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Reconfigurability in planetary surface vehicles

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Abstract

Traditionally, space systems have been built for fixed requirements and optimized for highest performance. Future systems for human exploration of Moon and Mars, however, require focus on new architectural strategies geared towards increased affordability and survivability in addition to performance. Reconfigurability is a new paradigm in system design that enhances these qualities. Reconfigurable systems can attain different states with new or modified capabilities, as required with changing needs, over time. Such systems can lower mission costs through mass savings by efficient use of a fixed set of hardware for multiple functions. Their survivability is improved through their ability to reconfigure into different states so that some level of over-all functionality is retained. This study, with a focus on planetary surface vehicles, presents a methodology for determining optimal designs of reconfigurable systems. It also proposes metrics for assessing the impact of reconfigurability. It is found that for the specific scenario considered, the mass utilization efficiency in a fleet of reconfigurable vehicles is increased by 27% while the survivability can be increased by a factor of 3.

Keywords: Reconfigurability; System architecture; Planetary surface vehicles; Rovers

1. Introduction

In a space exploration program that is geared towards human exploration of Moon and Mars, a fundamental and arguably perhaps the most important component will be the surface exploration system. Planetary surface vehicles (PSVs) will play a crucial role in meeting many mission objectives by extending the radius of exploration. It can be expected that future human missions to Moon and Mars will employ surface vehicles as one of the key elements for exploration [1].

Over the course of the last few decades, several types of vehicle concepts have been proposed [2–5]. The different types of vehicles identified for carrying out the necessary tasks include survey vehicles, science vehicles, site preparation vehicles (SPV), transport and assembly vehicles, astronaut transport vehicles (ATV), service and maintenance vehicles, mining vehicles, etc. [5]. Keeping in view the large variety of vehicle requirements, a few different types of vehicles have been proposed that combine the requirements of several types of tasks and leverage modularity and commonality in their proposed designs [5,6].

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This paper presents a different approach: it proposes that the PSVs should be reconfigurable. Reconfigurability is a new paradigm in system design. Typically, systems with differing requirements are either designed for the worst case or for average requirements. A reconfigurable system, in contrast, can undergo a reconfiguration such that it meets the changing requirements as they arise over the course of its operation. It attains different states at different times that are suited for the particular needs that exist, instead of being in one static state that has been designed for the worst or average use-case. Since a reconfigurable system can achieve different states (with different capabilities), it can potentially carry out a number of different or modified functions (albeit non-concurrently). The resources spent on the reconfigurable system (both financial and material) thus get utilized for multiple purposes. A higher degree of resource efficiency can therefore be achieved from these reconfigurable systems as compared to single-purpose systems. Additionally, the ability of a reconfigurable system to attain various states can improve its survivability. A reconfigurable system can degrade gracefully, in which it retains limited functionality, even in the presence of failures of certain components/subsystems [9].

It is clear that reconfigurability can especially benefit space systems where both mass and volume efficiency (that impacts the significant transportation costs), and greater survivability are highly desirable. PSVs that can account for several hundred kilograms should therefore be conceived with reconfigurable architectures.

The following sections in this paper provide a methodology for determining good reconfigurable designs, and introduce metrics that can be used to evaluate their merits. The design methodology is then applied to PSVs that are to be used for a human surface exploration mission on Mars. The reconfigurable design determined through the proposed framework is then evaluated for its resource efficiency. A Markov reliability analysis is also carried out to analyze the survivability aspects. The concluding remarks in the last section highlight key results and identify topics of further research.

2. Reconfigurable system design

This section develops a method for determining a good design for a system that needs to reconfigure between a small set of given, discrete configurations (or states).

Consider a system defined by a design vector, $\mathbf{x}$. Let the ith configuration (state), in which the system can exist, be denoted as $\mathbf{x}_i$. Each configuration, $\mathbf{x}_i$, will be defined by specific values of a set of n design variables, and can thus be expressed as

$$\mathbf{x}_i^{\mathrm{T}} = [x_{1i}, \ldots, x_{ji}, \ldots, x_{ni}] \tag{1}$$

If a total of m configurations are possible, then a larger vector $\mathbf{X}$ can be defined which is essentially a super set of all the configurations and will be expressed as

$$\mathbf{X}^{\mathrm{T}} = [\mathbf{x}_1^{\mathrm{T}}, \ldots, \mathbf{x}_i^{\mathrm{T}}, \ldots, \mathbf{x}_m^{\mathrm{T}}] \tag{2}$$

where $\mathbf{X} \in \Re^{nm\times 1}$.

An optimization problem can now be formulated in which the goal is to find $\mathbf{X}$ such that some desired criterion, $\mathbf{J}$ is maximized subject to constraints $\mathbf{g}(\mathbf{X})$.

It should be noted that this method essentially expands the design space to include all the required configurations for the complete design, not just a single design for a particular state. If the number of configurations/states, m, is large, or the number of design variables, n, in each state is large, then nm will be large, and the problem can quickly become computationally prohibitive. However, for many systems where the configurations can be expected to be only a few, and at the conceptual design stage (the number of design variables will be small), this method can be fruitfully employed.

A useful criterion for the design objective can be to minimize reconfiguration cost over the system life cycle and minimize the cost due to non-optimality (that may potentially result due to the system being reconfigurable). In this case only the cost minimization is factored in for simplicity. If z_{jk} is the cost of reconfiguration between states j and k, and s_{jk} is the total number of reconfigurations between states j and k over the system's operational life, then

$$\min \quad \mathbf{J} = \sum_{j=1}^{m}\sum_{k=1}^{m} s_{jk} z_{jk} \tag{3}$$

$$\text{s.t} \quad g_i(X_i) \leqslant 0 \tag{4}$$

In many situations s_{jk} may not be known and the designer may only have a probabilistic estimate at best. In that case the expected reconfiguration cost, $\bar{z}_{jk}$ can be used to obtain results.

3. Evaluation metrics

In order to evaluate the reconfigurable design, two metrics are proposed that allow comparison between a reconfigurable and non-reconfigurable/dedicated architecture.

3.1. Relative functional efficiency

This measure relates the efficiency of a reconfigurable system to that of an equivalent collection of dedicated systems. It is relevant when reconfigurability is desired for resource efficiency.

First, the functional efficiency, η_f is defined as the ratio of the functional capability (output) to resources (input):

$$\eta_f = \frac{\textit{Total functional capability}}{\textit{Resources}} \tag{5}$$

The functional capability will be based on the context of the system under analysis. For instance, for vehicles it can be the transport productivity [8]. The resources can be monetary in nature, or some other relevant quantity such as mass or energy.

