AE3200 DSE - Flying Carver

Design of a flying carver type modular vehicle

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Final Report
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Preface

This report is written by a group of 10 students performing the design synthesis exercise (DSE) in the spring of 2014. The design exercise DSE group 7 worked on the design of a flying car using a modular approach. The name of the flying car is Volucrem, which is Latin for flying object.

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Summary

Throughout history, there has always been a need for transportation. People are impatient beings and desire minimal travel times. In 1903, the Wright brothers commenced the flying revolution. Ever since, travelling times have decreased, with subsonic aircraft making the largest impact. However, since then the travelling time has not changed much and might even be increasing due to congestion and stringent security procedures. Demands for a quick paced life style are more prominent than ever before; a method of travel is sought that is rapid and versatile. Currently, distances up to 1000 km can be travelled by car but that is a time-consuming method of transportation. One can also go by plane. However, waiting times are longer than the flight time for these distances. The flying car on the other hand, can be converted within half an hour, has a high cruise speed, is independent of airline routes and can make use of preferred airports.

Hence there is reason to breathe new life into the concept of the flying car with the focus on high cruising speed, fast transition and ease of operation. To achieve this, the Volucrem has been designed. The trip starts when the customer steps in the three wheeled carver and drives to the airport. The driving experience is not comparable to that of a normal car though, as it banks in a similar manner to a motorcycle. This way driving is more comparable with flying and thus ensures easy operation. Furthermore, the car has a diesel engine similar to that designed for the smart car which has 58 kW of power and consumes 4.3L/100km. The car has automatic transmission and can be steered by an M-yoke, similar to the one found in a Concorde. Throttling and braking will be done in a similar manner to a motorcycle. The car will be optimally sized for two people and thus be 4 meters long, have a width of 1.2m and a height of 1.5m. Moreover, it will weigh approximately 465 kg, including the weight of the fuselage including roll cage, furnishing, electronics, cockpit systems and the engine for the car.

Once at the airport, the customer will attach the wings utilising an attachment based on three ball socket joints. The ball socket joints will be locked using electro-hydrostatic actuators which then will be locked with pins. The attachment system is designed to withstand 8g. Furthermore, the cables for the power-by-wire system should be connected and the mirrors should be stored inside in cabin. When this has been done, the flying car is ready to taxi during which the pre-flight checks can be performed.

During take off the flying car will accelerate to 36 m/s, at which it will rotate. It will then retract its wheels to a position in which they minimise the drag. The flying car will climb to an altitude of 7000m for cruise, for optimal, efficient flight. At this altitude pressurisation is required, which will be done by the turbocharger of the car engine. The cabin altitude of 2500m provides a comfortable commute for all passengers. The flying car will cruise with a true airspeed of 212 kts to its destination. With respect to the specifications of the flight module, the flying car will use a similar engine to the Diemech TP100 turboprop engine, which delivers 180 kW, weighs only 57 kg and consumes 0.5 kg/kW/h. The propeller accompanying the engine has a diameter of 2.04 m. The wing area is 13.08 m^2, has an aspect ratio of 7.4 and a taper ratio of 0.45 to get an approximately elliptical lift distribution. The wings also have winglets which make sure the fuel consumption is slightly less compared to a wing without them. The horizontal tail is designed for take off as this condition is more critical for the flying car than the stability, and has an area of 2.5 m^2 while both vertical tail areas sum up to be 1.64m^2.

In this report and during the project, the team has proven that by using a flying car, travelling ease improves and door-to-door time is reduced due to the elimination of waiting times, the ability to fly to local airports and the use of a personal vehicle. Using a personal vehicle at every moment to get everywhere is a paradigm shift that could form a new trend.

Contents

Nomenclature & abbreviations

Symbol	Unit	Description
A	[-]	Aspect ratio
A	[m^2]	Surface area
ac	[m]	Aerodynamic center location
A_h	[-]	Horizontal tail aspect ratio
b	[m]	Wing span
b_a	[m]	Aileron span
b_e	[m]	Elevator span
b_h	[m]	Horizontal tail span
b_r	[m]	Rudder span
b_v	[m]	Vertical tail span
c	[m]	Chord length
c	[$\frac{m}{s}$]	Rate of climb
c_h	[m]	Horizontal tail chord length
c_p	[$\frac{kg}{J}$]	Specific fuel consumption, propeller
c_r	[m]	Root chord length
c_t	[m]	Tip chord length
C_D	[-]	Drag coefficient
$C_{D,0}$	[-]	Zero lift drag coefficient
C_{fe}	[-]	Equivalent skin friction coefficient
C_L	[-]	3D Lift coefficient
C_l	[-]	2D Lift coefficient
C_{L_α}	[-]	Lift coefficient for angle of attack of wing
$C_{L_{\alpha_h}}$	[-]	Lift coefficient for angle of attack of horizontal tail
$C_{L_{\alpha_{A-h}}}$	[-]	Lift coefficient for angle of attack of aircraft minus horizontal tail
$C_{L_{max}}$	[-]	Maximum lift coefficient
C_m	[-]	Moment coefficient
$C_{m_{ac}}$	[-]	Aerodynamic centre moment coefficient
C_n	[-]	Normal force coefficient
C_R	[-]	Roll coefficient
D	[N]	Drag
D_{prop}	[m]	Propeller diameter
e	[-]	Oswald efficiency factor
E	[GPa]	Modulus of elasticity (Young's modulus)
E	[hrs]	Endurance
F	[N]	Force
f	[-]	Camber
f	[-]	Landing weight over take off weight
g	[$\frac{m}{s^2}$]	Gravitational acceleration ($g = 9.81\frac{m}{s^2}$)
h	[m]	Altitude
H_{cg}	[m]	Height of aircraft centre of gravity to ground
I	[m^4]	Moment of Inertia
K	[-]	Column effective length factor
K	[-]	Load alleviation factor
k_β	[-]	Fuselage sideslip constant
l	[m]	Length between two points
l_h	[m]	Distance between horizontal tail and neutral point
l_f	[m]	Fuselage length
L	[m]	Unsupported length of column
L	[N]	Lift
L_A	[N]	Aircraft lift
L_h	[N]	Horizontal tail lift
L_{A-h}	[N]	Aircraft minus horizontal tail lift
L_{ref}	[m]	Reference length
m	[kg]	Mass
$\dot{m}$	[$\frac{kg}{h}$]	Mass flow
M	[-]	Mach number
M	[Nm]	Moment
M_W	[Nm]	Wing moment
M_{ac}	[Nm]	Aerodynamic centre moment
MAC	[m]	Mean aerodynamic chord
M_{ff}	[-]	Mass fuel fraction
M_{tfo}	[-]	Mass trapped fuel and oils
n	[-]	load factor
P	[N]	Normal force
P	[W]	Power

P	[Pa]	Pressure
P	[-]	Viscous induced drag coefficient
P_{br}	[kW]	Break power
P_{Cr}	[N]	Critical force
P_{req}	[kW]	Power required
Q	[-]	Inviscid induced drag coefficient
q	[Pa]	Dynamic Pressure
r	[m]	Circle radius
R	[m]	Range
R	$[\frac{\mathrm{J}}{\mathrm{kgK}}]$	Gas constant for air ($R = 287.058 \frac{J}{kgK}$)
R_N	[N]	Nose gear load
Re	[-]	Reynolds number
S	[m^2]	Surface Area
S_A	[m^2]	Aileron surface area
S_E	[m^2]	Elevator surface area
S_f	[m^2]	Flap surface area
S_h	[m^2]	Surface area of horizontal tail
S_R	[m^2]	Rudder surface area
S_v	[m^2]	Surface area of vertical tail
s_{land}	[m]	Landing distance
$S.M.$	[m]	Stability margin
s_{to}	[m]	Take off distance
S_{wet}	[m^2]	Wetted area
t	[mm]	Thickness
T	[K]	Temperature
T	[N]	Thrust
T	[Nm]	Torsion
TOP_{Prop}	[-]	Takeoff parameter of propeller
V	[N]	Shear force
V	$[\frac{\mathrm{m}}{\mathrm{s}}]$	Cruise speed
V_h	$[\frac{\mathrm{m}}{\mathrm{s}}]$	Airspeed of horizontal tail
V_s	$[\frac{\mathrm{m}}{\mathrm{s}}]$	Stall speed
w	$[\frac{\mathrm{m}}{\mathrm{s}}]$	Downward velocity of the wind
W	[N]	Weight
W_L	[N]	Landing weight
$\frac{W}{S}$	$[\frac{\mathrm{N}}{\mathrm{m}^2}]$	Wing loading
$\frac{W}{P}$	$[\frac{\mathrm{N}}{\mathrm{kW}}]$	Power loading
x	[m]	Distance in x-direction
x_{ac}	[m]	Aerodynamic centre distance from nose
x_{cg}	[m]	Aircraft centre of gravity distance from nose
x_h	[m]	Horizontal tail distance from nose
x_m	[m]	Distance of main gear to aircraft centre of gravity
x_n	[m]	Distance of nose gear to aircraft centre of gravity
x_{np}	[m]	Neutral point distance from nose
X_{LEMAC}	[m]	location of leading edge mean aerodynamic chord
y	[m]	Distance in y-direction
y_t	[m]	Moment arm of flight engine thrust to aircraft centre of gravity
Y	[MPa]	Yield Strength
α	[rad]	Angle of attack
ϵ	[rad]	Downwash angle
β	[-]	Prandtl-Glauert compressibility factor
γ	[-]	Adiabatic index
Γ	[deg]	Dihedral angle
δ_a	[rad]	Aileron deflection
δ_e	[rad]	Elevator deflection
δ_r	[rad]	Rudder deflection
ϵ	[rad]	Downwash angle
ϵ_t	[deg]	Twist angle
η_p	[-]	Propulsive efficiency
λ	$[\frac{\mathrm{deg}}{\mathrm{m}}]$	Lapse rate ($\lambda = -0.0065 \frac{deg}{m}$)
λ	[-]	Taper ratio
Λ	[deg]	Sweep angle
μ	[Pa s]	Dynamic viscosity
μ	[-]	Equivalent mass ratio
μ	[-]	Dynamic friction coefficient of tires
ρ	$[\frac{\mathrm{kg}}{\mathrm{m}^3}]$	Air density
σ	[-]	Density ratio
σ	[MPa]	Normal stress
σ_τ	[MPa]	Shear stress
σ_{yield}	[MPa]	Yield stress
τ	[MPa]	Shear Strength

