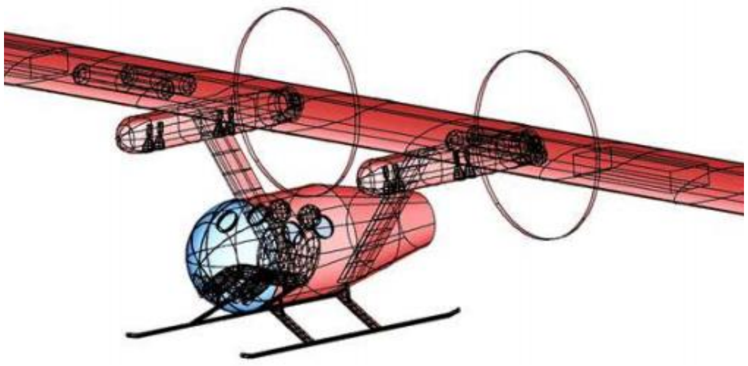
Takeoff Simulation



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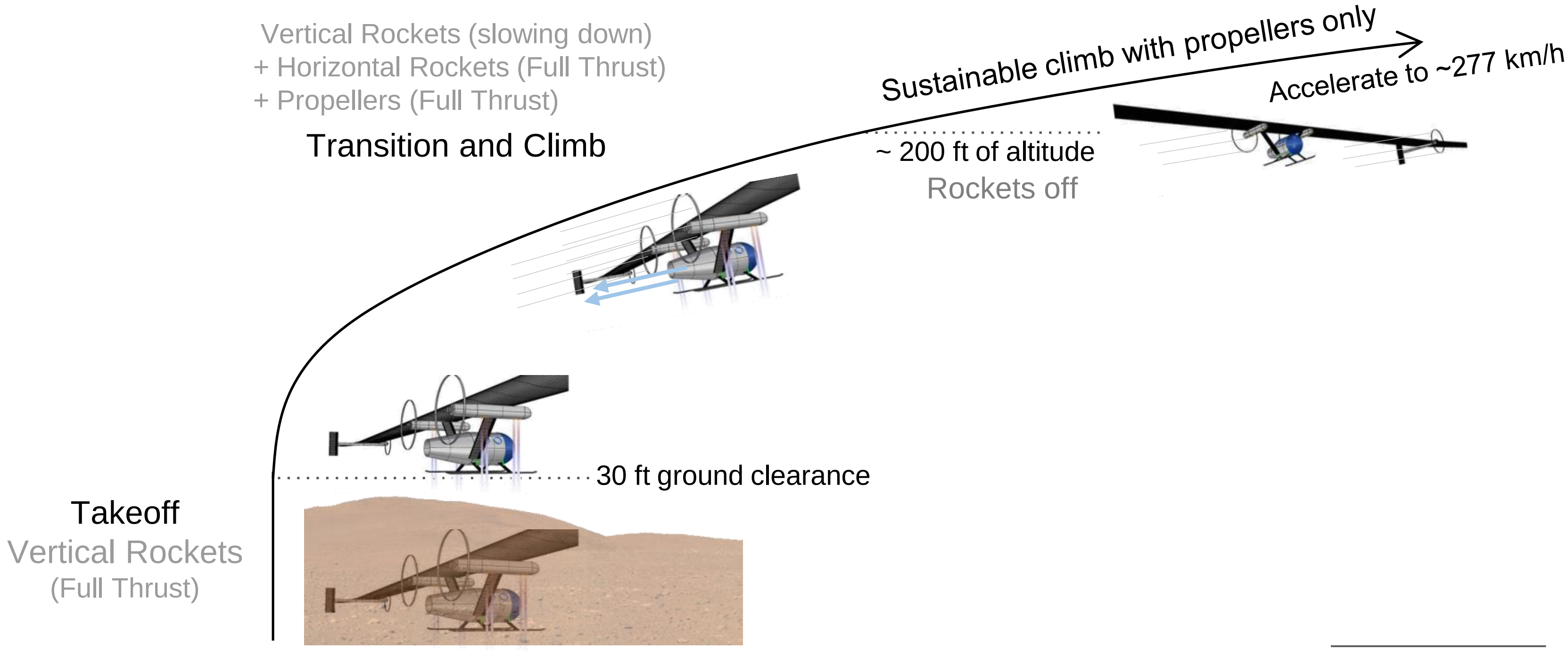
Summary of the presentation

- Takeoff mission profile and initial considerations;
- Dash-1 takeoff analysis, plots, and outputs (with and without horizontal rockets);
- Tradeoff studies;
- Dash-2 takeoff analysis, plots and outputs (with and without horizontal rockets);
- All RMMP Outputs for the takeoff segment

Takeoff mission profile



Considerations

- Mars gravity ~ 3.711 m/s^2
- Single rocket thrust ~ 300lbf ~ 1334N
- Rocket type ~ CO-LOX
- 8 vertical rockets ~ 10675N
- 2 horizontal rockets ~ 2668N
- Thrust of propellers ~ Actuator Disk Theory
- Drag coefficient ~ Estimated from VLM

