Introduction to Launch Vehicle Analysis and Design

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Lecture - 22
Variant Concept

Hello and welcome. In this lecture, as was mentioned in the last lecture, we will introduce the concept of variant of a launch vehicle, and look at some of the basic aspects of the process through which we can arrive at a variant configuration, which is an extremely useful idea from practical perspective. So let us begin.

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So, the concept of variant is essentially related to a much older design philosophy that has been practiced for many products for a long time called stretching a design. What it means is that, once you create a design which is the best possible design from a given mission perspective, then if your objectives get slightly modified, either you go through the whole exercise all over again to get another optimal configuration or you stretch the existing design so that it will meet a slightly modified requirement.

The variant is essentially an idea that is connected to this philosophy.

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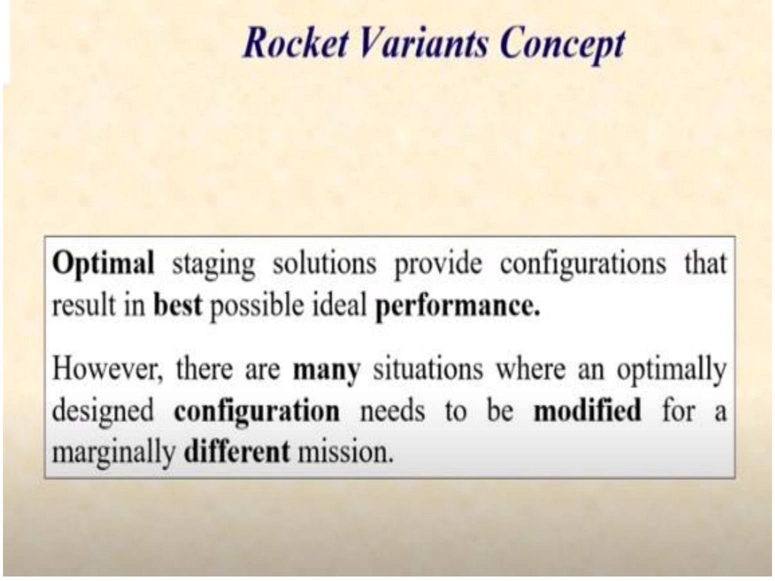

So, in the context of rocket design the optimal staging solutions that we have seen in the last couple of lectures provide us with a configuration which is going to give the best possible performance in the context in which it has been configured.

And then, we find that there are going to be many situations where an optimally designed configuration which is applicable to a specific m_* or a π_* or a specific V_* needs to be modified for a mission that might require either a marginally different V_* or a different m_* or π_*.

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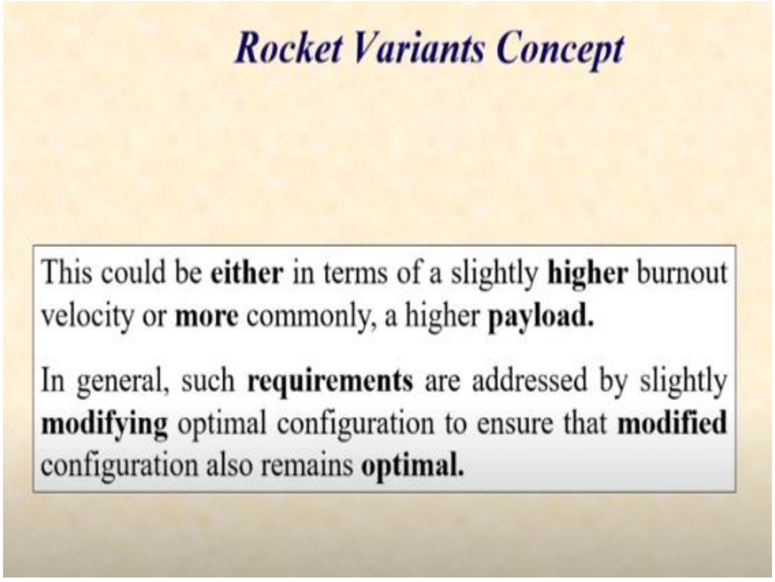

The two possibilities which commonly occur are that you might either need a slightly higher burnout velocity, so that you might want to perform a different mission with the same payload mass or what is more commonly encountered and practiced is that we may want a slightly higher payload for the same mission and this becomes an extremely desirable perspective as the spacecraft when they undergo development independent of the launch vehicle.

