

# Selection of Favorite Reusable Launch Vehicle Concepts by using the Method of Pairwise Comparison

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*The contribution of this paper to the space transportation system field is to select promising Reusable Launch Vehicle (RLV) concepts by using a formal evaluation procedure. The vehicle system is divided into certain design features. Every design feature can have alternative characteristics. All combinations of design features and characteristics are compared pairwise with each other. The innovation and novelty of this evaluation procedure is to assess these characteristics with respect to relative importance for a feasible vehicle concept as seen from technical, economic and political aspects. This valuation process leads to a ranked list of design features for suborbital and orbital applications. The result is a theoretical optimized suborbital and orbital vehicle each. The method of pairwise comparison allows us to determine not only the ranking but also the assessing of the relative weight of each feature compared to others.*

## INTRODUCTION

The potential for an introduction of reusable launch vehicles is derived from an expected increasing demand for transportation of passengers in the decades to come. The assumed future satellite market does not justify operating reusable launch vehicles only for satellites due to a low launch rate. Finding feasible vehicle concepts, which satisfy the operator's, passenger's and public's needs, will be a challenging task. Since it is not possible to satisfy all space tourism markets by one vehicle, different vehicles that are capable of serving one particular segment (suborbital or orbital) are needed. From a theoretical approach, one nearly optimized vehicle is developed for suborbital applications and one for orbital applications. These optimized vehicle characteristics are compared to 153 existing worldwide vehicle concepts.

## EVALUATION PROCEDURE

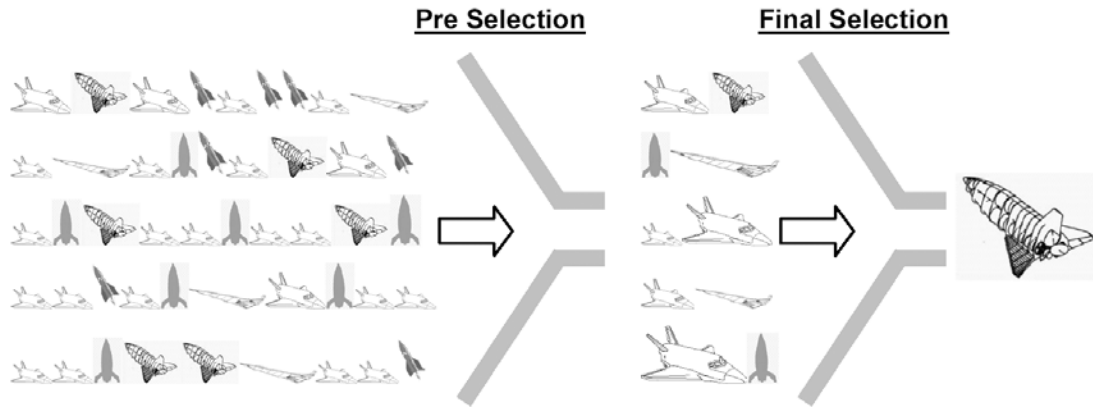
Figure 1 shows the evaluation procedure used for suborbital and orbital vehicle concepts. The procedure to select a nearly optimized vehicle concept is done

in three stages: Firstly, preferred key characteristics for a promising vehicle are determined in three groups with regard to technical, economic and political aspects by using the method of paired comparison. This evaluation process leads to a ranked list of design features for suborbital and orbital applications. The result of this investigation is a theoretical optimized suborbital and orbital vehicle each.

Secondly, in a pre-selection, the characteristics are compared to a total of 153 proposed concepts for reusable launch vehicles existing worldwide, from which 44 are for suborbital applications and 109 for the orbital ones. Those suborbital and orbital vehicle concepts that are closest to the theoretically optimized vehicles are selected. Thirdly, in a final selection, theoretical characteristics are compared in detail against the remaining 10 studies for reusable launcher concepts each for suborbital and orbital applications. One suborbital and one orbital vehicle concept that are closest to the theoretically optimized vehicles are selected. The result is a nearly optimized vehicle for suborbital flight and one for orbital flight. The necessity to use proposed vehicle concepts instead of a theoretically derived vehicle model is due to the lack of information on facilities, research budget, time and manpower to carry out experimental tests and various kinds of simulation, which have been available only for

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**Figure 1.** Evaluation Procedure based on Optimized Vehicle Characteristics.

some of the investigated vehicle concepts. The time frame covers the period from today to the year 2070 emphasizing the middle of this century. Separation in three groups of criteria (technical, economic and political aspects) allows us to obtain clearer results concerning the requirements for certification by authorities, attraction of potential investors and positive adventure for passengers.

#### METHOD OF PAIRED COMPARISON

The method of paired comparison [1] is used in this study for preliminary rating of alternative vehicle concepts with respect to the relative importance of design features as well as the preferred characteristics of each design feature. This is the first uncertain approach where detailed feasibility studies have not yet been performed.

