector or Other Effects
Green	Allowed User Input from Range
Purple	Solver Convergence Parameters
Blue	Outputs

I.a Inputs

I.a.1. Non-Technical K Factor Elements

G. Government Financial Incentive Programs

E. Overall Economic Influences

I.a.2. Technical K Factor Elements

P. Vehicle Performance Influences

W. Vehicle Weight Influences

C. Vehicle Cost Influences

M. Vehicle Operational Influences

R. Vehicle Reliability Influences

I.b Outputs

FY of Outputs 2000

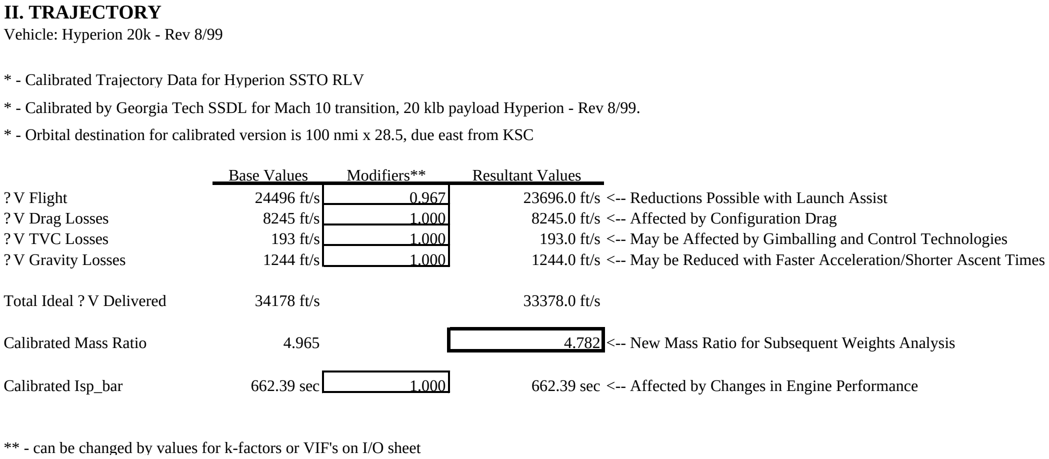
D. Design Convergence Criteria for MS Excel Solver (Used to Converge Vehicle for Required K Factors Above) - **USE CRTL+I TO ACTIVATE SOLVER**

No.	Name	Purpose	Discipline	Value	Units
D.1	NPV for Req'd IRR	Target For Zero	Economics	0.00	USD ($M)
D.2	Mass Ratio error	Constraint	Weights	0.00	
D.3	Total vehicle length (fuselage length)	Manipulate	Weights	154.0	ft
D.4	Static Yearly Launch Price - Government Cargo	Manipulate	Economics	9561.9	$/lb

O. RDS Model Outputs

No.	Output Factor Name	Current	Units	Comment
O.1	Gross Weight	554,041	lb	
O.2	Dry Weight	85,070	lb	
O.3	Fuselage Length	154.0	ft	
O.4	DDT&E cost	4,793	USD ($M)	FY$2000
O.5	Recurring cost / flight	1.14	USD ($M) / Flight	direct cost + insurance
O.6	Vehicle Turnaround Time	8.78	days	modified AATe result
O.7	Govt. Price / lb (required for IRR)	5,616.6	USD ($) / lb	FY$2000
O.8	Govt. Price / flight (required for IRR)	112.3	USD ($M) / Flight	FY$2000
O.9	NPV (for required IRR)	0	USD ($M)	FY$2000
O.10	NPV (at 25% discount rate)	0	USD ($M)	FY$2000
O.11	Life cycle cost (LCC)	63,406	USD ($M)	after Govt. contribution FY$2000
O.12	Safety Metric	339,960	# flights between loss of life	

Figure 6.5. Sample Sheet from RDS Model: RDS I/O



II. TRAJECTORY
Vehicle: Hyperion 20k - Rev 8/99

* - Calibrated Trajectory Data for Hyperion SSTO RLV

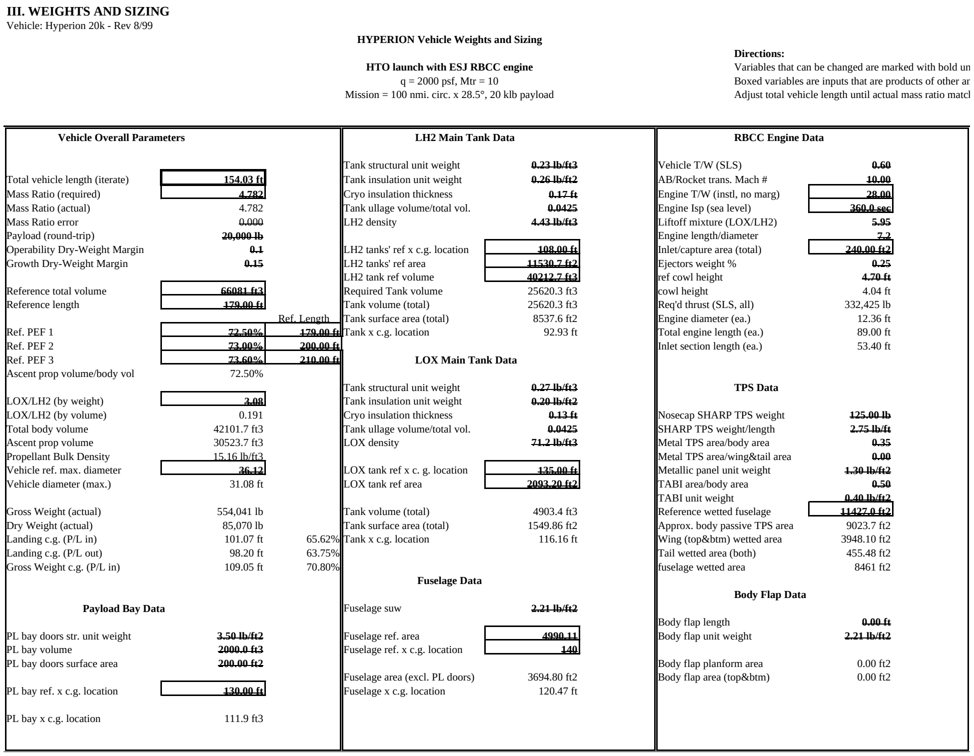
* - Calibrated by Georgia Tech SSDL for Mach 10 transition, 20 klb payload Hyperion - Rev 8/99.

* - Orbital destination for calibrated version is 100 nmi x 28.5, due east from KSC

	Base Values	Modifiers**	Resultant Values	
? V Flight	24496 ft/s	0.967	23696.0 ft/s	<-- Reductions Possible with Launch Assist
? V Drag Losses	8245 ft/s	1.000	8245.0 ft/s	<-- Affected by Configuration Drag
? V TVC Losses	193 ft/s	1.000	193.0 ft/s	<-- May be Affected by Gimballing and Control Technologies
? V Gravity Losses	1244 ft/s	1.000	1244.0 ft/s	<-- May be Reduced with Faster Acceleration/Shorter Ascent Times
Total Ideal ? V Delivered	34178 ft/s		33378.0 ft/s	
Calibrated Mass Ratio	4.965		4.782	<-- New Mass Ratio for Subsequent Weights Analysis
Calibrated Isp_bar	662.39 sec	1.000	662.39 sec	<-- Affected by Changes in Engine Performance

** - can be changed by values for k-factors or VIF's on I/O sheet

Figure 6.6. Sample Sheet from RDS Model: Trajectory



III. WEIGHTS AND SIZING
Vehicle: Hyperion 20k - Rev 8/99

HYPERION Vehicle Weights and Sizing

HTO launch with ESJ RBCC engine
q = 2000 psf, Mtr = 10
Mission = 100 nmi. circ. x 28.5°, 20 klb payload

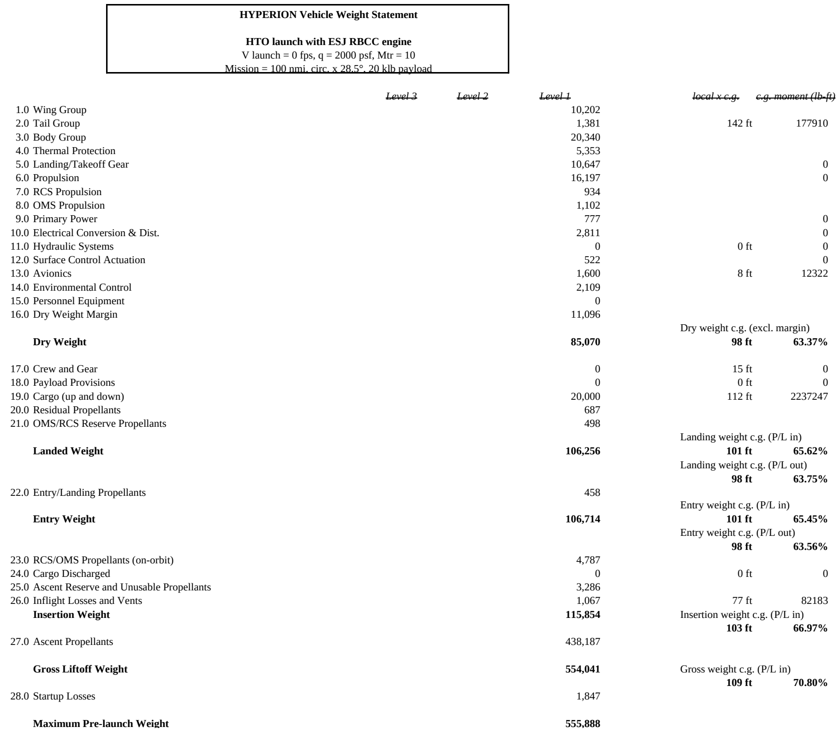
Directions:
Variables that can be changed are marked with bold un
Boxed variables are inputs that are products of other ar
Adjust total vehicle length until actual mass ratio matcl

Vehicle Overall Parameters		
Total vehicle length (iterate)	**154.03 ft**	
Mass Ratio (required)	~~**4.782**~~	
Mass Ratio (actual)	4.782	
Mass Ratio error	~~0.000~~	
Payload (round-trip)	~~**20,000 lb**~~	
Operability Dry-Weight Margin	~~**0.1**~~	
Growth Dry-Weight Margin	~~**0.15**~~	
Reference total volume	~~**66081 ft3**~~	
Reference length	~~**179.00 ft**~~	
		Ref. Length
Ref. PEF 1	~~**72.50%**~~	~~**179.00 ft**~~
Ref. PEF 2	~~**73.00%**~~	~~**200.00 ft**~~
Ref. PEF 3	~~**73.60%**~~	~~**210.00 ft**~~
Ascent prop volume/body vol	72.50%	
LOX/LH2 (by weight)	~~**3.08**~~	
LOX/LH2 (by volume)	0.191	
Total body volume	42101.7 ft3	
Ascent prop volume	30523.7 ft3	
Propellant Bulk Density	15.16 lb/ft3	
Vehicle ref. max. diameter	~~**36.12**~~	
Vehicle diameter (max.)	31.08 ft	
Gross Weight (actual)	554,041 lb	
Dry Weight (actual)	85,070 lb	
Landing c.g. (P/L in)	101.07 ft	65.62%
Landing c.g. (P/L out)	98.20 ft	63.75%
Gross Weight c.g. (P/L in)	109.05 ft	70.80%
Payload Bay Data		
PL bay doors str. unit weight	~~**3.50 lb/ft2**~~	
PL bay volume	~~**2000.0 ft3**~~	
PL bay doors surface area	~~**200.00 ft2**~~	
PL bay ref. x c.g. location	~~**130.00 ft**~~	
PL bay x c.g. location	111.9 ft3	

LH2 Main Tank Data	
Tank structural unit weight	~~**0.23 lb/ft3**~~
Tank insulation unit weight	~~**0.26 lb/ft2**~~
Cryo insulation thickness	~~**0.17 ft**~~
Tank ullage volume/total vol.	~~**0.0425**~~
LH2 density	~~**4.43 lb/ft3**~~
LH2 tanks' ref x c.g. location	~~**108.00 ft**~~
LH2 tanks' ref area	~~**11530.7 ft2**~~
LH2 tank ref volume	~~**40212.7 ft3**~~
Required Tank volume	25620.3 ft3
Tank volume (total)	25620.3 ft3
Tank surface area (total)	8537.6 ft2
Tank x c.g. location	92.93 ft
LOX Main Tank Data	
Tank structural unit weight	~~**0.27 lb/ft3**~~
Tank insulation unit weight	~~**0.20 lb/ft2**~~
Cryo insulation thickness	~~**0.13 ft**~~
Tank ullage volume/total vol.	~~**0.0425**~~
LOX density	~~**71.2 lb/ft3**~~
LOX tank ref x c. g. location	~~**135.00 ft**~~
LOX tank ref area	~~**2093.20 ft2**~~
Tank volume (total)	4903.4 ft3
Tank surface area (total)	1549.86 ft2
Tank x c.g. location	116.16 ft
Fuselage Data	
Fuselage suw	~~**2.21 lb/ft2**~~
Fuselage ref. area	~~**4990.11**~~
Fuselage ref. x c.g. location	~~**140**~~
Fuselage area (excl. PL doors)	3694.80 ft2
Fuselage x c.g. location	120.47 ft

RBCC Engine Data	
Vehicle T/W (SLS)	~~**0.60**~~
AB/Rocket trans. Mach #	~~**10.00**~~
Engine T/W (instl, no marg)	~~**28.00**~~
Engine Isp (sea level)	~~**360.0 sec**~~
Liftoff mixture (LOX/LH2)	~~**5.95**~~
Engine length/diameter	~~**7.2**~~
Inlet/capture area (total)	~~**240.00 ft2**~~
Ejectors weight %	~~**0.25**~~
ref cowl height	~~**4.70 ft**~~
cowl height	4.04 ft
Req'd thrust (SLS, all)	332,425 lb
Engine diameter (ea.)	12.36 ft
Total engine length (ea.)	89.00 ft
Inlet section length (ea.)	53.40 ft
TPS Data	
Nosecap SHARP TPS weight	~~**125.00 lb**~~
SHARP TPS weight/length	~~**2.75 lb/ft**~~
Metal TPS area/body area	~~**0.35**~~
Metal TPS area/wing&tail area	~~**0.00**~~
Metallic panel unit weight	~~**1.30 lb/ft2**~~
TABI area/body area	~~**0.50**~~
TABI unit weight	~~**0.40 lb/ft2**~~
Reference wetted fuselage	~~**11427.0 ft2**~~
Approx. body passive TPS area	9023.7 ft2
Wing (top&btm) wetted area	3948.10 ft2
Tail wetted area (both)	455.48 ft2
fuselage wetted area	8461 ft2
Body Flap Data	
Body flap length	~~**0.00 ft**~~
Body flap unit weight	~~**2.21 lb/ft2**~~
Body flap planform area	0.00 ft2
Body flap area (top&btm)	0.00 ft2