For a reconfigurable system the total functional capability is the sum of the capabilities of all the states in which the reconfigurable system can exist, and the resources are the total mass or cost of the reconfigurable system. Typically, a reconfigurable system will be compared with a dedicated fixed-functionality system to conduct trades. In such a case, a set of dedicated systems will be used that will correspond in functionality to various states of the reconfigurable system under study. Then, for the dedicated system set the total functional capability is the sum of the capability of all the dedicated systems in the set and the resources are the cost or mass, etc. of all the dedicated systems combined.

The relative functional efficiency ratio, Ξ is then defined as

$$\Xi_f = \frac{\textit{Functional efficiency of reconfigurable system}}{\textit{Functional efficiency of dedicated system set}} \tag{6}$$

$$= \frac{\eta_{f\,R}}{\eta_{f\,D}} \tag{7}$$

where functional efficiency of the reconfigurable system is computed using Eq. (5) as

$$\eta_{f_R} = \frac{\sum_{i=1}^{m} v_i}{\rho} \tag{8}$$

where m is the number of states, v_i is the capability of state (or configuration) i, and ρ represents the resources (such as cost, mass, etc.) of the complete system. The functional efficiency of the dedicated system set is computed as

$$\eta_{f_D} = \frac{\sum_{j=1}^{k} v_j}{\sum_{j=1}^{m} \rho_j} \tag{9}$$

where k denotes the total number of dedicated systems in the set (being compared against the reconfigurable system). The quantities v_j and ρ_j here are the capability and cost (resource) of the jth dedicated system.

When $\Xi_f > 1$, the reconfigurable design is favorable since it can provide more functionality per unit resource then the set of dedicated systems.

It should be noted that Ξ_f only accounts for the *non-recurring* cost. For resource efficiency purposes, the non-recurring cost of a reconfigurable system might be less as compared to a dedicated systems set (e.g. mass of reconfigurable system may be lower than combined mass of dedicated systems). However, if the reconfigurable system is highly sub-optimal its *recurring* costs may end up being more depending on the extent of usage.

For a more inclusive assessment, a performance efficiency, η_p, can be used:

$$\eta_p = \frac{\textit{Total life cycle performance}}{\textit{Total resources over life cycle}} \tag{10}$$

There can be several context appropriate definitions for 'total life cycle performance'. For vehicles, this can be the integral of transport productivity and the duration of travel. The 'total resources' here include both recurring and non-recurring costs. For PSVs the non-recurring cost could be mass of the vehicle and recurring cost could be mass of fuel consumed.

The relative performance efficiency ratio of a reconfigurable and dedicated system set can be defined (in a similar fashion as before):

$$\Xi_p = \frac{\textit{Performance efficiency of reconfigurable system}}{\textit{Performance efficiency of dedicated system set}} \tag{11}$$

$$= \frac{\eta_{p\,R}}{\eta_{p\,D}} \tag{12}$$

In this case also, the reconfigurable system is favorable (when life cycle considerations are made), for $\Xi_p > 1$.

3.2. Survivability

The rate of change of a system's expected productivity/capability, etc. with time, $\mathrm{d}\bar{C}/\mathrm{d}t$, can give a measure of how rapidly its usefulness changes. The relative degradability, defined as the ratio Λ, of the rate of change of expected capability of a reconfigurable system and dedicated system can be used as a measure of comparison:

$$\Lambda = \frac{\left(\dfrac{d\bar{C}_D}{dt}\right)}{\left(\dfrac{d\bar{C}_R}{dt}\right)} \tag{13}$$

For the reconfigurable system to be favorable, Λ should be greater than 1.

4. PSV modeling framework

The design methodology and metrics developed above were applied to the study of PSVs. For this purpose, a software tool was developed to model various kinds of vehicles. The model is based on physics of off-road vehicle motion and terrain interaction [8], and uses parametric models of component masses (such as wheels, motors, etc.) to get mass estimates [9]. Some of the primary input and output variables are shown in Table 1.

Fig. 1(a) shows the type of un-pressurized vehicles that the tool can model. Pressurized vehicles can also be modeled, but will not be discussed here (see [9] for details).

Table 1
Main inputs and outputs of model

Inputs	Outputs
# Crew	Mass (kg)
Cargo (kg)	Power (kW)
# Wheels	Energy (kW h)
Power source	Wheelbase (m)
Drive type	Track (m)
Average speed (km/h)	Wheel diameter (m)
Range (km)	Motor torque (N m)
Tow capacity (kg)	Motor power (W)

4.1. Benchmarking of PSV model

In order to verify the model estimates for un-pressurized vehicles, the lunar roving vehicle (LRV) that was used in Apollo 15–17 missions [10] was used for benchmarking. The LRV was an open un-pressurized vehicle, very much like a dune-buggy that allowed the astronauts on the Moon to easily carry equipment and samples, and explore a larger area around their landing sites. Fig. 1(b) shows a schematic of the LRV.

Table 2 shows the output data for the LRV comparison. It can be seen that the difference between the actual data and the model estimates for the total mass and power is within 10%. The dimensions, turning radius and some other parameters are different due to the

Table 2
Comparison of actual and estimated data for Apollo LRV

	Actual	Estimate	Difference (%)
Wheel diameter (m)	0.82	0.7	14.6
Wheel width (m)	0.23	0.18	21.7
Wheel mass (kg)	5.4	13.2	144
Wheelbase (m)	2.29	2.64	15.3
Track (m)	1.83	1.7	7
Length (m)	3.1	3.34	7.74
Width (m)	2.06	1.8	12.6
Height (m)	1.14	1.7	49
Battery capacity (W h)	8280	7400	10.6
Drive motor power (W)	191.5	193	0.8
Gradability (deg)	23	15	34.7
Turning radius (m)	3.1	4.73	52.5
Total mass (kg)	210	226	7.6

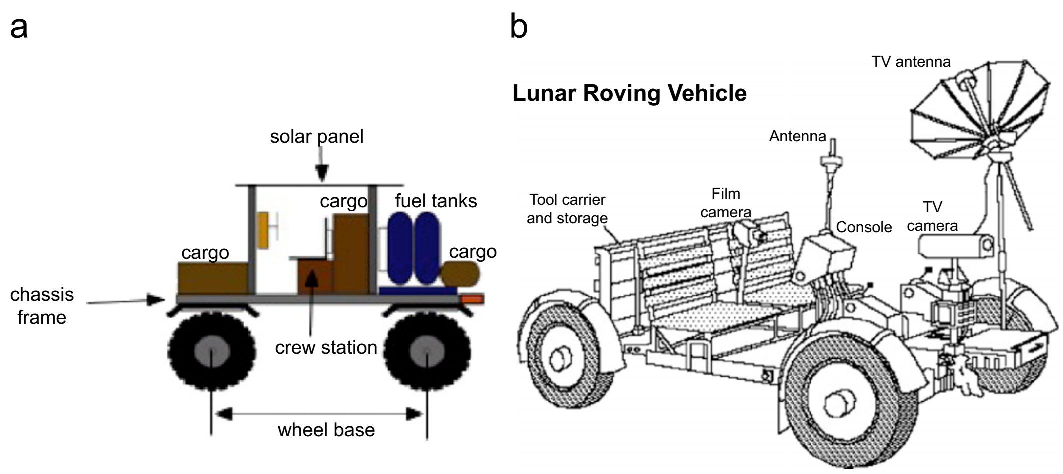

Fig. 1. Type of vehicle that can be analyzed with the PSV modeling framework. (a) Generic open PSV; (b) LSV used in Apollo 15–17.

specific design of the LRV and somewhat different assumptions made in the software model. However, although there are differences at the sub-system level, in terms of gross mass and power estimates model output matches actual data fairly well.