The vehicle system is defined using 13 design features (e.g. “Launch Method”, “Number of Stages”, “Turn-around Time”, etc.). All combinations of design features are compared pairwise with respect to the relative importance for a feasible vehicle concept as seen from the technical, economic and political points of view. Every design feature can have alternative characteristics (e.g. “Air Launch”, “Horizontal” and “Vertical” are characteristics that can be selected for the design feature “Launch Method”). Again, all combinations of alternative characteristics are compared pairwise with each other with respect to a relative preference for a feasible vehicle concept as seen from the technical, economic and political standpoints. The result is a two-dimensional list of ranked design features with ranked alternative characteristics for each design feature, or one list for technical aspects, one for economic aspects and one for political aspects respectively. Evaluation is performed in a qualitative and a quantitative assessment. For the qualitative assessment, evaluation is taken into account by shortly discussing

each design feature. For a quantitative assessment, the evaluation is considered by assigning a number on a scale from plus five to minus five representing the sum of all arguments. These arguments receive relative weights totaling 100 %. Any two desirable attributes may be in conflict with each other, resulting in the optimization of one at the cost of the other. Figure 2 shows an example of a method of paired comparison for design features. The design feature “Number of Stages” is expected to influence technical feasibility much more strongly than the design feature “Passenger Comfort”. Therefore, the value for this pair is set to “+5”. By doing this comparison for all criteria, the preliminary results are gained for the evaluation presented in this chapter.

#### APPLICATIONS AND LIMITATIONS

The method of pairwise comparison is a powerful tool to perform a fair and comprehensive transparent ranking of criteria of any kind. It allows us to determine not only the ranking but also the assessing of the relative weight of each feature compared to others. However, the results of the pairwise comparison have to be checked for plausibility. For further discussion consult H.H. Koelle [2].

Decision making in the conceptual design area under uncertainty might stay a challenging task as the necessary data for a reliable forecast is not available [3]. Economics has shown many pitfalls, complications and inconsistencies in its attempts to measure risk attitudes. Sensitivity to framing, preference reversal and the gap between willingness-to-accept and willingness-to-pay might well serve to put off any attempt to measure risk attitude [4]. In other words, strategic decisions to determine the “right” characteristics for space transportation systems have a complicated structure, and there are no overall experts. The need to assess alternatives and make significant business

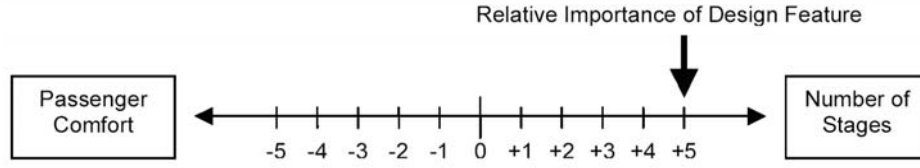


Figure 2. Example for Method of Pairwise Comparison

Table 1. Morphological Box of Design Features and Characteristics.

Design Features	Choice of Characteristics			
Number of Stages	1 Stage	1 Stage + Assist	2 Stages	2 Stages + Assist
Configuration	Tandem Staging	Parallel Staging	Nested	
Propellant	LOX/LH2	LOX/RP-1	LOX/C3H8	
Launch Method	Vertical	horizontal	Air Launch	
Landing Method	Ballistic (Rocket Eng.)	Ballistic (Parachute)	Aerodynamic (Jet Eng.)	Aerodynamic (Glider)
Impact Absorber	Landing Legs	Air Bags	Brake Rockets	
Mission Duration	Short	Medium	Long	
	Suborbit: < 0,5 hour Orbit: < 3 hours	Suborbit: 0,5-3 hours Orbit: 3-24 hours	Suborbit: > 3 hours Orbit: > 1day	
Mission Success	0,99 probability (low)	0,999 probability (medium)	0,9999 probability (high)	
Catastrophic Failure	0,0001 probability (low)	0,001 probability (medium)	0,01 probability (high)	
Reusability	< 100	100 to 1000	1001 to 10 000	> 10 000
Turn-around Time	< 2 days	2 days to 1 week	> 1 week	
Seat Capacity	< 10	10 to 50	> 50	
Passenger Comfort	Seatbound (low)	Some movement (medium)	Free floating room (high)	

decisions based on limited information causes many companies to address strategic decisions with models. The necessary requirement is to develop probabilities for the assumptions in the model based upon the uncertainty of each input value [5]. A solution might be a cost risk analysis to generate the range of cost and assign a probability level to each cost value in the range. The usual problem is not just to come up with an estimate of the cost of a project, but to predict the range of values into which the cost may fall and state the level of confidence the prediction is based on [6].

### DEFINING DESIGN FEATURES AND CHARACTERISTICS

A morphological box [7] listing typical alternative characteristics available for each design feature is determined for this study and shown in Table 1. This box can be used for deriving systematically promising vehicle concepts. There are many combinations possible that lead to vehicle concepts of different quality concerning technical, economic and political feasibility, which are investigated separately in the following three sections but only the criteria of technical feasibility is shown in detail due to the limitation of pages.

### CRITERIA OF TECHNICAL FEASIBILITY

The feasibility of a technical development within a schedule and the cost frame expected is enhanced if

the individual design concept is considered to be within the current state-of-the-art, well known, or easy to assess. If the individual design criterion is contributing to these goals, than it should get a high mark (+5) if compared with another design criteria that requires new technology or unknown risks (-5). A qualitative evaluation is given in the following paragraph.

- Number of Stages: Two-stage concepts are proven to enhance technical feasibility; single-stage concepts for orbital applications are marginal but common for suborbital applications.
- Configuration: A clean aerodynamic configuration without stage separation problems under high pressure is simple, proven and enhances feasibility.
- Propellant: Propellants that are available, well tested and classified as "non-toxic" enhance technical feasibility.
- Launch Method: Any launch method that is based on experience is favored since it reduces test effort required to provide evidence.
- Landing Method: A concept that comes close to practices applied in air-transportation deserves high marks since it enhances technical feasibility.
- Impact Absorber: A soft landing at low speed as applied in air transportation is well proven and enhances technical feasibility.