Abbreviation	Description
ABS	Anti-Lock Braking System
AC	Aircraft
ACARS	Aircraft Communications Adressing and Reporting System
ACC	Adaptive Cruise Control
ADAHRS	Air Data and Attitude and Heading Reference System
AFCS	Aircraft Flight Control System
AFRA	Aircraft Fleet Recycling Association
BRS	Ballistic recovery Systems
CAA	Civil Aviation Authority
CAN	Controller Area Network
CATIA	Computer Aided Three dimensional Interactive Application
CS	Certification Specifications
DSRC	Dedicated Short Range Communications
DTC	Direct Tilt Control
DVC	Dynamic Vehicle Control
EAS	Equivalent Airspeed
EASA	European Aviation Safety Agency
ECM	Engine Control Module
ECU	Electronic Control Unit
EFIS	Electronic Flight Instrument System
EHA	Electrohydrostatic Actuator
EMA	Electromechanical Actuator
ESC	Electronic Stability Control
ETC	Electronic Throttle Control
EVC	Electronic Valve Timing Control
FAA	Federal Aviation Administration
FBW	Fly-By-Wire
FCC	Flight Control Computer
FEM	Finite Element Method
GPS	Global Positioning System
GV	Ground Vehicle
IFR	Instrument Flight Rules
IMC	Istrument Meteorological Conditions
ISIS	Integrated Standby Instrument System
ISU	Integrated Standby Unit
KLM	Koninklijke Luchtvaart Maatschappij
LAMP	Light Aircraft Maintenance Programme
MAC	Mean Aerodynamic Chord
MAI	Manufacturing, assembly and integration plan
MFD	Multi-Function Display
MTOW	Maximum Take Off Weight
MZFW	Maximum Zero Fuel Weight
NACA	National Advisory Committee for Aeronautics
OEW	Operating Empy Weight
PBW	Power-By-Wire
PFD	Primary Flight Display
RDTE	Research, Development, Testing and Evaluation costs
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
SFC	Specific Fuel Consumption
SPK	Synthetic Paraffinic Kerosene
S.M.	Stability Margin
STC	Steering Tilt Control
VHF	Very High Frequency
VLS	Vertical Launch System

Chapter 1: Introduction

As a result of the final design synthesis exercise in the Bachelor of Aerospace Engineering given at the TU Delft, a group of ten students have been assigned to design a fast, modular, flying car. In particular the objective statement was formulated to be:

The design of a competitive, modular, flying carver type vehicle capable of flying within a 1000 km range and 200 knots cruise speed by 10 students within 10 weeks time.

The success of previous roadable aircraft has been limited, this can be attributed to the notion that the designed vehicles are neither good aircraft or good cars. Already in 1917 the first attempt of building a flying car was made by the rival of the wright brothers: Glenn Curtiss. His roadable aircraft only managed to hop, and sadly, due to the first world war was never further developed. Following his attempt, nineteen other designs were made by fellow engineers but sadly all attempts failed to reach mass production in one way or the other. One of the most successful flying cars is the Taylor Aerocar, a modular flying car which still flies today. Even this vehicle never made it to mass production, but this time due to a lack of interest by the general public. What this design did show the world, was that a flying car was possible, especially in a modular appearance.

Currently there is a problem with commute times in the lives of businessmen, time is money as the saying goes. Therefore there is a clear need to minimise door-to-door time during travel, as work cannot be done efficiently during travel. The flying car is an optimal solution for customers needing low door-to-door times for long travel distances. In particular the need statement can be formulated as follows:

There is a need for a safe, sustainable, modular, and attractive flying carver with minimum difference in operation concept, a minimal door-to-door time at 200 knots cruise speed for a 1000 km range and is available before 2025 and with a market price below 500 000 euros.

In this report the design of the Volucrem, a flying carver type vehicle will be explained. The report starts of with a market analysis, followed by a summary of the conceptual design phase as found in the mid-term report. In this part, the mission definition, concept generation, class I & II estimations and trade-offs are described. The next part of the report is the detailed design phase which is split into four subparts: the car module, the flight module, the attachment system and the operations. Each subpart will intensively describe the technical details accounted for during the detailed design. The final part of the report concludes the design synthesis project and among others includes sections explaining the compliance matrix, the verification & validation, the future planning, the social impact and finally the conclusion. The final pages of this report contain the bibliography and the appendices.

Chapter 2: Market analysis

The Volucrem is aiming to open up an entirely new market. The concept of a flying car implies freedom of takeoff and landing as well as private and fast transportation. Its competitiveness is determined by the door-to-door travel time gain. This travel time depends on three factors:

- Road travel time
- Conversion time
- Air travel time

On a day to day basis the road travel times will be similar to those of a car. Ideally the Volucrem is operated as an aircraft for distances over 150 km. In this case the road travel part will be characterised by the time required to reach the nearest airport and the time required to reach the final destination from the airport at which the Volucrem lands. This is where the Volucrem offers significant travel time advantages, since many smaller general aviation airports are available compared to large airline airports. On the other end of the flight the pilot can land on an airport closer to his or her target destination.

When addressing the air travel time, the comparison must be made to airline travel times, which are considered the biggest competition to the Volucrem. Assuming an average conversion time of 20 minutes on either side and a 20% delay due to climb and descent at a cruise velocity of 370 km per hour, travel times for several distances can be found. The total door-to-door travel time with the Volucrem is compared to door-to-door travel times when driving to an airport and use an airline for similar distances. This difference is presented in Table 2.1. Total airline travel times, are the time in the air [1] plus 45 minutes for ranges up to 400 km for daily (business class) travel, 75 minutes up to 700 km and 180 minutes up to 1000 km since this would no longer be travelling business class. This is due to time required for airline and airport procedures such as luggage handling and security. These added times originate from the expected use of the Volucrem; the further the flight, the more luggage needed and the less business related the flight is. An extra penalty of 45 minutes is added to the airline travel time due to the fact that clients are forced to drive to a large airport in order to arrive at their flight vehicle, as well as having to drive farther from the landing airport to their target destination. Using the penalisation in Table 2.1 it is assumed that the road travel part costs the same amount of time. Adding a final 30 minutes to both modes of transport for the ground travel time results in a rough estimate of the door-to-door travel times.

Table 2.1: Door-to-door travel time comparison between Volucrem and airlines

Distance [km]	Volucrem travel time [minutes]	Airline travel time [minutes]	Time saved [%]
200	109	170	35.9
300	128	180	28.9
400	148	195	24.1
500	177	240	26.3
600	187	240	22.1
700	206	240	14.2
800	226	355	36.3
900	245	370	33.8
1000	264	370	28.6

From Table 2.1 it can be seen that the Volucrem saves a lot of time in all expected ranges of travel. However, the Volucrem provides additional advantages because the client is not limited to an airline schedule or affected by delays and has a private vehicle available at the destination. Taking all this into account, the Volucrem will allow the owner to live for example far in the countryside while working in the city.

Part I

Conceptual design

Chapter 3: Mission definition

The design of the "Best of both worlds"-flying car concept cannot be started without a proper understanding of the tasks it will be fulfilling. This chapter discusses the requirements posed upon the design by the customer and the different scenarios the vehicle will encounter during its mission.

3.1 Requirements

In order to create a proper flying car, several requirements were set along which to design the vehicle. These requirements are listed below. A compliance matrix with these requirements is given in Chapter 30.

- The system shall contain a “Carver” type of roadable vehicle
- The flying carver shall have capacity for two or three passengers.
- The flight modules (flight control surfaces, flight propulsion, wings and empennage) shall be detachable
- A detailed cockpit interface concept (flight controls, display usage, and possibly pilot wearable avionics) shall be created
- The flying car shall be capable to carry standard cabin luggage per passenger
- The minimum range of the flying car shall be 1000 kilometres with a 15 minute reserve
- The difference in modes of operation shall be minimal (pilot control interface shall not differ much between drive and flight mode)
- The time to convert from drive to flight or vice versa shall takes less than 30 minutes including checks
- The design cruise speed shall be over 200 knots
- The cruise phase shall have a power setting of 80% of maximum power
- The minimum rate of climb shall be 500 feet per minute
- The field length shall be below 500 metres
- During takeoff and landing the noise levels shall be less than 65 decibels at a distance of 200 metres
- The flight equipment shall be easily stored in a safe environment
- The CO_2 emission shall be below 150 kilogrammes per hour
- The flying car shall be over 90% recyclable
- The unit cost shall be below 500,000 euros
- The first flight shall be possible in or before 2025
- The life span of the system shall be 25 years
- The flying car shall be designed for 20,000 flight hours
- The flying car shall comply with corresponding CS-23 regulations in flight setting

Some of these requirements need some additional information on why this is necessary, such as the requirement for the “Carver” type of roadable vehicle. In order to make the conversion car - aircraft more convenient, the car should turn in a same kind of way as an aircraft, which combines roll and yaw for a turn. A motorcycle or a Carver [2] banks for a turn which is similar to the rolling of an aircraft. This should make the conversion between the two modes more convenient.

In order to protect flight critical instruments from possible dangerous influences from life outside an airport (curious people, traffic, ...), the flight module, so the wing, should be detachable and able to be left behind at the airport, to be stored safely there. This way, nothing can happen to the critical elements that keep you flying.

3.2 Mission scenarios

The mission scenario is the guideline along which the flying car will be designed. These guidelines will be used when generating the concepts. The basic mission will be three flights per week, with a minimum flight time of three hours per day and a maximum flight time of six hours per day. The flight mission will be performed under instrument flight rules. The driving mission will provide the other two design pillars; the low door-to-door time and the personality of the vehicle.

Besides the previous points which describe the mission on a more general scale, the following points describe what the roadable aircraft is designed for specifically with respect to weather, location, terrain, payload, failure and certification.

- Weather

  Rain

  Sun

  Light Fog, Winds (39 kts during flight and 25 kts crosswind laning) and Snow/Ice

- Airport Location

  Elevation $< 2500m$

- Terrain

  Asphalt for roadable vehicle

  Tarmac for flying vehicle

- Payload

  Two persons and basic luggage (200 kg payload)

  Maximum and minimum fuel mass

- Failure

  Emergency procedure during flight failure

  Car safety

- Certification

  CS-23

  Motorbike registration

Chapter 4: Concept generation

Now that the outline of the design task is known preliminary concepts can be made. This process was followed through by the entire group. Everyone drew some preliminary possibilities which were then compared and distilled into eight different wing configurations. These basic configurations are given in Table 4.1. The distilling process involved combining subcategories such as a delta wing into more general configurations.

Table 4.1: Different concept configurations

Wing Configuration	
I	Conventional low
II	Conventional mid
III	Conventional high
IV	Blended mid-wing
V	Biplane
VI	Tandem
VII	Closed wing
VIII	Conventional canard

4.1 Trade-off method

In the preliminary design phase three concepts were elaborated upon in more detail. Therefore a trade-off was made between the eight concepts to continue working on the best configurations. In the trade-off table every concept was given a grade from 1 (poorest) to 5 (best) on the different criteria which will be described below.

4.1.1 Trade criteria

Aerodynamics The wing configuration should be traded off according to its capability to produce lift, and the amount of drag that it produces.

Structures This involved comparing complexity of, for example, the wing structure. Another large part of the consideration was the weight and ease of implementation of stiffening elements.

Performance The ability of the aircraft to fly at the given airspeed of 200 knots, and for a given range of 1000 km has to be investigated. It is very difficult to rate this requirement when looking at an individual configuration. Therefore any wings which do not give major problems will get a score of 3, and if there is a configuration which clearly offers (dis)advantages, it will get a higher or lower grade.

Propulsion This criterion has a lot to do with drag. The power required and thus the fuel consumption depends on the drag. Another point is the integration of the engine in the wing; the least complex solution attains the highest score.