Figure 6.7. Sample Sheet from RDS Model: Weights (1)



HYPERION Vehicle Weight Statement

HTO launch with ESJ RBCC engine
V launch = 0 fps, q = 2000 psf, Mtr = 10
Mission = 100 nmi. circ. x 28.5°, 20 klb payload

		~~*Level 3*~~	~~*Level 2*~~	~~*Level 1*~~	~~*local x c.g.*~~	~~*c.g. moment (lb-ft)*~~
1.0	Wing Group			10,202		
2.0	Tail Group			1,381	142 ft	177910
3.0	Body Group			20,340		
4.0	Thermal Protection			5,353		
5.0	Landing/Takeoff Gear			10,647		0
6.0	Propulsion			16,197		0
7.0	RCS Propulsion			934		
8.0	OMS Propulsion			1,102		
9.0	Primary Power			777		0
10.0	Electrical Conversion & Dist.			2,811		0
11.0	Hydraulic Systems			0	0 ft	0
12.0	Surface Control Actuation			522		0
13.0	Avionics			1,600	8 ft	12322
14.0	Environmental Control			2,109		
15.0	Personnel Equipment			0		
16.0	Dry Weight Margin			11,096		
					Dry weight c.g. (excl. margin)	
	Dry Weight			**85,070**	**98 ft**	**63.37%**
17.0	Crew and Gear			0	15 ft	0
18.0	Payload Provisions			0	0 ft	0
19.0	Cargo (up and down)			20,000	112 ft	2237247
20.0	Residual Propellants			687		
21.0	OMS/RCS Reserve Propellants			498		
					Landing weight c.g. (P/L in)	
	Landed Weight			**106,256**	**101 ft**	**65.62%**
					Landing weight c.g. (P/L out)	
					98 ft	**63.75%**
22.0	Entry/Landing Propellants			458		
					Entry weight c.g. (P/L in)	
	Entry Weight			**106,714**	**101 ft**	**65.45%**
					Entry weight c.g. (P/L out)	
					98 ft	**63.56%**
23.0	RCS/OMS Propellants (on-orbit)			4,787		
24.0	Cargo Discharged			0	0 ft	0
25.0	Ascent Reserve and Unusable Propellants			3,286		
26.0	Inflight Losses and Vents			1,067	77 ft	82183
	Insertion Weight			**115,854**	Insertion weight c.g. (P/L in)	
					103 ft	**66.97%**
27.0	Ascent Propellants			438,187		
	Gross Liftoff Weight			**554,041**	Gross weight c.g. (P/L in)	
					109 ft	**70.80%**
28.0	Startup Losses			1,847		
	Maximum Pre-launch Weight			**555,888**		

Figure 6.8. Sample Sheet from RDS Model: Weights (2)

VI. OPERATIONS

Vehicle: Hyperion 20k - Rev 8/99

* - Response Surface Estimation of AAT&E Operations Cost Model Using Modified Central Composite Design
* - Calibrated by Georgia Tech SSDL for Mach 10 transition, 20 klb payload Hyperion - Rev 8/99.
* - Orbital destination for calibrated version is 100 nmi x 28.5, due east from KSC

VI.a Inputs

No.	Name	Minimum Value	Maximum Value	Value	Units	Comment
VI.a.1	Airframe Life (MTBR)	100	2,000	1,000	Flights	
VI.a.2	Dry Weight	100,000	2,000,000	85,070	lbs	
VI.a.3	Vehicle Length	150	250	154	ft	
VI.a.4	Overall Vehicle Reliability (MTBF)	1,000	10,000,000	9,780	Flights	
VI.a.5	Overall Vehicle Reliability (MTBF)	0.999	0.9999999	0.9998978	Probability	
VI.a.6	LH2 Propellant Weight			109,729	lbs	From Weights Sheet
VI.a.7	LOX Propellant Weight			339,761	lbs	From Weights Sheet
VI.a.8	LH2 Propellant Cost			$ 0.250	$/lb	in FY$1999
VI.a.9	LOX Propellant Cost			$ 0.100	$/lb	in FY$1999

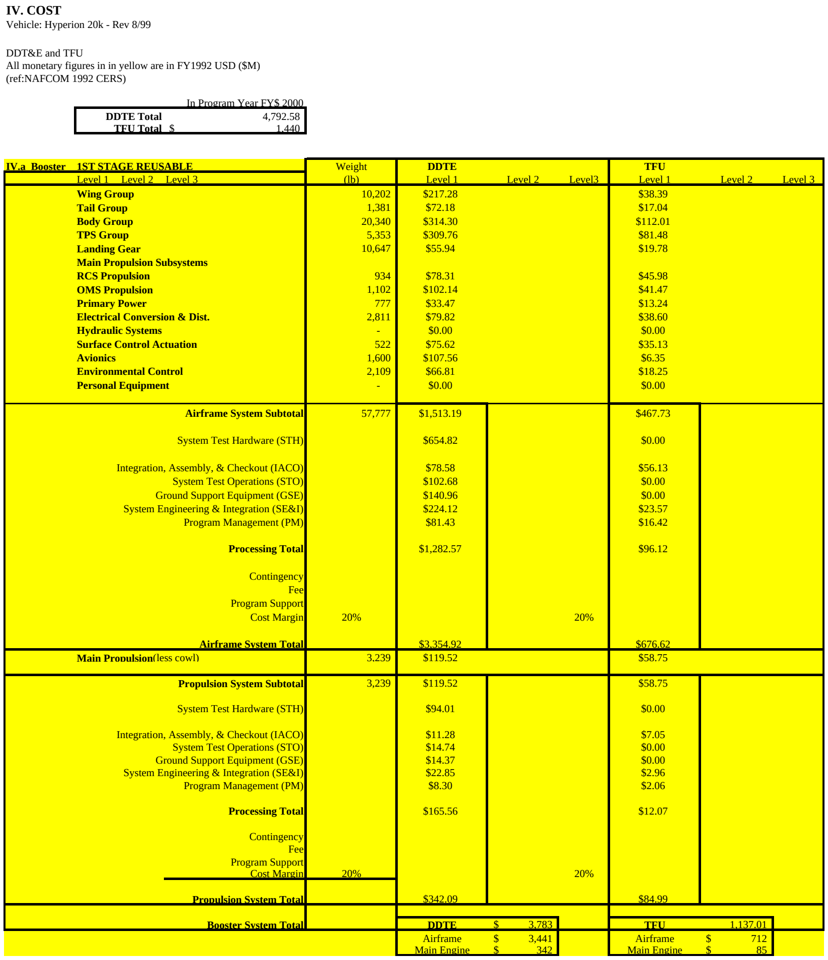
VI.b Parameter Estimates

				in FY$1999		in FY$1999	
		For Ground Turn-Around-Time (Days)		For Facilities Cost		For Labor Cost per Flight	
No.	Name	Parameter Est.	Value	Parameter Est.	Value	Parameter Est.	Value
VI.b.1	Intercept	1314.3668	1314.3668	5780.9176	5780.9176	85.162974	85.162974
VI.b.2	AFLIFE	0.0011122	1.1122	-0.010137	-10.137	-0.001004	-1.004
VI.b.3	DRYWT	0.000529	45.00207889	0.0047516	404.2190511	0.0001301	11.06761902
VI.b.4	LENGTH	3.2695895	503.6013026	58.665618	9036.021691	0.8077666	124.4169373
VI.b.5	AFREL	-1300.943	-1300.809983	-5660.375	-5659.796247	-83.63356	-83.62500877
VI.b.6	AFLIFE*AFLIFE	0.0000004	0.4	0.0000043	4.3	7.2536E-08	0.072536
VI.b.7	DRYWT*AFLIFE	-2.39E-11	-0.002033175	-2.02E-10	-0.017184159	-4.82E-12	-0.000410038
VI.b.8	DRYWT*DRYWT	-1.44E-13	-0.001042117	-2.19E-12	-0.015848856	2.713E-15	1.96338E-05
VI.b.9	LENGTH*AFLIFE	-1.824E-07	-0.028094315	-0.000002	-0.3080517	-3.316E-08	-0.005107497
VI.b.10	LENGTH*DRYWT	7.7273E-09	0.10125076	0.0000001	1.310299331	1.6012E-09	0.020980513
VI.b.11	LENGTH*LENGTH	0.0001908	4.526532052	0.0027616	65.51609494	0.0000306	0.725953254
VI.b.12	AFREL*AFLIFE	-0.00204	-2.039791417	0.0011254	1.125284932	0.000854	0.853912682
VI.b.13	AFREL*DRYWT	-0.000526	-44.7422934	-0.004736	-402.8507634	-0.00013	-11.05798126
VI.b.14	AFREL*LENGTH	-3.321968	-511.6166293	-59.38659	-9146.134762	-0.816685	-125.7777399
VI.b.15	AFREL*AFREL	0	0	0	0	0	0

VI.c Outputs

No.	Name	Value	Units	Comment
VI.c.1	Ground Turn-Around-Time (TAT)	8.8	days	From AATE Response Surface Equation
VI.c.2	Facilities Cost	148.3	USD ($M)	in FY$1999
VI.c.3	Labor Cost per Flight	0.85069	USD ($M) / Flight	in FY$1999
VI.c.4	LRU Cost per Flight	0.15522	USD ($M) / Flight	in FY$1999
VI.c.5	Propellant Cost per Flight	0.06141	USD ($M) / Flight	in FY$1999
VI.c.6	Total Labor Personnel Required per Flight	699	people	Based on total yearly labor cost with FTE salary of $150K in FY$1999
VI.c.7	Maximum Flight Rate	30.7	Flights / year	

Figure 6.9. Sample Sheet from RDS Model: Operations



IV. COST
Vehicle: Hyperion 20k - Rev 8/99

DDT&E and TFU
All monetary figures in in yellow are in FY1992 USD ($M)
(ref:NAFCOM 1992 CERS)

	In Program Year FY$ 2000
DDTE Total	4,792.58
TFU Total $	1,440

IV.a Booster **1ST STAGE REUSABLE** Level 1 Level 2 Level 3	Weight (lb)	**DDTE** Level 1	Level 2	Level3	**TFU** Level 1	Level 2	Level 3
Wing Group	10,202	$217.28			$38.39		
Tail Group	1,381	$72.18			$17.04		
Body Group	20,340	$314.30			$112.01		
TPS Group	5,353	$309.76			$81.48		
Landing Gear	10,647	$55.94			$19.78		
Main Propulsion Subsystems							
RCS Propulsion	934	$78.31			$45.98		
OMS Propulsion	1,102	$102.14			$41.47		
Primary Power	777	$33.47			$13.24		
Electrical Conversion & Dist.	2,811	$79.82			$38.60		
Hydraulic Systems	-	$0.00			$0.00		
Surface Control Actuation	522	$75.62			$35.13		
Avionics	1,600	$107.56			$6.35		
Environmental Control	2,109	$66.81			$18.25		
Personal Equipment	-	$0.00			$0.00		
Airframe System Subtotal	57,777	$1,513.19			$467.73		
System Test Hardware (STH)		$654.82			$0.00		
Integration, Assembly, & Checkout (IACO)		$78.58			$56.13		
System Test Operations (STO)		$102.68			$0.00		
Ground Support Equipment (GSE)		$140.96			$0.00		
System Engineering & Integration (SE&I)		$224.12			$23.57		
Program Management (PM)		$81.43			$16.42		
Processing Total		$1,282.57			$96.12		
Contingency							
Fee							
Program Support							
Cost Margin	20%			20%			
Airframe System Total		$3,354.92			$676.62		
Main Propulsion(less cowl)	3,239	$119.52			$58.75		
Propulsion System Subtotal	3,239	$119.52			$58.75		
System Test Hardware (STH)		$94.01			$0.00		
Integration, Assembly, & Checkout (IACO)		$11.28			$7.05		
System Test Operations (STO)		$14.74			$0.00		
Ground Support Equipment (GSE)		$14.37			$0.00		
System Engineering & Integration (SE&I)		$22.85			$2.96		
Program Management (PM)		$8.30			$2.06		
Processing Total		$165.56			$12.07		
Contingency							
Fee							
Program Support							
Cost Margin	20%			20%			
Propulsion System Total		$342.09			$84.99		
Booster System Total		**DDTE**	$	3,783	**TFU**		1,137.01
		Airframe	$	3,441	Airframe	$	712
		Main Engine	$	342	Main Engine	$	85

Figure 6.10. Sample Sheet from RDS Model: Cost

V. Economics
Vehicle: Hyperion 20k - Rev 8/99

* - All monetary figures in FY2018 USD ($M) constant dollars

V.a Programmatic Schedule and Economic Environment

No.	Name	Value	Units	Comment
V.a.1	Program Start Year and Fiscal Year	2018	FY	
V.a.2	IOC (Initial Operating Capability):	2025	Year	
V.a.3	Number of Years In Program	28	Years	
V.a.4	Number of Flight Years In Program	21	No. of years	
V.a.5	Inflation rate	3.0%	%	
V.a.6	Tax Rate	30.0%	%	
V.a.7	Capital On-hand at Program Start	$ 1,000	USD ($M)	
V.a.8	Amount of Each Equity Offering:	$ 1,000	USD ($M)	Equity Market Accessed 3 Times In Early Part of Program
V.a.9	Average Ann. Interest Rate:	8.00%	%	
V.a.10	Tax Holiday Program Duration	0	No. of years	Item G.4 in VIFs
V.a.11	Commercial Market Growth Factor	30%	%	Item E.2 in VIFs
V.a.12	SG&A Expense Per Year	5	USD ($M)	

V.b Vehicle and Propulsion Cost

No.	Name	Value	Units	Comment
V.b.1	Booster Frame DDT&E Cost	$ 7,421	USD ($M)	From Cost Sheet
V.b.2	Booster Frame TFU Cost	$ 1,536	USD ($M)	From Cost Sheet
V.b.3	Booster Engine DDT&E Cost	$ 738	USD ($M)	From Cost Sheet
V.b.4	Booster Engine TFU Cost	$ 183	USD ($M)	From Cost Sheet

V.c Facilities, Operations and Maintainence (O+M), and Insurance Cost

No.	Name	Value	Units	Comment
V.c.1	Overall Vehicle Reliability (MTBF)	9,780	Flights	Item R.1 in VIFs
V.c.2	Module Based Facilities Cost per Site	$ 260.0	M $/module/site	From Operations Sheet
V.c.3	Ground Turn-Around-Time (TAT)	8.8	days	From Operations Sheet
V.c.4	Labor Cost per Flight	$ 1.492	USD ($M) / Flight	From Operations Sheet
V.c.5	LRU Cost per Flight	$ 0.272	USD ($M) / Flight	From Operations Sheet
V.c.6	Propellant Cost Per Flight	$ 0.108	USD ($M) / Flight	From Operations Sheet
V.c.7	Total Vehicle Recurring Cost / Flight	$ 1.684	USD ($M) / Flight	Item C.6 In VIFs
V.c.8	Max Vehicle Flight Rate Per Year	30.7	Flights / year	From Operations Sheet
V.c.9	Insurance Premium (over estimated loss)	5.0%	%	
V.c.10	Expected Failure Rate	1.022E-04		
V.c.11	Liability Insurance Cost Per Flight	0.26	USD ($M) / Flight	