**Table 2.** Morphological Box of Design Options concerning Technical Aspects

Design Features	1. Choice of Characteristics	2. Choice of Characteristics	3. Choice of Characteristics	4. Choice of Characteristics
Catastrophic Failure (13,3%)	0,01 probability (60,0%)	0,001 probability (33,3%)	0,0001 probability (6,7%)	-
Mission Success (12,6%)	0,99 probability (60,0%)	0,999 probability (33,3%)	0,9999 probability (6,7%)	-
Mission Duration (12,4%)	Suborbit: < 0,5 hour Orbit: < 3 hours (60,0%)	Suborbit: 0,5-3 hours Orbit: 3-24 hours (30,0%)	Suborbit: > 3 hours Orbit: > 1day (10,0%)	-
Reusability (11,5%)	< 100 (45,0%)	100 to 1000 (35,0%)	1001 to 10 000 (20,0%)	> 10 000 (0,0%)
Launch Method (9,1%)	Air Launch (50,0%)	Vertical (33,3%)	Horizontal (16,7%)	-
Number of Stages (8,5%)	2 Stages + Assist (38,3%)	2 Stages (36,7%)	1 Stage + Assist (18,3%)	1 Stage (6,7%)
Propellant (7,8%)	LOX/LH2 (56,7%)	LOX/RP-1 (26,7%)	LOX/C3H8 (16,7%)	-
Landing Method (7,6%)	Aerodynamic (Jet Eng.) (38,3%)	Aerodynamic (Glider) (28,3%)	Ballistic (Parachute) (23,3%)	Ballistic (Rocket Eng.) (10,0%)
Configuration (5,2%)	Parallel Staging (46,7%)	Tandem Staging (33,3%)	Nested (20,0%)	-
Impact Absorber (5,1%)	Landing Legs (53,3%)	Air Bags (33,3%)	Brake Rockets (13,3%)	-
Turn-around Time (4,4%)	> 1 week (60,0%)	2 days to 1 week (30,0%)	< 2 days (10,0%)	-
Seat Capacity (2,4%)	< 10 (60,0%)	10 to 50 (30,0%)	> 50 (10,0%)	-
Passenger Comfort (0,0%)	Seat bound (50,0%)	Some movement (40,0%)	Free floating room (10,0%)	-

- **Mission Duration:** Extended flights require more technical effort and equipment. They are a matter of technical feasibility because long flight durations need bigger vehicles. Those vehicles increase the development risk.
- **Mission Success:** The problem of mission success is a matter of achieving a high degree of mission reliability, vehicle characteristics that are based on available and proven hardware components, and a large number of tests and operational flights. Low mission success rates are therefore easier to achieve from a technical viewpoint.
- **Catastrophic Failures:** A concept with low probability of catastrophic failure should get low marks with respect to chances of achieving this design goal.
- **Reusability:** A high degree of reuses (design lifetime) of subsystems like engines and equipment requires a special effort and should get low marks. Proven systems should get high marks since they enhance chances of early availability and good economy.
- **Turn-around Time:** Accessibility and maintainability are design criteria that insure short time intervals between two missions, but require high technical development efforts. Vehicle concepts that are designed with this objective deserve low marks.
- **Number of Pax Seats:** Vehicles with large seat capacity are promising better cost-effectiveness. On the other hand, vehicles with few passengers are smaller and easier to realize from technical aspects and should therefore get higher marks.
- **Passenger Comfort:** The higher the comfort, the larger the vehicle and the higher the technical effort to achieve this. From a technical viewpoint, a low comfort should get high marks.

Table 2 shows the results of a quantitative evaluation using the method of paired comparison. Full documentation of the necessary tables is published by R.A. Goehlich [8]. The first column shows design features in a ranked order concerning relative importance, while the other columns show corresponding characteristics in a ranked order for each design feature as well as their relative weights. For ranking purposes, figures are shown with one decimal. If technical aspects would be the only ones, a conservative vehicle close to the state-of-the-art would be the preferred one, as it does require only a low level of effort and is associated with small risks to implement its development. Thus, design criteria receives a high share of maximum points of merit if the concept considered promises to have only a low technical problem potential. In general, concepts using mature technology and proven subsystems are most desirable because they have the highest potential

