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Trade-off Study, Review and Anatomical Study of Launch Vehicles in use and under-development

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Abstract

This paper provides trade-off study, review and anatomical study of launch vehicles presently in use and under development by various government space organisation and aerospace corporation. The launch vehicles are categorized on the basis of consideration parameters they are being used for. The launch systems are categorized on the basis of usage i.e. expendable or reusable, launch platform, payload weight parameter, and flight regime. Launch vehicle vary depending on the type of launch assistance i.e. launch platform they require for example land-based such as Spaceport in Sierra County, water-based such as mobile-platform and air-based launchers such as Virgin Galactic's Launcher One.

1. Introduction

Launch Vehicle refers to the transport system that is used to carry payload from earth's surface to orbit, outer space, or interplanetary transfer. In concept, rockets are simple machines that follow Newton's third law of motion that for every action there is equal and opposite reaction, rocket propels mass in one direction and moves in the other. But such was the case of beginning of the space era, modern launch vehicle system are very complex and critically tuned systems. Most of the launch vehicles developed earlier were expendable i.e. either destroyed during the flight or drifted to the graveyard orbit. Market focus to reduce cost per launch led to the development of reusable launch vehicles. This paper provides trade-off study, review and anatomical study of launch vehicles presently in use and under development by various government space organisation and aerospace corporation. The launch vehicles are categorized on the basis of consideration parameters they are being used for. The launch systems are categorized on the basis of usage i.e. expendable or reusable, launch platform, payload weight parameter, and flight regime. Launch vehicle vary depending on the type of launch assistance i.e. launch platform they require for example land-based such as Spaceport in Sierra County, water-based such as mobile platform and air-based launchers such as Virgin Galactic's Launcher One. The primary review study was conducted on categorisation of launch vehicle based on the payload weight they can carry. To provide effective insight in the review of launch vehicle, trade-off study is conducted between various parameters such as weightage, fuel load, reusability, net impulse, development time period and the most critical trade-off factor being the ease of manufacturing of space launch vehicle because reduction of critical mass directly affects the mass capability in exploration missions. These are the basic trade-off factors which are changed based on the categorisation being considered for the launch vehicle. Flight regime of launch vehicles refer to the service altitude level such as suborbital level, orbital level, outer space or interplanetary distance. Distributed launch vehicle which are currently under development are the next revolution in space transportation after reusable launch vehicles. This type of launch vehicle involves in-space launching mechanism, propellent transfer such as the BFR system of SpaceX. The paper also reviews market focus study on cost per launch based on payload weightage for all the reviewed launch vehicles.[1]–[3]

2. Anatomy of Launch Vehicle

The launch vehicle is versatile modular vehicle which is comprised of various stages. The basic concept behind the working of the launch vehicle is newton's third law of motion. Although the principle of the launch vehicle is relatively simple but the modern-day machines all in all very complex in working and design. As already stated, they have

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numerous numbers of stages which individually consists of many subsystems responsible for navigation, propulsion and guidance of the vehicle. Each stage has 4 basic subsystems which are as follows[3][4]:

- Propulsion
- Structure
- Avionics System
- Tankage

The launch vehicle system is divided into 5 basic stages which are mentioned as follows starting from ground up:

1. First Stage: This is the main thrust unit of the launch vehicle which is responsible for taking the vehicle out from the orbit of the earth. It consists of main propulsion unit with multiple engines. The stage only consists of Liquid-Oxygen tank, propulsion unit, casing structure of the rocket and avionics bay that largely depends on the build of the rocket.
2. Inter-stage: This serves as the main connect structure between the different stages of the launch vehicle. This serves as the attachment bearing section which house the avionics line-up, depending upon the build of the launch vehicle.
3. Upper Stages: Depending on the build and the orbital altitude the launch vehicle is intended to achieve; the launch vehicle can have 2 or more stages. These stages generally serve the purpose of providing extra lift and orbit manoeuvrability in the orbit to achieve the required attitude and coordinate plane.
4. Payload Fairing: The top blunt part of the launch vehicle is referred to as the Payload bay and the shielings which protect the payload inside are referred to as the payload fairings. They generally come in different shapes and sizes depending on the mass and sizing offered by the launch vehicle to be lifted.
5. Side Boosters: Also referred to as the Strap-on boosters are used in heavy lift launch vehicles which require large amount thrust to lift-off. Most commonly used these days are the liquid fuel propelled booster because they have relatively high specific impulse rate.