5. Mars exploration mission

The requirements for a PSV design were formulated by first considering a surface operations scenario. It was assumed that five crew members land on a planetary surface and use a vehicle for base set-up operations. The towing and cargo carrying capacity of such a vehicle will thus have to be large. However, its speed can be expected to be fairly slow since its operations will be performed with utmost care and may also require a reasonable degree of accuracy (especially if various surface modules need to be connected together). Its total range (the distance it can traverse before it needs to be refueled) will also be small since it is expected that the modules will be delivered to the planetary surface in close proximity (a few hundred meters or few kilometers apart).

After setting up the base, the astronauts will start the exploration phase of the mission in which they will make different sorties. The short range sorties (that do not require extended stay away from the base) can be conceived to be carried out by vehicles that can transport one crew member and some equipment and tools. The cargo carrying capacity will not need to be large; however, its top speed and range will be higher.

For long range excursions that will require the crew to be away for several days from the base, a *planetary camper* will be used. The camper would essentially be a vehicle that provides a pressurized, habitable volume to a crew of 2 for a few days. In each long excursion, the camper will be hauled by an un-pressurized vehicle with sufficient towing capacity, to a 'camping site'. An additional un-pressurized vehicle is also brought along to scout the way. Once at the site, the camper will be parked, and the two un-pressurized vehicles will be used to explore the surrounding area. After the exploration, the camper will be hauled back to the main base.

For the scenario described above, there can be two options in the context of reconfigurability for architecting the un-pressurized mobility system. In the first option, there is a fleet of three types of vehicles:

- Site Preparation Vehicle (SPV) for transporting and placing modules, shelters, and lander to desired locations.
- Long haul vehicle (LHV) for towing a camper to various planetary sites for over-night excursions.
- Astronaut Transport Vehicle (ATV) to be used for high speed, long range, traverses for exploration.

Fig. 2 illustrates the mission scenario schematically and shows when the three types of vehicles will be used along the mission time line. The desired specifications of range, tow capacity, cargo capacity, and speed for each type are shown in Table 3.

Fig. 3 shows the specification in a radar plot to illustrate how the three different vehicles vary in terms of

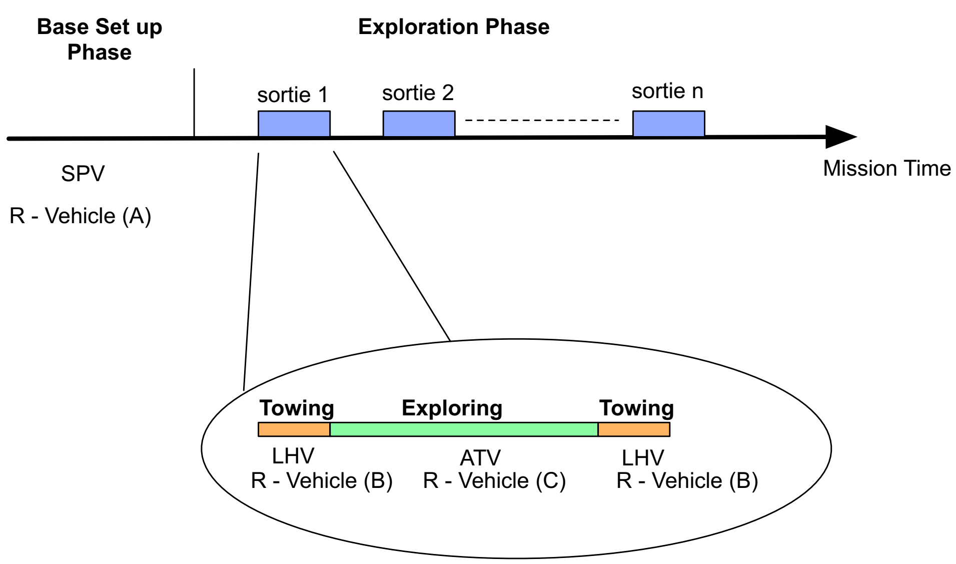

Fig. 2. Mission scenario.

Table 3
Performance specifications for dedicated vehicles

	SPV	LHV	ATV
Range (km)	5	50	100
Speed (km/h)	3	8	12
Tow capacity (kg)	5000	2500	5
Cargo capacity (kg)	500	200	50

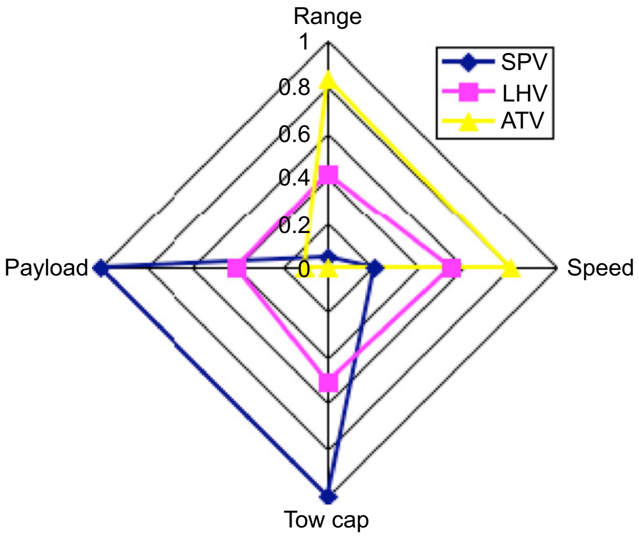

Fig. 3. Radar plot showing specifications of dedicated vehicles required for different tasks.

their capabilities. It is assumed that the exploration operations consist of two teams of two people each that explore the surface at a given time. Each team brings a dedicated camper, and two LHVs for the trip. One person stays on the base for maintenance and support and uses an ATV. Aside from the camper (which is not factored in as being reconfigurable), for this scenario a total of six vehicles will be needed: 1 SPV, 2 LHVs and 3 ATVs.