Typically, we aim to enhance their capabilities in terms of sensors, payloads, etc., so that generally their mass would increase and you may now want to achieve the same mission with a higher mass. And in the context of variant instead of designing a new rocket afresh from the scratch such requirements are addressed by slightly modifying the optimal configuration which is designed for a different V_* and m_* to ensure that modified configuration will meet the requirement of a different mission.

And by doing that, it also remains optimal in a broad sense.

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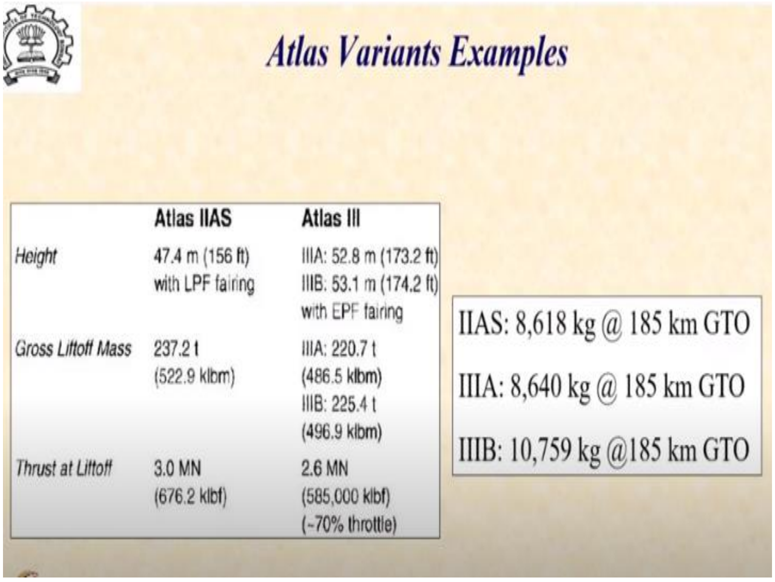

I want to show you a couple of examples just to illustrate this point. And I have taken as a case in point Atlas rocket, which the USA uses for many of its applications. And you will see here that I have given two versions of Atlas, one is called Atlas IIAS and other one is Atlas III. If you look at the numbers, like for example height, instead of 47 meters, you have 52 meters which is about 5 meters higher.

The lift-off mass which is 237 tons for Atlas IIAS becomes 220.7 tons for Atlas IIIA and 225.4 tons for Atlas IIIB. If you look at the thrust at lift-off, Atlas IIAS generates 3 MN while Atlas III generates 2.6 MN. The implication of this table is that both of them are called Atlas. But within the context of the same so-called family of rocket, there are marginal differences in their configuration, and it is expected that they will perform different functions.

Even though these numbers might look a little larger as percentage of the basic or the base configuration, these are within the range of about 5 to 10% which is considered to be small change for the overall rocket. Let us look at what kind of missions these particular variants are expected to perform.

So, Atlas IIAS is expected to launch a mass of 8618 kg to achieve a 185 km geotransfer orbit while Atlas IIIA which uses a slightly smaller liftoff mass is expected to perform the same mission with a slightly larger payload of 8640 kg. Atlas IIIB in which there is about 5 tons extra mass compared to Atlas IIIA, we are able to launch almost a 2000 kg extra mass for the same mission.

So, we realize that the variants are essentially slightly modified versions of a base configuration which defines the family which would mean that Atlas as a generic name would have a base configuration and then it would have a number of variants. I would suggest that you look at literature to find out which are other variants of Atlas and what kind of missions they can and are expected to perform.