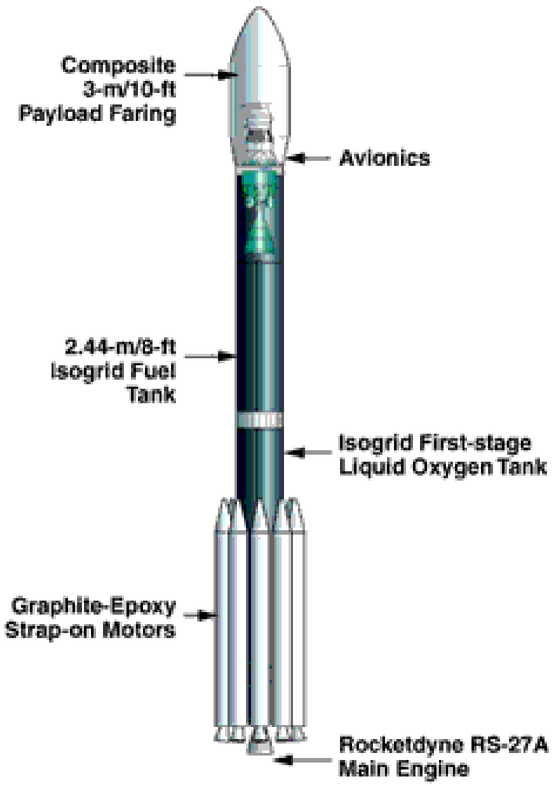

Figure 1: Delta 2 Launch Vehicle: Parts of Launch Vehicle

When considering the propulsion system of a launch vehicle, the engine is considered which are having specific impulse from 300 sec above range. Specific impulse refers to the net thrust impulse offered by the engine per unit fuel. The higher the specific impulse of the engine, the more thrust it provides with less amount fuel. This is not only economic but helps on cutting short on the Gross lift-off mass (GLOW) of the launch vehicle[5]–[7].

3. Trade-off Study

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3.1 Payload Parametric

"Payload" refers to the useful weight that can be lifted by the orbital launch vehicle. The payload capacity of the orbital launch vehicle is largely affected by the number of stages, net weight, specific impulse and thrust produced. Planned orbital altitude also affects orbital launch vehicle payload lifting capacity. The higher the mission altitude, the more fuel is required for the flight or extra boosters are required for more thrust resulting in increase in the Gross Lift-off Weight (GLOW) of the orbital vehicle. Another factor that is important for the orbital launch vehicles is the net specific impulse. This unit is used to define the efficiency of the launch systems. Therefore, the launch vehicles with high specific impulse requires relatively less fuel to produce the same amount of thrust as the vehicles with low specific impulse with high amount of fuel will produce. The following table provides comparative data on various parametric details of the launch vehicle[5]–[7][8]–[10].

Table 1: Payload Parametric of the Launch Vehicles

Launch Vehicle	**Manufacturer**	**Payload (kgs)**			**GLOW (kgs)**	**Stages**	**Thrust (kN)**	**Specific Impulse (sec)**	**Launch till date**
		LEO	**GSO**	**Other**					
Alpha	Firefly	1000	-	630 (SSO)	54000	2	736, 70	295.6, 322	0
Beta	Firefly	4000	400	3000 (SSO)	149000	2	2208, 163	295.6, 324	0
Angara 1.2	Khrunichev	3500	-	1600 (ULEO)	171000	2			1
Angara A3	Khrunichev	14000	1000	2400 (MEO)	480000	3			0
Angara A5	Khrunichev	24000	2800	5400 (MEO)	780000	3			1
Antares 230	NG Innovation	8000	-	3000 (SSO)	298000	2	212.6, 56.8	339, 296	5
Ariane 5	Ariane Space	20000	10000	10000 (SSO) 6600 (Elliptic) 7000 (Moon Transfer)	780000	2, 2 Side Booster	1390, 67, 7000	432, 446, 274.5	98
Ariane 6.2	Ariane Space	7100	4640	5800 (SSO) 2400 (Earth Escape) 2800 (Moon Transfer) 1700 (MEO)	530000	2, 2 Side Boosters	1370, 180	431, 465	0
Ariane 6.4	Ariane Space	16100	10880	14100 (SSO) 7400 (Earth Escape) 8200 (Moon Transfer)	860000	2, 4 Side Boosters	1370, 180	431, 465	0
Atlas V 401	ULA	9800	-	4750 (GTO) 8910 (ISS)	333320	2	3826, 101.8	311, 450.5	38
Atlas V 411	ULA	12030	1935	5950 (GTO)	374120			311, 450.5,	5