In the second alternative, a set of identical reconfigurable vehicles is used. The reconfigurable vehicles can undergo changes in their capabilities so that any one vehicle can be configured or morphed, between states A, B and C, to carry out any of the three types of tasks (of SPV, LHV, and ATV respectively) at a given time (see Fig. 2). For the scenario described above, this would require five reconfigurable vehicles. One vehicle will be used by the person at base, and the two teams out on exploration will use two vehicles each.

5.1. Dedicated vehicle designs

The PSV model (described in Section 4) was used to model various vehicles. Table 4 shows the details

Table 4
Design details of dedicated vehicles

	SPV	LHV	ATV
Total power (kW)	2.68	3.47	0.94
Fuel capacity (kg)	2.7	11.4	4.1
Wheelbase (m)	2.54	2.54	2.54
Track (m)	1.52	1.52	1.52
Wheel diameter (m)	1.13	1.12	1.09
Wheel width (m)	0.34	0.28	0.27
Max torque (Nm)	34.6	16.65	2.7
Traction drive power (W)	646	842	211
Total mass (kg)[a]	358	401	245

[a] A Polaris 700 single passenger, All-Terrain Vehicle with 135 kg cargo, and 680 kg tow capacity weighs 350 kg (for use on Earth) [11].

of the SPV, LHV, and ATV that were described in the previous section, and designed for minimum mass. The power system consists of fuel cells and solar panels. The vehicles are modeled, using inputs in Table 3, to be used on Mars, with four independently driven wheels, and each having one crew seating capacity. For modeling simplicity, the vehicle dimensions are estimated based on the number of passengers. The consideration for cargo capacity is made in computing the structural aspects (such as thickness and size of chassis frame cross-section), and power and energy requirements (to carry the load), but not in the vehicle's size. The wheelbase and track values are therefore the same for each of the three types of vehicles in this case because the number of passengers is the same in each.

5.2. Reconfigurable vehicle design

After designing the vehicles for dedicated tasks, a 'good' reconfigurable vehicle design was obtained by using the methodology presented in Section 2. In this problem, the vector that described the ith configuration (or state) was defined as

$$\mathbf{x}_i^{\mathrm{T}} = [r_i, V_i, T_{mi}, M_i] \quad (14)$$

where r is the range (km), V is the speed (km/h), T_m is the mass (kg) the vehicle can tow, and M is the mass (kg) the vehicle can carry as payload. It was assumed that the reconfigurable vehicle needs to exist in three different configurations, A, B, and C in order to carry out the three types of tasks discussed earlier. The full design vector that needed to be determined through optimization consisted of three sub-vectors (each with four variables) for a total of 12 variables. It was denoted by

$$\mathbf{X}^{\mathrm{T}} = [\mathbf{x}_A^{\mathrm{T}}\ \mathbf{x}_B^{\mathrm{T}}\ \mathbf{x}_C^{\mathrm{T}}] \quad (15)$$

The problem was formulated as

$$\begin{aligned}\min\quad & \mathbf{J} = z_{AB} + z_{BC}\\ \text{s.t.}\quad & 0.5 \leqslant r_A \leqslant 8, \quad 60 \leqslant r_B \leqslant 80, \quad 50 \leqslant r_C \leqslant 100\\ & 0.5 \leqslant V_A \leqslant 5, \quad 4 \leqslant V_B \leqslant 10, \quad 6 \leqslant V_C \leqslant 15\\ & 4000 \leqslant T_{mA} \leqslant 7000, \quad 2500 \leqslant T_{mB} \leqslant 4000\\ & 5 \leqslant T_{mC} \leqslant 5000\\ & 500 \leqslant M_A \leqslant 800, \quad 100 \leqslant M_B \leqslant 200\\ & 30 \leqslant M_B \leqslant 180 \end{aligned} \qquad (16)$$

The objective function $\mathbf{J}$ was the sum of reconfiguration costs in changing from state A to B, z_{AB}, and in changing from state B to C z_{BC}. It was assumed that $z_{AB} = z_{BA}$ and $z_{BC} = z_{CB}$.

5.2.1. PSV reconfiguration cost

The reconfiguration costs, z_{ij}, were computed on the simplifying assumption that the cost is directly related to the amount of mass that is interchanged during a reconfiguration process. Thus, greater the mass of the components that need to be substituted, higher will be the costs. In reality, other costs such as energy, crew time, etc. will also be involved.

The determination of which components are substituted and which are transformed was based on the type of the component. It was assumed that the chassis frame, fuel tanks, and thermal system could only be altered through discrete addition and removal. Thus in order to reconfigure an LHV to an ATV, the necessary modules will have to be carried as payload during the sortie. The wheels and traction drives were considered to have variable capability within some range. It was assumed that the wheel diameter and width could vary by 10%, and the max power level of the traction drives could be altered by 10% (perhaps by channeling extra-power from non-essential devices when needed).

If the required change in the component characteristics in configuring from one state to another was greater than what could be achieved within the given range, then substitution would be carried out. The mass of the component removed and that of the one installed are both summed up to get the total mass that is inter-changed. It should be noted that the reconfiguration cost is a lower bound on the actual costs (in terms of mass) that may be incurred.

The optimization was carried out by using a heuristic method, simulated annealing [12], which is suitable for problems with both continuous and discrete variables. Although in this specific analysis only continuous variables were involved, in other more general analyses discrete variables are also involved such as number of wheels, power source type, drive type, etc.

Table 5
Optimal configurations for reconfigurable vehicle

	A	*B*	*C*
Range (km)	8	60	95.7
Speed (km/h)	0.67	4.5	12.5
Tow capacity (kg)	5527	2522	42.2
Cargo capacity (kg)	501	118	171

Table 6
Design details of reconfigurable vehicles

	A	*B*	*C*
Total power (kW)	0.73	1.92	1.36
Fuel capacity (kg)	4.48	13.1	5.4
Wheelbase (m)	2.54	2.48	2.48
Track (m)	1.52	1.52	1.48
Wheel diameter (m)	1.13	1.11	1.11
Wheel width (m)	0.32	0.27	0.28
Max torque (Nm)	37.5	15.7	3.9
Traction drive power (W)	156.8	455.6	315.3
Total mass (kg)	245	311	270

The optimal solution found for the problem posed in Eq. (16) was: $\mathbf{J}^* = 182\,\text{kg}$, and $\mathbf{X}^* = [8, 0.67, 5527, 501, 60, 4.5, 2522, 118, 95.7, 12.5, 42.2, 171]^{\mathrm{T}}$. The total mass of the reconfigurable vehicle system (with all the required parts/modules) was computed to be 330 kg. Table 5 shows this solution. Each configuration was modeled with the same number of passengers (i.e. one), drive system, power system, etc. as the fixed/dedicated vehicles. It can be seen from Table 5 that the cargo capacity for configuration C is fairly high (than is necessarily needed). This is because the results were obtained by only minimizing reconfiguration cost (and not penalizing deviations from the 'target' specification set given in Table 3).