V.d Government Contribution Assumptions (exclusive of launch prices)

No.	Name	Value	Units	Comment
V.d.1	Airframe DDT&E	25%	%	
V.d.2	Propulsion DDT&E	25%	%	
V.d.3	Airframe TFU	0%	%	
V.d.4	Propulsion TFU	0%	%	
V.d.5	Facilities	100%	%	
V.d.6	Ops. & Maint.	0%	%	

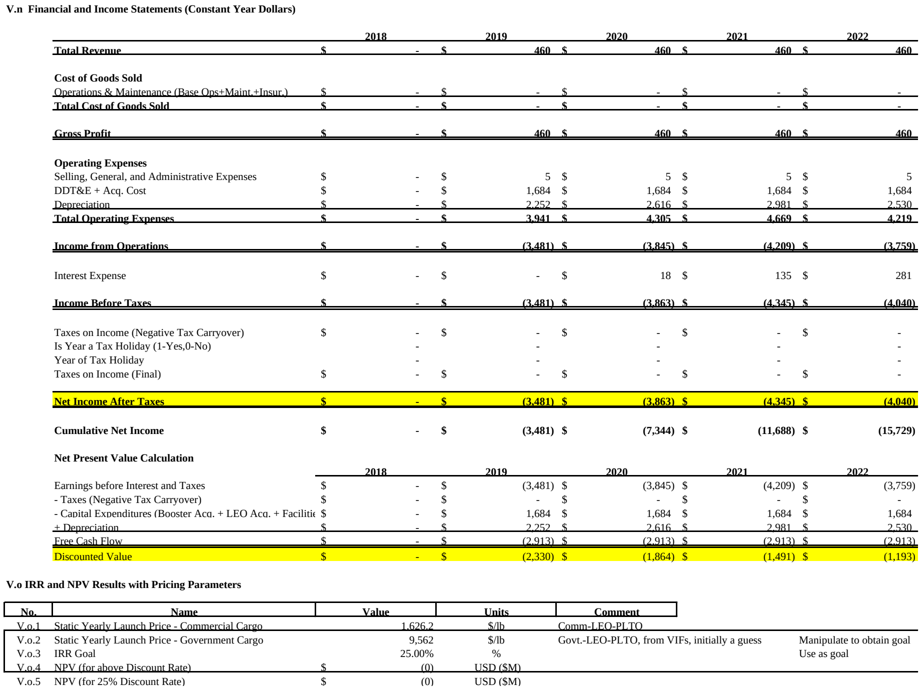
V.e Commercial Cargo (LEO-PLTO) Pricing Summary

No.	Name	Value	Units	Comment
V.e.1	PL Capability (LEO Equiv.)	20,000	lb	
V.e.2	Static Yearly Launch Price	1626.24	$/lb	
V.e.3	Static Yearly Launch Price	32.52	M$/flight	
V.e.4	FY of CSTS Price Curve	1994	FY	Less than FY of Static Yearly Launch Price above
V.e.5	Annual Payload for Charged Price w/o Growth	772	klb	Based upon curve fit of CSTS LEO Cargo Delivery elastic market curve, loses vali
V.e.6	Annual Payload for Charged Price w/Growth	1,003	klb	
V.e.7	Fractional Flight per Year	59.0	Flights / year	
V.e.8	Total Flights in Program	1,239.2	Flights	

V.f Commercial Passenger (LEO-SSA) Pricing Summary

No.	Name	Value	Units	Comment
V.f.1	PL Capability	6	passengers	
V.f.2	Static Yearly Launch Price	1.260	M$/passenger	
V.f.3	Static Yearly Launch Price	7.56	M$/flight	

Figure 6.11. Sample Sheet from RDS Model: Economics (1)



V.n Financial and Income Statements (Constant Year Dollars)

	2018	2019	2020	2021	2022
Total Revenue	**$ -**	**$ 460**	**$ 460**	**$ 460**	**$ 460**
Cost of Goods Sold					
Operations & Maintenance (Base Ops+Maint.+Insur.)	$ -	$ -	$ -	$ -	$ -
Total Cost of Goods Sold	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**
Gross Profit	**$ -**	**$ 460**	**$ 460**	**$ 460**	**$ 460**
Operating Expenses					
Selling, General, and Administrative Expenses	$ -	$ 5	$ 5	$ 5	$ 5
DDT&E + Acq. Cost	$ -	$ 1,684	$ 1,684	$ 1,684	$ 1,684
Depreciation	$ -	$ 2,252	$ 2,616	$ 2,981	$ 2,530
Total Operating Expenses	**$ -**	**$ 3,941**	**$ 4,305**	**$ 4,669**	**$ 4,219**
Income from Operations	**$ -**	**$ (3,481)**	**$ (3,845)**	**$ (4,209)**	**$ (3,759)**
Interest Expense	$ -	$ -	$ 18	$ 135	$ 281
Income Before Taxes	**$ -**	**$ (3,481)**	**$ (3,863)**	**$ (4,345)**	**$ (4,040)**
Taxes on Income (Negative Tax Carryover)	$ -	$ -	$ -	$ -	$ -
Is Year a Tax Holiday (1-Yes,0-No)	-	-	-	-	-
Year of Tax Holiday	-	-	-	-	-
Taxes on Income (Final)	$ -	$ -	$ -	$ -	$ -
Net Income After Taxes	**$ -**	**$ (3,481)**	**$ (3,863)**	**$ (4,345)**	**$ (4,040)**
Cumulative Net Income	**$ -**	**$ (3,481)**	**$ (7,344)**	**$ (11,688)**	**$ (15,729)**

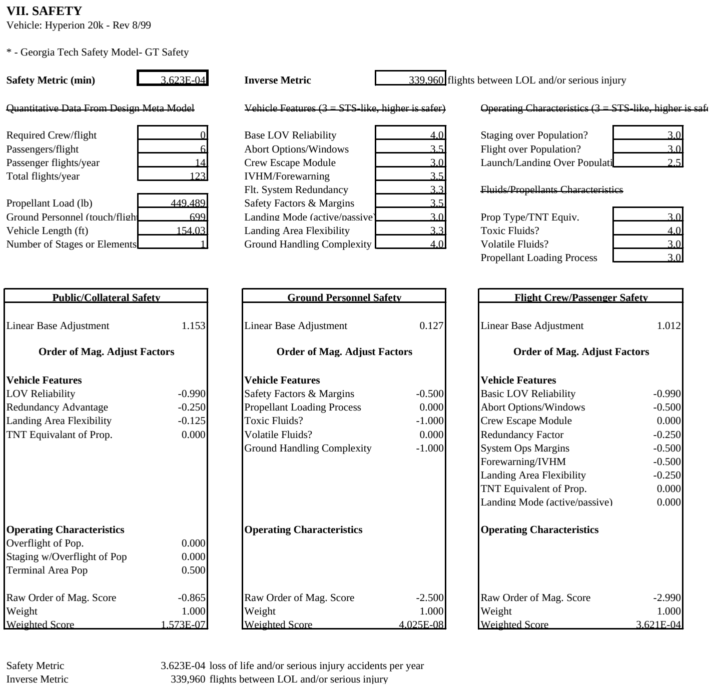
Net Present Value Calculation

	2018	2019	2020	2021	2022
Earnings before Interest and Taxes	$ -	$ (3,481)	$ (3,845)	$ (4,209)	$ (3,759)
- Taxes (Negative Tax Carryover)	$ -	$ -	$ -	$ -	$ -
- Capital Expenditures (Booster Acq. + LEO Acq. + Facilitie	$ -	$ 1,684	$ 1,684	$ 1,684	$ 1,684
+ Depreciation	$ -	$ 2,252	$ 2,616	$ 2,981	$ 2,530
Free Cash Flow	$ -	$ (2,913)	$ (2,913)	$ (2,913)	$ (2,913)
Discounted Value	$ -	$ (2,330)	$ (1,864)	$ (1,491)	$ (1,193)

V.o IRR and NPV Results with Pricing Parameters

No.	Name	Value	Units	Comment	
V.o.1	Static Yearly Launch Price - Commercial Cargo	1,626.2	$/lb	Comm-LEO-PLTO	
V.o.2	Static Yearly Launch Price - Government Cargo	9,562	$/lb	Govt.-LEO-PLTO, from VIFs, initially a guess	Manipulate to obtain goal
V.o.3	IRR Goal	25.00%	%		Use as goal
V.o.4	NPV (for above Discount Rate)	$ (0)	USD ($M)		
V.o.5	NPV (for 25% Discount Rate)	$ (0)	USD ($M)		

Figure 6.12. Sample Sheet from RDS Model: Economics (2)



VII. SAFETY
Vehicle: Hyperion 20k - Rev 8/99

* - Georgia Tech Safety Model- GT Safety

Safety Metric (min) 3.623E-04 **Inverse Metric** 339,960 flights between LOL and/or serious injury

~~Quantitative Data From Design Meta Model~~		~~Vehicle Features (3 = STS-like, higher is safer)~~		~~Operating Characteristics (3 = STS-like, higher is saf~~	
Required Crew/flight	0	Base LOV Reliability	4.0	Staging over Population?	3.0
Passengers/flight	6	Abort Options/Windows	3.5	Flight over Population?	3.0
Passenger flights/year	14	Crew Escape Module	3.0	Launch/Landing Over Populati	2.5
Total flights/year	123	IVHM/Forewarning	3.5		
		Flt. System Redundancy	3.3	~~Fluids/Propellants Characteristics~~	
Propellant Load (lb)	449,489	Safety Factors & Margins	3.5		
Ground Personnel (touch/fligh	699	Landing Mode (active/passive	3.0	Prop Type/TNT Equiv.	3.0
Vehicle Length (ft)	154.03	Landing Area Flexibility	3.3	Toxic Fluids?	4.0
Number of Stages or Elements	1	Ground Handling Complexity	4.0	Volatile Fluids?	3.0
				Propellant Loading Process	3.0

Public/Collateral Safety		**Ground Personnel Safety**		**Flight Crew/Passenger Safety**	
Linear Base Adjustment	1.153	Linear Base Adjustment	0.127	Linear Base Adjustment	1.012
Order of Mag. Adjust Factors		**Order of Mag. Adjust Factors**		**Order of Mag. Adjust Factors**	
Vehicle Features		**Vehicle Features**		**Vehicle Features**	
LOV Reliability	-0.990	Safety Factors & Margins	-0.500	Basic LOV Reliability	-0.990
Redundancy Advantage	-0.250	Propellant Loading Process	0.000	Abort Options/Windows	-0.500
Landing Area Flexibility	-0.125	Toxic Fluids?	-1.000	Crew Escape Module	0.000
TNT Equivalant of Prop.	0.000	Volatile Fluids?	0.000	Redundancy Factor	-0.250
		Ground Handling Complexity	-1.000	System Ops Margins	-0.500
				Forewarning/IVHM	-0.500
				Landing Area Flexibility	-0.250
				TNT Equivalent of Prop.	0.000
				Landing Mode (active/passive)	0.000
Operating Characteristics		**Operating Characteristics**		**Operating Characteristics**	
Overflight of Pop.	0.000				
Staging w/Overflight of Pop	0.000				
Terminal Area Pop	0.500				
Raw Order of Mag. Score	-0.865	Raw Order of Mag. Score	-2.500	Raw Order of Mag. Score	-2.990
Weight	1.000	Weight	1.000	Weight	1.000
Weighted Score	1.573E-07	Weighted Score	4.025E-08	Weighted Score	3.621E-04

Safety Metric	3.623E-04	loss of life and/or serious injury accidents per year
Inverse Metric	339,960	flights between LOL and/or serious injury

Figure 6.13. Sample Sheet from RDS Model: Safety

7.0 APPENDIX B: RESPONSE SURFACE GENERATION OF AATE MODEL FOR RDS MODEL

Since the original AATe spreadsheet-based model developed by NASA KSC is very large in terms of file size, a proxy for AATe to be used in the RDS model was developed using Response Surface Methodology (RSM). The first step was to set up a design of experiments (DoE) using JMP. Four independent variables were inputted into JMP with their corresponding high and low values, these variables and their RSE symbols include:

1.) Airframe Life (MTBR) or AFLIFE
2.) Dry Weight or DRYWT
3.) Vehicle Length or LENGTH
4.) Overall Vehicle Reliability (MTBF) or AFREL

The DoE was then used for response surface generation. A face-centered central composite design (CCD) was chosen for the DoE. A CCD spans a set of quantitative factors with fewer points than a standard Fractional Factorial multi-level design, without a large loss of efficiency. The CCD for the four market variables was a 3-level orthogonal design. This table was then put into AATe in order to obtain the values for the responses. For each of the 25 combinations, five output metrics of interest were recorded; the include 1.) Ground Turn-Around-Time (TAT); 2.) Facilities Cost; 3.) Labor Cost per Flight; 4.) LRU Cost per Flight; and 5.) Maximum Flight Capability per Year.

JMP is a statistical analysis software package that can be used to generate a Design of Experiments (DoE) table, perform an Analysis of Variance (ANOVA), to create Screening Tests and Prediction Profiles, and to attain the regression analysis results. For this portion, JMP was used to create the DoE table for use in the analysis of the response surface equations. The response surface equation approximates the relationship between the response and the design variables. The ANOVA analysis in JMP was used to generate the coefficients for the RSE. The regression analysis shows how good the fit is for the approximation. JMP was also used to create the higher fidelity 3-level DoE prediction profile tables. These were used to generate graphical plots of the response vs. each contributing variable. The prediction profiles show how the variability of each variable affected the given response.

The most popular response surface design is the central composite design. This design combines a two-level fractional factorial with axial points and center points. Axial points are those points in the design for which one variable is set to the outer value and all others are set to their mean value. One of the benefits of using axial points is that one can choose points that are not only on the face of the design, but points outside of the design. These points that are outside of one’s design allow you to get more accurate readings for those values near the edge. Center points are those points for which all the variable values are set at their mean values. Several center points can be used in order to take into account the possibility of experimental error. The experiments were comprised of only computer simulations in which no experimental error was present. Therefore, only one center point was used in the design.

Normalization of the independent variables was the next step in creating the experimental design. This was done mainly for bookkeeping purposes, as it makes the output of the design of experiments grid more legible. It also makes it easier to compare the experimental values with the high and low values. The four independent variables are listed below with their high and low values as well as their respective normalization parameters.

A response surface equation can now be generated using the data collected for each output metric for each simulated DoE case. The general form of a 2nd order polynomial response surface equation is shown below.

$$R = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2 \qquad (2)$$

The first term of this equation (b_o) represents the intercept of the quadratic equation. The second term is linear and represents the main effects of the independent variables. The third and forth terms represent higher order bilinear and quadratic factors of the independent variables. The response surface equation parameters for the 2nd order RSE were calculated using JMP. The results of these calculations can be seen below in Tables 7.1 and 7.2.