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				10670 (ISS)		2, 1 Side Booster	3826, 101.8, 1690	279.3	
Atlas V 421	ULA	13600	2480	6890 (GTO) 10670 (ISS)	414920	2, 2 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	7
Atlas V 431	ULA	15260	2820	7700 (GTO) 13250 (ISS)	461180	2, 3 Booster	3826, 101.8, 1690	311, 450.5, 279.3	3
Atlas V Starliner	ULA	-	-	13250 (ISS)	414920	2, 2 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	0
Atlas V 501	ULA	8210	-	3780 (GTO) 7540 (ISS)	337290	2	3826, 101.8	311, 450.5	6
Atlas V 511	ULA	11000	-	5250 (GTO) 10160 (ISS)	374120	2, 1 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	0
Atlas V 521	ULA	13500	2540	6480 (GTO) 12510 (ISS)	429810	2, 2 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	2
Atlas V 531	ULA	15530	3080	7450 (GTO) 14480 (ISS)	476070	2, 3 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	3
Atlas V 541	ULA	17410	3530	8290 (GTO) 16290 (ISS)	522330	2, 4 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	6
Atlas V 551	ULA	18850	3850	8900 (GTO) 17720 (ISS)	568590	2, 5 Side Booster	3826, 101.8, 1690	311, 450.5, 279.3	9
Delta IV Heavy	ULA	28370	6580	14210 (GTO) 25980 (ISS)	733000	2	3122, 110.09	362, 465.5	11
Vulcan 522	ULA	17800	2100	7600 (GTO) 15400 (ISS)	-	2, 2 Side Boosters	4893	335	0
Vulcan 562	ULA	27400	6700	13,700 (GTO) 24300 (ISS)	-	2, 6 Side Boosters	4893	335	0
Vulcan Centaur Heavy	ULA	37300	7300	15000 (GTO) 26600 (ISS)	-	2, 6 Side Boosters	-	-	0
Tsyklon-4M	KB Yuzhoe	5000	-	910 (GTO) 3350 (SSO)	272000	2	3469.59, 77.47	332, 330	0

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Electron	Rocket Lab	225	-	150 (SSO)	12550	2	162, 22	303, 333	0
Falcon 9	Space X	22800	-	8300 (GTO) 4020 (MARS Orbit)	549054	2	8227, 934	311, 311	71
Falcon Heavy	Space X	63800	-	26700 (GTO) 16800 (Mars Orbit) 3500 (Pluto Orbit)	1420788	2, 2 Side Booster	22819, 934	311, 311	2
PSLV- XL	ISRO	-	-	1425 (GTO) 1750 (SSO)	320000	4, 6 Side Booster	4800, 799, 240, 15.2, 719	-	44
GSLV Mk II	ISRO	5000	-	2500 (GTO)	414750	3, 4 Side Booster	4700, 800, 75, 680	-	10
GSLV Mk III	ISRO	8000	-	4000 (GTO)	640000	3, 2 Side Boosters	-	-	3
H-IIB	Mitsubishi	10000	-	4000 (GTO) 3800 (SSO) 2500 (IPM)	289000	2, 2 Side Booster	1098, 137, 2520	440, 448, 283	7
Zhuque-2	Landspace	3600	-	1100 (SSO)	230000	2	659, 765	283, 334	0
Zhuque-1	Landspace	300	-	200 (SSO)	264870	3			1
Zenit-3SLB / 3M	Yuzhnoye Design Bureau	13500	1600	3750 (GTO) 4830 (MEO)	462650	3	7887, 833, 83.4	7887, 833, 83.4	6
Zenit- 3SL	Yuzhnoye Design Bureau	13500		5700 (MEO) 6060 (GTO)	465800	3	7887, 833, 83.4	7887, 833, 83.4	36
Yenisei	TSSKB-Progress RSC Energia	-	294300	-	231514	2	29037, 5591		0
SSLV	ISRO	300	500	500 (LPEO) 300 (SSO)	116000	4			4
Soyuz-5	TsSKB-Progress		9810		5640750	2	3825, 716.1	358, 372	
Minotaur-V	NG Innovation			532 (GTO) 342 (TLI)	89000	5	2224, 1223, 289	284, 308, 300	1