Ease of integration In order to protect critical flight instruments from outside influences when being outside of an airports environment, the wing and other flight critical elements should be able to be detached and left behind at the airport. The question asked here is whether the wing module can easily be attached to the car or not.

Maintenance Is every part easily accessible for maintenance? Is it simple to maintain, or does it require a lot of knowledge and time because of the configuration's complexity? This one is very important for the life cycle of 25 years that has to be met.

Stability & Control The aircraft should be stable, to make it user-friendly. Ease of use is very important for the class of customers that this aircraft is designed for. It should also be controllable.

Certification The certification of this flying car will be difficult since it is an exotic product. Conventional wing configurations are more easily certified than unconventional configurations.

Marketing appeal To be able to sell the product, it must look nice and appeal to the market designed for. A gadget lover or a business man will not spend 500,000 euros on an unattractive flying car.

4.1.2 Criteria weights

The different requirements listed in the previous section are important to take into account, but not every requirement is equally important. It is, for example, more important that the product is able to fly in a stable way, than that it is a good looking product or that parts are easy to reach for maintenance. Stability is also more important than high manoeuvrability, so control gets a lower weight than stability. Since the key requirement for this product is to minimise the door-to-door time, the ease of integration is rated highly as well. Leaving out that requirement would give a much lower weight for this criteria. The aerodynamics of the aircraft are as important as the stability and control. The most important stakeholder requirements are the speed and the range for the aircraft, such that performance is rated highest in the trade-off. The weights can be found in Table 4.2.

4.2 Trade-off results

Using the trade-off table generated in the previous section, grades were given for each wing configuration for all criteria. The results can be found in Table 4.2. The different wing configurations are listed at the start of this chapter.

Table 4.2: Trade-off for different wing configurations

Configuration / Trade-off requirement	Weight	I	II	III	IV	V	VI	VII	VIII
Aerodynamics (lift, drag)	15	3	4	3	5	2	2	5	3
Structures	10	3,4	3	3,4	3,2	3,6	3,2	2,6	3,4
-Weight	*60%*	*3*	*3*	*3*	*4*	*4*	*4*	*3*	*3*
-Complexity	*40%*	*4*	*3*	*4*	*2*	*3*	*2*	*2*	*4*
Performance (Weight, speed)	20	3	3	3	3,5	2,5	2,5	3	3
- Speed (how adequate is it to fly at 200 kts)	*50%*	*3*	*3*	*3*	*3*	*2*	*2*	*3*	*3*
- Range	*50%*	*3*	*3*	*3*	*4*	*3*	*3*	*3*	*3*
Propulsion	10	2,5	3	3,5	3	1,75	2,5	4,5	3
- Consumption	*50%*	*3*	*3*	*3*	*5*	*2*	*2*	*5*	*3*
- Integration complexity	*50%*	*2*	*3*	*4*	*1*	*1,5*	*3*	*4*	*3*
Ease of integration (attachment system)	15	4	3	4	4	1	1	2	2
Maintenance	3	4	4	4	2	3	3	2	4
Stability & Control	15	3,33	3	3,66	1,33	3	2,66	3,33	2,66
- Stability	*66,5%*	*3*	*3*	*4*	*1*	*3*	*2*	*3*	*2*
- Control	*33,5%*	*4*	*3*	*3*	*2*	*3*	*4*	*4*	*4*
Certification	7	5	5	5	2	4	2	1	4
Marketing appeal	5	3,57	3,14	2,28	4,42	2,42	1,57	3,86	3,86
Total	100	3,39	3,33	**3,47**	3,29	2,43	2,23	3,18	2,98

As can be seen in this table the high conventional wing turns out to be the best option for the flying car design. The second and third best are the low and the mid conventional wing respectively.

However, the team decided not go with this top 3. It was decided that two conventional and one more unconventional configuration should be elaborated. The blended wing body and the closed wing configuration are in line after the top 3, but the choice was made to elaborate on the canard configuration. Both the blended wing body (flying wing) and the closed wing seem to be good alternatives for the conventional wing configurations, but considering that there are almost no reference aircraft for both configurations, and there is even no working example of the closed wing configuration, the team chose the canard to elaborate on. Designing a flying car is already something new, designing a flying car with a wing configuration that has no or almost no predecessors is out of the scope of this project, and considered not possible in the amount of time given to the team.

Chapter 5: Class I weight estimation

After selection of the three configurations a class I weight estimation is performed to get some preliminary sizes from which decisions can be made. The process and the results are described in this chapter.

5.1 Power and wing loading

In order to make a class I weight estimation the power and wing loading for the propeller aircraft has to be computed. For the optimum power and wing loading for this design it is desired to have a high ratio on $\frac{W}{S}$ and $\frac{W}{P}$.

To impose restrictions on the design, the requirements and CS-23 regulations [3] are applied with respect to:

- Stall speed
- Take off field length
- Landing requirement
- Rate of climb
- Climb gradient
- Manoeuvring
- Cruise conditions

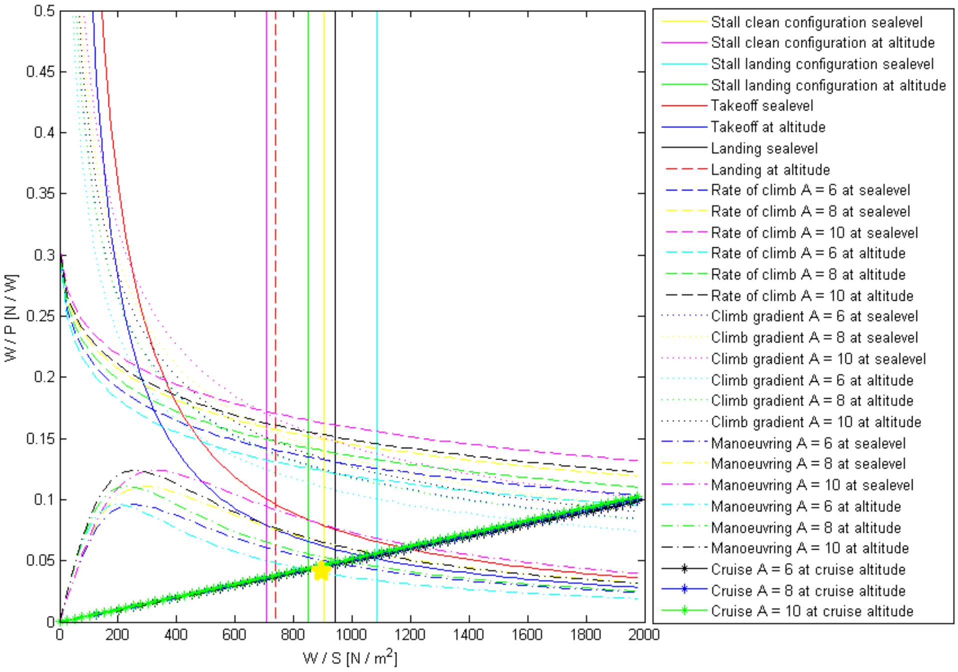

Figure 5.1: Power and wing loading diagram

All restrictions result in the diagram shown in Figure 5.1. The design point is given with a star and the wing loading (904.8 N/W) and power loading (0.05035) can be estimated.

5.2 Fuel fractions

For a class I estimation of the fuel weight, the fuel fraction method was used. The flight mission of the flying car is depicted in Figure 5.2. The phases of the mission are defined in Table 5.1.

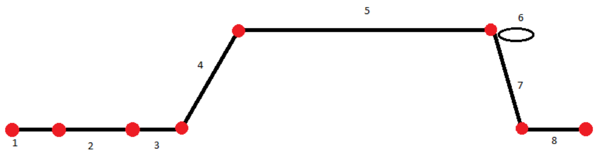

Figure 5.2: The mission profile

Using reference data for the low fuel intensive sections (1, 2, 3, 4, 7 & 8) and analytical (Breguet) equations for the cruise and holding segments the calculations were performed for three different engine setups: turboprop, single- and twin prop piston engine. The fuel fractions for these configurations are given in Table 5.2.

Table 5.1: Mission parts

Number	Mission part
1	Engine start and warm-up
2	Taxi
3	Take off
4	Climb
5	Cruise
6	Holding
7	Descent
8	Landing, taxi and shut-down

Table 5.2: Fuel fractions for three engine setups

Engine setup	Fuel fraction
Single prop piston engine	0.821
Twin prop piston engine	0.815
Turboprop	0.860

5.3 Configuration weights

Now that the wing loading, power loading and fuel fractions are known, the final weights of the three configurations can be determined. In order to do so, the maximum take off weights and operational empty weights of different aircraft are gathered and plotted against each other. Using this relation the values in Tables 5.3 to 5.5 are found. Two people with luggage, for a total of 200kg, were taken into account here.

Table 5.3: All weights, surface area and power required with different engine configurations for conventional high wing

	Turboprop	Twin engine prop	Single engine prop
Take off weight [N]	8179.4	9814.3	8341.7
Empty weight [N]	5074.7	6036.2	5170.1
Fuel weight [N]	1142.7	1816.1	1209.5
Surface area [m^2]	11.5	13.8	11.8
Power [hp]	302.75	363.26	308.75

Table 5.4: All weights, surface area and power required with different engine configurations for conventional low wing

	Turboprop	Single engine prop	Twin engine prop
Take off weight [N]	9011.7	9127.6	10112.3
Empty weight [N]	55790.7	5842.1	6279.0
Fuel weight [N]	1259.0	1323.5	1871.2
Surface area [m^2]	12.7	12.9	14.3
Power [hp]	333.55	337.85	374.29

Table 5.5: All weights, surface area and power required with different engine configurations for canard

	Turboprop	Single engine prop	Twin engine prop
Take off weight [N]	6040.3	6174.3	7420.3
Empty weight [N]	3234.4	3317.1	4085.2
Fuel weight [N]	843.9	895.3	1373.1
Surface area [m^2]	8.5	8.7	10.5
Power [hp]	223.57	228.53	274.65

Chapter 6: Final trade-off

The three different concepts (conventional high, conventional low and canard) were thoroughly analysed and researched. Using this information, a trade-off will be performed. Section 6.1 states how the concepts are traded off and Section 6.2 contains the final trade-off between the three concepts.

6.1 Trade-off method

In order to select the most effective concept the design is evaluated within given categories which have a specific weight assigned. The different categories are aerodynamics, structures and materials, propulsion, operations, stability and control, operational empty weight, sustainability and marketing appeal. These categories can be broken down further, as shown below, in order to accurately assess the strengths and weaknesses of each design concept.

6.1.1 Aerodynamics (15)

The overall aerodynamics category has been assigned a weight of 15. The main aerodynamic properties of the configurations are the lift, drag and stall properties. The airfoil and planform selection depend on these properties, which are of influence for the structures and weight. Because the canard can obtain the lift criteria with the smallest surface areas it is aerodynamically the most beneficial. Aerodynamics is an important section, but due to many overlapping properties between the configurations it has a weight of 15. The weighing categories within aerodynamics are aerodynamics of the attachment, stall behaviour, spin recovery, wetted surface area and the ground effect.