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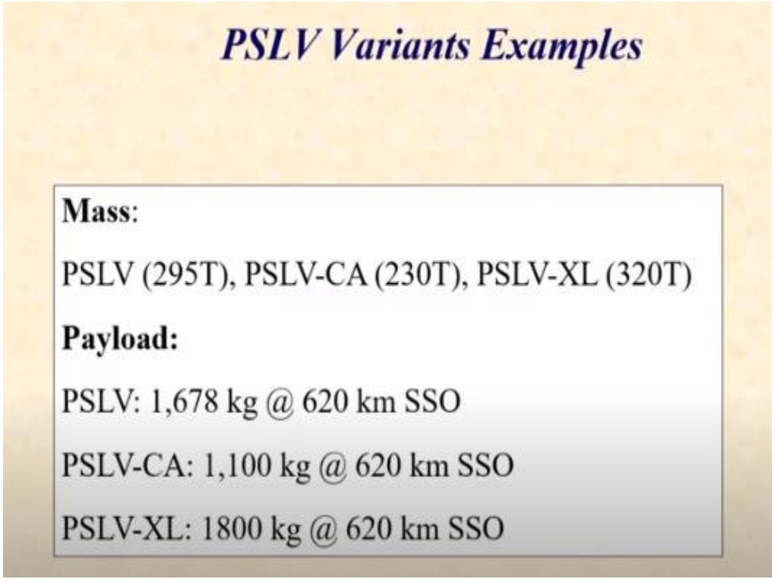

Let us look at one more launch vehicle, the Indian PSLV and let us look at its variants and what they are expected to achieve. So PSLV has three possible variant configuration all connected to the same base conceptual design. The plain PSLV which is 295 tons. The PSLV-CA, CA standing for core alone. So, it does not have any zero stage or booster stage weighs only 230 tons.

So, it is about 65 tons lighter, which is about 20% less than the basic PSLV. And then you have PSLV-XL that is extra-large at 320 tons. That is about 25 tons extra and about 8% heavier. Let us now look at what kind of applications these three versions of the PSLV are commonly put to use for. So, the basic PSLV is designed to launch a 1678 kg in 620 km sun-synchronous orbit.

The PSLV-CA does the same job for a significantly lighter payload of about 1100 kg. While the PSLV- XL does the same job for a significantly higher payload at 1800 kg. You would also be interested in knowing that the same PSLV is also used for a few interplanetary missions that India has flown and I would request you to look at the mission that is expected to be flown along with the mass that is attached to the mission and the version of the PSLV which is used for that specific mission.

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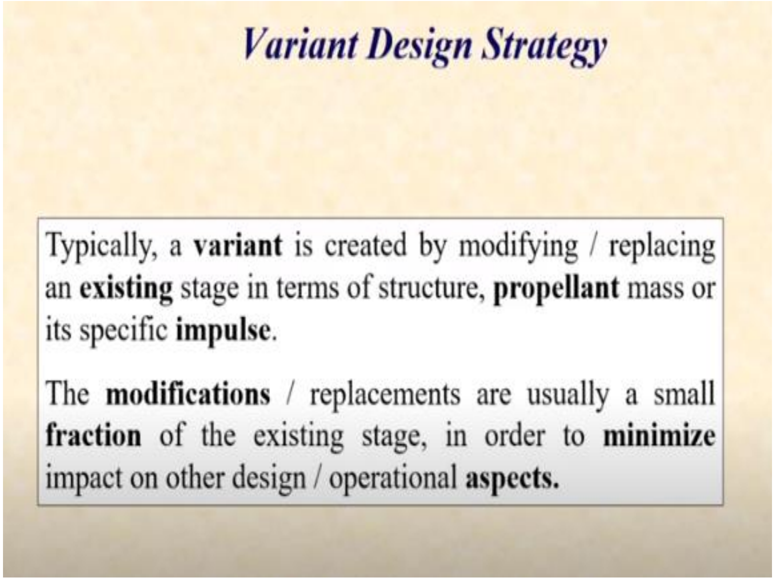

So, this brings us to some discussion on the design strategy. So how does one do this exercise or how does it happen? Typically, a variant is created by modifying or replacing an existing stage in terms of either structure or propellant or its specific impulse. For example, you might still be using the same stage I of PSLV. May have the same mass for propellant, but you may pack it with a propellant which is maybe a slightly higher I_{sp}.