5.2.2. Reconfiguration details

The detailed design specifications for each of these configurations are given in Table 6. It is observed that the fuel tank sizes need adjustment in changing from configuration A to B and B to C. The changes are needed in order to reduce the mass of the vehicles. In calculating the mass of the power subsystem of each configuration it was assumed that the tank size and other hardware elements are sized according to its maximum fuel capacity. Thus, if the largest tank size (which is used in B) is also used on other configurations with partially filled fuel, the mass of configuration A (245 kg) and for C (270 kg) will be higher.

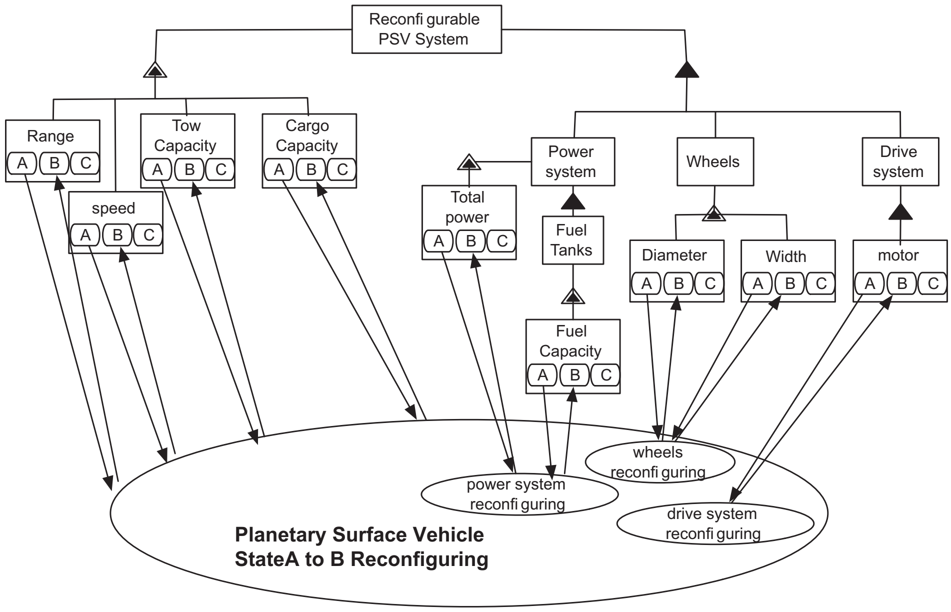

Fig. 4. Object-process diagram of PSV reconfiguration.

The traction drive powers are markedly different in all the three states so they are also changed. The wheel diameters and widths do not undergo a change larger than 10% so they are not assumed to be changed out for the different configurations. These results can aid in making architectural decisions about the interface designs between the sub-systems that would allow for installations, removals, and transformations. Fig. 4 shows an object-process diagram [7] of the key features of the reconfiguration. For simplicity only a reconfiguration from state A to B is shown.

An 'all-size fits all' approach can be compared in which a vehicle is designed for the maximum specifications so that it can be used for all of the different tasks (so it has 100 km range, 12 km/h average speed, 5000 kg tow capacity and 500 kg cargo capacity). The mass of such a vehicle is determined to be 800 kg which is significantly more than the reconfigurable vehicle system.

6. Comparison of fleet of reconfigurable vs dedicated vehicles

Using the specific designs for the vehicles, a fleet of dedicated and reconfigurable vehicles was then compared for mass efficiency and reliability.

6.1. Mass efficiency

In the most general case, it is easy to see that since one reconfigurable PSV can do the functions of three different dedicated PSVs, some significant mass savings can be realized. The combined dry mass of 1 SPV, 1 LHV and 1 ATV is 985 kg, while one reconfigurable vehicle is 317 kg. So in terms of pure mass savings the ability to configure a single vehicle to perform multiple functions is clearly very beneficial.

An important aspect, however, is the time at which the various functions are required. A reconfigurable system that can perform one type of task at a time, will not be able to provide multiple concurrent functions that may be required. The time requirement of the various functions will thus play a critical role in determining the extent of benefit that can be obtained through reconfigurability.

If the whole exploration mission scenario is considered, for the initial base setup phase at least one SPV is required. Then for two simultaneous EVA teams, a total of 2 LHVs and 2 ATVs required. Furthermore it was assumed that the fifth crew member who stays at the base (while the other four are out on EVA) has an ATV available at the base for local work and rescue operations. The whole fleet of surface vehicles will thus at a minimum consist of 1 SPV, 2 LHVs and 3 ATVs. For the reconfigurable case, however, at any given time a total of five vehicles need to be available (two each for the two EVA teams and one at the base). Therefore five vehicles can deliver the same functions at the required times instead of six for the dedicated case.

The different scenarios are shown in Fig. 5(a). Three different cases are plotted. In the first case there is only

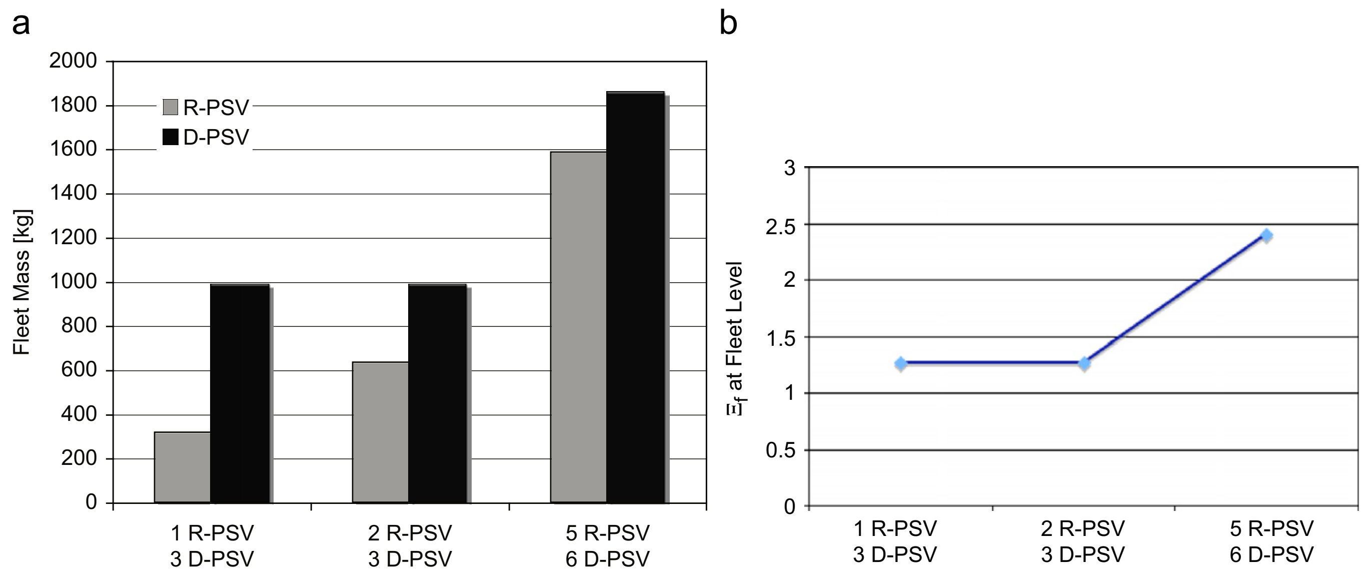

Fig. 5. Comparison between reconfigurable and dedicated PSV fleets. (a) Dry mass comparison; (b) $\Xi_f (=\eta_{f_R}/\eta_{f_D})$ comparison.