6.1.2 Structures and materials (20)

The structures and materials category has been given a weight of 20. The structure is one of the most important factors in a design. Without a good structure the design could collapse in flight or drive mode and the whole design could not be used. The weight of this section must be significant so 20 is chosen. There are various sections within structures. For the three different configurations the landing gear implementation, the ease of attachment, the fuel storage and the maintenance accessibility have been taken into account. Since the structures are viably implemented in all configurations with each configuration having its own benefits, the numbers are close.

6.1.3 Propulsion (20)

The propulsion category has been assigned an overall weight of 20 as this is most important for the door-to-door time. The engine concept of the three configurations is going to be more or less the same. the main trade-off categories will be not be between different engines, but a trade-off for modular transmission integration, fuel system integration, flexibility with relation to change in engine selection and the required engine power.

6.1.4 Operations (15)

The operations category has been assigned an overall weight of 15. The weighting factors within this category are the ease of attachment, the ease of flight operations, the implementation of avionics, the implementation of a fly-by-wire system, storage space and certification. The operations contain a lot outside the design itself when looking at comfort and practical systems. It is an important section, because without good systems people are not going to buy the product, but it is less important for the design parameters. For this reason operations has been assigned a weight of 15.

6.1.5 Stability and control (20)

The stability and control category has been assigned an overall weight of 20. Having a stable and controllable aircraft is of large importance to minimise pilot workload as well as decreasing complexity. The stability and control can be further divided into subcategories such as engine placement options, the longitudinal static stability, the controllability of the aircraft, the lateral stability, the horizontal tail surface, the vertical tail surface, the tail arm and the longitudinal position of leading edge mean aerodynamic chord. The grading of the concepts is based on preliminary calculations.

6.1.6 Operative empty weight (20)

The operational empty weight category has been assigned a weight of 20. This category is based on the estimated weights obtained via the class II weight estimation method. Since the high wing concept was the lightest, that concept obtained the highest score followed by the low wing and lastly the canard concept. The weight of an aircraft during design is linked to the amount of fuel used, drag, etc. Therefore it is necessary to favour the lightest concept.

6.1.7 Sustainability (10)

The sustainability category has been attributed with a weight of 10. The sustainability category has not been further broken down as the difference between the sustainability approach of the three concepts only has minor variations. The weight of 10 was given due to the fact that the stakeholders have a large interest in having a sustainable product. Furthermore, having a sustainable product ensures that the market appeal of the product increases.

6.1.8 Marketing appeal (5)

The marketing appeal category has been assigned a weight of 5 due to its lack of technical aspects but still taken into consideration due to the stakeholders' interest for an appealing product. The assessment of the different concepts for the marketing appeal category was taken as an average of all the group members opinion on the appeal of the vehicle.

6.2 Concept trade-off table

The final concept trade-off table is presented in Table 6.1. The concept that scored the highest is the high conventional wing configuration with a score of 8.954 meaning this will be the final concept being worked with in detailed design. Four main design aspects (car module, flight module, attachment system and operations, presented in Part II can be distinguished which will be emphasised on in detailed design of the high wing configuration.

Table 6.1: *Final concept trade-off table*

Field		Concepts			
Department	Specification	Weight	High wing	Low wing	Canard
Aerodynamics		**15**	7.9	7.45	**9**
	Aerodynamics of Attachment	30%	8	7	9
	Stall behaviour	20%	10	7	8
	Spin recovery	10%	10	10	8
	S_{wet}	35%	6	7	10
	Ground Effect	5%	8	10	8
Structures and materials		**20**	**9.15**	8.35	8.25
	Implementation of landing gear	15%	6	9	8
	Ease of integration	45%	10	7	8
	Availability for fuel storage	15%	10	9	8
	Accesability for maintanance	25%	9	10	9
Propulsion		**20**	8	8.5	**9.5**
	Modular transmission integration	30%	9	10	9
	Modular fuel system integration	20%	9	10	9
	Flexibility to engine changes	10%	7	3	10
	Power required	40%	7	8	10
Operations		**15**	**9.65**	8.25	7.95
	Ease of attaching system	20%	10	7	8
	Ease of flight operations	30%	10	8	7
	Implementation of avionics	15%	10	10	7
	Implementation of fly by wire systems	15%	9	9	10
	Storage space	10%	8	7	10
	Certification	10%	10	9	7
Stability and control		**20**	**9.7**	8.425	7.9
	Engine placement options	10%	10	6	9
	Longitudinal Static Stability	20%	10	9	7
	Controlability	20%	10	10	8
	Lateral stability	20%	10	10	8
	Horizontal tail surface	7.5%	7	8	10
	Vertical tail surface	7.5%	9	9	6
	Tail arm	7.5%	10	7	8
	X_{LEMAC}	7.5%	10	3	8
Operational empty weight		**20**	**10**	9	7
Sustainability		**10**	8	8	**10**
Marketing appeal		**5**	7.8	**8.7**	8.4
Total		125	**8.954**	**8.356**	**8.394**

Chapter 7: Class II weight estimation

Having decided on the final configuration, a more in-depth analysis of the concept was performed. This class II weight estimation was calculated using the Raymer method [4]. The adjustments made to accommodate the design and the results are described here.

7.1 Adjustments

The Raymer method accounts only for one kind of engine set-up. As the vehicle will have both a flight engine and a driving engine, the engine weight calculation method was adjusted to incorporate this. Additionally, the class II weight estimation revealed that flying at a higher altitude is beneficial with respect to power required. It was then decided to fly at an altitude of 7000 metres. An added benefit to flying at such an altitude is the efficient use of a turboprop engine, resulting in a significant reduction of weight. Furthermore, the weight calculation method was set to incorporate the weight penalty due to the pressurisation of the cabin, now necessary due to the increased altitude.

7.2 Results

The build-up of the different components of the flying car is shown in Figure 7.1. Using these weights an estimation of the power and measurements can be made. The final weights, power requirements and measurements are shown in Table 7.1.

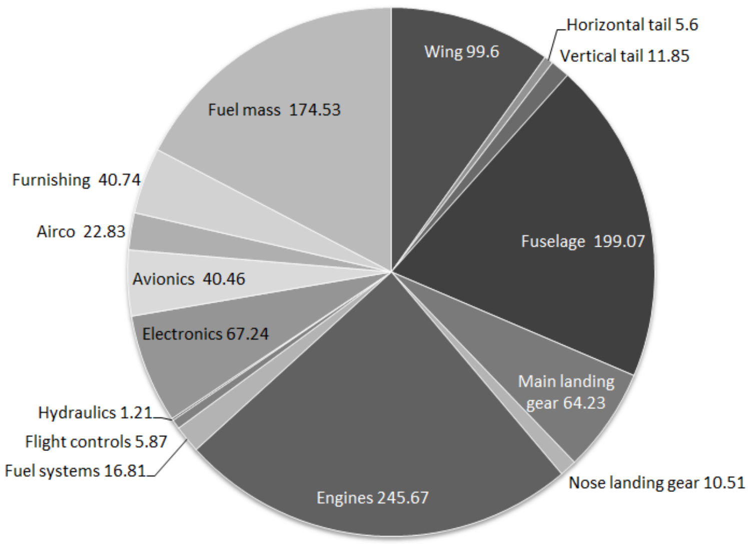

Figure 7.1: A pie chart detailing the weights (in kg) of different components of the flying car

Table 7.1: The parameters gained from the class II estimation

Parameter	Value	Unit
S	13.08	m^2
b	9.87	m
c_r	1.83	m
X_{LEMAC}	2.7	m
S_{ht}	1.21	m^2
b_{ht}	2.46	m
$c_{r_{ht}}$	0.68	m
l_t	3.3	m
S_{vt}	1.64	m^2
b_{vt}	1.14	m
$c_{r_{vt}}$	1.02	m
l_{vt}	3.3	m
OEW	831.68	kg
MTOW	1206.14	kg
P_{req}	147.25	kW

Part II

Detailed Design

Subpart A

Car module

Chapter 8: Car exterior and structure

Road vehicles come in all shapes and sizes and they are often the subject of discussion and pride. The exterior of a car says a lot about the type of vehicle it is, off-road vehicles are often bulky while sports cars are usually very aerodynamic. This is also the case with the Volucrem, which has designed to be effective during flight. The roadable part of the Volucrem can seen in Figure 8.1.

Through out history, multiple attempts at designing a flying car have failed. A flying car is best when both the car module and flight module are of good quality, which is not the simplest of things to do as you need to take an extensive amount of things in to account. The Volucrem is based on a three wheeled "Carver" type of vehicle with space for two passengers. The most important reason for choosing a three wheeled carver is the way it turns: it banks when making a (high-speed) turn, which is similar to the rolling of an aircraft. The three wheeled configuration is also chosen from a practical point of view. For this configuration the regulations of a motorcycle apply instead of the more strict car regulations, which gives more design freedom. The first prototype of the Volucrem is mainly designed for business people, so space for the driver and one colleague, partner or friend is sufficient. For the shape of the car, the aerodynamics are an important factor since this would minimise the drag, which is especially beneficial for flight. As the flight module is detachable (see Section 3.1 and Chapter 19) the car has smooth lines and the attachment mechanism for the flight module is smoothly covered with three fins. There is one big standard door to enter the vehicle and it has a large window for a good view on the road and in the air. Small NACA air inlets have been placed at the rear for the cooling of the engine, without losing its aerodynamic shape.

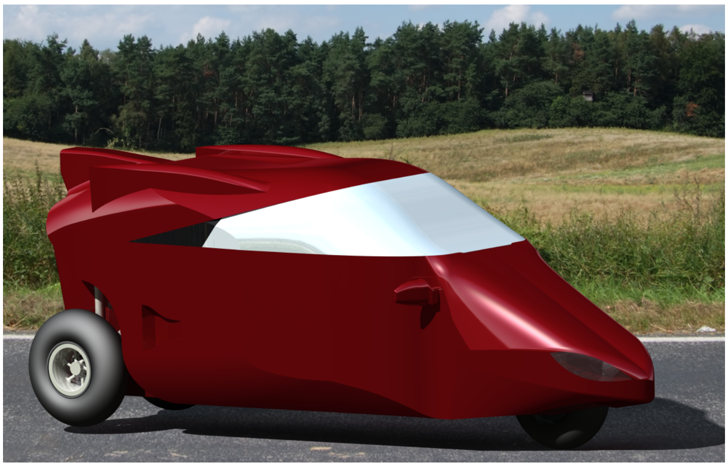

Figure 8.1: Volucrem car module

8.1 Roll cage

As a safety measure in case of collision as well as for the transfer of loads between the flight module and the carver through the attachment system, a roll cage carrying the exterior structure is designed.

This structural component can be made of different materials. The car industry normally uses different types of steels. However, since this product is designed for flight, the material to be chosen must be the one that allows the minimum weight, which results to be beneficial in terms of fuel consumption and CO_2 emissions. Thus, the material to be employed is aluminium 2024T3. In addition, aluminium alloys have a high strength and energy absorption. The roll cage cross-section elements will be circular tubes. These will carry the loads, since the body panels have little to no structural function. Regarding the use of an aluminium frame, it has been employed in other cars like the Rolls Royce Phantom, the Lamborghini Gallardo, the Ferrari 360, the Mercedes-Benz SLS AMG and the Audi A8 series. Furthermore, the Audi A8 was the first mass production car with an aluminium space frame, named by Audi as "Audi Space Frame" [5].