**Table 3.** Morphological Box of Design Options concerning Economic Aspects

Design Features	1. Choice of Characteristics	2. Choice of Characteristics	3. Choice of Characteristics	4. Choice of Characteristics
Catastrophic Failure (14,9%)	0,0001 probability (60,0%)	0,001 probability (30,0%)	0,01 probability (10,0%)	-
Mission Success (11,3%)	0,9999 probability (56,7%)	0,999 probability (36,7%)	0,99 probability (6,7%)	-
Seat Capacity (11,2%)	> 50 (56,7%)	10 to 50 (36,7%)	< 10 (6,7%)	-
Reusability (11,0%)	> 10 000 (38,3%)	1001 to 10 000 (31,7%)	100 to 1000 (25,0%)	< 100 (5,0%)
Mission Duration (10,8%)	Suborbit: 0,5-3 hours Orbit: 3-24 hours (50,0%)	Suborbit: > 3 hours Orbit: > 1day (40,0%)	Suborbit: < 0,5 hour Orbit: < 3 hours (10,0%)	-
Turn-around Time (8,2%)	< 2 days (60,0%)	2 days to 1 week (30,0%)	> 1 week (10,0%)	-
Number of Stages (6,5%)	1 Stage (40,0%)	1 Stage + Assist (33,3%)	2 Stages (20,0%)	2 Stages + Assist (6,7%)
Launch Method (6,4%)	Horizontal (53,3%)	Air Launch (36,7%)	Vertical (10,0%)	-
Passenger Comfort (6,0%)	Some movement (46,7%)	Free floating room (40,0%)	Seat bound (13,3%)	-
Configuration (4,6%)	Parallel Staging (50,0%)	Nested (33,3%)	Tandem Staging (16,7%)	-
Landing Method (3,8%)	Aerodynamic (Glider) (38,3%)	Ballistic (Parachute) (33,3%)	Aerodynamic (Jet Eng.) (21,7%)	Ballistic (Rocket Eng.) (6,7%)
Propellant (3,6%)	LOX/RP-1 (46,7%)	LOX/C3H8 (40,0%)	LOX/LH2 (13,3%)	-
Impact Absorber (1,7%)	Landing Legs (63,3%)	Air Bags (30,0%)	Brake Rockets (6,7%)	-

for achieving high marks in reducing catastrophic failures and increasing mission success.

### CRITERIA OF ECONOMICAL FEASIBILITY

The economical feasibility of a vehicle concept is enhanced if the individual design concept selected promises to contribute heavily to cost-effectiveness of the operational commercial transportation system. A qualitative evaluation is given in the following paragraph.

- Number of Stages: Two-stage concepts have a lower economical potential than single-stage concepts, but the latter present a greater development risk especially for orbital applications.
- Configuration: A clean aerodynamic configuration, without stage separation problems under high air pressure, leads to low development and production cost.
- Propellant: Propellants that are available at a reasonable cost at launch sites are considered to enhance cost-effectiveness.
- Launch Method: Launch methods requiring a small launch crew and modest launch support equipment are favored since this reduces the operational cost.
- Landing Method: A concept that allows a return to the launch site and that comes close to practices applied in air-transportation enhances low operational cost.
- Impact Absorber: Simple mechanical designs are more cost-effective than those requiring application of thrust to break the landing speed.
- Mission Duration: From the passenger's point of view, a longer flight duration enhances attractiveness of such an adventure, thus the market potential is enhanced. This in turn improves the economic potential. Therefore, the mission duration provided by actual performance of the concept should resemble passenger expectations as closely as possible.
- Mission Success: A high mission reliability potential will obviously greatly enhance system cost-effectiveness.
- Catastrophic Failures: A low risk of catastrophic failures can only be achieved by a robust design, various emergency features and well thought-out operational emergency procedures requiring high development effort. Nevertheless, if a vehicle concept has adequate provisions in this respect, it would enhance system cost-effectiveness and should get high marks. Thus, emergency procedures included in the design concept are needed but normally at a high price.

**Table 4.** Morphological Box of Design Options Concerning Political Aspects.

Design Features	1. Choice of Characteristics	2. Choice of Characteristics	3. Choice of Characteristics	4. Choice of Characteristics
Catastrophic Failure (15,1%)	0,0001 probability (60,0%)	0,001 probability (30,0%)	0,01 probability (10,0%)	-
Mission Success (12,4%)	0,9999 probability (56,7%)	0,999 probability (36,7%)	0,99 probability (6,7%)	-
Propellant (11,0%)	LOX/RP-1 (50,0%)	LOX/C3H8 (40,0%)	LOX/LH2 (10,0%)	-
Launch Method (10,3%)	Horizontal (50,0%)	Air Launch (40,0%)	Vertical (10,0%)	-
Landing Method (9,5%)	Aerodynamic (Jet Eng.) (36,7%)	Aerodynamic (Glider) (30,0%)	Ballistic (Parachute) (23,3%)	Ballistic (Rocket Eng.) (10,0%)
Mission Duration (8,5%)	Suborbit: < 0,5 hour Orbit: < 3 hours (60,0%)	Suborbit: 0,5-3 hours Orbit: 3-24 hours (30,0%)	Suborbit: > 3 hours Orbit: > 1day (10,0%)	-
Impact Absorber (6,8%)	Landing Legs (56,7%)	Air Bags (26,7%)	Brake Rockets (16,7%)	-
Reusability (6,3%)	< 100 (35,0%)	100 to 1000 (28,3%)	1001 to 10 000 (21,7%)	> 10 000 (15,0%)
Turn-around Time (5,8%)	> 1 week (43,3%)	2 days to 1 week (33,3%)	< 2 days (23,3%)	-
Passenger Comfort (4,4%)	Seat bound (46,7%)	Some movement (36,7%)	Free floating room (16,7%)	-
Configuration (3,6%)	Parallel Staging (43,3%)	Tandem Staging (33,3%)	Nested (23,3%)	-
Seat Capacity (3,3%)	< 10 (50,0%)	10 to 50 (30,0%)	> 50 (20,0%)	-
Number of Stages (3,1%)	1 Stage (35,0%)	1 Stage + Assist (28,3%)	2 Stages (21,7%)	2 Stages + Assist (15,0%)