Table 7.1. AATe RSE Parameters for Selected Variables (1)

No.	Name	For Ground Turn-Around-Time (Days) Parameter Est.	For Max. Yearly Flight Rate (flights/year) Parameter Est.
VI.b.1	Intercept	1314.3668	-4688.675
VI.b.2	AFLIFE	0.0011122	-0.036095
VI.b.3	DRYWT	0.000529	0.0008426
VI.b.4	LENGTH	3.2695895	4.0576245
VI.b.5	AFREL	-1300.943	4719.29
VI.b.6	AFLIFE*AFLIFE	0.0000004	-6.599E-07
VI.b.7	DRYWT*AFLIFE	-2.39E-11	-5.26E-12
VI.b.8	DRYWT*DRYWT	-1.44E-13	1.359E-12
VI.b.9	LENGTH*AFLIFE	-1.824E-07	7.1228E-08
VI.b.10	LENGTH*DRYWT	7.7273E-09	4.5547E-09
VI.b.11	LENGTH*LENGTH	0.0001908	-0.000237
VI.b.12	AFREL*AFLIFE	-0.00204	0.037566
VI.b.13	AFREL*DRYWT	-0.000526	-0.000852
VI.b.14	AFREL*LENGTH	-3.321968	-4.011351
VI.b.15	AFREL*AFREL	0	0

Table 7.2. AATe RSE Parameters for Selected Variables (2)

No.	Name	in FY$1999 For Facilities Cost Parameter Est.	in FY$1999 For Labor Cost per Flight Parameter Est.	in FY$1999 For LRU Cost per Flight Parameter Est.
VI.b.1	Intercept	5780.9176	85.162974	14.790715
VI.b.2	AFLIFE	-0.010137	-0.001004	-0.000173
VI.b.3	DRYWT	0.0047516	0.0001301	0.000021
VI.b.4	LENGTH	58.665618	0.8077666	0.1503536
VI.b.5	AFREL	-5660.375	-83.63356	-14.52124
VI.b.6	AFLIFE*AFLIFE	0.0000043	7.2536E-08	1.141E-08
VI.b.7	DRYWT*AFLIFE	-2.02E-10	-4.82E-12	-7.69E-13
VI.b.8	DRYWT*DRYWT	-2.19E-12	2.713E-15	2.214E-16
VI.b.9	LENGTH*AFLIFE	-0.000002	-3.316E-08	-6.228E-09
VI.b.10	LENGTH*DRYWT	0.0000001	1.6012E-09	2.966E-10
VI.b.11	LENGTH*LENGTH	0.0027616	0.0000306	0.0000052
VI.b.12	AFREL*AFLIFE	0.0011254	0.000854	0.0001497
VI.b.13	AFREL*DRYWT	-0.004736	-0.00013	-0.000021
VI.b.14	AFREL*LENGTH	-59.38659	-0.816685	-0.151864
VI.b.15	AFREL*AFREL	0	0	0

8.0 APPENDIX C: VISUAL BASIC FOR APPLICATIONS (VBA) SCRIPTS FOR RDS MODEL

8.1 LEARNING CURVE ROUTINE

```
Option Explicit

Function Learningcurve(lcpercent As Double, produced As Integer, toproduce As Integer) As Double


' Calculates effect of the learning curve given the number of units being produced

'

' Inputs:

'   lcpercent = learning curve percentage (expressed as a decimal)

'   produced = number of units already produced

'   toproduce = number of units to produce in a given interval

'

' Outputs:

'   Learningcurve = number of cumulative units made (fractional)

'

' Multiply the output,

' Learningcurve, by TFU cost to obtain the acquisition cost for toproduce units

'

'Application.Volatile


If (toproduce <= 0 Or lcpercent = 0 Or produced < 0) Then


Learningcurve = 0


Exit Function


End If
```

```
Dim k As Integer

Dim lcmatrix() As Double


' Create a matrix, lcmatrix to hold the learning curve effect on each kth unit


ReDim lcmatrix(produced + toproduce, 2)

Dim sumtoproduce As Double

sumtoproduce = 0


' First column in lcmatrix is signifier of kth unit made


For k = 0 To (produced + toproduce - 1)

    lcmatrix(k, 1) = k + 1

Next k


' Second column in lcmatrix is signifier of the learning curve effect on each kth unit


For k = 0 To (produced + toproduce - 1)

    lcmatrix(k, 2) = lcmatrix(k, 1) ^ (Application.WorksheetFunction.Ln(lcpercent) / Application.WorksheetFunction.Ln(2))

Next k


' sumtoproduce = number of cumulative units made

' from number of units already produced to the number of units to produce


For k = (produced) To (produced + toproduce - 1)

    sumtoproduce = sumtoproduce + lcmatrix(k, 2)
```

```
Next k

Learningcurve = sumtoproduce

End Function
```

8.2 IO SOLVER ROUTINE

```
Option Explicit
Sub IOSolver()

' Uses MS Solver to converge the vehicle for a given set of inputs
' Performs the solver routine until the value of the "solved for" value
' reaches s specifiued tolerance below
'Application.Volatile

' Initialize static variables
Dim counter_continue As Integer
Dim tolerance_temp As Double
Dim end_iterations As Integer
Dim iterations_counter As Integer

' Define static variables
' Tolerance_temp for convergence
' End_interations to determine the number of overall iterations to stop at
' Define an iterations counter
counter_continue = 1
tolerance_temp = 0.01
end_iterations = 5
```

```
iterations_counter = 1


' Select the inputs and outputs sheet

Worksheets("Inputs & Outputs").Activate


' Reset the solver for this iteration

SolverReset


' Perform until the value of the "solved for" value is less than the tolerance_temp value

' Acts to initiate a new solver iteration, resetting solver and running

While (counter_continue = 1 And iterations_counter < end_iterations)


    ' Set up the options for solver

    SolverOptions MaxTime:=30, Iterations:=100, Precision:=0.01, _

        AssumeLinear:=False, StepThru:=False, Estimates:=2, Derivatives:=2, _

        SearchOption:=1, IntTolerance:=5, Scaling:=True, Convergence:=0.01, _

        AssumeNonNeg:=False


    ' Set up the constraint for solver

    SolverAdd CellRef:="$F$84", Relation:=2, FormulaText:="0"


    ' Initialize the solver and run

    SolverOK SetCell:=Range("$F$83"), MaxMinVal:=3, ValueOf:="0", _

        ByChange:=Range("$F$85:$F$86")

    SolverSolve UserFinish:=True


    ' If the value of the "solved for" value is less than the tolerance than stop

    If Abs(Range("$F$83").Value) < tolerance_temp Then
```

```
        counter_continue = 0
    End If


    ' Increment the iteration counters
    iterations_counter = iterations_counter + 1


Wend


End Sub
```

8.3 DETERMINISTIC DOE ROUTINE

```
Option Explicit
Sub DeterministicDOE()


' Uses MS Solver to converge the vehicle for a given set of inputs
' Performs the solver routine until the value of the "solved for" value
' reaches a specified tolerance below
' Performs for a given input DOE set of possible technologies and
'  guesses for vehicle length and government price per lb
'Application.Volatile


Dim main_counter As Integer
Dim end_counter As Integer


main_counter = 91
end_counter = 92


While main_counter <= end_counter
```

```
' Copy the initial values of the DOE run
Sheets("Determ. DOE").Select
Range(Cells(main_counter + 4, 3), Cells(main_counter + 4, 13)).Select
Selection.Copy

Sheets("Tech. Select").Select
Cells(14, 3).Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=False

Sheets("Inputs & Outputs").Select

' Paste an initial guess for Solver
' Initial guesses in cells for vehicle length and government price per lb
Range(Cells(94, 8), Cells(95, 8)).Select
Selection.Copy
Cells(85, 6).Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=False

' Uses MS Solver to converge the vehicle for a given set of inputs
' Performs the solver routine until the value of the "solved for" value
' reaches a specified tolerance below
'Application.Volatile

' Initialize static variables
Dim counter_continue As Integer
Dim tolerance_temp As Double
Dim end_iterations As Integer
```

```
Dim iterations_counter As Integer


' Define static variables

' Tolerance_temp for convergence

' End_interations to determine the number of overall iterations to stop at

' Define an iterations counter

counter_continue = 1

tolerance_temp = 0.001

end_iterations = 5

iterations_counter = 1


' Select the inputs and outputs sheet

Worksheets("Inputs & Outputs").Activate


' Reset the solver for this iteration

SolverReset


' Perform until the value of the "solved for" value is less than the tolerance_temp value

' Acts to initiate a new solver iteration, resetting solver and running

While (counter_continue = 1 And iterations_counter < end_iterations)


    ' Set up the options for solver

    SolverOptions MaxTime:=30, Iterations:=100, Precision:=0.01, _

        AssumeLinear:=False, StepThru:=False, Estimates:=2, Derivatives:=2, _

        SearchOption:=1, IntTolerance:=5, Scaling:=True, Convergence:=0.01, _

        AssumeNonNeg:=False


    ' Set up the constraint for solver
```

```
    SolverAdd CellRef:="$F$84", Relation:=2, FormulaText:="0"

    ' Initialize the solver and run
    SolverOK SetCell:=Range("$F$83"), MaxMinVal:=3, ValueOf:="0", _
        ByChange:=Range("$F$85:$F$86")
    SolverSolve UserFinish:=True

    ' If the value of the "solved for" value is less than the tolerance than stop
    If Abs(Range("$F$83").Value) < tolerance_temp Then
        counter_continue = 0
    End If

    ' Increment the iteration counters
    iterations_counter = iterations_counter + 1

Wend

' Copy the current values of the output variables to the Deterministic DOE table
Range(Cells(91, 4), Cells(104, 4)).Select
'Range("D91:D102").Select
Selection.Copy
Sheets("Determ. DOE").Select

Cells(main_counter + 4, 15).Select
'Range("O5").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=True

' Increment the main counter by 1
```

```
main_counter = main_counter + 1


Wend


End Sub
```

9.0 APPENDIX D: LISTING OF COMPUTATIONAL CODES

Cost And Business Analysis Module (CABAM)

CABAM is an economic and business model for evaluating reusable launch vehicles. The model is a complete life cycle cost model developed as a Microsoft Excel spreadsheet. CABAM was developed and is currently being maintained at the Georgia Institute of Technology under Dr. John Olds. Assumptions about the economic environment (tax rate, inflation rate, etc.), payload size of vehicle, component vehicle weights, complexity factors, operations costs, and facilities costs are coupled with market forecast models and a pricing strategy to yield various economic results like IRR, NPV, cash flows, and complete Life Cycle Costs.

Crystal Ball

Crystal Ball is a Monte Carlo simulation tool used as an add-in to the Microsoft Excel spreadsheet. Various distributions can be selected for assumption cells to yield statistical results for forecast cells that are outputs of the assumption cells. Crystal Ball is a user-friendly, graphically oriented forecasting and risk analysis program that provides the probability of certain outcomes (Crystal Ball Manual). It uses Monte Carlo simulation to forecast the entire range of results possible for a given situation. Furthermore, it shows the designer's confidence levels, so that the likelihood of a specific event taking place is known. Crystal Ball is preferred for such research work since it allows the designer to determine whether the project will stay within budget, the chance that the project will finish on time, and how likely it is to achieve a certain level of profitability.

JMP

JMP is a statistical analysis software package that was used to generate the Design of Experiments (DoE) table, perform the Analysis of Variance (ANOVA), to create the Screening Tests and Prediction Profiles, and to attain the regression analysis results. The ANOVA was performed on the DoE in order to determine the relationship between the response and the noise/control variables.

10.0 APPENDIX E: DETERMINISTIC RDS MODEL OUTPUTS

Table 10.1 Technology Combinations for TOPSIS Top 25 Deterministic Rankings

Case	Technologies (1 = Inclusion, -1 = Exclusion)										
	A	B	C	D	E	F	G	H	I	J	K
1	1	1	1	1	1	1	1	1	-1	1	1
2	1	1	1	1	1	1	1	1	-1	1	-1
3	1	1	1	1	1	1	1	1	-1	-1	1
4	1	1	1	1	1	1	1	1	-1	-1	-1
17	1	1	1	1	1	-1	1	1	-1	1	1
18	1	1	1	1	1	-1	1	1	-1	1	-1
19	1	1	1	1	1	-1	1	1	-1	-1	1
20	1	1	1	1	1	-1	1	1	-1	-1	-1
33	1	1	1	1	-1	1	1	1	-1	1	1
34	1	1	1	1	-1	1	1	1	-1	1	-1
35	1	1	1	1	-1	1	1	1	-1	-1	1
49	1	1	1	1	-1	-1	1	1	-1	1	1
50	1	1	1	1	-1	-1	1	1	-1	1	-1
51	1	1	1	1	-1	-1	1	1	-1	-1	1
97	1	1	1	-1	-1	1	1	1	-1	1	1
98	1	1	1	-1	-1	1	1	1	-1	1	-1
99	1	1	1	-1	-1	1	1	1	-1	-1	1
113	1	1	1	-1	-1	-1	1	1	-1	1	1
129	1	1	-1	1	1	1	1	1	-1	1	1
131	1	1	-1	1	1	1	1	1	-1	-1	1
257	1	-1	1	1	1	1	1	1	-1	1	1
258	1	-1	1	1	1	1	1	1	-1	1	-1
259	1	-1	1	1	1	1	1	1	-1	-1	1
260	1	-1	1	1	1	1	1	1	-1	-1	-1
273	1	-1	1	1	1	-1	1	1	-1	1	1
274	1	-1	1	1	1	-1	1	1	-1	1	-1
275	1	-1	1	1	1	-1	1	1	-1	-1	1
276	1	-1	1	1	1	-1	1	1	-1	-1	-1
289	1	-1	1	1	-1	1	1	1	-1	1	1
290	1	-1	1	1	-1	1	1	1	-1	1	-1
291	1	-1	1	1	-1	1	1	1	-1	-1	1
305	1	-1	1	1	-1	-1	1	1	-1	1	1
307	1	-1	1	1	-1	-1	1	1	-1	-1	1
353	1	-1	1	-1	-1	1	1	1	-1	1	1
354	1	-1	1	-1	-1	1	1	1	-1	1	-1
369	1	-1	1	-1	-1	-1	1	1	-1	1	1
385	1	-1	-1	1	1	1	1	1	-1	1	1
387	1	-1	-1	1	1	1	1	1	-1	-1	1
401	1	-1	-1	1	1	-1	1	1	-1	1	1
513	-1	1	1	1	1	1	1	1	-1	1	1
515	-1	1	1	1	1	1	1	1	-1	-1	1
516	-1	1	1	1	1	1	1	1	-1	-1	-1
529	-1	1	1	1	1	-1	1	1	-1	1	1
531	-1	1	1	1	1	-1	1	1	-1	-1	1
545	-1	1	1	1	-1	1	1	1	-1	1	1
546	-1	1	1	1	-1	1	1	1	-1	1	-1
547	-1	1	1	1	-1	1	1	1	-1	-1	1
561	-1	1	1	1	-1	-1	1	1	-1	1	1
609	-1	1	1	-1	-1	1	1	1	-1	1	1
769	-1	-1	1	1	1	1	1	1	-1	1	1
770	-1	-1	1	1	1	1	1	1	-1	1	-1
771	-1	-1	1	1	1	1	1	1	-1	-1	1
772	-1	-1	1	1	1	1	1	1	-1	-1	-1
785	-1	-1	1	1	1	-1	1	1	-1	1	1
786	-1	-1	1	1	1	-1	1	1	-1	1	-1
787	-1	-1	1	1	1	-1	1	1	-1	-1	1
788	-1	-1	1	1	1	-1	1	1	-1	-1	-1
801	-1	-1	1	1	-1	1	1	1	-1	1	1
803	-1	-1	1	1	-1	1	1	1	-1	-1	1
817	-1	-1	1	1	-1	-1	1	1	-1	1	1
865	-1	-1	1	-1	-1	1	1	1	-1	1	1