And in the process, you would achieve a higher burnout velocity. Or for the given burnout velocity, you might be able to launch a slightly larger payload. Similarly, you could make the structure slightly lighter. And because the structure is made slightly lighter, you may either pack in a little bit more propellant to keep the stage mass same or you may add a little bit more of payload so that the overall rocket launch mass remains the same.

But then you can perform a slightly different mission with the same rocket and nothing else changed. In this regard, you must realize that these modifications or replacements are usually a small fraction of the existing stage. The implication is that in order to minimize the impact on other design and operational aspects, we need to keep these changes small.

If there is a need to make large changes, then anyway it would be better to design a new rocket itself. For example, we have done this with the concept of GSLV which is a different rocket altogether.

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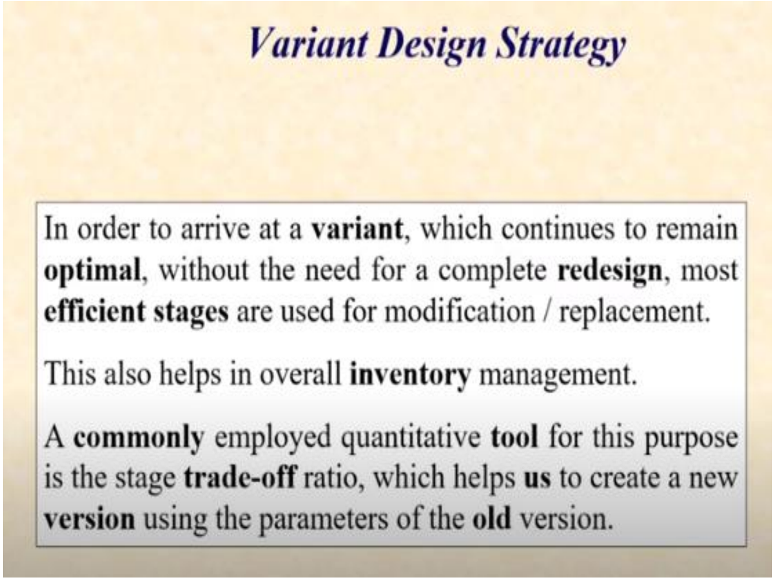

Now if we accept except this idea that the basic configuration that we have designed is an optimal one, that any change that we make is going to make the new solution suboptimal. Now why if the changes are small a suboptimal rocket might still be acceptable, but if we can also incorporate some ideas of optimal performance, while making these modifications, it would definitely be a desirable objective.

And in order to do that, there are two things that are commonly practiced. One, we need to find out among the various stages the ones which are the most efficient in terms of their operation, so that a small change in the stage would reap large benefits. Which means, if a stage is such that the performance is very sensitive to small changes, then a small change will result in a significant improvement in performance and which in turn means that a small change is what will make a new rocket feasible.

Another important practical point which the variant concept brings in is the overall inventory management of the design agency that you do not really need to keep too many different rockets as your whole because sometimes that would also require different fabrication facilities, different infrastructure related requirements etc.

So, you may keep a modular configuration and only store the various stages and then depending upon the requirement generate a combination of stages for a specific mission. Now how does one do this? That is how does one identify the stage or stages which are more efficient where a small change would result in a large change in the performance and also will keep the rocket as close to optimal performance as possible.

And we realize that a concept called the tradeoff ratio is useful quantitative tool which helps us to create a new version using the parameters of the old version. So, we make use of the parameters of the old version and then perform a tradeoff analysis to find out which stage we should modify and in what manner to achieve the desired modified performance.