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LauncherOne	Virgin Orbit	500	-	-	25854	2	34, 2.26	-	1
Glenn	Blue Origin	40000	-	13000 (GTO)	-	2	17100, 1100	-	-

3.2 Versatility and Reusability

As already stated in the introduction, with the advancement in the technologies it is important for launch vehicles to be versatile in nature, i.e. they should be able to developed, manufactured and ready for launch conditions in minimum amount of time and most importantly, the launch vehicles should be able to launch from any terrain. In today's date, the orbital launch vehicles are being developed that can be launched from launch pads, spaceports, assist aircrafts and sea launch platforms and with the recent launch of Long March 11 China achieved a new feat of launch from mobile sea platform. The platforms are divided as follows:

1. Land Launch Platforms (LLP)
2. Spaceport (SP)
3. Aircraft Assisted (AA)
4. Mobile Sea Launch Platform (MSLP)

Another major factor that plays a major role is reusability. With the launch of SpaceX's falcon series and Blue Origin's Shephard series introduced world to a new orbital launch vehicle concept of using launch vehicles multiple times. This not only helps in reducing the cost of launch by a major percentage but also helps in reducing space debris. The following table provides comparative details on all the launch vehicles currently in use or under development on the basis of reusability, versatility and costing[5]–[7][10].

Table 2: Versatility and Reusability of the Launch Vehicles

Launch Vehicle	**Reusability**	**Versatility**	**Cost per Launch ($)**	**Launch Vehicle**	**Reusability**	**Versatility**	**Cost per Launch ($)**
Alpha	No	LLP	15 Mil	Beta	No	LLP	NA
Angara 1.2	No	LLP		Angara A3	No	LLP	
Angara A5	No	LLP		Antares 230	No	LLP	85 Mil
Ariane 5	No	LLP	220 Mil	Ariane 6.2	No	LLP	84.8 Mil
Ariane 6.4	No	LLP	101.7 Mil	Atlas V 401	No	LLP	109 Mil
Atlas V 411	No	LLP	115 Mil	Atlas V 421	No	LLP	123 Mil
Atlas V 431	No	LLP	130 Mil	Atlas V Starliner	No	LLP	123 Mil

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Atlas V 501	No	LLP	120 Mil	Atlas V 511	No	LLP	130 Mil
Atlas V 521	No	LLP	135 Mil	Atlas V 531	No	LLP	140 Mil
Atlas V 541	No	LLP	145 Mil	Atlas V 551	No	LLP	153 Mil
Delta IV Heavy	No	LLP	350 Mil	Vulcan 522	No	LLP	-
Vulcan 562	No	LLP	-	Vulcan Centaur Heavy	No	LLP	-
Tsklyon-4M	No	LLP	45 Mil	Falcon 9	Yes	LLP	50 Mil
Falcon Heavy	Yes	LLP	90 Mil (Reusable) 150 Mil (Expendable)	PSLV XL	No	LLP	31 Mil
GSLV Mk II	No	LLP	47 Mil	GSLV Mk III	No	LLP	47 Mil
HII-B	No	LLP	90 Mil	Zhuque-2	Yes	LLP	43.2 Mil
Zhuque-1	No	LLP	-	Zenit-3SLB / 3M	No	LLP	45 Mil
Zenit-3SL	No	MSLP	NA	Yenisei	No	LLP	-
SSLV	No	LLP	4.3	Soyuz-5	No	LLP	-
Minotaur-V	No	LLP	-	Launcher One	No	AS	30 Mil
Glenn	Yes	LLP	-	-	-	-	-

3.3 Flight Regime

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Flight Regime refers the orbital altitude level of the launch vehicle. As already mentioned, planned orbital altitude affects the type of launch vehicle needed for the mission. The launch vehicles are designed with a particular altitude as defined by their respective manufactures or mission. Not every launch vehicle is compatible with every altitude, therefore selecting the correct launch vehicle is important for a space mission. The altitudes levels are divided as:

1. Low-Earth Orbit (200-2000 Km)
2. Sun-Synchronous Orbit (500-700 Km)
3. Geo-stationary Orbit (35786 Km)
4. Polar Earth Orbit (700-1700 Km)
5. High-Earth Orbit (above 35,000 Km)
6. Heliocentric Orbit
7. Trans-Lunar Injection
8. Trans-Mars Injection

The following table provides comparative details on all the previously reviewed launch vehicles on the basis of the altitude levels[1][5]–[7][9][11]:

Table 3: Flight Regime of different launch vehicles

Launch Vehicle	Altitude Level (Km)				Launch Vehicle	Altitude Level (Km)			
	LEO	SSO	GSO	Other		LEO	SSO	GSO	Other
Alpha	200	500	-	-	Beta	200	500	35786	-
Angara 1.2	200	-	35786	5500 (MEO)	Angara A3	200	-	35786	5500 (MEO)
Angara A5	200	-	35786	5500 (MEO)	Antares	200	550	-	-
Ariane 5	260	800	35943	1300000 (Apogee Elliptical)	Ariane 6.2	300	900	35786	23200 (MEO)
Ariane 2.4	300	900	35786	23200 (MEO)	Atlas V 401	200	-	-	35786 (GTO 27º)
Atlas V 411	200	-	35786	35786 (GTO 27º)	Atlas V 421	200	-	35786	35786 (GTO 27º)
Atlas V 431	200	-	35786	35786 (GTO 27º)	Atlas V Starliner	-	-	-	407 (ISS)
Atlas V 501	200	-	-	35786 (GTO 27º)	Atlas V 511	200	-	-	35786 (GTO 27º)
Atlas V 521	200	-	35786	35786 (GTO 27º)	Atlas V 531	200	-	35786	35786 (GTO 27º)
Atlas V 541	200	-	35786	35786 (GTO 27º)	Atlas V 551	200	-	35786	35786 (GTO 27º)
Delta IV Heavy	200	-	35786	35786 (GTO 27º)	Vulcan 522	200	-	35786	35786 (GTO 27º)
Vulcan 562	200	-	35786	35786 (GTO 27º)	Vulcan Centaur Heavy	200	-	35786	35786 (GTO 27º)
Tsyklon-4M	200	700	-	35786 (GTO 45.2º)	Falcon 9	200	-	-	35786 (GTO)
Falcon Heavy	200	-	-	35786 (GTO)	PSLV XL	-	600	-	35786 (GTO)
GSLV Mk II	200	-	-	35786 (GTO)	GSLV Mk III	200	-	-	35786 (GTO)

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H-IIA	300	800	-	36000 (GTO)	Zhuque-2	200	700, 500	-	-
Zhuque-1	300	200	-	-	Zenit-3SLB / 3M	200	500	-	-
Zenit-3SL	200	-	-	10000 (MEO)	Yenisei	200	500	-	-
SSLV	400				Soyuz-5	230	-	-	-
Minotaur-V	200	500	-	-	Launcher One	200	-	-	-
Glenn	200	-	-	35786 (GTO)	-	-	-	-	-

4. Conclusion

As science and technology advancing in space domain, it has become vital to gain easy access to the space now more than ever. All the space organisation and government agencies have one particular goal set in mind that is to reach Mars and not only Mars but to extend their reaches beyond anyone in space. The primary of gaining access to space is through the launch vehicles. More and more experiments require more launches; hence it comes down to the reality where manufacturers are going to provide effective launch systems in the minimum time period and at competitive costs, and considering the most important factor of all, reusability of the launch vehicles. Launch vehicles use lot of fuel and lot of material to build and the conventional designs only serve to increase the mass debris, therefore with the introduction of the reusable launch vehicles, it has not only helped in bringing the material and launch cost down, it has helped in launching the satellites with minimum to no contribution to space debris and these systems also use less amount of fuel compared to the previous launch vehicles, which is also beneficiary in terms of environmental safety. For the upcoming endeavours in space, we should aim to develop more launch vehicles like the Falcon 9 and Falcon Heavy and Glenn which is currently under development by the Blue Origin which have the concept of reusability bound to the core of the designing. This also brings us to the under development, the distributed launch systems, which is a term used for the launch vehicles who will be responsible of taking humans on interplanetary missions. The concept behind these launch vehicles that they will be assembled on part by part basis in space and then the vehicle will be used to transport humans and goods to other planets.

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