Other considerations:

- Vertical thrust control function after ground clearance
- Thrust control without thrust vectoring
- Vertical rockets only to y-direction
- Horizontal rockets only to x-direction

MAJOR INPUTS		Source
Cd (wing + fus)	0.04	Estimated
Motor Power	125 (hp)	RMMP
Rocket Thrust (x8)	10675 (N)	RMMP
Propeller Diameter	2.26 (m)	RMMP
Propeller Thrust (x4)	3760 (N)	Estimated
Specific Impulse	260 (s)	RMMP
Wing Area	193 (m^2)	RMMP
Maximum Lift Coeff.	1.6	RMMP
Climb Lift Coeff.	90% Clmax ~1.44	Estimated
Date of inputs	November 07	

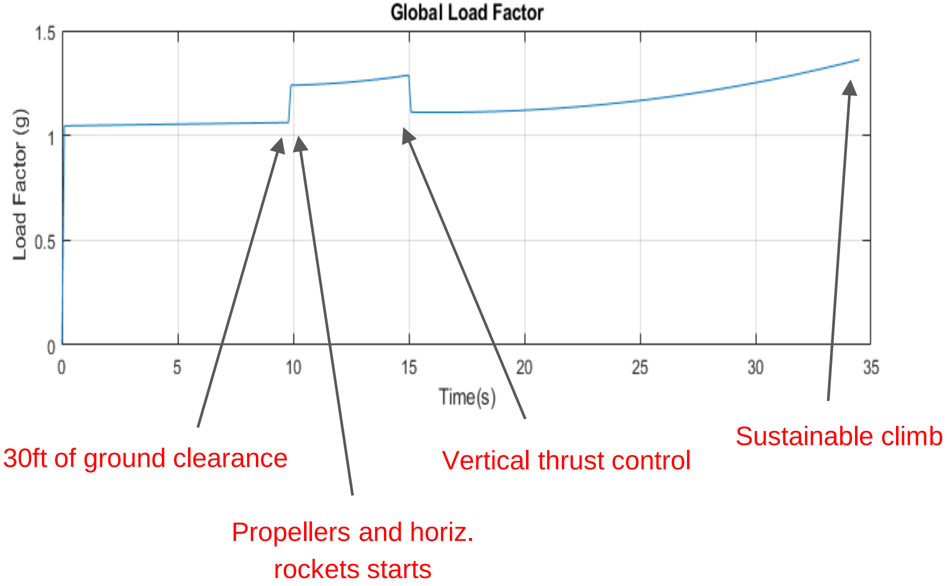
Considerations - MATLAB code

- The takeoff modeling was implemented at the MATLAB environment
- The calculations were done by a routine using simple mechanics equations
- A mathematical thrust control function was implemented to appropriately reduce the vertical thrust after reaching the ground clearance
- Routine from time=0 (ground) to the time when the vehicle achieves sustainable climb level (Stop Criteria: Horizontal Velocity > Stall velocity, same as Lift > Weight)

** When mentioned "sustainable climb" in the presentation means the phase that the aircraft can climb using only the propellers, above the stall velocity*

Load Factor

- Max. load achieved until sustainable climb ~ 1.36g (much less than in the V-n diagram that the structures team performed).
- Until the ground clearance of 30ft, the vehicle rose vertically at a load fator of about 1.05g.
- After the ground clearance, the global vehicle load factor increases due to the full thrust from propellers, horizontal rockets, and the lift force.
- After 15s, a vertical thrust control function was implemented in order to properly reduce the vertical thrust as the lift force increases rapidly and consequently, the load factor. *Without a vertical thrust control, the thrust rapidly explodes in terms of load factor and altitude (achieving more than 2g and more than 1000ft)*

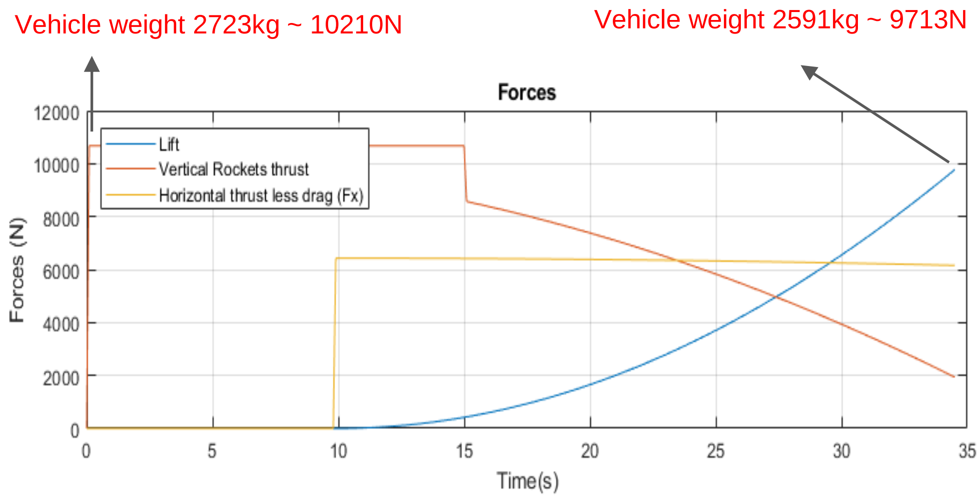


Major Actuating Forces

- Plot showing the major actuating forces during the takeoff and transition segment;