- **Reusability:** A high degree of reuses of expensive subsystems like engines, hot structure and equipment requires special development effort. In general, an optimum number of reuses should exist for each concept because additional development effort and savings in production and operational cost compensate for each other. Integration of proven subsystems in a vehicle concept should therefore get high marks since they enhance chances of early availability and good economy.
- **Turn-around Time:** Accessibility and maintainability are design criteria that determine time intervals between two missions. Consequently, this would reduce the number of vehicles required and thus keep production costs low. Vehicle concepts that are designed to meet this objective deserve high marks.
- **Number of Pax Seats:** The passenger capacity of a commercial vehicle has a great impact on the price that is charged to the customer. Vehicles with a large capacity clearly promise better cost-effectiveness.
- **Passenger Comfort:** Comfort with respect to available room per passenger, mobility and environmental precervations is important for market appeal, but will lead to bigger vehicles associated with increased production costs. An adequate compromise for the time period considered should be achieved to keep

a good balance between cost and customer appeal. Early vehicle systems obviously provide less comfort than vehicles of the next generation.

Table 3 shows the results of a quantitative evaluation by using the method of paired comparison. If economical feasibility would be the only criterion of choice, then the preferable concepts should be those promising the highest contribution to achieve good system cost-effectiveness during the program life-cycle. Thus, those design criteria receive a high share of maximum points of merit where the concept considered promises to have a good cost-effectiveness potential.

#### CRITERIA OF POLITICAL FEASIBILITY

The political, and consequently, the public acceptance of a vehicle is enhanced if the individual design concept promises further political and public acceptance, particularly as far as facilitation of the certification process by responsible institutions is concerned. Limited environmental effects, avoid legal hurdles and lead to acceptable insurance arrangements. If the individual design concept is clearly contributing to these goals, then it should get a high mark, as compared with other design criteria that require a high level of development and public relations effort to achieve certification as a public transportation system. A qualitative evaluation is given in the following paragraph.

**Table 5.** The Morphological Box of a Suborbital Vehicle.

Design Features	1. Choice of Characteristics	2. Choice of Characteristics	3. Choice of Characteristics	4. Choice of Characteristics
Catastrophic Failure (14,3%)	0,0001 probability (38,7%)	0,001 probability (31,3%)	0,01 probability (30,0%)	-
Mission Success (12,3%)	0,9999 probability (36,7%)	0,999 probability (35,3%)	0,99 probability (28,0%)	-
Mission Duration (10,5%)	< 0,5 hour (50,0%)	0,5-3 hours (34,0%)	> 3 hours (16,0%)	-
Reusability (9,3%)	< 100 (33,0%)	100 to 1000 (30,3%)	1001 to 10 000 (23,0%)	> 10 000 (13,7%)
Launch Method (9,0%)	Air Launch (43,3%)	Horizontal (37,3%)	Vertical (19,3%)	-
Propellant (8,2%)	LOX/RP-1 (40,0%)	LOX/C3H8 (30,7%)	LOX/LH2 (29,3%)	-
Landing Method (7,6%)	Aerodynamic (Jet Eng.) (34,3%)	Aerodynamic (Glider) (31,0%)	Ballistic (Parachute) (25,3%)	Ballistic (Rocket Eng.) (9,3%)
Number of Stages (5,9%)	2 Stages (27,3%)	1 Stage + Assist (25,3%)	2 Stages + Assist (22,7%)	1 Stage (24,7%)
Turn-around Time (5,7%)	> 1 week (43,3%)	2 days to 1 week (31,3%)	< 2 days (25,3%)	-
Impact Absorber (5,1%)	Landing Legs (56,7%)	Air Bags (30,0%)	Brake Rockets (13,3%)	-
Seat Capacity (4,5%)	< 10 (45,3%)	10 to 50 (31,3%)	> 50 (23,3%)	-
Configuration (4,4%)	Parallel Staging (46,0%)	Tandem Staging (30,0%)	Nested (24,0%)	-
Passenger Comfort (3,0%)	Seat bound (41,3%)	Some movement (40,0%)	Free floating room (18,7%)	-

**Table 6.** The Morphological Box of Orbital Vehicle.

Design Features	1. Choice of Characteristics	2. Choice of Characteristics	3. Choice of Characteristics	4. Choice of Characteristics
Catastrophic Failure (14,5%)	0,0001 probability (44,0%)	0,001 probability (31,0%)	0,01 probability (25,0%)	-
Mission Success (11,9%)	0,9999 probability (41,7%)	0,999 probability (35,7%)	0,99 probability (22,7%)	-
Mission Duration (10,8%)	3-24 hours (40,0%)	< 3 hours (35,0%)	> 1 day (25,0%)	-
Reusability (10,2%)	100 to 1000 (28,7%)	1001 to 10 000 (26,1%)	< 100 (23,0%)	> 10 000 (22,2%)
Launch Method (8,0%)	Horizontal (41,7%)	Air Launch (41,4%)	Vertical (17,0%)	-
Seat Capacity (7,0%)	> 50 (35,4%)	10 to 50 (33,4%)	< 10 (31,4%)	-
Turn-around Time (6,6%)	< 2 days (37,7%)	> 1 week (31,7%)	2 days to 1 week (30,7%)	-
Number of Stages (6,4%)	1 Stage (29,0%)	1 Stage + Assist (27,8%)	2 Stages(25,4%)	2 Stages + Assist (17,8%)
Propellant (6,3%)	LOX/RP-1 (41,4%)	LOX/C3H8 (33,0%)	LOX/LH2 (25,7%)	-
Landing Method (6,1%)	Aerodynamic (Glider) (33,6%)	Aerodynamic (Jet Eng.) (29,7%)	Ballistic (Parachute) (28,3%)	Ballistic (Rocket Eng.) (8,4%)
Configuration (4,6%)	Parallel Staging (47,7%)	Nested (27,3%)	Tandem Staging (25,0%)	-
Passenger Comfort (3,9%)	Some movement (42,7%)	Seat bound (31,0%)	Free floating room (26,3%)	-
Impact Absorber (3,7%)	Landing Legs (59,0%)	Air Bags (30,3%)	Brake Rockets (10,7%)	-