1 R-PSV (reconfigurable PSV) for 3 D-PSVs (dedicated PSVs which are 1 SPV, 1 LHV and 1 ATV). This is the case when none of the tasks are required simultaneously. So in principle one R-PSV is sufficient. The second case is for 2 R-PSVs and 3 D-PSV (which is when both LHV and ATV are required for operation simultaneously). The third case is of the fleet described above with 5 R-PSVs and 6 D-PSVs. It is clear that in a reconfigurable system, the amount of benefit (in terms of mass savings here) that can be realized is closely tied to the operation scenario.

6.1.1. *Relative functional efficiency*

The reconfigurable and dedicated vehicle fleets can also be assessed from the relative functional efficiency, Ξ_f, perspective. The Ξ_f was determined by first computing the functional efficiency, η_{f_D}, of a set of dedicated vehicles (consisting of 1 SPV, 1 LHV and 1 ATV). The η_{f_D} had been defined earlier in Eq. (9). Here the v_j is the transport capability [8] and ρ_j is the mass of each vehicle. The v is defined as the product of a vehicle's average speed with the payload it transports. In this case the total transported payload is the sum of cargo mass (carried on the vehicle) and the mass towed by the vehicle. Therefore

$$v = V \times (T + M) \tag{17}$$

The specific equation used for calculating η_{f_D} was

$$\eta_{f_D} = \frac{v_{SPV} + v_{LHV} + v_{ATV}}{m_{SPV} + m_{LHV} + m_{ATV}} \tag{18}$$

The η_{f_R} for the reconfigurable vehicle, with states A, B, and C was also computed in a similar manner using Eq. (8)

$$\eta_{f_R} = \frac{v_A + v_B + v_C}{m_R} \tag{19}$$

where m_R is mass of total reconfigurable vehicle system (with all the parts required for the various configurations along with the base vehicle). The ratio of η_{f_R} and η_{f_D} was then computed which was the Ξ_f, and was found to be 1.275. This indicates that the reconfigurable system offers more efficiency (by 27%) in terms of delivering unit transport capability per unit of mass as compared to the dedicated system. A similar computation was carried out for the other two cases described above. Fig. 5(b) summarizes the results. It should be noted that the masses of the reconfigurable system give a lower bound since any mass penalty of having components that can transform, or be installed and removed easily has not been factored in. The difference of mass thus provides the limiting value of reconfigurability, i.e. the reconfigurable option is better strictly in terms of mass if the mass penalties due to having reconfigurable components/sub-systems are lower than the difference. However, even if all the mass difference were consumed by the heavier reconfigurable components, there still is a benefit to the reconfigurable fleet because as failures occur components can be swapped out more easily and multi-functionality is retained longer at the fleet level.

In addition to the mass savings, the volume savings are implicit. If there are fewer vehicles that can do the

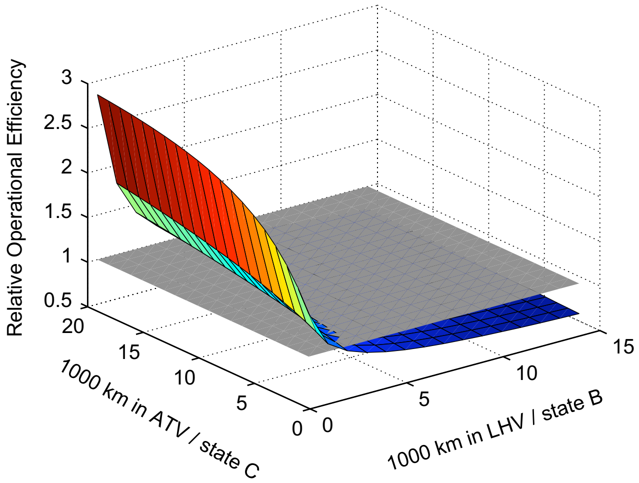

Fig. 6. Relative performance efficiency of planetary surface vehicles fleet.

job, there will be volume savings as well. It is, however, difficult to quantify those at this stage since they will depend on the stowage capabilities of the vehicles, and the design of the PSVs did not have that level of detail as they were primarily parametric.

Another important aspect is the extent of usage. This is because any difference in performance (usually worse for the reconfigurable system as compared to its ideal dedicated case) may weigh out over its life cycle if it is used extensively. An assessment based on the relative performance efficiency Ξ_p of the reconfigurable and dedicated vehicles was therefore carried out.

The vehicles have been modeled to use H_2–O_2 fuel cells, both of which are not found in free states on Moon or Mars. In the event that the total fuel for the mission has to be transported (considering the fuel cells are not regenerative for the worst case), then the total mass associated with the mobility system will be the mass of the vehicles plus the fuel they will use over the course of the entire mission. The total resources are then mass of the vehicles (non-recurring cost) along with the fuel mass of H_2 and O_2 (recurring cost).

Fig. 6 shows the relative performance efficiency, Ξ_p. This was obtained by first computing the performance efficiency, η_{p_D} (defined in Eq. (10)) of the dedicated set of vehicles (consisting of 1 SPV, 1 LHV and 1 ATV). The transport capability of each vehicle was multiplied with the total time it was used for in the mission to get the total life cycle performance. The specific equation used was

$$\eta_{p_D} = \frac{v_{SPV} T_{SPV} + v_{LHV} T_{LHV} + v_{ATV} T_{ATV}}{m_{SPV} + m_{LHV} + m_{ATV} + m_{H_2} + m_{O_2}} \tag{20}$$

where T is the time of use of each vehicle and is computed by dividing the distance traversed by the vehicle with its speed. The m_{H_2} and m_{O_2} are the mass of fuel.

Similarly for the reconfigurable system:

$$\eta_{p_R} = \frac{v_A T_A + v_B T_B + v_C T_C}{m_R + m_{H_2} + m_{O_2}} \tag{21}$$

Note that the mass of fuel comes out differently since the vehicle designs are different for the reconfigurable and dedicated case, so even for equal distance of travel the fuel consumption is different.