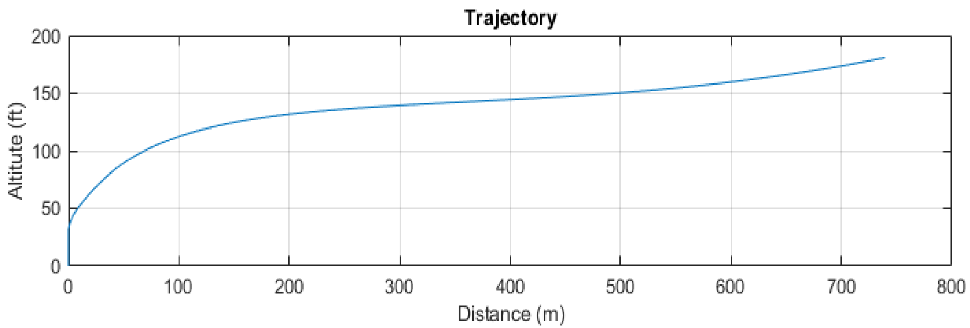
- In contrast with the initial assumptions that the takeoff would take about 15s, even the lift force grown rapidly supported by the horizontal rockets and propellers, it takes a while to perform this rapidly growth.

- Preliminary results (in the Figure beside) shown that the vehicle took around twice (~35s) the initial time assumed to reach the stall velocity.



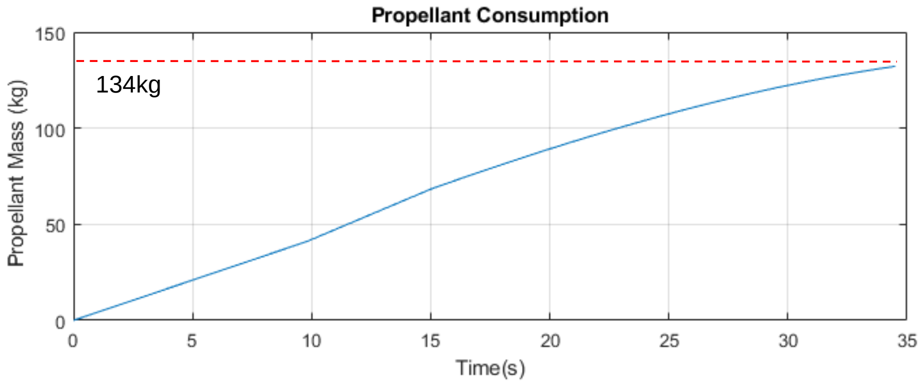
Trajectory

- The implementation of a vertical thrust control allowed the aircraft to perform a smooth transition from takeoff to sustainable climb.
- Sustainable climb reached under 200ft of altitude as initially proposed. ✅
- Horizontal distance traveled around 750m.
- After this segment, the vehicle would perform the climb using only propellers to reach the cruise speed and altitude.



Propellant Consumption

- For the calculation of propellant mass consumed, and following basic rocket equations, was taken into account the thrust and mass flow rate at each time segment.
- The propellant mass consumption was calculated considering vertical and horizontal rockets.
- Propellant mass consumed ~ 132.2kg (291.4lb)
- Propellant mass Initially proposed: 134.7kg (296,9 lb) for 2 TO cycles. A probable reason for the difference: as described before, as the aircraft spent twice the time in this segment, the aircraft consumed around twice the propellant estimated initially. Then, considering the total amount of propellant mass estimated initially, according to the new estimations, the aircraft would be able to perform only 1 TO & LND cycle.



To overcome this and perform 2 takeoff and landing cycles, a larger amount of propellant would be needed.

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Major Outputs

- This slide is presented the major outputs from the takeoff segment, **using 8 vertical rockets and 2 horizontal rockets.**

- The main difference from the first estimations is the time to achieve the sustainable climb. With 2 horizontal rockets and the available thrust from 4 propellers, the aircraft can perform a sustainable climb (i.e. without the need of rockets) after 34.5s, instead of 15s as initially proposed. This led to the consumption of 132.19kg of propellant, twice as initially proposed.

- Moreover, at the point of sustainable flight, the aircraft achieved a vertical velocity of 4.41 m/s, which is close to the value of 4.99m/s proposed for the sustainable climb segment until the cruise level.