- **Number of Stages:** Concepts resembling features of other aeronautical vehicles and using state-of-the-art technologies, such as simple single-stage concepts, have a better chance of certification and should get high marks. Concepts requiring a considerable extension of the state-of-the-art will require more time and cost to be certified.
- **Configuration:** A clean aerodynamic configuration has a better chance of certification and should get high marks.
- **Propellant:** Propellants that have little effect on environment are mandatory for the introduction and public acceptance.
- **Launch Method:** Launch methods with features providing a superior passenger safety and protection of the environment near the launch site are favored, since these aspects are important for the certification process.
- **Landing Method:** A concept that insures a safe return to the launch site and comes close to practices applied in air-traffic enhances certification.
- **Impact Absorber:** Concepts resembling features of other aeronautical vehicles provide the best safety and comfort for passengers. They have a better chance of certification and should get high marks.
- **Mission Duration:** Passenger safety requirements as well as insurance coverage increase with the duration of a mission. Thus, they delay the certification process and should get lower marks.
- **Mission Success:** A high mission reliability must be demonstrated in ground and flight tests before the certification process can be concluded successfully. Thus, accumulated experience with human space transportation system at the time of certification in general and results of flight tests of the vehicle to be certified will influence the speed of the certification process.
- **Catastrophic Failures:** While an "unsuccessful mission" is capable of returning to the launch site without hurting passengers, a catastrophic failure leads to a loss of vehicle and mostly passengers, too. Design verification and evaluation by safety experts will be the basis of judgment during the risk assessment process by the responsible government institution. Maturity of the concept in general and robustness of vehicle design and operational procedures will enhance certification. If a vehicle concept has adequate provisions to demonstrate these requirements, it would enhance public acceptance.
- **Reusability:** A high degree of reuses of subsystems enhances confidence of the potential, but requires a

great deal of ground testing, which in turn will delay the certification process.

- **Turn-around Time:** Accessibility and maintainability are design criteria that tend to increase reliability and passenger safety. Vehicle concepts designed to meet this objective have a better chance to be certified. However, as seen in airline operations, realizing short turn-around times for novel aircraft requires more effort than using long turn-around times and should therefore get a lower mark.
- **Number of Pax Seats:** Vehicles with a large passenger capacity will be subjected to requirements that are more rigid and will thus tend to slow the certification process. Therefore, high passenger capacity vehicles should get a low mark.
- **Passenger Comfort:** A low level of passenger comfort such as a requirement to always use seatbelts would tend to make it easier to be certified and to realize lower insurance rates.

Table 4 shows the results of a quantitative evaluation by using the method of pairwise comparison. If political feasibility and public acceptability are the only criteria of choice, then the preferable concepts should be those promising the easiest process leading to a certification as a transportation system. Thus, a design criterion receives a high share of maximum points of merit if the concept considered promises to pass the certification process relatively fast. It is also a matter of general concern of social institutions, particularly media and travel organizations.

## RESULTS

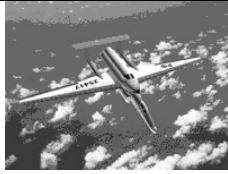





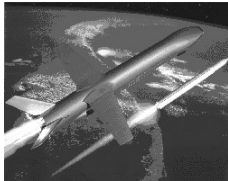


For suborbital applications, special emphasis should be given to low development risk and high safety rather than low-cost aspects. Suborbital vehicles can demonstrate the realization of mass space tourism market by airline-like operations. Therefore, the relative weights are set to 40 % for technical feasibility (low risk), 20 % for economic feasibility (low cost) and 40 % for political feasibility (high safety) resulting in an aggregated ranked list as shown in Table 5.

As a summary of the list, the ideal vehicle applicable for suborbital market should apparently be designed to meet the following first choice of characteristics ranked according to their relative importance:

"A low catastrophic failure rate, a high mission success rate, a short mission duration of less than 30 minutes, low reusability of less than 100 times, using liquid oxygen and kerosene as propellants, landing aerodynamically with jet engines, a two-stage vehicle, a turn-around time of more than one week, using landing legs, a low seat capacity of less than 10 seats, parallel staged and low passenger comfort permanently wearing seatbelts."