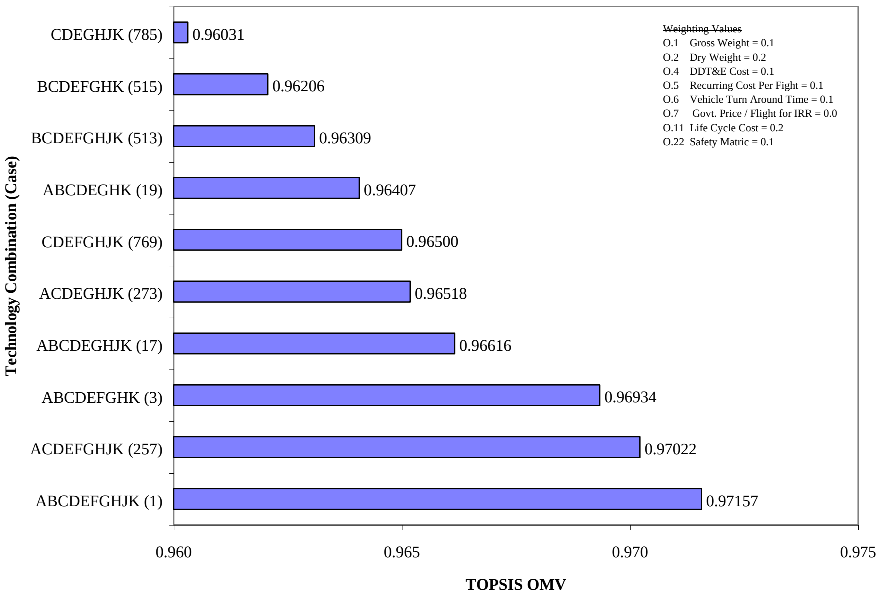


Figure 10.1. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 1

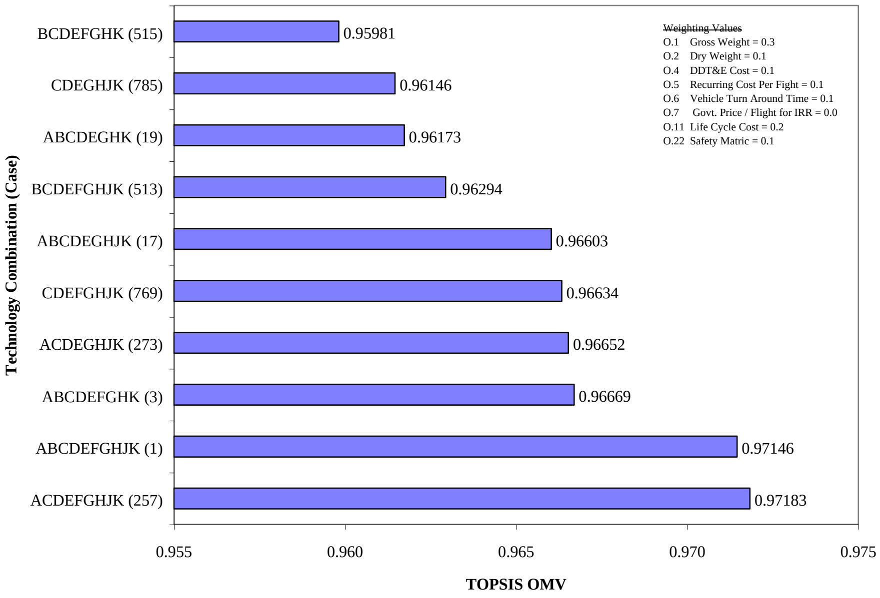


Figure 10.2. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 2

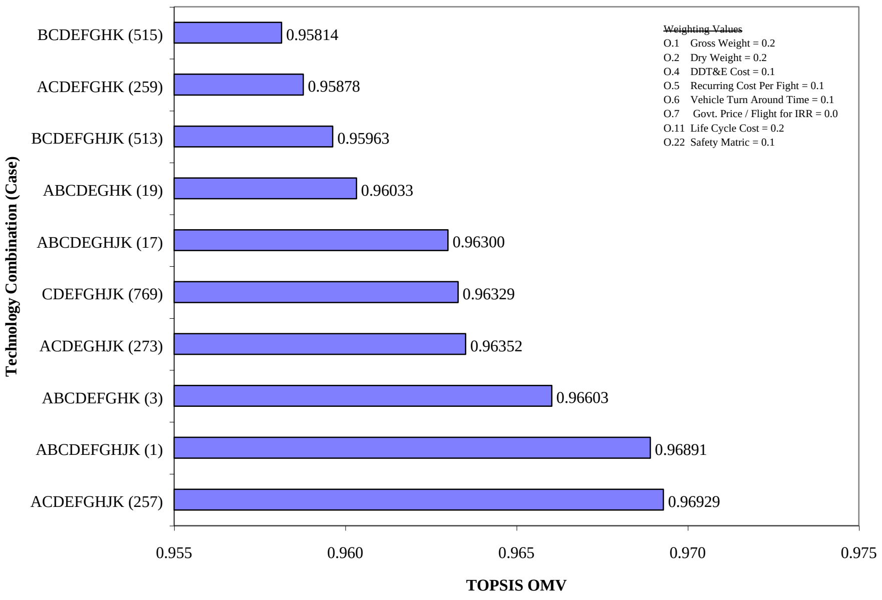


Figure 10.3. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 3

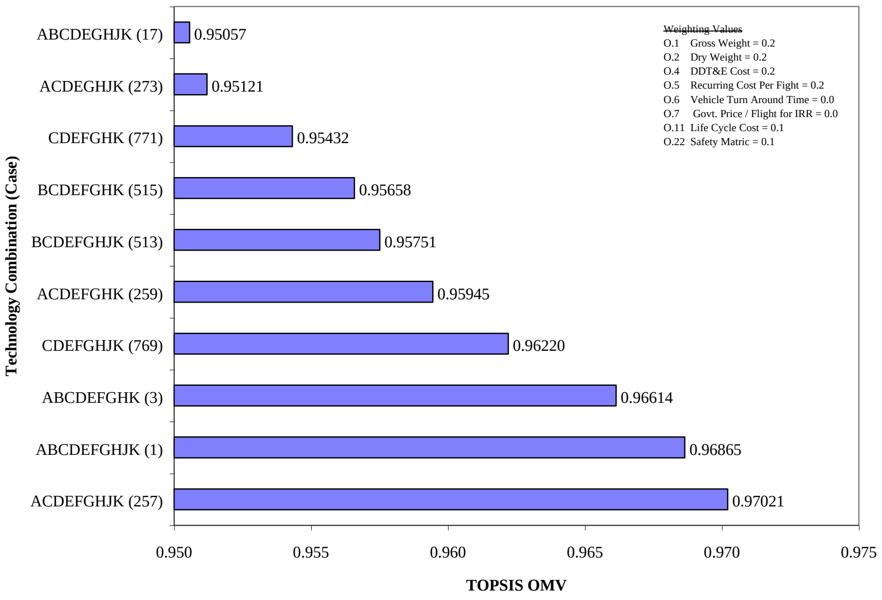


Figure 10.4. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 4

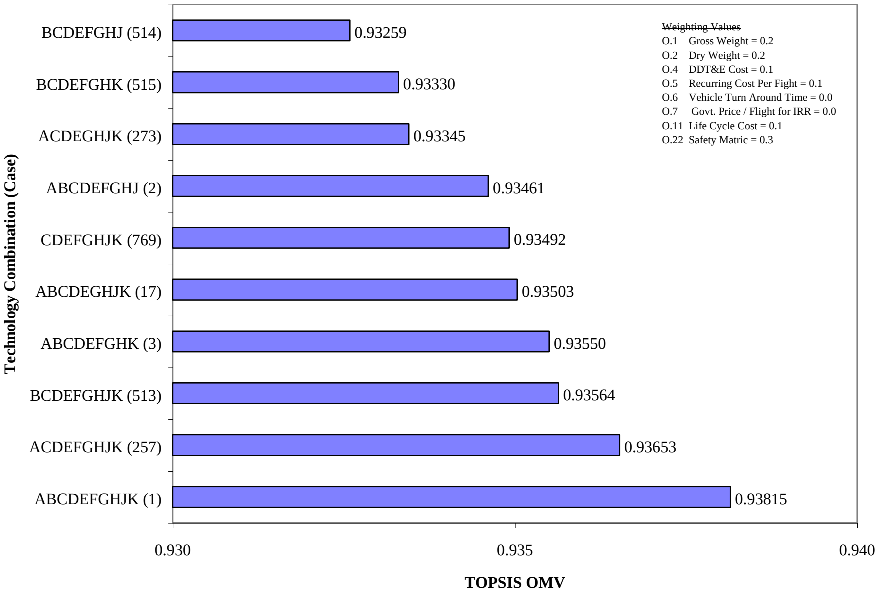


Figure 10.5. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 5

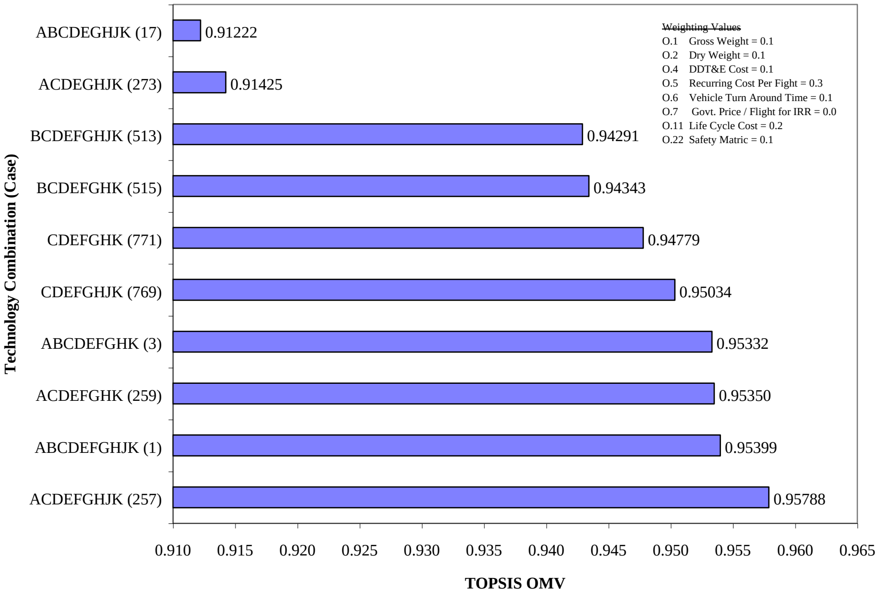


Figure 10.6. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 6

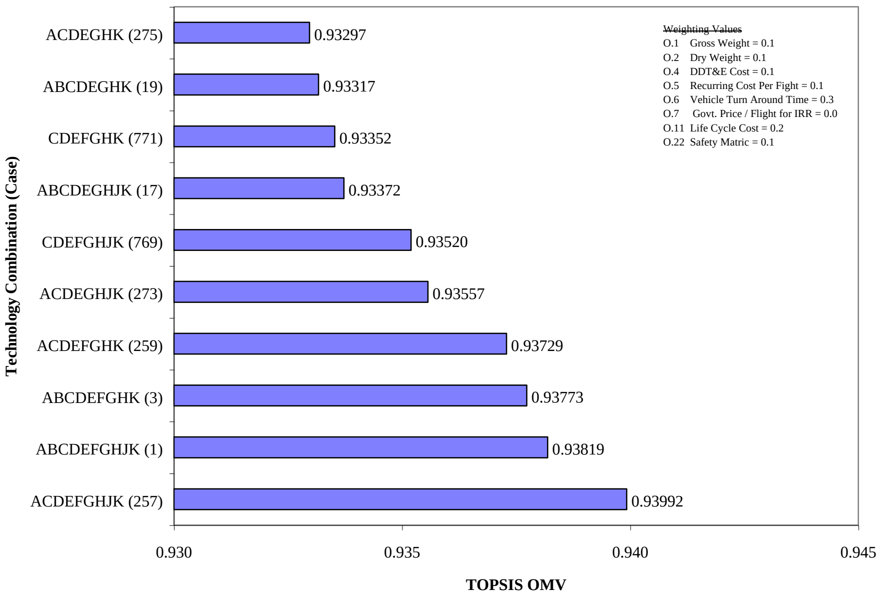


Figure 10.7. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 7

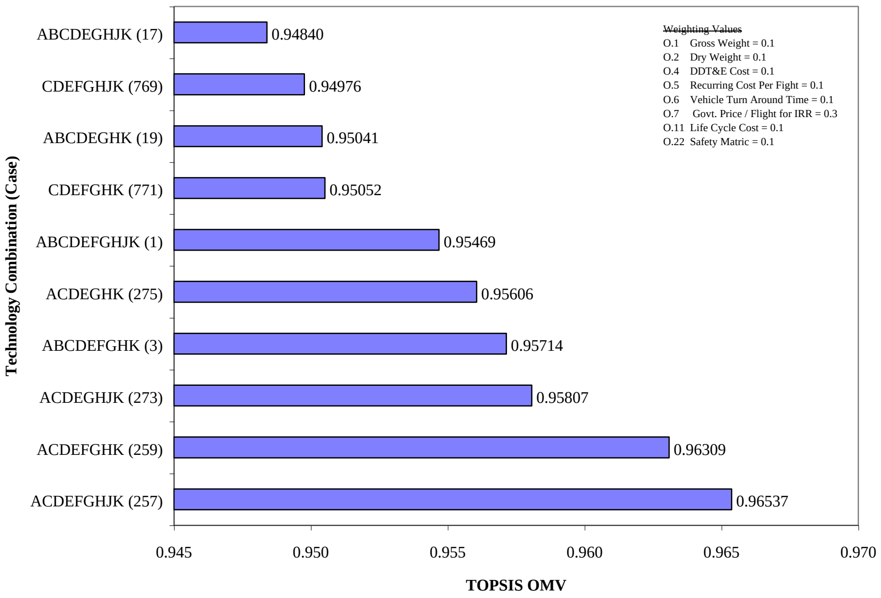


Figure 10.8. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 8

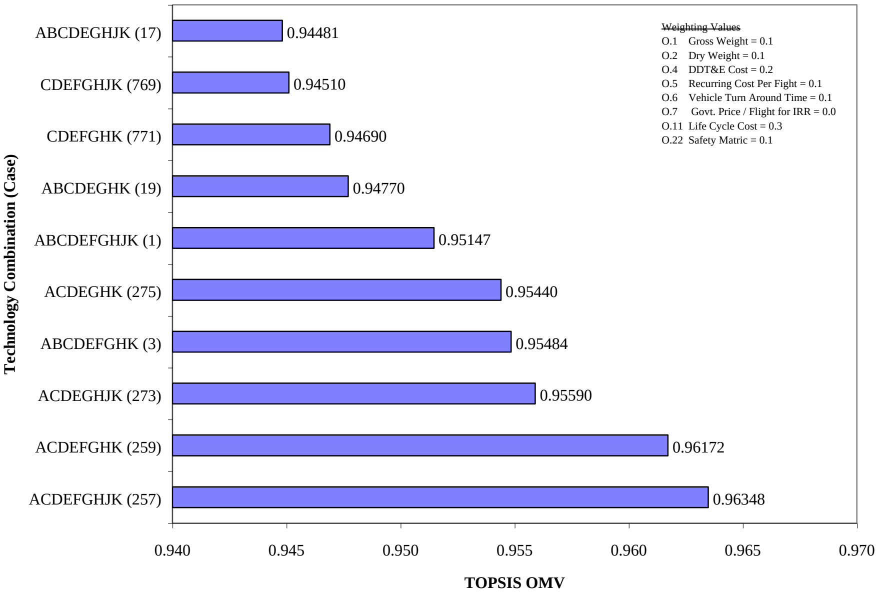


Figure 10.9. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 9

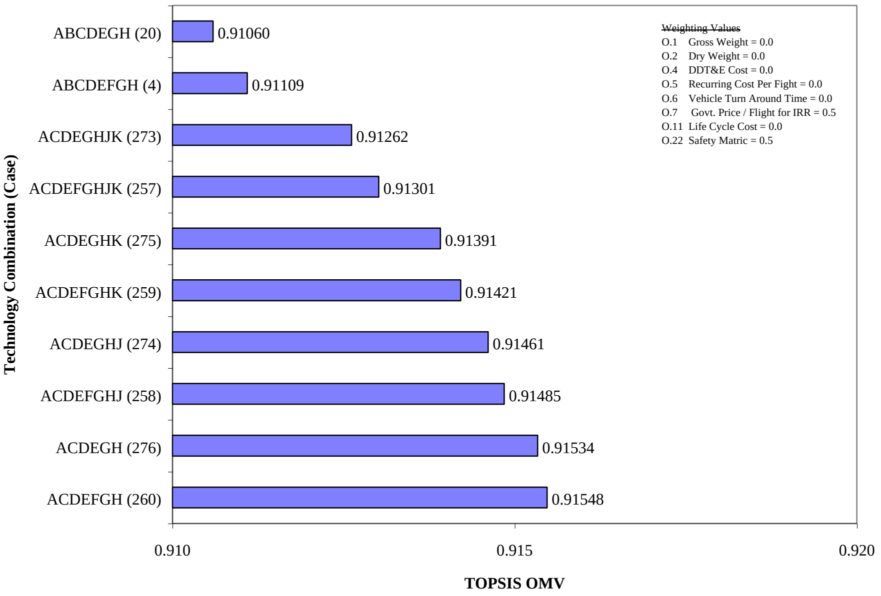


Figure 10.10. TOPSIS OEC Ranking of Top 10 Technology Combinations for WS 11

11.0 APPENDIX E: PROBABILISTIC RDS MODEL OUTPUTS

Table 11.1. Probabilistic Forecast Statistics (1)

Statistics	Dry Weight	Gross Weight	Fuselage Length
Trials	1000	1000	1000
Mean	51,117	321,567	126.6
Median	50,968	321,574	126.6
Mode	---	---	---
Standard Deviation	2,659	20,796	3.1
Variance	7,072,244	432,484,553	9.7
Skewness	0.08	0.04	-0.07
Kurtosis	2.79	2.57	2.53
Coeff. of Variability	0.05	0.06	0.02
Range Minimum	43,607	267,528	118.1
Range Maximum	59,553	382,284	135.0
Range Width	15,946	114,757	16.9
Mean Std. Error	84.10	657.64	0.10

Table 11.2. Probabilistic Forecast Statistics (2)

Statistics	DDT&E cost	Recurring cost / flight	Vehicle Turnaround Time
Trials	1000	1000	1000
Mean	3,875	0.94	6.55
Median	3,881	0.94	6.55
Mode	---	---	---
Standard Deviation	141	0.05	0.45
Variance	19,970	0.00	0.20
Skewness	-0.13	-0.13	-0.08
Kurtosis	3.02	2.71	2.79
Coeff. of Variability	0.04	0.05	0.07
Range Minimum	3,383	0.78	5.00
Range Maximum	4,325	1.07	7.77
Range Width	942	0.29	2.77
Mean Std. Error	4.47	0.00	0.01

Table 11.3. Probabilistic Forecast Statistics (3)

Statistics	Govt. Price / lb (required for IRR)	Life cycle cost (LCC)	Safety Metric
Trials	1000	1000	1000
Mean	3,988.3	46,740	393,071
Median	3,990.9	46,771	392,194
Mode	---	---	---
Standard Deviation	178.0	1,813	17,401
Variance	31,695.6	3,288,170	302,806,995
Skewness	-0.06	-0.03	0.22
Kurtosis	2.95	2.99	2.59
Coeff. of Variability	0.04	0.04	0.04
Range Minimum	3,391.5	40,671	350,471
Range Maximum	4,602.5	52,871	439,977
Range Width	1,211.0	12,201	89,506
Mean Std. Error	5.63	57.34	550.28

Table 11.4. Percentiles

Percentiles	Dry Weight	Gross Weight	Fuselage Length	DDT&E cost	Recurring cost / flight	Vehicle Turnaround Time	Govt. Price / lb (required for IRR)	Life cycle cost (LCC)	Safety Metric
0.0%	43,607	267,528	118.1	3,383	0.78	5.00	3,391.5	40,671	350,471
2.5%	45,899	282,239	120.5	3,582	0.83	5.63	3,634.4	43,108	362,800
5.0%	46,571	287,222	121.3	3,631	0.85	5.80	3,680.1	43,637	366,525
50.0%	50,968	321,574	126.6	3,881	0.94	6.55	3,990.9	46,771	392,194
95.0%	55,602	356,472	131.6	4,100	1.01	7.27	4,280.6	49,729	423,892
97.5%	56,291	363,031	132.5	4,139	1.02	7.44	4,334.4	50,239	429,398
100.0%	59,553	382,284	135.0	4,325	1.07	7.77	4,602.5	52,871	439,977