Outputs at sustainable flight (Vx > Vstall)	
Time	34.5 (s)
Max load factor	1.36g
Horizontal velocity	59.54 (m/s)
Vertical velocity	4.41 (m/s)
Vertical distance	180.78 (ft)
Horizontal distance	739.36 (m)
Propellant mass	132.19 (kg)
Energy Consumed	9.1385 (MJ)
Vehicle mass	2591 (kg)

Major Outputs - Without horizontal rockets

- Without the horizontal rockets, the aircraft cannot sustain a stable flight with the same initial conditions as with rockets because of the lower horizontal velocity (and consequently, lower lift).
- To overcome this issue, the vertical thrust control was softened, allowing more thrust to lift the aircraft until the sustainable climb segment.
- As a result, the main change was an increase by 17s in the time to achieve the sustainable climb, which led to an increase by 18kg (39.7lb) in the propellant mass. Following initial considerations of component weights, without using the horizontal rockets would save around 15kg (30lb). Therefore, would add only ~3kg (6,6lb) overall considering the increase in mass consumption.

Values at sustainable flight (Vx > Vstall)		
Time	**51.9** (s)	→ +17s
Max load factor	1.19g	
Horizontal velocity	59.08 (m/s)	
Vertical velocity	**3.09** (m/s)	→ -2.4m/s
Vertical distance	218 (ft)	
Horizontal distance	**1253** (m)	→ +513m
Propellant Mass	**150.36** (kg)	→ +18kg
Energy Consumed	15.6287 (MJ)	
Vehicle Mass	2572 (kg)	

Tradeoff Studies

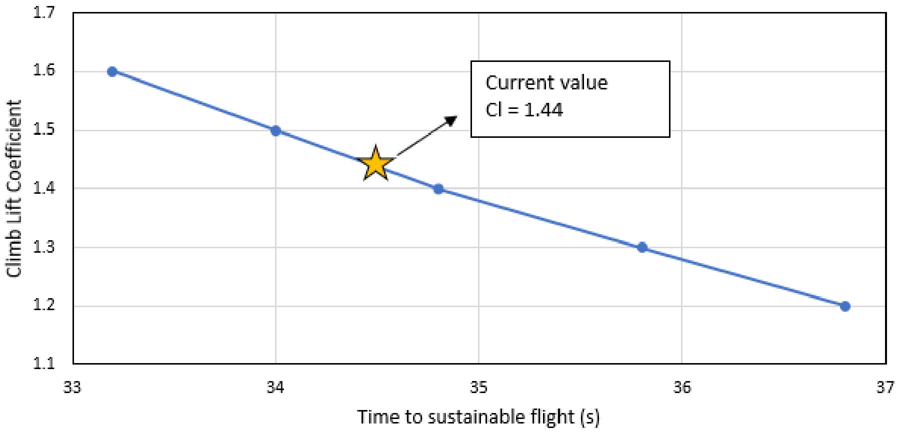
- **Climb lift coefficient and time to sustainable climb**
  - To verify if there is significant gains by increasing the climb lift coefficient in order to reduce the necessary time to achieve the sustainable flight, and maybe the propellant mass.
- **Engine hp and time to sustainable climb**
  - To verify if there the reduction in motor power (as proposed by Joabe) will significantly influence the takeoff performance until the sustainable flight.
- **Engine hp and time to sustainable climb**
  - To verify if there the reduction in motor power (as proposed by Joabe) will significantly influence the propellant mass until the sustainable flight.

Tradeoff - Climb lift coefficient vs time to sustainable flight

- Once was mentioned that a Clmax of 1.6 would be required, but would be difficult to achieve it due to the low Reynolds condition, it was assumed a climb lift coefficient of 90% of this value, which means a climb lift coefficient of 1.44.

- **The variation of the climb lift coefficient does not impact significantly the time to sustainable flight.**

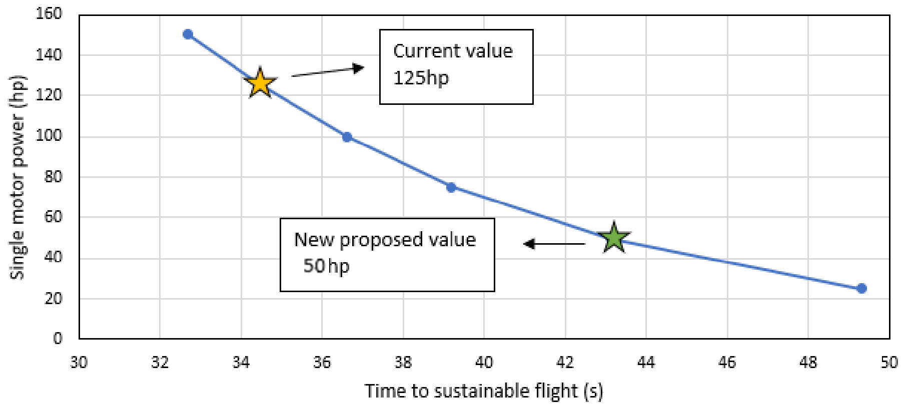
- Also, was identified that increasing the climb lift coefficient significantly impacted (in a bad way) the maximum load factor at the takeoff segment, and therefore the value of 1.44 seems to be a target point for the design.