The static and dynamic loads the roll cage must withstand are [6]:

- The weight of the body, the passengers with cargo and the flight module
- The vertical and torsional twisting transmitted by going over uneven surfaces
- The transverse lateral forces caused by road conditions, side wind, and steering the vehicle
- Torque from the engine and transmission
- Longitudinal tensile forces from starting and acceleration, as well as compression from braking
- Sudden impacts from collision

Among the main peculiarities of the obtained roll cage, it is worth mentioning the presence of the necessary space for one standard car door (sealed with an inflatable tube for pressurisation purposes) as well as an emergency exit on the roof of the vehicle with a semi-permanent locking mechanism. The door has not been sized specificaly and an off the shelf car door will be looked for in further iterations. The front seat will fold forward such that the car door is present on the side of the driver. This is also the reason an escape hatch is present in the roof; this way the passenger will be able to escape safely in case of an emergency. Other important aspects are the high loads present in the interface between the carver and the wing module. To cope with all the induced forces, reinforcements have been created to meet the required structural rigidity.

In order to check that the structure is not excessively over-designed, a Finite Element Method (FEM) was carried out by employing CATIA. This Finite Element Method was performed for the most critical load cases assuming an acceleration of gravity of 9.80655 m/s^2. These load cases are:

- Maximum manoeuvring load of 38490.71 N due to an upwards acceleration of 5g of the wing module. The mass considered is the approximated carver mass of 785 kg. The carver is assumed to be clamped at its lower part.
- Maximum landing load of 94142.88 N due to an downwards acceleration of 8g of the carver and the flight module. The mass considered is the maximum takeoff mass of 1200 kg. The carver is assumed to be clamped at the vertical structure behind the passenger seat. The load is applied in upwards direction at the vertical struts in the rear part of the carver, since the shock absorbers of the rear wheels are connected to these struts. In addition, as a conservative approach, the damping effect of the shock absorbers are ignored such that the maximum landing load is distributed at both rear struts.

The yield stress of the alloy 2024T3 is 345 MPa. Thus, the stress in the roll cage must remain below that value. Several iterations were carried out to achieve a weight of approximately 60 kilograms. However, the weight of the structure can be decreased by performing a more in depth iterative process.

The results of the Finite Element Method for both extreme load cases are presented in Figures 8.2 to 8.7. As it can be observed, the clamped parts of the roll cage have been marked with yellow while the locations where the distributed load is applied have been marked in green.

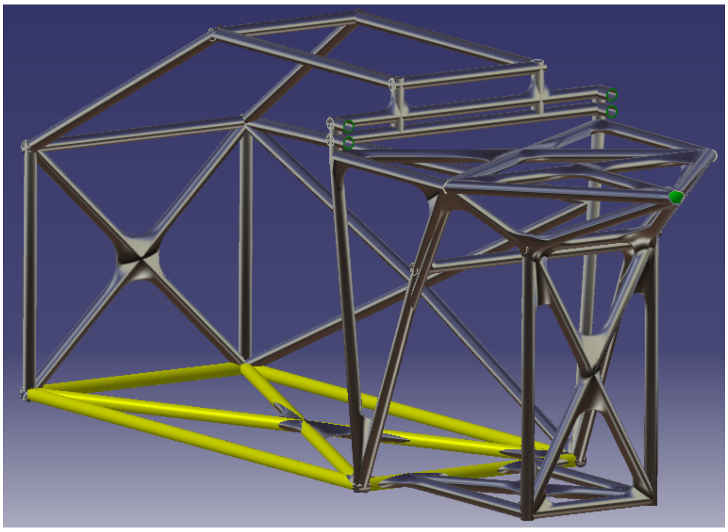

Figure 8.2: Load and clamping placements for the FEM of the roll cage in the extreme manoeuvring case

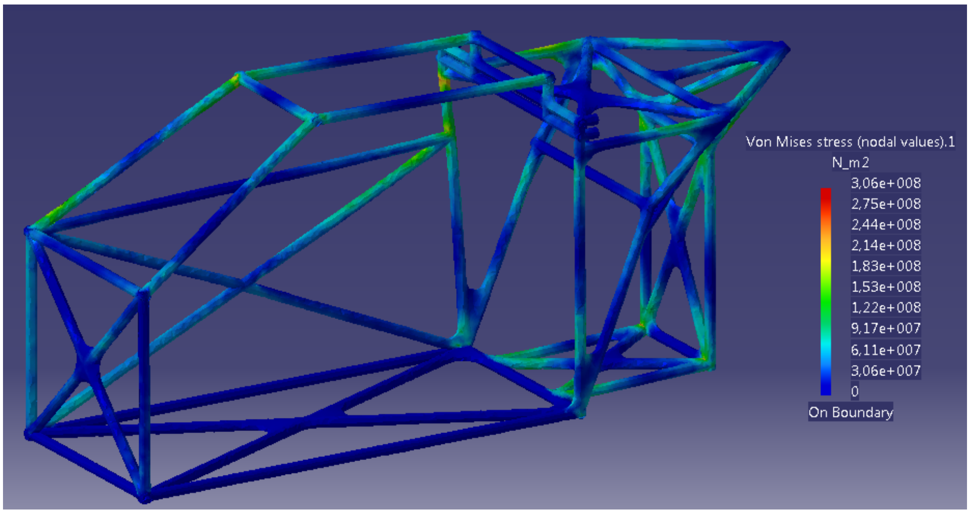

Figure 8.3: Front side view of FEM results of the roll cage for the extreme manoeuvring case

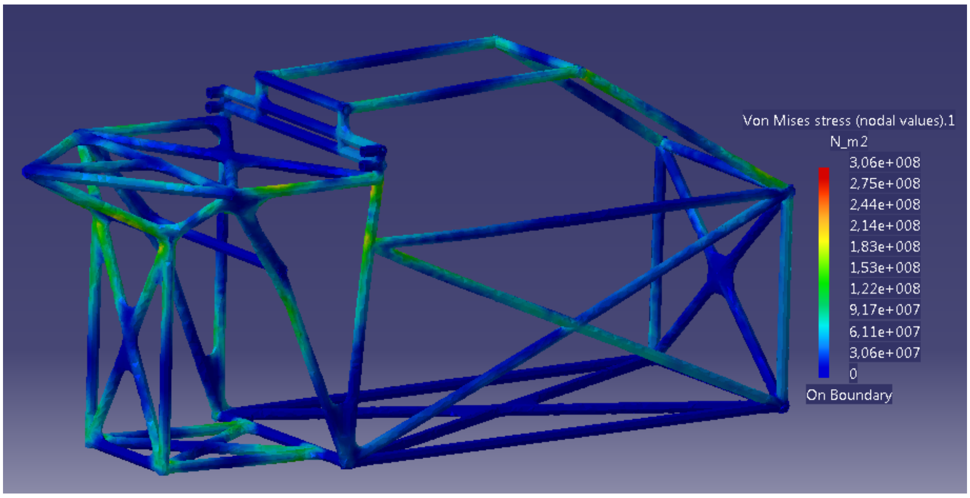

Figure 8.4: Back side view of FEM results of the roll cage for the extreme manoeuvring case

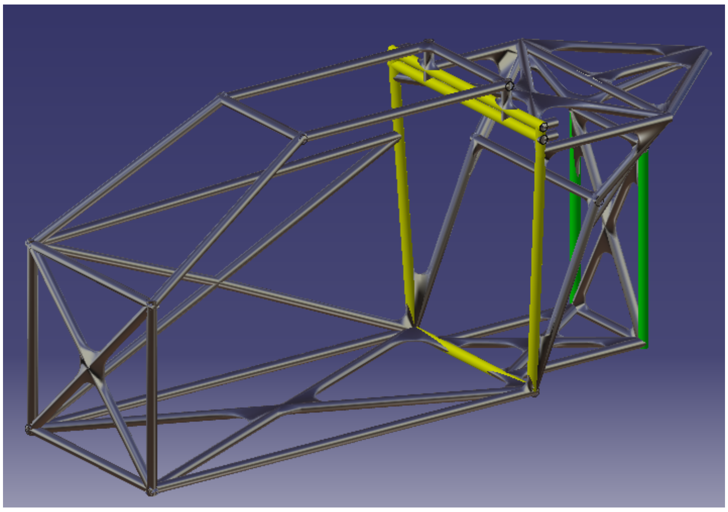

Figure 8.5: Load and clamping placements for the FEM of the roll cage in the extreme landing case

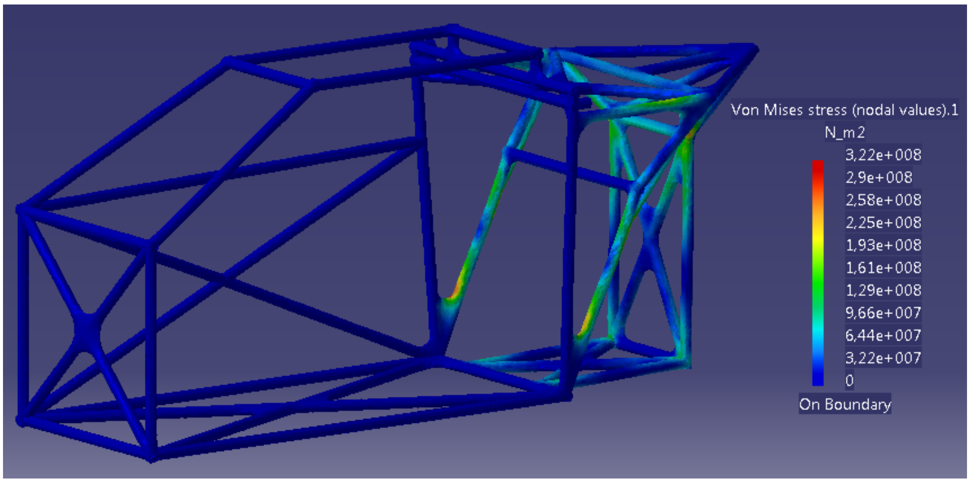

Figure 8.6: Front side view of FEM results of the roll cage for the extreme landing case

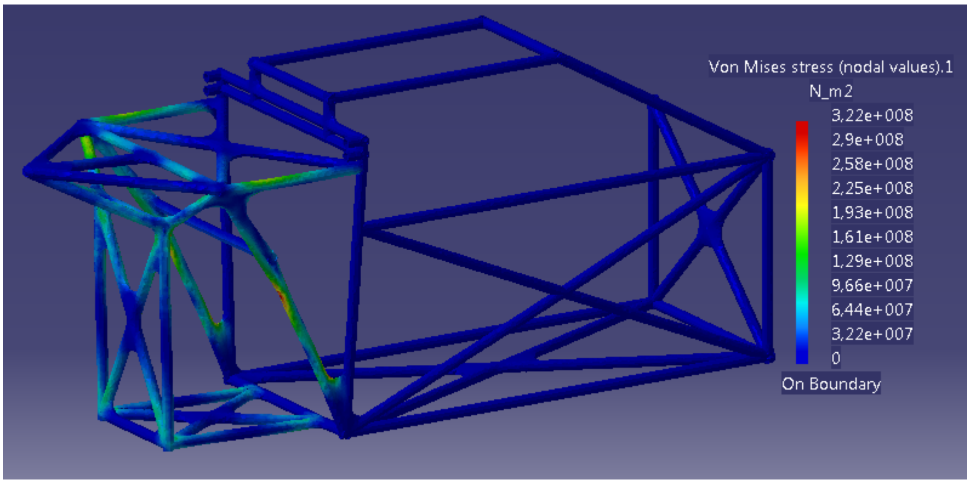

Figure 8.7: Back side view of FEM results of the roll cage for the extreme manoeuvring case

8.2 Vibrational analysis

In order to assure that the structure copes with the vibrations during its operation, a vibrational analysis has been performed.