In order to do a trade over different usage extent, the distances traversed over the total mission by the LHV (the towing vehicle) and ATV (which is the light ATV) were varied between several thousand kilometers. The total distance traversed by the SPV (used for base set up is fixed to 50 km over the two year Mars surface mission). Then for each set of distances (axes X and Y in Fig. 6) a corresponding value of η_{p_D} was calculated. A similar procedure was carried for computing η_{p_R} for the reconfigurable vehicle that could adopt states A, B and C. The ratio of the two efficiencies was then taken to obtain Ξ_p and was plotted on the z-axis in the figure. For values of greater than 1 of the relative performance efficiency, the reconfigurable system offers an advantage. It is clear to see from Fig. 6 that the reconfigurable vehicle is better for small traverses of configuration B (that corresponds to the LHV). After approximately more than 5000 km of travel, the fuel consumption gets high enough to make the dedicated system better in terms of over all mass (resources) involved. The implicit assumption here is that the fuel is transported to the surface, and it is therefore very costly to consume more fuel. This figure illustrates the typical trade-off that may exist in many systems when subjected to analysis for reconfigurability. The reconfigurable system may give benefits in terms of using less non-recurring resources, but over the long run it may end up being more expensive due to sub-optimalities.

In a 600-day mission to Mars it maybe unlikely that this much distance will be traveled cumulatively by the vehicles, however, if the vehicles are to be used in subsequent missions (that maybe part of a long exploration campaign) then a dedicated fleet may merit a more closer look.

6.2. Markov reliability analysis for functional availability

As mentioned earlier, reconfigurability can also be a means for increasing a system's survivability. For the PSV study, a Markov reliability analysis was conducted at the fleet level to determine the effect of reconfigurability. Each 'state' of the fleet was defined by the number of vehicles of each type that are functional. The initial 'state' at the start of the mission, for the dedicated case, was denoted as [1, 2, 2] in which it was assumed that there is 1 SPV, 2 LHV, and 2 ATVs. The failures were modeled at the vehicle level, and each vehicle was assumed to have a specific mean time to failure (MTTF). The transition rate, λ_{ij}, between each state i and j was then simply the reciprocal of the MTTF of the vehicle that fails as the fleet moves from state i to j. Fig. 7(a) shows the Markov model for the dedicated fleet. The initial state is 1, and the transition rate of moving to state 2 (which is [0, 2, 2]) is λ_1 which is the failure rate of the SPV. State 3 is [1, 1, 2] and can be attained from state 1 if one of the LHVs fail. The transition rate is $2\lambda_2$ since there are two LHVs and if the first or the second LHV fails, the fleet will be in state 3. The final state 18 is [0, 0, 0] in which all three vehicles have failed. Based on this Markov model the probabilities of the fleet of being in any particular state at a specific time were computed by defining a vector Π, of 18 elements in which the ith element π_i was the probability of being in state i. Thus at any time the sum of the elements of Π would be 1. For this continuous time model, the following equations hold:

$$\frac{d}{dt}\Pi(t) = A\Pi(t) \tag{22}$$

$$\Pi(t) = e^{At}\Pi_0 \tag{23}$$

where $\Pi_0^T = [1, 0, \ldots, 0]$ (and is the initial state at time 0) and $A \in \Re^{n\times n}$ is given by

$$A = \begin{bmatrix} -(\lambda_1 + 2\lambda_2 + 2\lambda_3) & 0 & 0 & \cdots & 0 \\ \lambda_1 & -(2\lambda_2 + 2\lambda_3) & 0 & \cdots & 0 \\ \lambda_2 & 0 & -(\lambda_1 + \lambda_2 + 2\lambda_3) & \cdots & 0 \\ \vdots & 0 & 0 & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

In the reconfigurable fleet, each vehicle could deliver the functionality of an SPV, LHV or ATV. Since there were two LHVs and ATVs in the dedicated case, two reconfigurable vehicles were considered for a somewhat equal comparison in a functional sense. The failures were assumed to be at the configuration level. So a reconfigurable vehicle could for instance have a particular failure so that it could only be operate in states of an SPV and an LHV but not as an ATV. This can happen if some specific part fails that was needed for the ATV configuration but not required for the SPV and LHV configurations. The initial state was set to [2, 2, 2] since at the start of the function, the fleet could deliver the functionality of 2 SPVs or 2 LHVs or 2 ATVs. A Markov model was made and the state probabilities were computed in a similar way as for the dedicated case discussed above (see Fig. 7(b)). A value of 10 years for the MTTF for each dedicated vehicle (and configuration in the reconfigurable vehicle case) was assumed. Although more realistically, the MTTF for the configurations would be higher since it would occur due to partial failure of the vehicle (so that for instance it can only operate in two out of its three possible configurations). The estimate for the reconfigurable case will be therefore conservative.

Fig. 8(a) shows the probability of having at least one of each kind of vehicle (or configuration) being available. This essentially means that all the different functions/tasks can be carried out since one of each type of vehicle is functional. This was computed by summing the probabilities of all the states (given in general by $[i, j, k]$) in which i, j, and k were greater than or equal to 1. It can be seen that the chances of having the capability to perform all the types of tasks is improved for the reconfigurable case. For a two-year mission the dedicated fleet has a probability of 60% that all types of tasks can be performed as compared to the 82% chance for the reconfigurable vehicles fleet.

In order to assess the performance degradation over time of the fleet, the transport capability metric, v [8] was used. The v of a fleet is simply the sum of the v of each vehicle in the fleet. Fig. 8(b) shows how the *expected transport capability* of the fleet degrades over time. The expected transport capability is defined as

$$ETC = \mathbf{v}^T\Pi(t) \tag{24}$$

where $\mathbf{v}^T = [v_1 \cdots v_i \cdots v_n]$ (for n configurations) and v_i is the transport capability of the fleet in configuration i. It can be seen that the plots are not linear, and the derivatives vary as a function of time. The derivatives of the ETC for each case were therefore computed by taking the mean derivative between two sets of points each along the line. It is clear to see simply from the plots alone that the reconfigurable system degrades more slowly as compared to the fixed