Tradeoffs - Engine hp vs time to sustainable flight

- In one of the group meetings was suggested by the performance team a significant reduction in the motor power. Then, was investigated the influence of this reduction in the time to sustainable flight**.**

- Based on the initial 125hp motor power, the aircraft spend 34.5s to achieve a sustainable flight. In contrast, the aircraft would take 43s using the 50hp motors. In terms of time, a power decrease does not represent a relevant chance, however, the increase in time would come with an increase in propellant mass.



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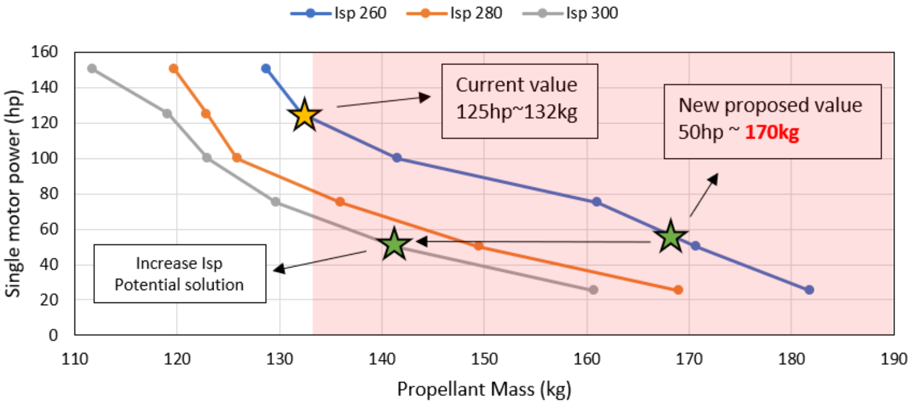
Tradeoffs - Engine hp vs time to sustainable flight

- Following the previous slide, once the aircraft would have less power (then, less thrust) available to increase its lift, the rocket contribution should be reinforced to maintain a stable flight.

- Decreasing the motor power 50hp would increase the propellant mass consumed to 170kg, which is 32kg higher than using 125hp motors.

- In order to overcome this issue, a potential solution identified would be an increase in the Specific Impulse (Isp) value of 260s as initially proposed. An increase to 300s would significantly reduce the propellant consumed by 19kg, making it a promising solution in case of power reduction.

- After a team discussion and according to NASA's paper, we decided to use an Isp of 295s. All the analysis and results using this value will be presented in the following slides.



"Carbon Monoxide and Oxygen Combustion Experiments: A Demonstration of Mars In Situ Propellants", AIAA-91-2245, 1991

"Isp in the range of 260-280s is realistic for the assumption of a low pressure engine, and 290-300s for higher pressure."

"Theoretical studies and experimental tests indicate that with care engine design, a CO-LOX rocket engine can be developed with reasonable efficiency"

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Summary and Outputs for the Dash-1 design

Initial assumptions:

- Time under 15s for takeoff. ✗
- Altitude of 200ft until the sustainable climb. ✓
- Propellant mass of 134kg for 2 TO cycles. ✗

Other aspects:

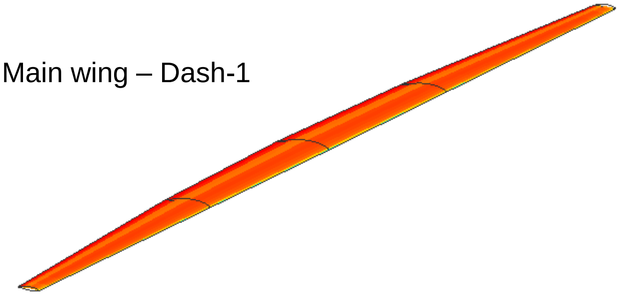
- Smooth transition to sustainable flight. ✓
- Low load factor at takeoff. ✓

With horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	34.5 (s)
Max load factor	1.36g
Horizontal velocity	59.54 (m/s)
Vertical velocity	4.41 (m/s)
Vertical distance	180.78 (ft)
Horizontal distance	739.36 (m)
Propellant mass	132.19 (kg)
Energy monsumed	9.1385 (MJ)
Vehicle mass	2591 (kg)

Without horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	**51.9** (s)
Max load factor	1.19G
Horizontal velocity	59.08 (m/s)
Vertical velocity	**3.09** (m/s)
Vertical distance	218 (ft)
Horizontal distance	**1253** (m)
Propellant mass	**150.36** (kg)
Energy monsumed	**15.6287** (MJ)
Vehicle mass	2572 (kg)

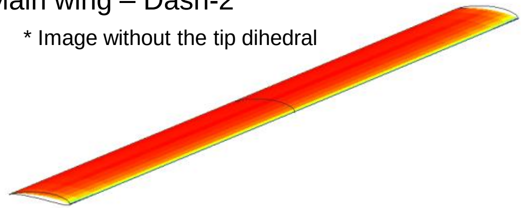
New analyzes for the Dash-2 design

Main wing – Dash-1



Main wing – Dash-2

* Image without the tip dihedral



After an improved main wing design by Dr. Raymer, the takeoff segment was recalculated.