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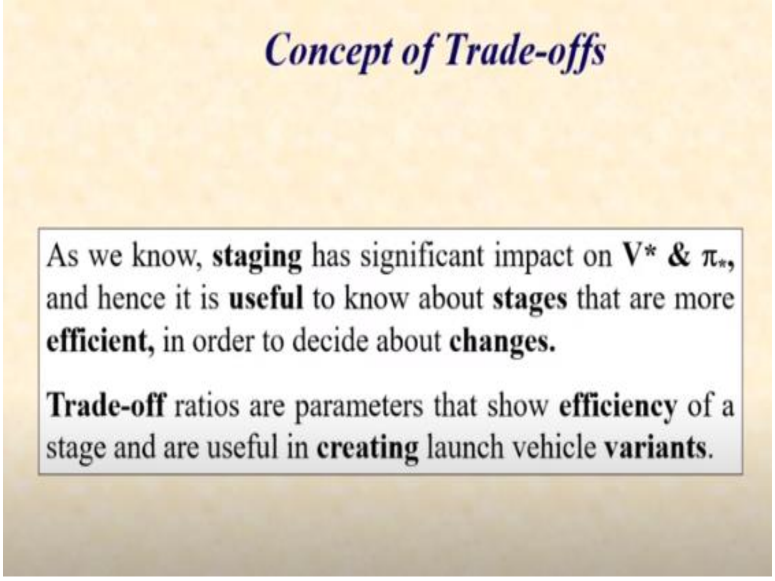

Now what is the basic concept of this trade off? So, as we know, the staging has significant impact on both V_* and π_*. And hence, it is useful to know about stages that are more efficient in order to decide about the change. Which means, we pick V_* and π_* as the fundamental driver of the procedure that will tell us which stage is going to be more efficient.

What it means is that we would like to find out the sensitivity of V_* and π_* to small changes in different stages. Which means, if I take for example first stage and change the propellant I_{sp} by a small amount, by what amount might V_* or π_* will change. And the small changes context is very adequately and elegantly captured through the concept of derivative or partial derivatives.

In partial derivatives, we take one stage parameter at a time and then see that a small change in that stage parameter makes what difference to the V_* or π_*. And immediately we realize that these ratios are directly going to show us the efficiency of a stage, because these ratios are in the form of sensitivities. And we know that sensitivity is directly related to the efficiency.

Which means, a stage which is efficient will be more sensitive to changes, so that a small change in the stage configuration will result in a large change in the burnout parameters. So, by looking at the sensitivity magnitude, we will be in a position to determine which are the more efficient stages for making a particular kind of change, and then of course, going to be useful in creating the launch vehicle variants.

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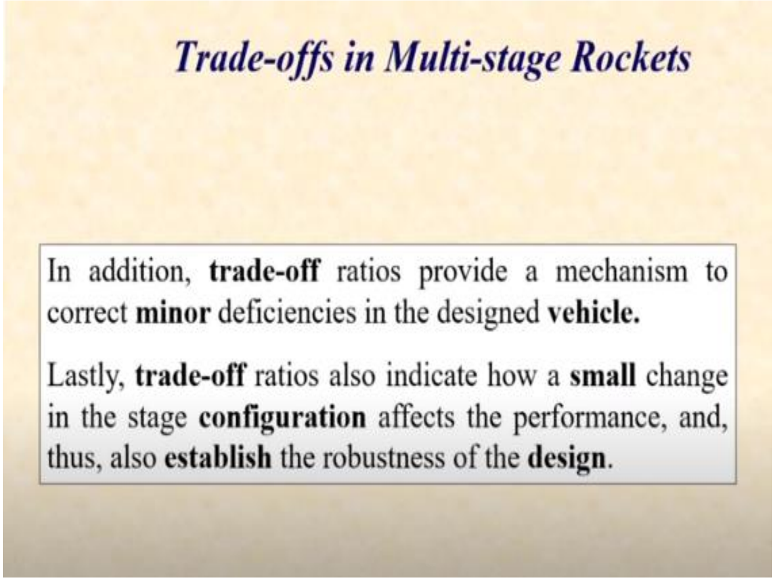

There is another aspect, which is not commonly realized that is that the tradeoff ratios provide a mechanism to also correct minor deficiencies in the designed vehicle.