To determine the range of frequencies safe for operation, the natural frequency had to be determined for the most critical load cases. These are the extreme manoeuvring and the extreme landing scenarios presented in Chapter 8. To determine the natural frequency for each operational case, CATIA was employed. The natural frequencies are:

- 29.67 Hz for the extreme manoeuvring scenario
- 30.40 Hz for the extreme landing scenario

The natural frequencies must be avoided in order to guarantee the structural integrity. In order to determine if the natural frequencies obtained are safe enough, they were compared to the natural frequency of an airplane in an analysis performed by Boeing [7]. According to this analysis, an expected frequency during aircraft operation can reach up to 20 to 25 Hz depending on the mass of the vibrating component. These frequencies are below the natural frequencies. Thus, it is is possible to say that natural frequencies of approximately 30 Hz are high enough to guarantee operational safety of this roadable aircraft. In addition, another element to consider from the vibrational point of view is the carver engine. An engine similar to the Smart 800 CDI engine will run approximately at 1000 revolutions per minute at idle speed. This implies a frequency of less than 17 Hz. Therefore, it can be stated that the engine will not represent a menace from the point of view of vibrations. However, at higher revolutions per minute, the frequency increases, approaching the natural frequency. Due to the fact that there are damping elements like the suspension system among others, it is assumed that higher regimes of the carver engine do not represent a vibrational problem. Nonetheless, this is a subject for further analysis in future considerations.

Chapter 9: Car engine

The roadable vehicle must provide smooth travelling. However, one of the most limiting factors does not come from the roadable part. To achieve efficiency during flight, the total module must be as light as possible. Therefore, the carver engine must be chosen from the small car segment. Other factors included low emissions and low fuel consumption. Research led to the following three car engines found in table 9.1 as well as the BMW motorcycle engine found in the PAL-V.

Table 9.1: Car engine specifications [8]

Engine	Mass [kg]	Power [hp]	Power [kW]	Emissions [g/km]	Fuel [L/100km]
Honda 1.6L i-DTEC	170	120	88	94	3.6
Smart 800CDI	65	80	58	86	4.3
Chevrolet Spark LS 1.2L	-	86	64	119	4.9
BMW K1200LT	113	98	72	-	4.3

As mentioned previously, the main requirements for the car engine is that it must be lightweight and have low polluting emissions. Regarding the weight, the Honda engine is the heaviest. However extra weight is compensated by having the lowest fuel consumption. Additionally, the Honda engine runs on diesel. This makes the bio-diesel a usable option. On the other hand, the Smart engine has the lowest emissions and it is also the lightest, weighting only 65 kg. The Chevrolet engine weight was not available and its specifications in both emissions and fuel consumption are worse compared to the other two engines. The BMW motorcycle engine has similar power and fuel consumption as the Honda engine, but it is lighter. Taking these points into consideration, an engine similar to the Smart engine would be the most desirable for the roadable vehicle.

9.1 The Smart 800CDI engine

The setup similar to the Smart 800CDI engine and gearbox together will be approximately 290mm in length, 200mm in height and 600mm in width. This means that the total engine module can be fit into a 0.035m^3 volume. The total mass of the engine and gearbox is 65kg and 14kg respectively. This implies a propulsion system mass of 79kg [9]. To avoid the car engine to be dead weight, it will be used during flight for the pressurisation of the cabin and to provide power to all electronic systems. Therefore, the system will have a turbocharger similar to the Garrett GT20 with a mass of 15 kg to provide the extra engine bite and to assist during cabin pressurisation[10]. Furthermore, this engine runs on diesel, which again allows the possibility of using bio-diesel during drive mode. The five gear gearbox used with this engine is a similar one used for the Smart Fortwo car. The transmission is semi-automatic: there is no clutch pedal or lever, but the driver does have the option to manually change gears using a stick or a buttom [11].

9.2 Fuel system

The fuel system is dependent on the range that must be achieved by the roadable vehicle. It has been decided that a distance of between the 200km and 300km would be optimal, since this covers regular travel distances to and from the airport. Therefore, it was decided that a 10 liter tank would be sufficient, since with this volume the ground vehicle would be able to drive 230km with the Smart engine under optimal conditions. As the system will not be coupled with the flight engine, the fuel tanks will not need to be physically linked. Therefore, the fuel system previously designed in the conceptual design phase can be utilised [12]. It will look similar to the flight engine system as presented in Section 15.4 only using one fuel tank in the ground module instead of two fuel tanks in the wing.

Chapter 10: Car interior

Riding or flying the Volucrem will be a great experience. In order to accomplish that, the car interior is made luxurious, comfortable, modern and easy to use. The placing of the seats, the tilting device, the steering column, pressurisation, electronic systems and the dashboard layout are all designed such that the driver will enjoy every minute of his journey. All systems that help to accomplish that are presented in this chapter.

10.1 Seating configuration

The vehicle is designed for two passengers. These must travel in a comfortable way and good seats and enough space are important design factors for this. Every person is different, but the seats and space must fit everybody. To obtain the right seat dimensions, human dimensions are needed. Anthropometric data of the average human dimensions per country or region all around the world are obtained. The dataset describing people of most sizes can be found in Table 10.1.

Table 10.1: Anthropometric data

		People Size
	5th *%ile* (Female)	95th *%ile* (Male)
Stature [mm]	1461	1913
Weight [kg]	40	113
Whole body depth [mm]	229	405
Sitting height [mm]	782	996
Shoulder breadth (deltoid) [mm]	358	563
Hip breadth (deltoid) [mm]	293	522
Hip breadth, maximum, sitting [mm]	486	690
Buttock to front of knee, sitting [mm]	366	559
Buttock to back of knee, sitting [mm]	415	593
Top of knee height, sitting [mm]	331	518
Knee height (tibia) standing [mm]	381	517
Knee height (popliteal) standing [mm]	396	482
Elbow height (to seat, sitting) [mm]	180	302

In Table 10.1 the sizes are split in two sections, one being the 5th percentile and the second being the 95th percentile. These percentiles describe the smallest and biggest people coming from a distribution curve we will be designing for. Having these human parameters the size of the seats and their placement in the car can be determined. In Figure 10.1 The placing of the seats with its distances can be found. In Table 10.2 the seat and other dimensions are stated. All dimensions are to ensure optimal passenger comfort while making sure the vehicle is optimally controllable from the driver seat location.

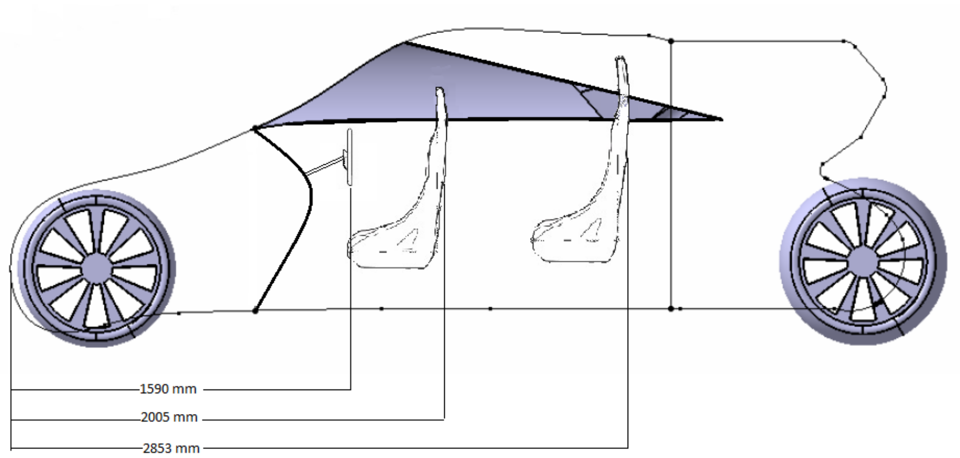

Figure 10.1: Seating configuration inside the vehicle

Table 10.2: Additional dimensions seating layout

Seat Dimensions	
Height	850mm
Width	700mm
Depth	405mm
Luggage area	
Volume	150L
Head Clearance (Seat-Roof)	
Front seat	178mm
Back seat	115mm

Height seats	
Front Seat	270mm
Back seat	320mm
Seats	
Front seat	Adjustable
Back seat	Fixed

10.2 Tilting device

For making turns, a car needs a steering mechanism. In moderate cars steering is done by turning the wheels, however the steering on a motorcycle is done by banking. The roadable vehicle in the design is a three wheeled enclosed motorcycle, so in between of a car and a motorcycle. This configuration has the comfort, safety and convenience of a car with the low emmissions, low noise and the road envelopes of a motor cycle. It is also not a normal roadable vehicle, but a flying carver, so used as a fuselage in flight mode. When thinking of a steering mechanism with these aspects in mind a tilting mechanism was found as the best choice. When using this mechanism, the car banks when making a turn. This gives the passenger the same feeling as making a rolling turn in the air.

10.2.1 Tilting control principles

In order to make the vehicle able to bank without tipping over, a powered system is needed to control the turns. There are different tilting control principles: The Direct Tilt Control (DTC), the Steering Tilt Control (STC) and the Dynamic Vehicle Control (DVC) [13].

The DTC is also called the active tilt control. An actuator between the tilting and the non-tilting part of the vehicle allows control of the tilting position. A feedback system is implemented to make the vehicle self-balancing. For the DTC usually a lateral acceleration sensor is placed in the tilting part which measures the side force and is used as an input for the actuator. The disadvantage of the DTC is the delayed vehicle response, the risk of vehicle oscillations and the high power requirements to generate the required tilting motion.

The STC system works with proper steering of the front wheel of a free tilting vehicle. This is the mechanism commonly used on motorbikes. The big disadvantage of this system is the lack of balance at low speeds and stand still. To deal with this, motorcyclist put their foot on the ground. In an enclosed motorcycle this is not possible and gyros or outriggers have to be used. However this makes the vehicle heavier and the switch from 'locked' to 'balancing' is difficult.

The DVC system is a mixture of the DTC and the STC system with some modifications. In this system the steering input of the driver is distributed between the front wheel steering angle and the tilting angle of the chassis. Due to this the vehicle stays stable at varying speeds and road conditions. At lower speeds the system only uses the front wheel and the vehicle stays upright. At high speeds the steering input is more translated to the tilting angle. It uses a combination of hydraulic and mechanical technology which gives it a high reliability, quick response and natural feel [13].