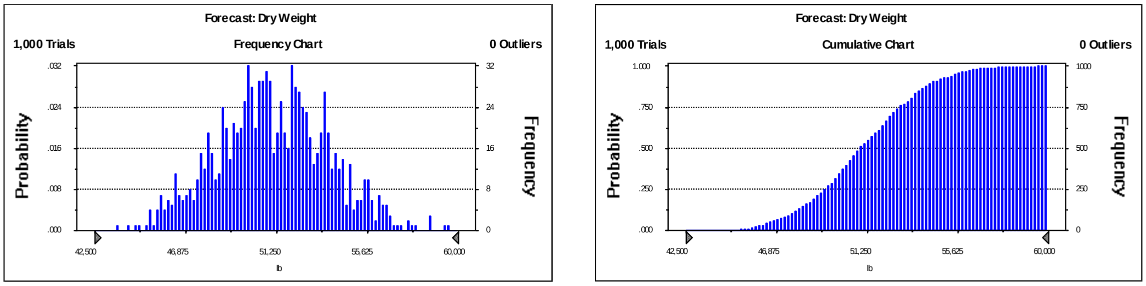


Figure 11.1. Dry Weight Frequency and Cumulative Distributions

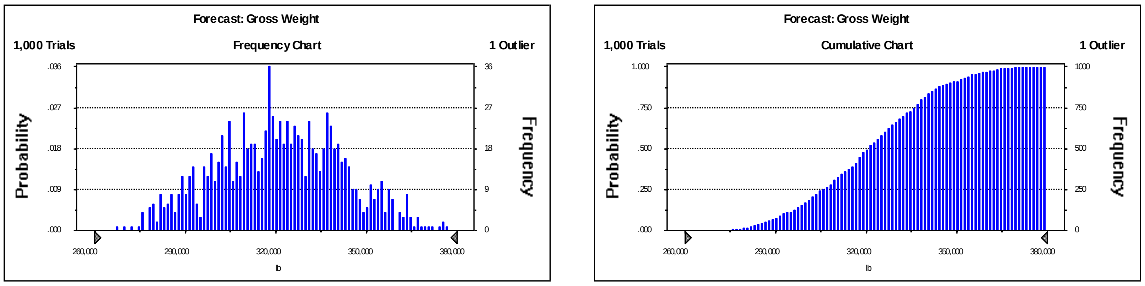


Figure 11.2. Gross Weight Frequency and Cumulative Distributions

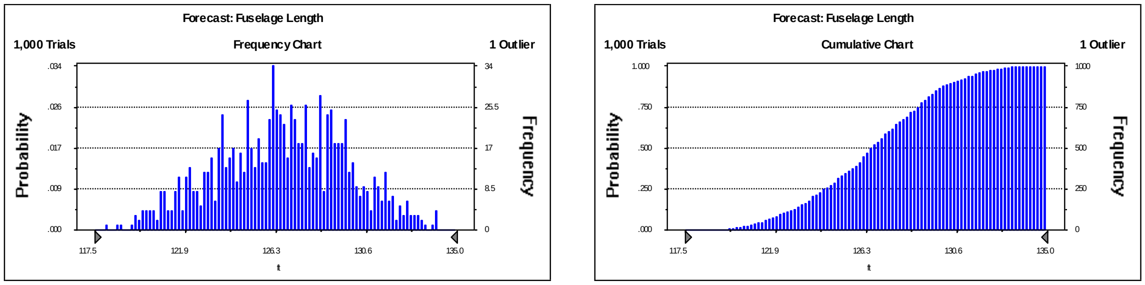


Figure 11.3. Fuselage Length Frequency and Cumulative Distributions

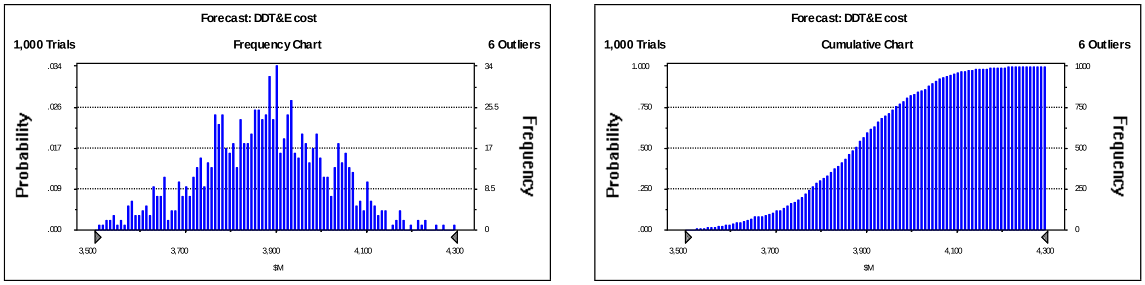


Figure 11.4. DDT&E Cost Frequency and Cumulative Distributions

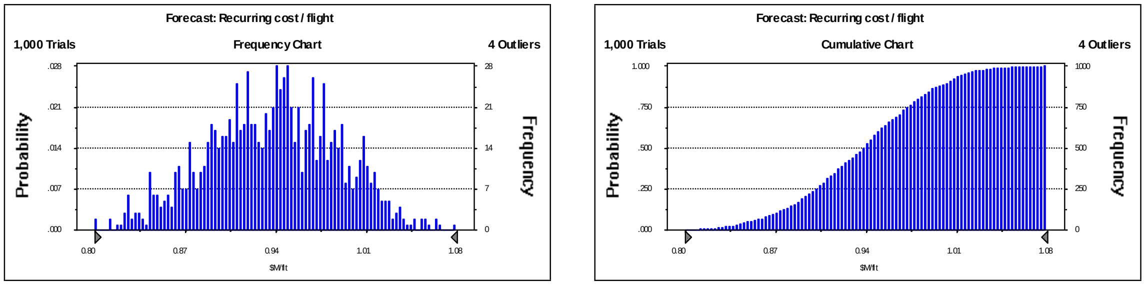


Figure 11.5. Recurring Cost per Flight Frequency and Cumulative Distributions

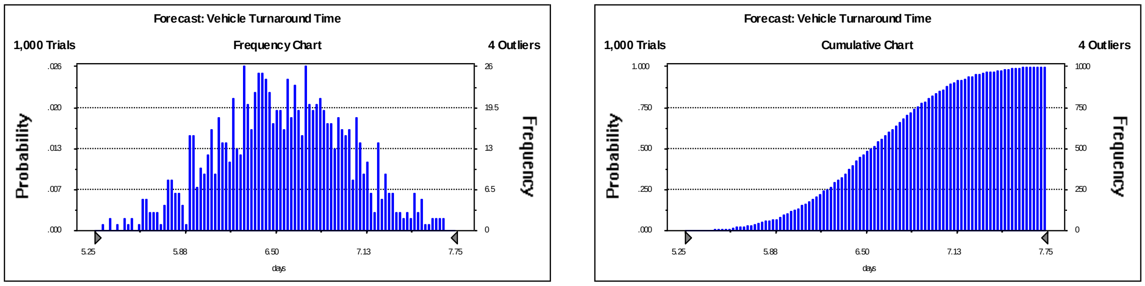


Figure 11.6. Vehicle TAT Frequency and Cumulative Distributions

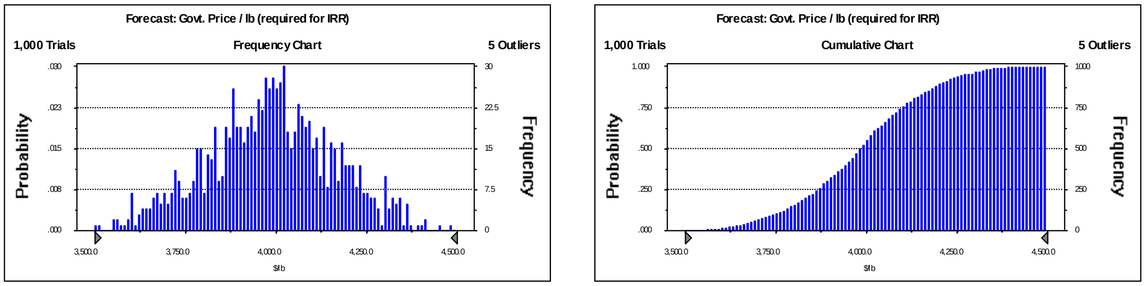


Figure 11.7. Government Price per lb Frequency and Cumulative Distributions

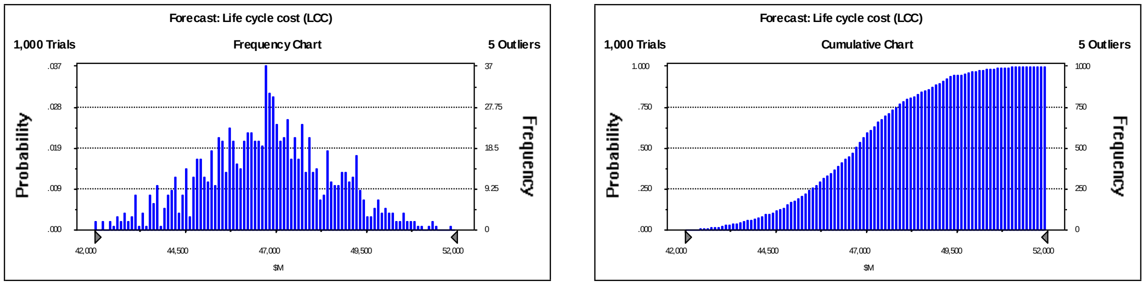


Figure 11.8. Life Cycle Cost (LCC) Frequency and Cumulative Distributions

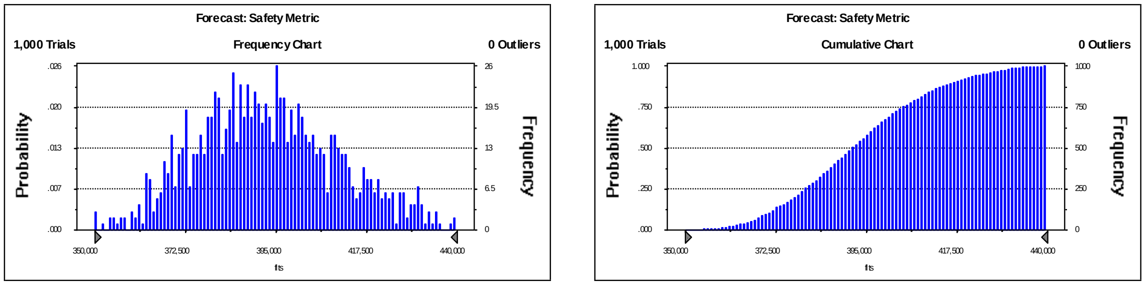


Figure 11.9. Safety Metric Frequency and Cumulative Distributions

Table 11.5. Absolute Sensitivity Data

Tech. + k factor*	Dry Weight	Gross Weight	Fuselage Length	DDT&E cost	Recurring cost / flight	Vehicle Turnaround Time	Govt. Price / lb (required for IRR)	Life cycle cost (LCC)	Safety Metric
A.16	0.0	0.0	0.0	0.5	0.0	0.0	0.4	0.4	0.0
B.16	0.0	0.0	0.0	0.2	0.1	0.0	0.1	0.2	0.0
B.18	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
B.7	0.2	0.2	0.2	0.1	0.0	0.0	0.2	0.2	0.0
C.15	0.2	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0
C.16	0.1	0.1	0.1	0.2	0.1	0.0	0.1	0.2	0.0
C.18	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
C.6	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0
C.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C.8	0.1	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0
D.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D.20	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.1	0.1
D.21	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
D.24	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.4
E.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E.19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
E.20	0.0	0.0	0.0	0.1	0.7	0.0	0.1	0.1	0.0
E.21	0.0	0.0	0.0	0.1	0.0	0.4	0.0	0.1	0.0
E.24	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.8
F.20	0.0	0.1	0.1	0.1	0.4	0.0	0.1	0.1	0.0
G.11	0.2	0.1	0.1	0.2	0.0	0.0	0.2	0.2	0.0
G.15	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0
G.20	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0
G.21	0.1	0.1	0.1	0.0	0.0	0.4	0.0	0.1	0.0
G.24	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.4
G.4	0.2	0.2	0.2	0.1	0.0	0.1	0.1	0.1	0.0
G.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
H.1	0.8	0.9	0.9	0.6	0.1	0.1	0.6	0.6	0.0
H.17	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
H.19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H.23	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
H.24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
H.9	0.2	0.1	0.1	0.1	0.0	0.0	0.2	0.2	0.0
I.17	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
I.19	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0
I.23	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
I.24	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
I.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
J.16	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0
J.18	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
J.2	0.2	0.2	0.2	0.1	0.0	0.1	0.1	0.1	0.0
J.8	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0
K.16	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0
K.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
K.20	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0
K.21	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
K.22	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
K.8	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0

Note: * Nomenclature indicates [Technology I.D. Letter].[Technical k factor I.D. Number]