Here it is worth recalling that, when we complete the design exercise based on the given requirements, there is a possibility that once the whole design is frozen and all the task is complete, we may find that the actual performance is marginally different from what you had designed for. Now as we will see in some context that a small change in the burnout performance can significantly affect the spacecraft mission performance.

It may be desirable to correct this small deficiency at the design stage itself before a mission is executed. And if you really want to do this in an efficient and optimal manner, then we immediately realize that the tradeoff ratios are going to tell us how to correct these minor deficiencies in the performance by suitably going and modifying the design of a particular stage which is the most efficient.

There is another aspect which is an integral part of any design exercise where you want to establish the robustness of the design, which means that if you have made a design the design goes for manufacturing, assembly etc. And there could be additional minor changes during fabrication, the fabrication errors, the tolerances, the assembly issues etc., so that the finally realized launch vehicle might be slightly different from the launch vehicle that has been designed.

Now if you know what are the changes which have happened because of manufacturing related issues, which anyway cannot be helped, at least you would like to assess how much the performance has changed because of the changes in the fabrication from the designed vehicle. And that will also tell you that in case there are certain modifications to the environmental conditions or other parameters, in what way the performance will change?

Will the change be drastic? Can the change be absorbed by the existing rocket? And whether the rocket in a sense is robust enough to withstand the minor errors.

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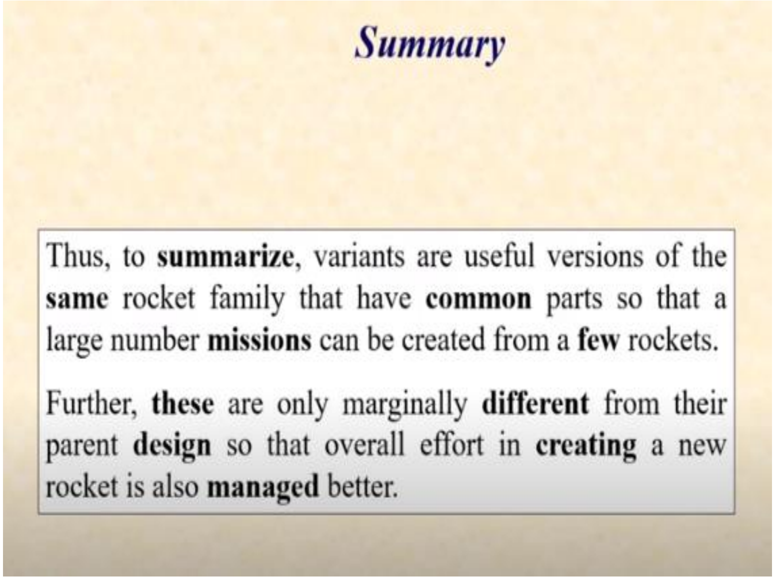

Thus, to summarize, variants are useful versions of the same rocket family that have common parts so that a large number of missions can be created from a few rockets. For that, these are only marginally different from their parent design so that overall effort in creating a new rocket is also managed better.

Hi, so we have seen that the variants are extremely useful elements of any launch vehicle development program, which provide a significant flexibility in machine design and performance using a reasonably smaller number of launch vehicle. And we have also noted that tradeoff ratios which we are going to have a look at subsequently provide an important quantitative parameter called the sensitivity or the efficiency of a stage in order for us to make an assessment of how the rocket should be modified.

In the next lecture, we will further explore the tradeoff ratios, look at their formulation aspects and some solution features. And we will connect it to the ability to modify a rocket appropriately for a slightly different mission. So, bye, see you and thank you.