10.2.2 DVC system

Since an enclosed three wheeled motorcycle is used in the design, which has to be comfortable at low and high speeds and has to be nice to ride, the DVC system is chosen as the best system for the vehicle. A roadable aircraft is designed instead of a normal car, so this system needs some modifications. Before looking at these modifications the principle of the DVC system in the carver is described.

The main DVC principle during banking is shown in Figure 10.2. In this figure the carver is shown with tilting cylinders attached between the non-tilting and the tilting part of the vehicle in such a way that the activation of the cylinders cause a tilting action of the front compartment. The hydraulic valve acts as a main sensor. It measures the torque of the steering wheel relative to the front wheel and depending on this pressurises the hydraulic oil to one cylinder and withdraws the oil from the other cylinder. The tilting will lead to the release of the torque on the front wheel, causing the pressure in the system to go back to normal. This keeps the passenger compartment in dynamic balance [13].

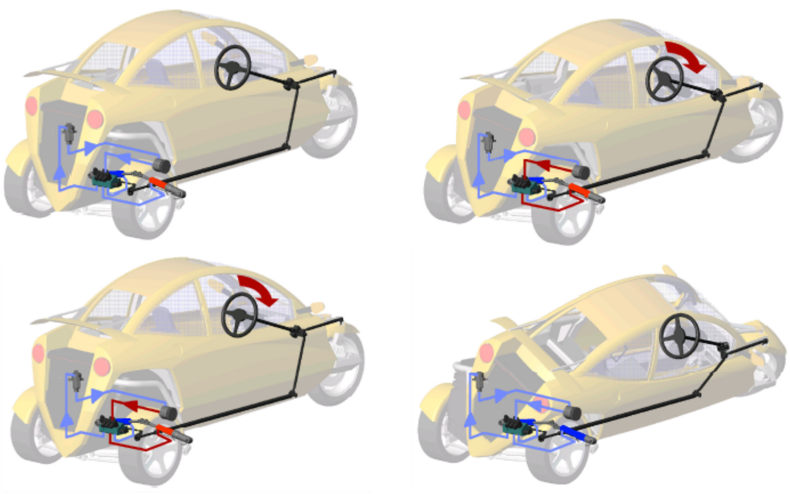

Figure 10.2: Principle of the DVC system [13]

A figure of the schematic lay out of the DVC sytem in the carver can be viewed in Figure 10.3. The numbers in the figure comply with the systems stated below.

1. Hydraulic pump
2. Crankshaft of the engine
3. Accumulator (maintains the hydraulic system pressure together with 1 and 2)
4. Steering valve (measures torque between the steering wheel and the front wheel and controls 5)
5. Hydraulic cylinders (the movement of these cylinders determine the leaning position of the vehicle.)
6. Speed sensor (activates 7 to disengage the system under 10 km/h and in reverse)
7. Shut-off valve

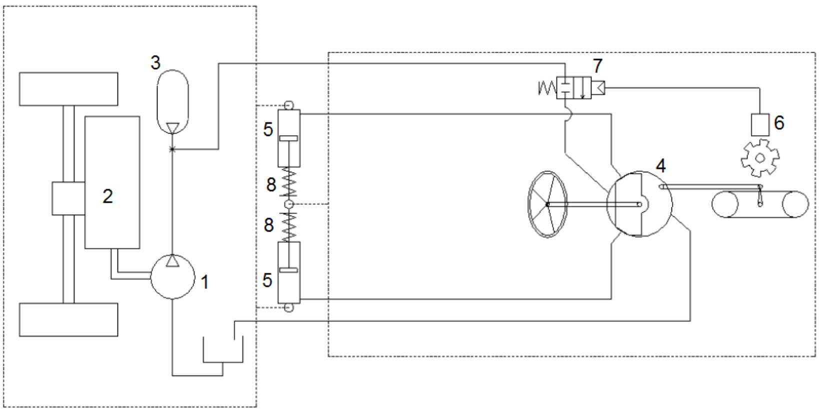

Figure 10.3: DVC system in a carver [14]

To refine the DVC system, several components can be added. This results in an advanced DVC system which can be viewed in Figure 10.4. In this figure the numbers correspond to the following [14]:

9. Power steering. At low speeds high steering forces are needed. To reduce these forces for the driver, the power steering becomes active at these speeds.

10. Steering force limiter. The tilting response in normal conditions is fast and small torques are sufficient for accurate control. With large steering torques the tilting speed reduces. To avoid the driver to give a big spin on the wheel in a panic situation, a steering force limiter reduces that torque to a maximum of 25Nm.
11. Banking angle feedback. Due to the tilting in corners, the driver is always in equilibrium. The disadvantage of this is the lack of feedback on the cornering speed (centrifugal force with normal steering). This causes the driver to make the turns at dangerously high speeds. To avoid this the banking angle feedback gives a torque compliant with the banking angle on the steering wheel.
12. Cylinder damping valve. Is used to correct the disadvantages of the steering damper. It makes the tilting response more smoother and faster, which increases the safety.
13. Steering damper. On an uneven road the vehicle can act nervous due to the linear relation between the steering torque and the pressure difference on the tilting cylinders. To smooth this, a damper is placed on the steering valve.

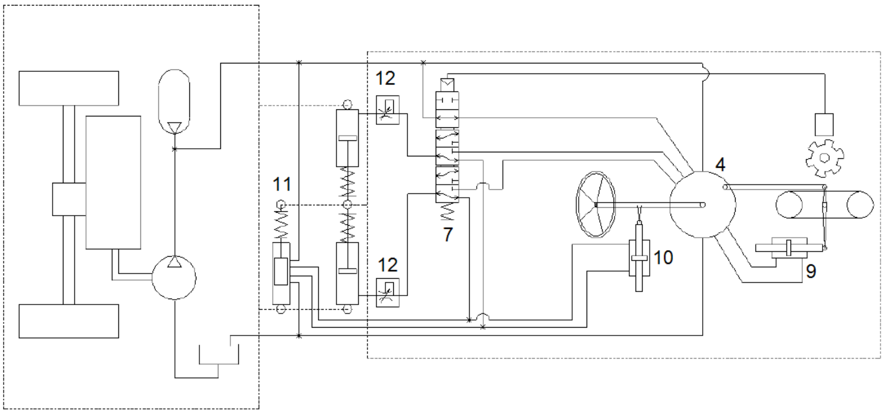

Figure 10.4: Advanced DVC system in a carver [14]

The DVC system works the most satisfactorily at speeds between 10 and 180 km/h. Below 10 km/h the system switches from tilting to front wheel steering. Due to the DVC system being unstable above 180 km/h this will be the limit on the ground vehicle which the car engine can handle. The system has a weight of less then 20 kg, costs approximately 400 euro and has an average power consumption of less then 0.1% of the total vehicle power required [13].

The DVC system is also used in the road vehicle of the Pal-V [15]. Pal-V has made some modification on this system, which are also beneficial for the design, so the tilting system used is more or less the same system as the one of the Pal-V. In the design, the wheels of the vehicle are also used as landing gear. This means a different suspension is needed than a normal car/motorcycle, which is calculated in Chapter 11. The design of the three wheeled enclosed motorcycle is controlled as one piece meaning there is not a tilting and a non-tilting part, but the whole vehicle banks in turns. Furthermore, the shut-off valve must not only be controlled by speed, but also with a separate switch. With this, the banking can be switched off in flight mode so the wings do not touch the ground when making a turn and tilting.

10.3 Steering column

For the steering of the car, a modification of the DVC system is employed. To provide an input to this system, a control column is needed. This control column is used in both flight and drive mode, so it must be practical and easy to use in both modes. When looking at control columns, there are a lot of different versions. For the road, the normal car steering wheel and the motorcycle steer are the logical options and for in the air case, a yoke or a side/centre stick is chosen. When looking at resemblances between the car and the flight controls, a yoke is more similar to a road control steering wheel than a centre/side stick. There are a lot of different yokes; most of them are U- or W- shaped, but there are also yokes in an M-shape or shaped like a car steering wheel. To make a decision between the shapes, the controls need to be evaluated. In flight mode, roll, pitch and yaw are the desired control motions. Roll is done with standard steering, pitch with moving the stick to- and afwards from the pilot and yaw with an automatic computer system collaborated with roll or rudders for redundancy purposes. To decelerate and accelerate in the air, two options can be described. The throttle handle on the yoke is used in a same way as for driving. It can be locked at the speed you want such that its operation is as a regular aircraft throttle stick. However, a regular flight throttle can also be placed at the right side of the pilot (due to the door at the left side) to control the flight engine. A decision between throttle on the yoke, throttle at the side, or a combination can only be made based on a market analysis. This is a future issue based on a pilot's preference. In drive mode, regular steering is needed to turn the car. Furthermore, the car must be able to brake, shift and accelerate. This is done in regular cars with the use of pedals. However, to avoid confusion between flight and drive mode, the use of pedals in drive mode is avoided. The acceleration and braking can be done as in a motorcycle. They are both on the steering wheel, throttling by turning the right hand and handles for the brakes. For shifting, an automatic gearbox is used. This way there is no clutch pedal, only a shifting knob on your right for reverse, park, neutral, drive, taxi and flight mode. Searching for the most convenient control column for drive and flight mode, an M-shaped yoke is chosen as used in the Concorde. This control column can be seen in Figure 10.5.

Figure 10.5: An M-yoke

The M-shaped control column looks like a motorcycle steering wheel. The throttle and brakes are like a motorcycle and can easily be placed on the outer grips. When providing thrust, the throttle can be set in a position such that the driver can operate other systems during driving. A turning knob is placed at the right of the dashboard to shift between modes. In drive mode the DVC system is used and the control column is locked to for- and aftwards motion by locking/clamping the mechanism. For steering at low speeds the front wheel is controlled and at high speeds the tilting system is used (see Section 10.2.2). When turning the knob to taxi mode, the tilting system is disabled with the shut-off valve and the front wheel is used for steering. Right before take-off, the knob can be turned to flight mode and the normal steering is changed from front wheel steering, to aileron control and the control column can be moved for- and aft-wards to control the elevators. The control surfaces are controlled by fly-by-wire, this way a switch can be implemented in the wires to the control surfaces, so they can be dis- and enabled in the different modes. The screens with indication meters change with the turning of the shifting knob, to the preferred setting. On the left side of the steering wheel a trim tab is placed for easy trimming of the aircraft. Also the indication lights and the screen wipers have a button the wheel. For yaw, an automatic system is used to decrease the pilot workload. The system is the one used by Airbus on their newest models (A320, A330, A340, A350 and A380). In these aircraft they make use of a flight computer which ensures that the aircraft operates under the so called 'Airbus control laws'. These laws make sure that the aircraft does not create excessive forces during flight and stays controllable. In a simple analogy the control laws could be compared to a children's lock: manoeuvres are controlled and danger averted by the flight control system. The laws are split into three modes: Ground, Flight and Flare mode, each mode specifically designed to interpret steering inputs in the right manner for each situation. These modes, adjusted to the Volucrem design, are summarised in Table 10.3 Additionally protections are described relating to aversion of unsafe situations. For redundancy small rudder pedals will be available for the pilot.