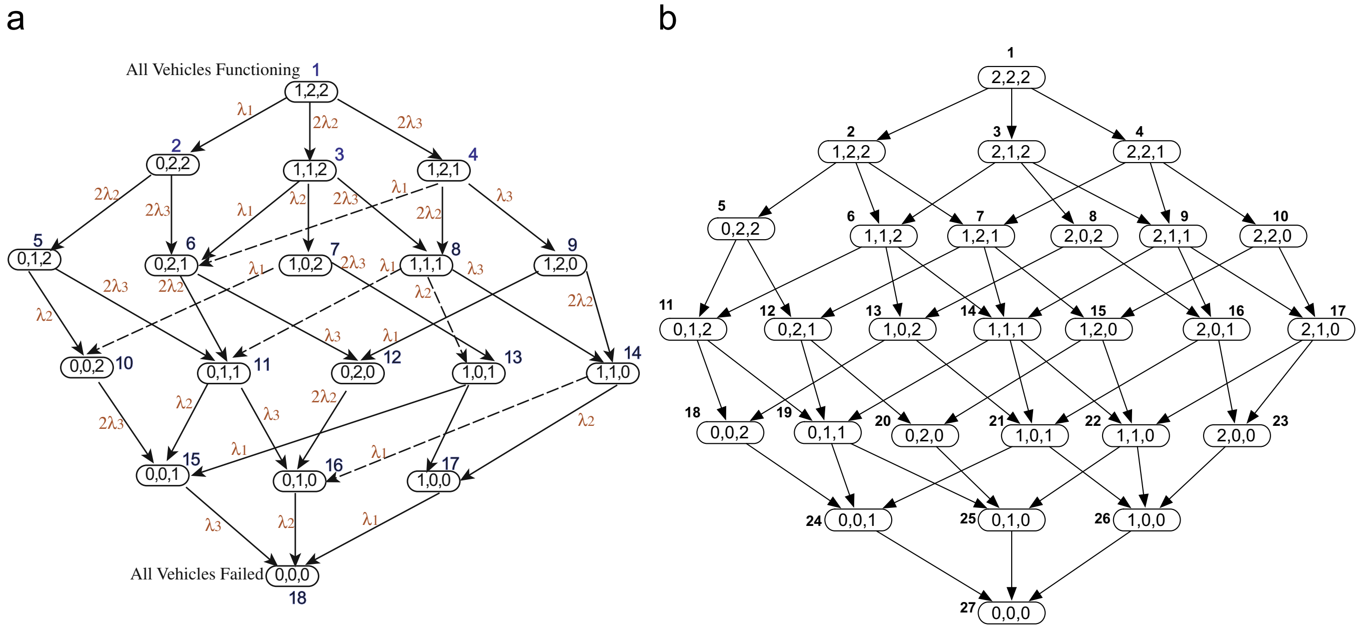

Fig. 7. Markov models of vehicle fleet. (a) Dedicated vehicle fleet; (b) reconfigurable vehicle fleet.

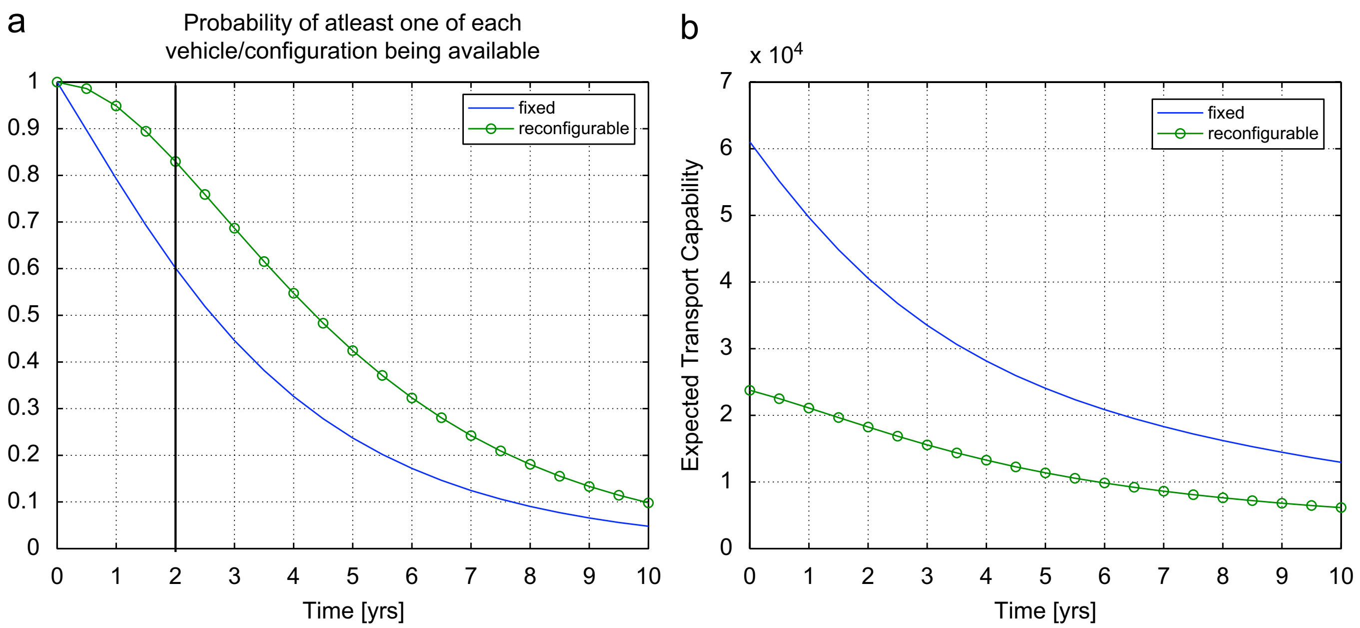

Fig. 8. Markov reliability analysis at fleet level. (a) Probability of having functional capability of each type; (b) expected transport capability of fleet.

system. However, in numerical terms, for the dedicated case, the mean $dETC/dt$ was found to be -4.80×10^3 [kg km/h/year], and for the reconfigurable case it was -1.76×10^3 [kg km/h/year]. The ratio, which is the relative degradability, Λ was thus 2.72 showing that the reconfigurable system is almost three times more favorable from a degradability perspective.

7. Conclusions

This work highlights how the new paradigm of reconfigurability in systems can allow for several beneficial qualities to be realized. In space systems, where mass and volume are at a premium, every kilogram transported to a planetary surface should be viewed as a resource that should not be limited for single-purpose applications. Such systems, whenever possible, should be architected for carrying out a range of functions so that maximum utility can be obtained from a fixed set of hardware (material resources). It is shown, through a detailed study of PSVs, how reconfigurable systems can be designed so that they can attain different states for carrying out non-concurrent different/modified functions. Furthermore, through Markov reliability analysis, the survivability of the reconfigurable system can be evaluated. For the specific scenario considered in the study, of a surface exploration mission of Mars, the relative functional efficiency is found to be at least 1.275. The reconfigurable vehicles fleet thus provides 27.5% more transport functionality per unit of mass as compared to a corresponding non-reconfigurable/dedicated vehicles fleet. The relative degradability of the two types of fleet was determined to be 2.72, i.e. the reconfigurable fleet is almost 3 times better in retaining some level of functionality.

In future studies, methods for determining the reconfiguration costs will be explored in more detail (since these costs have a direct impact on the selection of a good design). Additionally, concepts for reconfigurable vehicle designs and technologies (such as smart materials, drive-by-wire, etc.) that can enable transformation and easy substitution of the components will be investigated.

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