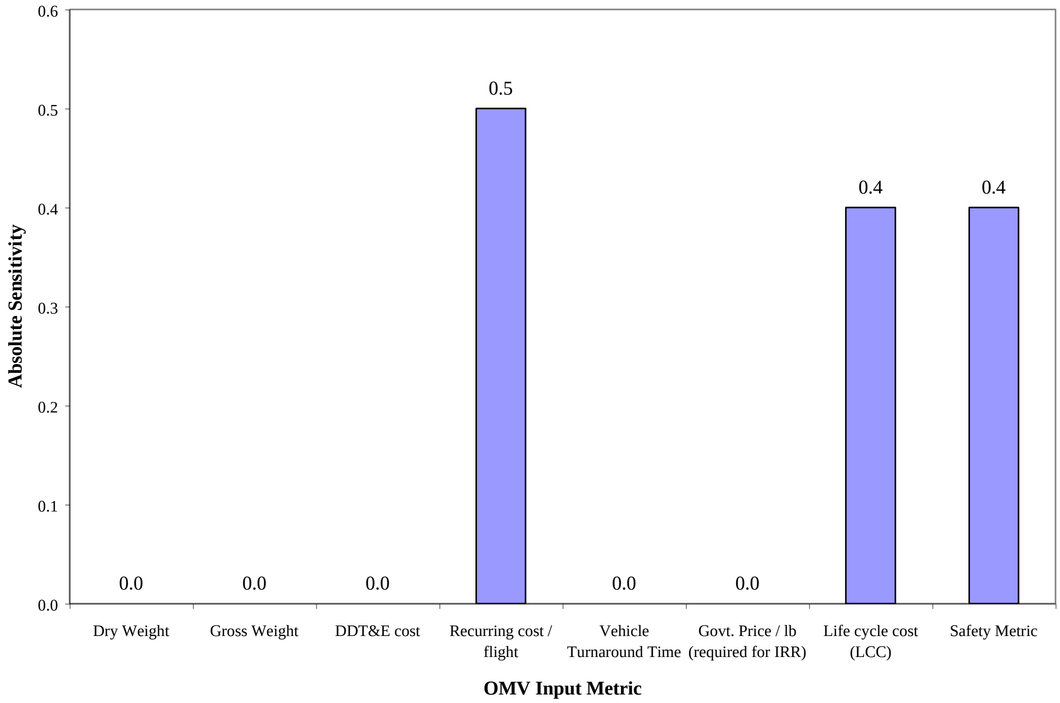


Figure 11.10. Sensitivity of Technology A on OEC Input Metrics

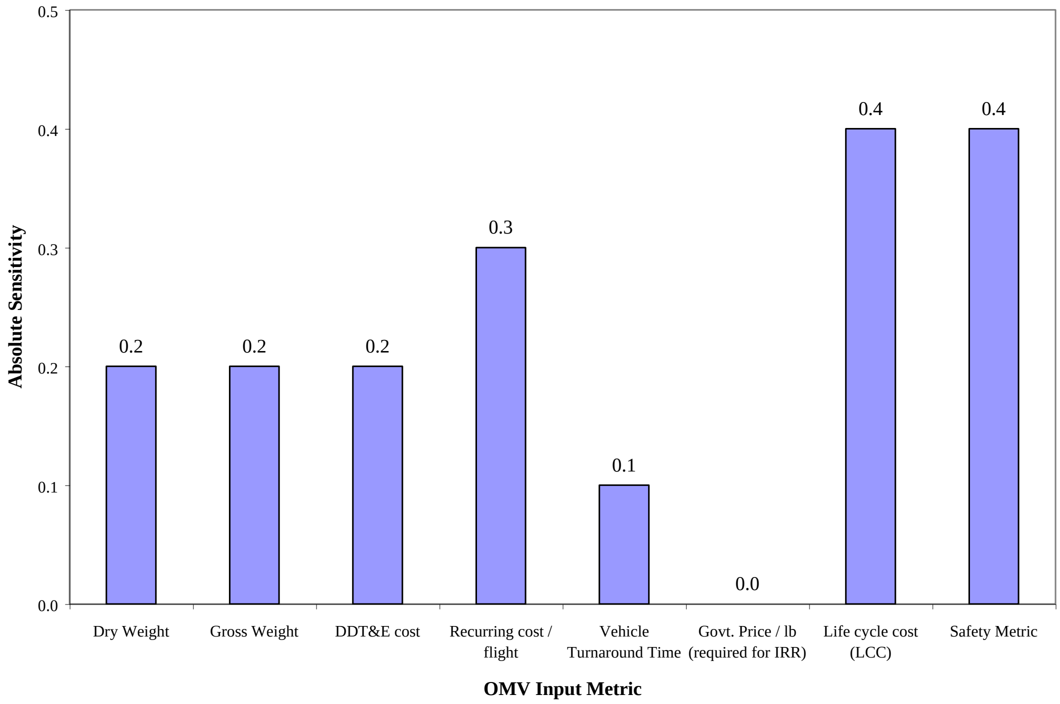


Figure 11.11. Sensitivity of Technology B on OEC Input Metrics

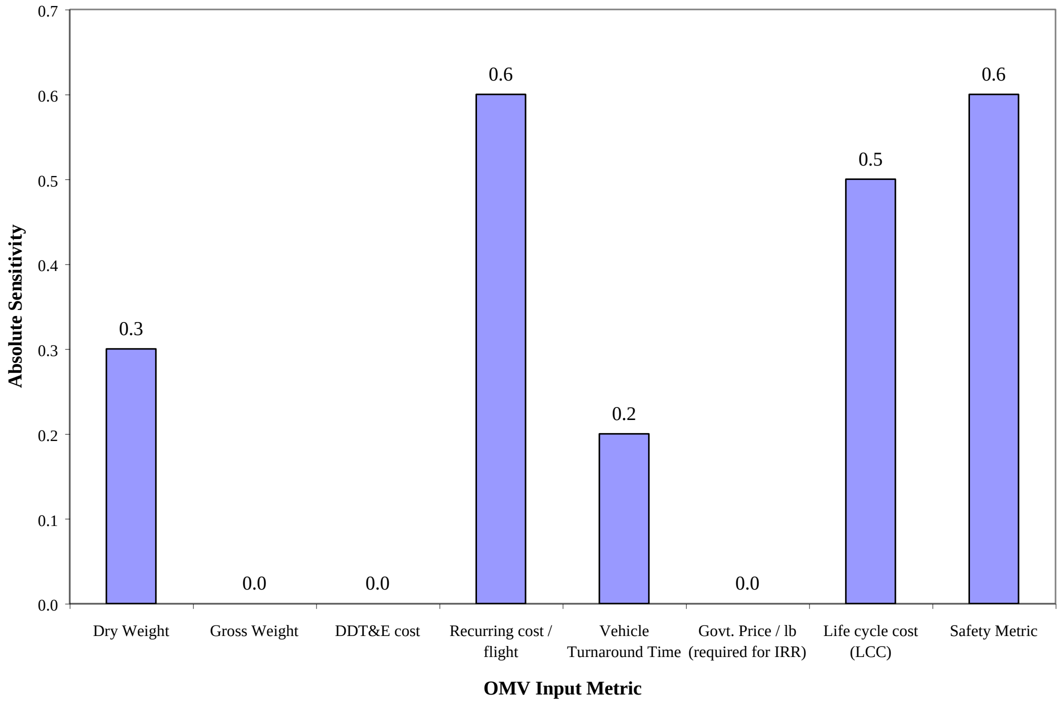


Figure 11.12. Sensitivity of Technology C on OEC Input Metrics

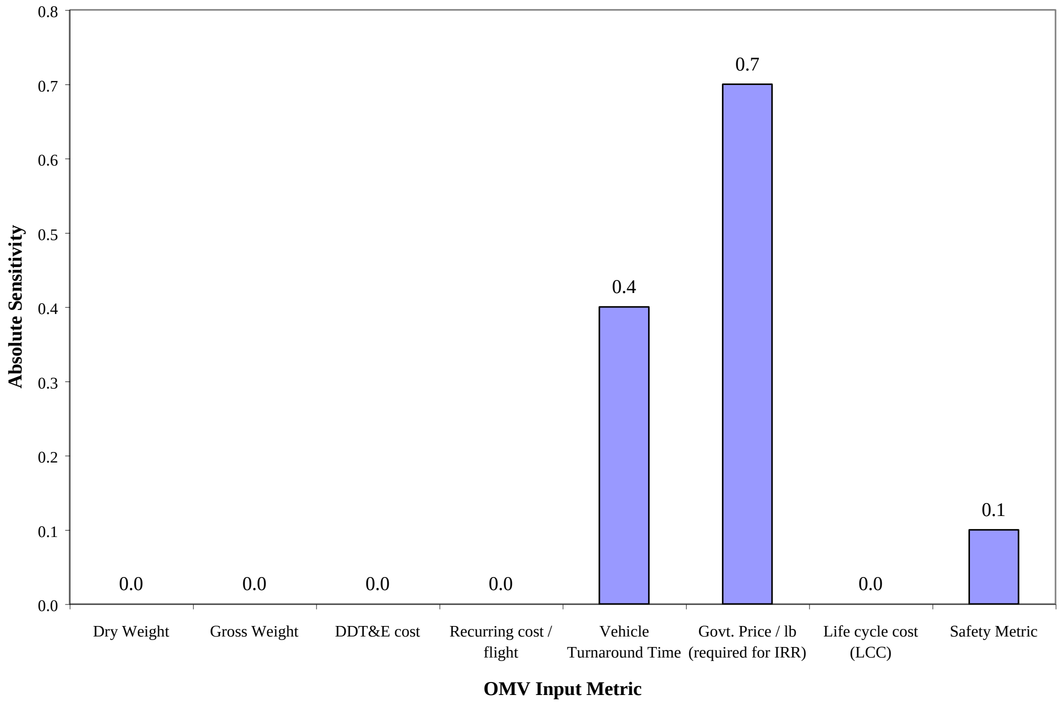


Figure 11.13. Sensitivity of Technology D on OEC Input Metrics

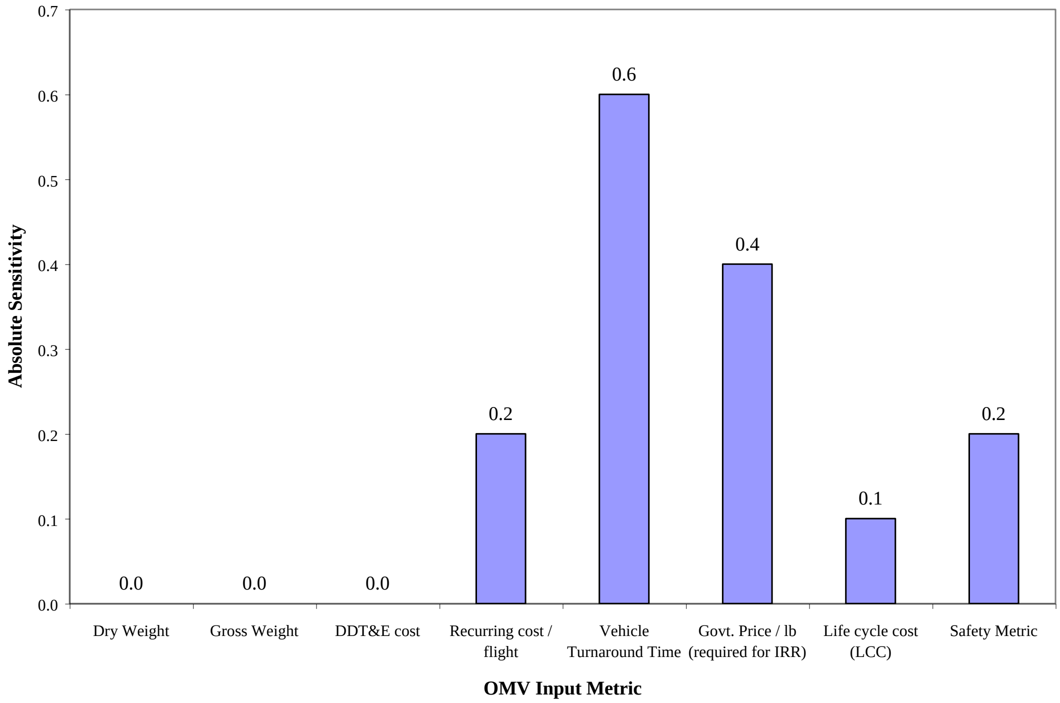


Figure 11.14. Sensitivity of Technology E on OEC Input Metrics

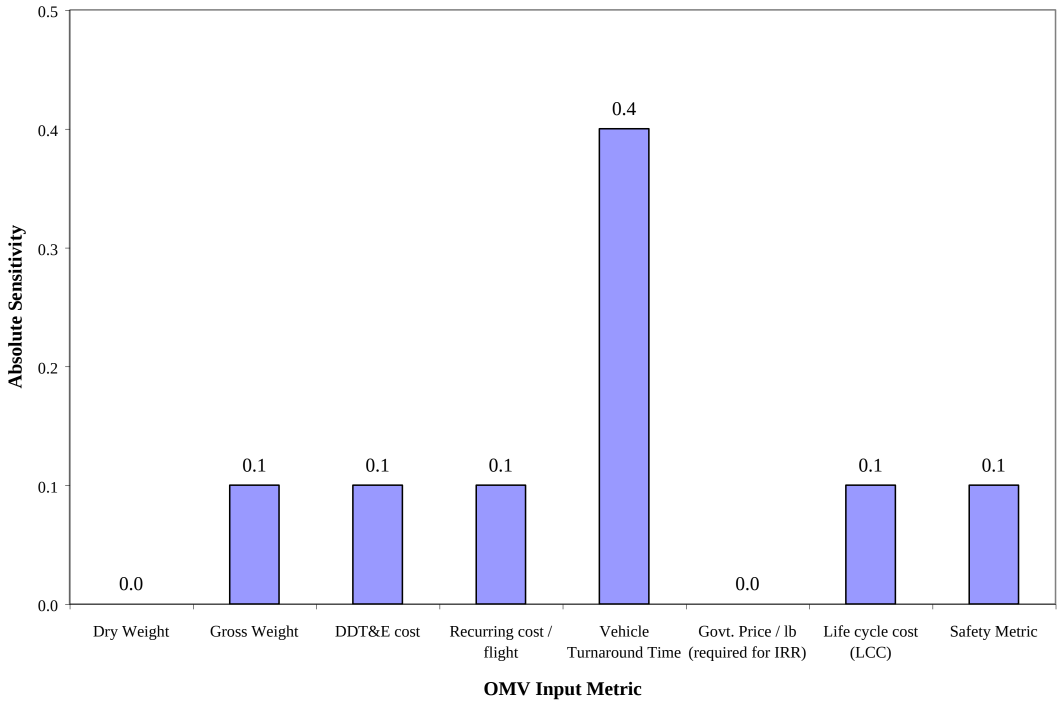