- Specific Impulse (Isp) updated: 260s to 295s
- Drag coefficient updated
- Calculations was performed with the use and without horizontal rockets

Considerations

- Update in the Specific Impulse to 295s, considering a technology maturity after the year 2030.
- Update in the drag coefficient using new CFD values with the new airfoil.
- The new Maximum Lift Coefficient (Clmax) using the new airfoil is 1.6. Thus, the climb lift coefficient of 1.44 (90% of Clmax) was kept the same.

MAJOR INPUTS		Source
Cd (wing + fus)	0.03	CFD Results
Motor Power	125 (hp)	RMMP
Rocket Thrust (x8)	10675 (N)	RMMP
Propeller Diameter	2.26 (m)	RMMP
Propeller Thrust (x4)	3760 (N)	Estimated
Specific Impulse	295 (s)	Projection +2030
Wing Area	193 (m^2)	RMMP
Climb Lift Coeff.	90% of 1.6 ~1.44	Approximation
Date of inputs	November 07	

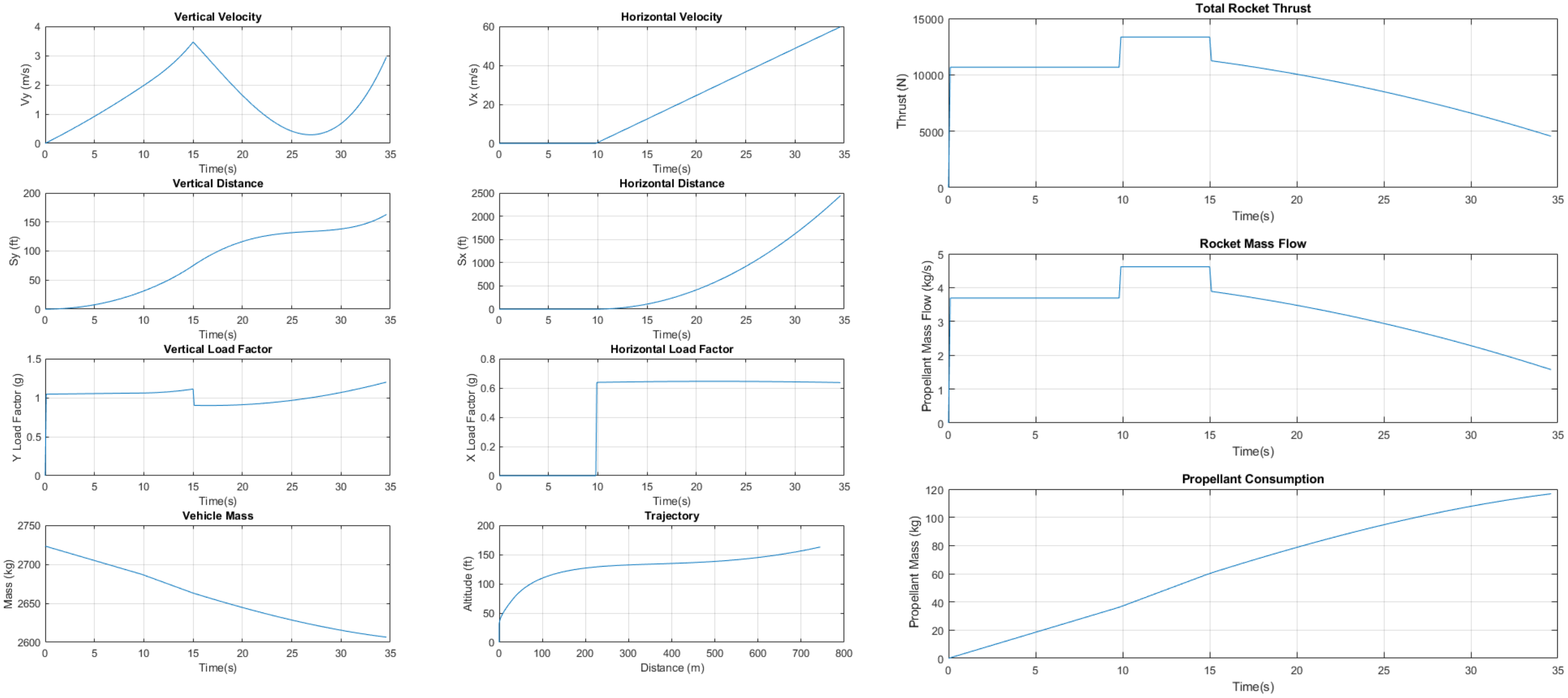
Major Outputs Dash-2

- Using the update, the outputs can be seen in the table beside.