**Table 7.** Pre-selection of Suborbital Vehicle Concepts.

Design:				
Vehicle:	C-21	Eclipse Astroliner	Hopper (suborbital)	Hopper (once-around-earth)
Inventor:	Cosmopolis XXI	Kelly Space and Technology	Astrium	Astrium
Country:	Russia	USA	Germany	Germany
Launch Mass:	27 Mg (incl. M-55X)	327 Mg	491 Mg	491 Mg
Payload:	2 pax + 2 crew	(40 pax)	7,5 Mg	> 7,5 Mg
Status:	active	inactive	active	active
Design:				
Vehicle:	MiG 31 System	Rocketplane XP	Star Booster 200	X-15 System
Inventor:	n.a.	Pioneer Rocketplane	Buzz Aldrin	NASA
Country:	Russia	USA	USA	USA
Launch Mass:	46 Mg (incl. MiG 31)	n.a.	n.a.	204 Mg (incl. B-52)
Payload:	2 pax + 2 crew	2 pax + 1 crew	n.a.	0 Mg + 1 crew
Status:	active	active	active	inactive; realized
Design:		-	-	-
Vehicle:	Xerus	-	-	-
Inventor:	XCOR Aerospace	-	-	-
Country:	USA	-	-	-
Launch Mass:	n.a.	-	-	-
Payload:	1 pax + 1 crew	-	-	-
Status:	active	-	-	-

Designing a vehicle with less preferable characteristics is possible, but would result in a reduced feasibility. Suborbital vehicles should have low development risk and high safety standards by operating space vehicles similar to aircraft. However, for orbital applications, special emphasis should be given to low cost aspects. Therefore, relative weights are set to 30 % for technical feasibility (low risk), 50 % for economic feasibility (low cost) and 20 % for political feasibility (high safety) resulting in a ranked list as shown in Table 6.

As a summary of the list, the ideal vehicle applicable to the orbital market should apparently be designed to meet the following first choice of characteristics ranked according to their relative importance:

“A low catastrophic failure rate, a high mission success rate, a medium mission duration of 3 to 24 hours, a medium reusability between 100 to 1000 times, horizontal launch, a high capacity of more than 50



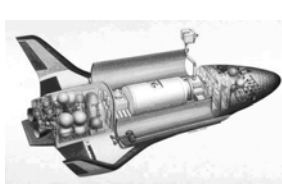

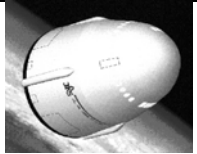

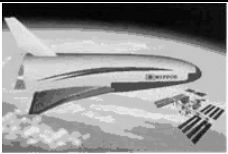



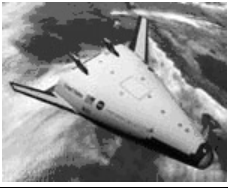
seats, a turn-around time of less than 2 days, a two-stage vehicle, using liquid oxygen and kerosene as propellants, landing aerodynamically as a glider, a medium passenger comfort allowing some movements and using landing legs.”

Designing a vehicle with less preferable characteristics is possible, but would result in reduced feasibility. If two characteristics are in conflict to (here: “1 Stage” and “Parallel Staging”), the characteristic that corresponds to the design feature of higher importance (“Number of Stages” is more important than “Configuration”) should receive priority.

## PRE-SELECTION

There are a total of 153 proposed concepts, of which 44 are for suborbital vehicles and 109 for orbital vehicles. A pre-selection is necessary because each vehicle concept causes 130 data for technical, 130

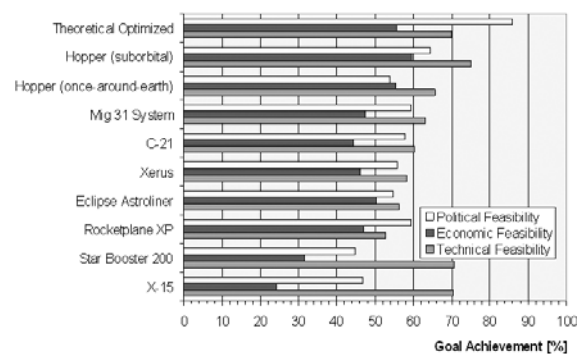
**Table 8.** Pre-selection of Orbital Vehicle Concepts.

Design:				
Vehicle:	ALS	Buran	HOPE	K-1
Inventor:	Boeing/Thiokol	RSC Energia	NASDA	Kistler Aerospace
Country:	USA	Russia	Japan	USA
Launch Mass:	363 Mg (incl. B747)	2525 Mg (incl. Energia)	430 Mg (incl. H2-D)	382 Mg
Payload:	3 Mg	30 Mg	3,0 Mg	4,0 Mg
Status:	active	inactive; realized	active	active
Design:				
Vehicle:	Kankoh Maru	MAKS-M	Rocket Plane	SLI (Bimese)
Inventor:	Japanese Rocket Society	NPO Molniya	NAL	Boeing
Country:	Japan	Russia	Japan	USA
Launch Mass:	550 Mg	620 Mg (incl. An-225)	n.a.	n.a.
Payload:	50 pax + 4 crew	7 Mg	n.a.	n.a.
Status:	active	active	active	active
Design:				-
Vehicle:	SLI 2	Space Shuttle	Venture Star	-
Inventor:	Northrop Grumman	NASA	Lockheed Martin	-
Country:	USA	USA	USA	-
Launch Mass:	n.a.	2035 (incl. ET and SRB)	1200 Mg	-
Payload:	n.a.	25 Mg + 7 crew	23 Mg	-
Status:	active	active; realized	inactive	-

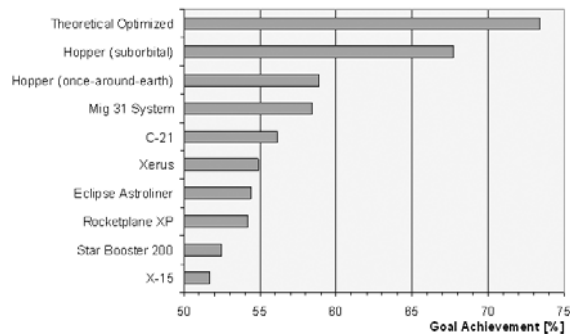
data for economic and 130 data for political aspects, resulting in a total of about 60,000 data, which is not manageable any more. Resulting from the pre-selection, 9 suborbital vehicles and 11 orbital vehicles are left for detailed investigations to determine possible suitability for space tourism flights which are summarized in Table 7 for suborbital vehicle concepts and Table 8 for orbital vehicle concepts.