Figure 11.15. Sensitivity of Technology F on OEC Input Metrics

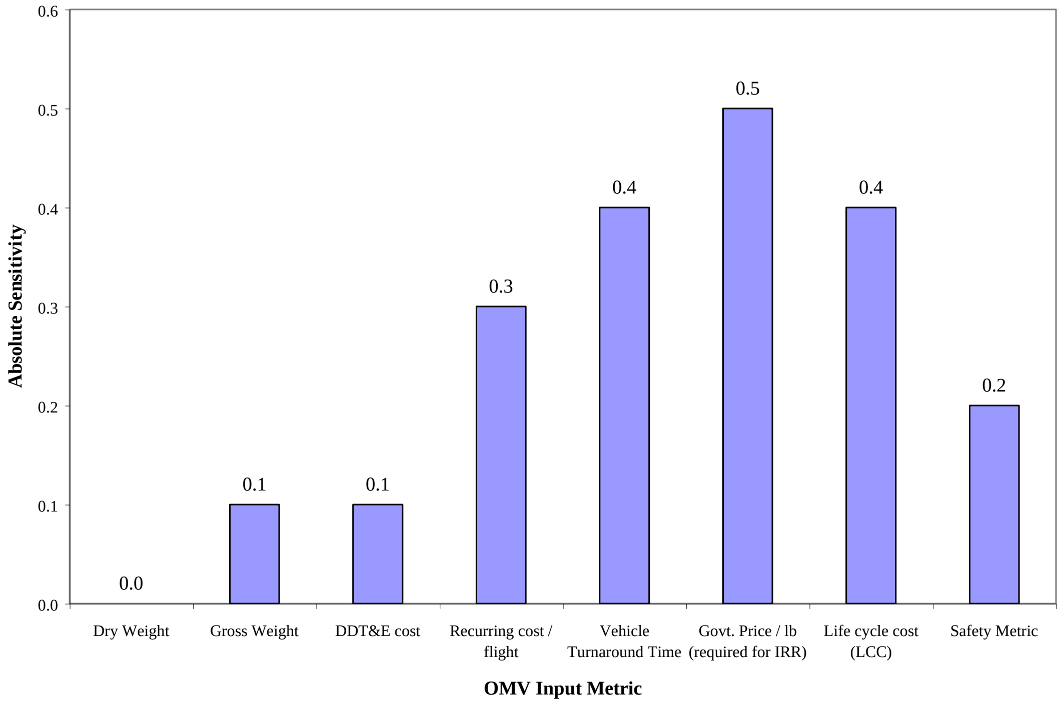


Figure 11.16. Sensitivity of Technology G on OEC Input Metrics

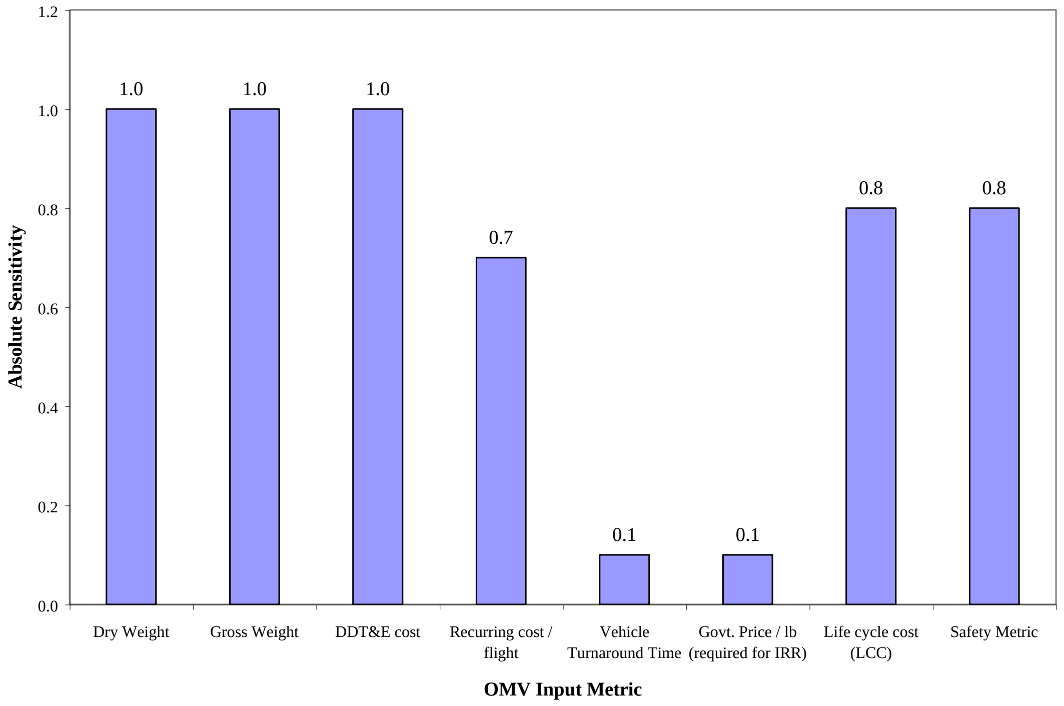


Figure 11.17. Sensitivity of Technology H on OEC Input Metrics

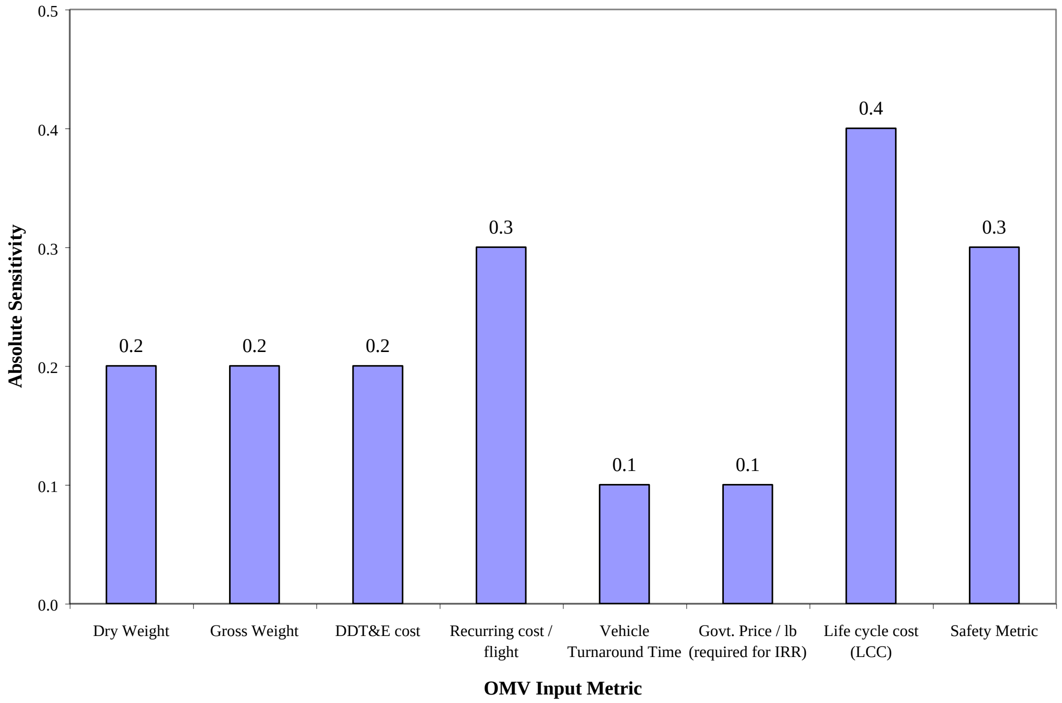


Figure 11.18. Sensitivity of Technology J on OEC Input Metrics

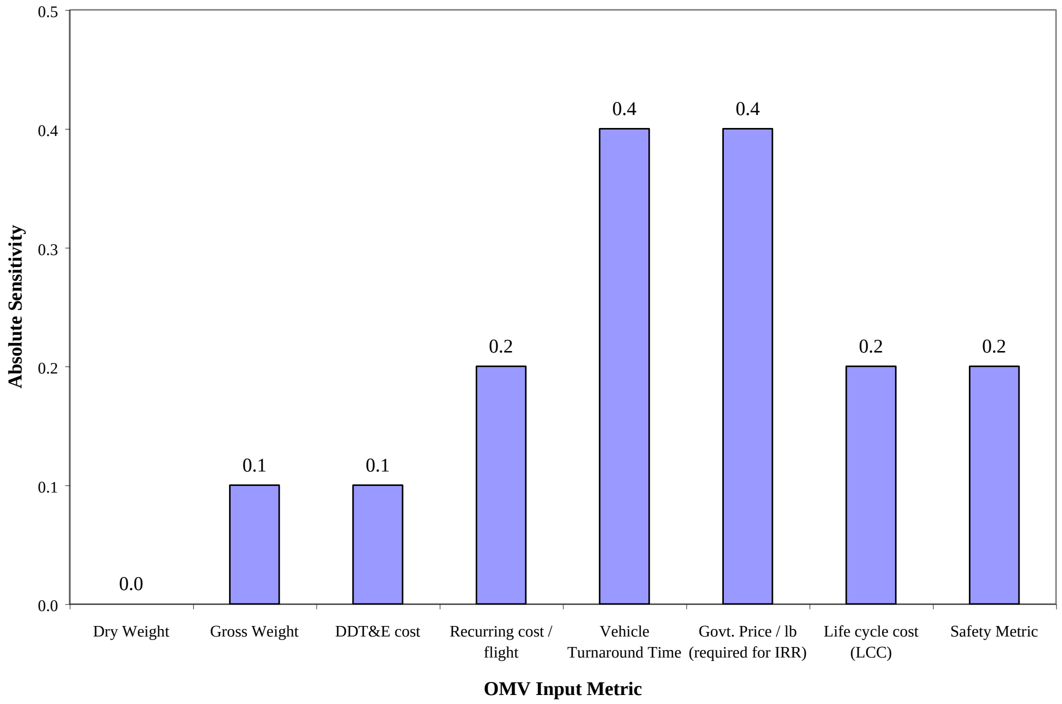


Figure 11.19. Sensitivity of Technology K on OEC Input Metrics

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