- The main difference from Dash-1 is the propellant mass consumed because of the increase in Isp. Using all vertical and horizontal rockets, the Dash-2 consumed 116.66kg of propellant, which is 15.5kg less than the Dash-1 concept.

With horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	34.6 (s)
Max load factor	1.35g
Horizontal velocity	59.74 (m/s)
Vertical velocity	2.95 (m/s)
Vertical distance	162.86 (ft)
Horizontal distance	744.07 (m)
Propellant mass	116.66 (kg)
Energy consumed	9.17 (MJ)
Vehicle mass	2606 (kg)

Major Plots Dash-2



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Major Outputs Dash-2 - Without horizontal rockets

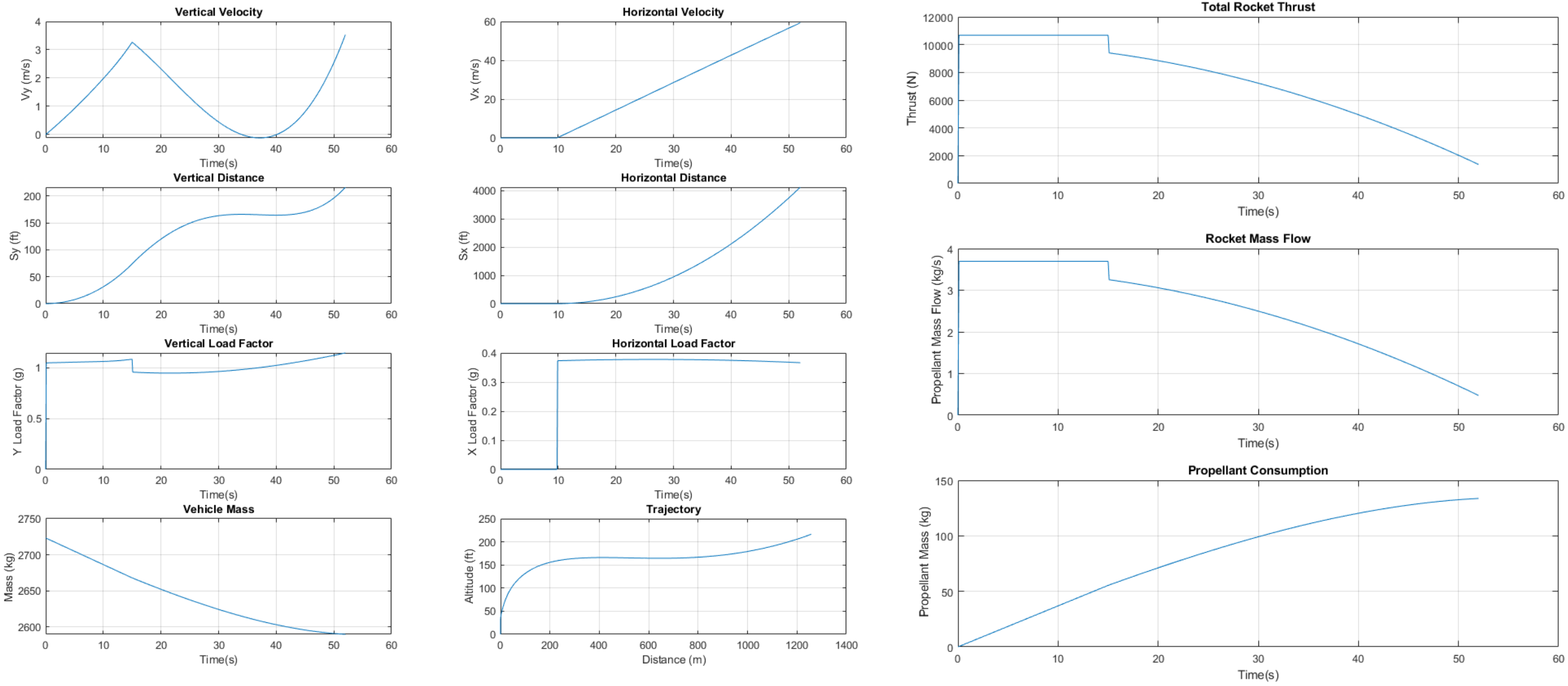
- Using the update values of Cd and Specific Impulse, without using horizontal rockets, the outputs can be seen in the table beside.

- In comparison with the Dash-2 with rockets, without using rockets the time to achieve the sustainable flight increase to 52s, the horizontal distance increase to 1258m, and the propellant mass to 133kg. Using an Isp of 295s without rockets, the propellant mass consumed was the same as Dash-1 using rockets.

- Observation: moving on with the Dash-2 without horizontal rockets would not only simplify the fuselage rear cone but also provide a safer place for the occupants inside the fuselage.