### FINAL SELECTION

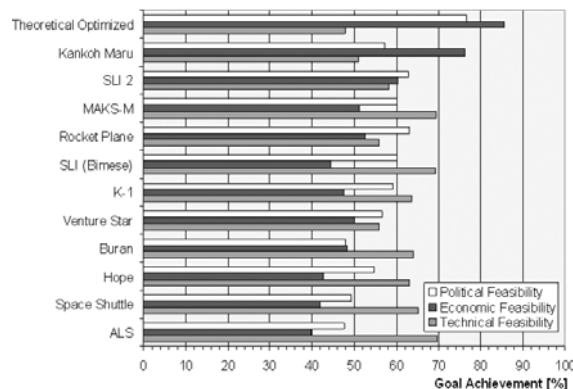
Preferred design criteria from the first part of this paper are used to measure the goal achievement of pre-selected vehicles. However, for fine-tuning, it is necessary to extend the limited decision options of three or four to a ten-scale goal achievement matrix. With this, it is also possible to determine values in between. It is not possible to achieve more than 85

**Figure 3.** Estimated Shared Goal Achievement of Suborbital Vehicle Concepts.

% of the goal because some of the attributes result in conflicting demands. On the other hand, vehicle



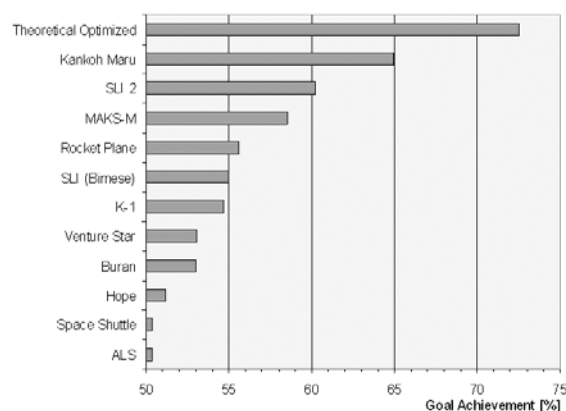
**Figure 4.** Estimated Total Goal Achievement of Sub-orbital Vehicle Concepts.



**Figure 5.** Estimated Shared Goal Achievement of Orbital Vehicle Concepts.

concepts should succeed in each category (technical, economical and political) at least 50%.

The 13 design features used in this evaluation constitute a basic approach to selecting vehicles for space tourism. More design features combined with detailed procedures using mathematical utility functions leave less room for intuitive judgments and could improve the quality of selection. However, considering that available specifications of investigated vehicles are very rare, detailed investigations are decidedly limited. It



**Figure 6.** Estimated Total Goal Achievement of Orbital Vehicle Concepts.

is obvious that this evaluation process is transparent but subjective, and it depends on the expertise and preferences of the person performing this valuation. Thus, it is judged to be typical but not representative.

The results of the suborbital concepts evaluated and ranked by the author with respect to the overall goal achievement are shown in Figures 3 (divided in groups) and 4 (after weighing each group). Weighed goal achievements vary from 52% to 73% with Hopper (suborbital) concept - achieving 68 % - closest to the theoretically optimized concept.

The results of the orbital concepts ranked by the author with respect to the overall goal achievement are shown in Figures 5 (divided in groups) and 6 (after weighing each group). Weighed goal achievements vary from 50% to 73% with the Kankoh Maru concept achieving the highest score of 65% next to the theoretically optimized concept.

## CONCLUDING REMARKS

Many vehicle concepts have been assessed and a few have even been tested and built. However, the majority has not reached the development stage due to numerous show-stoppers of either technical, economic or political nature. In case of technical issues, the area in which developers need to make major progress is for example in-flight experiments. Many of the phenomena influencing the mission of a reusable launcher cannot be reproduced on the ground and in-flight experiments are the only means of verifying theoretical predictions to reduce technological risks, before starting a full-scale vehicle development. The Space Shuttle is currently providing a large amount of flight data, which the USA can use to design a second generation of reusable launch vehicles. In case of economic issues being dominant, more advanced technologies could enable the design of an RLV with full reuse capability and specific transport costs lower than those of an expendable launch vehicle in near future (2010-2015). In the case of political issues, even if cost benefits of RLVs are not yet clear, governments are advised to support RLV programs to invest in its future space market prospective.

In general, investigation on selecting vehicle concepts has shown that vehicle concepts which have a high goal achievement do not necessarily have to fulfill all criteria of the theoretically optimized concept. For example, the theoretically optimized concept for orbital applications is a single-stage winged body, but Kankoh Maru is a ballistic vehicle concept and SLI 2 is a two-stage vehicle concept. Therefore, the author supposes that the “right” vehicle concept for tourism transportation application will not depend on one main specific design criterion such as single-stage, two-stage, winged or ballistic. Much more important for the feasibility will be the “right” mixture of all criteria,

i.e. a single-stage ballistic vehicle concept as well as a two-stage winged vehicle concept would be conceivable vehicles that could be realized at the right time.

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