Without horizontal rockets		From Dash-2 with horizontal rockets
Outputs at sustainable flight (Vx > Vstall)		
Time	52 (s)	→ +17.4s
Max load factor	1.2g	
Horizontal velocity	59.31 (m/s)	
Vertical velocity	3.53 (m/s)	
Vertical distance	216.44 (ft)	→ +52.5m
Horizontal distance	1258.1 (m)	→ +517m
Propellant mass	133.69 (kg)	→ +17kg
Energy consumed	15.66 (MJ)	→ +6.49MJ
Vehicle mass	2589 (kg)	

Major Plots Dash-2 - Without horizontal rockets



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Dash-2 - Propellant Mass

Using 2 horizontal rockets:

- Propellant consumed during takeoff segment: **116.66kg** (Takeoff modeling in Matlab)
  - Total propellant mass estimated from Raymer's estimations: 269.37kg (594lb) -> 2 TO & LND cycles
  - Without taking credit for the 2 landing cycles: 134.68kg required for the LND (to be eventually investigated in detail later)
  - Then, for 2 TO cycles: 134.68kg
  - For 2 TO of Dash-2: 116.66kg x (2 cycles) = 233.32kg. Using the 134.68kg we already have -> 98.64kg (233.32kg - 134.68kg)
  - So, in order to perform 2 TO cycles, we have a debt of **98.64kg**, which can come from the Dash-2 wing weight reduction.

Without using horizontal rockets:

+19kg

- Propellant consumed during takeoff segment: **133.69kg** (Takeoff modeling in Matlab)
  - Using the same logic from above...
  - For 2 TO of Dash-2: 133.69kg x (2 cycles) = 267.38kg. Using the 134.68kg we already have -> 132.7kg (267.38kg - 134.68kg)
  - So, in order to perform 2 TO cycles, we have a debt of **132.7kg**, which can come from the Dash-2 wing weight reduction.
  - Considering the weight reduction of 15kg from the abstention of 2 rockets, we have a debt of **117.7kg**.

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Dash-2 - Propellant Mass

Some considerations for the decision of using or not horizontal rockets.

Not using horizontal rockets - PROS:

- Reduction in complexity in the installation of horizontal rockets in the rear fuselage (mainly fuel pumps and propellant supply wires);
- A safer cabin environment for the occupants;
- Fewer rockets mean less maintenance and less possibility of failures;
- During landing, the horizontal rockets do not perform any function.

Not using horizontal rockets - CONS:

- Horizontal rocket assistance not available in case of propeller failure during takeoff. Once there is a lot of power available according to Joabe's calculations, the 125hp motors would provide enough power in the case of 1 or 2 motors failures (not a big issue).
- More time to achieve the sustainable time (not a real issue);
- More battery energy consumed.
- Increase in weight debt for 2 TO cycles by 19kg;

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All Outputs

Dash-1	
With horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	34.5 (s)
Max load factor	1.36g
Horizontal velocity	59.54 (m/s)
Vertical velocity	4.41 (m/s)
Vertical distance	180.78 (ft)
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Propellant mass	132.19 (kg)
Energy consumed	9.1385 (MJ)
Vehicle mass	2591 (kg)

Dash-1	
Without horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	**51.9** (s)
Max load factor	1.19g
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Horizontal distance	**1253** (m)
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Vehicle mass	2572 (kg)

Dash-2	
With horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)	
Time	34.6 (s)
Max load factor	1.35g
Horizontal velocity	59.74 (m/s)
Vertical velocity	2.95 (m/s)
Vertical distance	162.86 (ft)
Horizontal distance	744.07 (m)
Propellant mass	116.66 (kg)
Energy consumed	9.17 (MJ)
Vehicle mass	2606 (kg)

Dash-2	
Without horizontal rockets	
Outputs at sustainable flight (Vx > Vstall)q	
Time	**52** (s)
Max load factor	1.2g
Horizontal velocity	59.31 (m/s)
Vertical velocity	**3.53** (m/s)
Vertical distance	216.44 (ft)
Horizontal distance	**1258.1** (m)
Propellant mass	**133.69** (kg)
Energy consumed	**15.66** (MJ)
Vehicle mass	2589 (kg)

Final Considerations - Takeoff segment

- The aircraft can perform its takeoff segment appropriately according to the proposed mission.
- Even without the implementation of an optimization process, the takeoff ride is smooth and present coherent values.
- An automatic or assistive takeoff would be required in order to do not allow the aircraft to overcome the structural load factor, in combination with techniques of load alleviation (maybe using the ailerons) in the case of gust winds and high load factors.
- An automatic or assistive takeoff also would be required, once it is more challenging than the takeoff.
- As mentioned, the use of horizontal rockets seems to have a small overall benefit, only decreasing the time to achieve the sustainable flight and therefore I believe I shouldn’t use them.

Suggestions for the takeoff segment for future works:

- Perform the modeling of a complete segment, i.e., takeoff, climb, cruise, descent, and landing.
- Optimize the use of rockets in combination with the propellers in order to save more propellant and battery.
- Optimize the mission for a reduced load fator.