Table 10.3: *Volucrem control laws [16]*

Ground Mode	*Active when Volucrem is on the ground. *Direct proportional relationship between the yoke deflection and deflection of the flight controls. *Is active until shortly after lift off. *After touchdown, ground mode is reactivated and resets the stabiliser trim to zero.
Flight mode	*Becomes active shortly after takeoff and remains active until shortly before touchdown. *Yoke deflection and load factor imposed on the aircraft are directly proportional, regardless of airspeed. *With yoke neutral and wings level, system maintains a 1 g load in pitch. *No requirement to change pitch trim for changes in airspeed, configuration, or bank up to 33 degrees. *At full aft/forward yoke deflection system maintains maximum load factor for flap position. *Yoke roll input commands a roll rate request. *Roll rate is independent of airspeed. *A given yoke deflection always results in the same roll rate response. *Turn coordination and yaw damping are computed by the ELACs (Elavator Aileron Computer) and transmitted to the FACs (Flight Augmention Computer). *No redundant rudder pedal feedback for the yaw damping and turn coordination functions. *Yaw will be controlled by the flight computer given the roll input for a coordinated turn.
Flare mode	*Transition to flare mode occurs at 5° RA during landing. *System memorises pitch attitude at 50° and begins to progressively reduce pitch, forcing pilot to flare the aircraft *In the event of a go-around, transition to flight mode occurs again at 50° RA.
Protections	Load factor limitation: *Prevents pilot from overstressing the aircraft even if full yoke deflections are applied. Attitude Protection: *Pitch limited from overstressing *These limits are indicated by green signs on the PFD. *Bank angles in excess of 33 deg require constant yoke input. *If input is released the aircraft returns to and maintains 33 deg of bank. High Angle of Attack Protection : *When α exceeds α_{prot}, elevator control switches to α protection mode in which angle of attack is proportional to yoke deflection. *α_{max} will not be exceeded even if the pilot applies full aft deflection High Speed Protection: *Prevents exceeding VMO or MMO (Maximum Operating Limit Speed) by introducing a pitch up load factor demand. *The pilot can NOT override the pitch up command.

10.4 Pressurisation

To ensure a comfortable environment for passenger and pilot during flight, the cabin will have to be pressurised due to the fact that cruise flight will be at 7000m, as is described in Section 7.1. The pressurisation systems include the compressor, the values and the sealing will be described in the following section.

10.4.1 Ambient and cabin pressure

The minimum pressure that most humans experience to be pleasant before hypoxia starts effecting them is at around 2500m of altitude. At this altitude the standard barometric pressure is approximately 76 kPa (11.01 psi) [17]. Now the aircraft will be in cruise flight at 7000m altitude, where the standard barometric pressure is 43 kPa (6.23psi). Therefore the differential pressure is 33 kPa (4.78 psi) [17], which needs to be coped with by the structure, valves and the compressor.

10.4.2 Compressor power

The compressor power is very much dependant on the amount of cabin leakage that occurs at cruise altitude. The cabin leakage is calculated using the rate of climb of the flying car, using the following formula: $w = \frac{V(\rho g)}{53.3T}\frac{dH}{d\tau}$ [18]. Here w is the leakage flow in lb/min, V is the volume in ft^3, T the outside temperature at cruise in Rankine and $\frac{dH}{d\tau}$ is the rate of climb in ft/min. The values for which the leakage was calculated can be found in Table 10.4.

Table 10.4: Values leakage formula

V [ft^3]	88.3
$\rho[\frac{lb}{\text{ft}^3}]$	0.037
$g[\frac{\text{ft}}{s^2}]$	32.174
T [Rankine]	546.48
$\frac{dH}{d\tau}[\frac{\text{ft}}{min}]$	500

The leakage flow was calculated to be equal to $1.8\frac{lb}{min}$ which is equivalent to $0.67\frac{m^3}{min}$ of air flowing out of the cabin due to leakage. Using statistics found in the SAE document on pressurisation [18] it was computed that leakage is approximately 31% of the power the compressor will have to be able to pump into the cabin. Therefore it was derived that the compressor should be able to cope with an inflow of $2.16\frac{m^3}{min}$ into the cabin.

To achieve this amount of power there are several ways of driving a compressor. These are listed below [18]:

- Direct bleed
- Bleed air drive
- Engine shaft drive
- Electric drive

The direct bleed method uses the compressed air made by the engine directly to pressurise the cabin. In conventional aircraft this is quite a simple system, but as the flying car will have a detachable flight module the compressed airstream will have more difficulty reaching the cabin. Furthermore turboprops have significant fuel penalties when using this system.

The bleed air drive method is based on bleed air driving a turbine which in turn drives a compressor. This method is usually used when the bleed air is not suitable for human intake. This system poses the same problem as the direct bleed method with respect to difficulty reaching the cabin.

The engine shaft drive method is based on the fact that an engine mechanically powers the compressor using its torque. In the flying car system this could be done using the car engine. There is one slight drawback in that the faster the engine turns, the faster the compressor will turn. Therefore for constant compressor air flow, the engine would have to be able to stay at the same speed at all times.

The electric drive method is based on an electric compressor which compresses the cabin, the electricity would have to be created by the car engine in the same method that is done for conventional car electronics. The drawback is that the compressor will take quite some power.

The car engine that is explained in Chapter 9 has a turbocharger capable of producing around $16\frac{m^3}{min}$. This was calculated using the following formula: $CFM = \frac{3.14(\text{turbocompressorwheelsize}/2)^2}{3}$ where CFM is the outflow of the compressor and stands for cubic feet per minute [19]. Instead of using the flight engine as would be done in conventional aircraft, it has been decided to use the turbocharger of the car engine to provide the bleed air for the pressurisation of the cabin as it has more then enough outflow to pressurise the cabin. In this scenario directing the bleed air to the cabin compressor is much easier then it would be coming from the flight module. It is furthermore more efficient and simpler than driving the compressor by means of the engine shaft or by electricity. The bleed air will have to be conditioned by putting it through the air conditioner before entering the cabin.

10.4.3 Valves

To control the pressure inside the cabin, the pressure is not regulated by the compressor but by different valves. The valves regulate the pressure mostly by letting the air exit the cabin during pressurisation, due to the fact that the compressors usually supply a constant inflow of air which is regulated to cope with the maximum leakage. The different valves that exist are the following [20]:

- Outflow valve. *Main controlling valve which makes sure that a constant cabin altitude pressure is maintained. In the case of the flying car this would mean a pressure of 76kPa and not higher. If this pressure is exceeded the valve automatically lets out the excess pressure.*
- Differential control valve. *Makes sure that the differential pressure, for which the fuselage is designed to cope with, is not exceeded. If this is exceeded the valve automatically lets air out of the cabin preventing structural damage.*
- Vacuum relief valve. *Prevents the outside pressure to exceed the cabin pressure, this is handy when descending back from cruise altitude. If outside pressure does exceed inside pressure, this valve automatically corrects this by letting the pressure in.*
- Dump valve. *Directly controlled by the pilot, on use this valve dumps all cabin pressure.*

All these valves will be incorporated in the cabin pressurisation design, to ensure maximum safety and comfort.

10.4.4 Sealing

Another important aspect when pressurising an aircraft cabin is the cabin sealing. There are three main components that have to be sealed to ensure minimum leakage: the door, the fuselage and the cables and rods. The door is the aircraft part that comprises of the biggest movable section that needs to be sealed. In commercial aircraft plug doors are most often used, these are doors which open towards the inside and are kept in place during flight due to the pressure difference. As the cabin of the flying car is too small for such a system, an alternative was sought. By using hollow seals with openings towards the inside of the cabin, it is possible to inflate the seals using the cabin pressure causing them to expand against the cabin door. This system then supplies a (near) airtight sealing[21]. For the sealing of the fuselage, the same system is used as found in commercial aircraft. First, the skins and the formers are securely fastened in to place, after which holes are drilled. Next, the skins are removed and a sealer is applied to the formers, over which the skins are then refitted. Bolting and riveting the two together before the sealant dries up leads to an airtight assembly[21]. The cables and rods are perhaps the most leakage prone parts to seal, for this so called labyrinth seals are applied [21]. Labyrinth seals are seals which make air movement difficult using complex paths consisting of groves and teeth, limiting the escape of pressured air from the cabin [22].

10.5 Electronic systems

Modern cars consist of more electronic parts than others, and take care of passenger comfort, driver assistance, sustainability and so much more. In the Volucrem these systems can be split up in the flight systems, which are mainly the avionics, and the car systems, of which a lot are also used in flight.

10.5.1 Avionics

For the avionics system in the flying car, a research was performed on modern, compact glass cockpits. In the Midterm Report [12] a system like the Garmin G3X was proposed as the final system. This system is very elaborate, compact and of high quality, however, it appeared to be incompatible with turbine engines. Since a turboprop engine is chosen for the Volucrem in Chapter 15.1, the Garmin G3X is not suitable for the product.

One of the most important issues for the choice of the avionics system, is that it has to be modular, such that a solution can be found for the car cockpit system as well. The displays that are used during flight should also be used during driving, or the system should be modular as such that the displays during flight replace the ones during driving and vice versa, using some sort of a mechanical system. Since the first option would be the more compact and more lightweight solution, this was investigated first. If it is proven that this solution is not feasible, a research would be done on the changing of displays.

10.5.1.1 Electronic flight instrument system

The electronic flight instrument system (EFIS) is the complete avionics system in a glass cockpit, in which everything is electronic and digitally displayed. It consists of a primary flight display (PFD) and the multi-function display (MFD) [23]. The first one shows all flight critical data that are necessary for flight, including calibrated airspeed, altitude, heading, attitude, vertical speed and yaw. The MFD shows information about aircraft systems, such as fuel and electrical systems, and gives more information that can help the pilot with his job, such as navigation, weather information etc. [24] . The PFD will provide:

- altitude
- airspeed
- attitude
- vertical speed
- heading
- rate-of-turn
- slip-and-skid
- navigation
- transponder
- ...

While the MFD provides other data, such as:

- engine instrumentation
- moving maps
- satellite wheather
- checklists
- system information
- waypoint information
- weather sensor data
- traffic awareness information
- entertainment systems
- ...

Using two screens in the cockpit gives the benefit of redundancy: if one of the two screens fail, the other one can enter a 'breakdown mode' in which it shows all the primary flight information, and also some information that is wanted from the MFD.

Since this system will preferably also be used in driving mode, at least one of the two displays should be touchscreen for a modern interface (see Section 10.5.2 for more information). Both displays being touchscreen is not favourable since a touchscreen is very hard to operate when flying with turbulence. Hence, it is chosen to have the PFD as a normal screen, while the MFD will be a touchscreen. Both screens should be able to be connected to two different computers, the flight computer and the car computer, such that in each mode the right input can be given.

Having only the displays in the EFIS is not enough: a flight computer and some sensor systems are needed to provide and compute all the information and programs needed that will be shown on these displays. An air data and attitude and heading reference system (ADAHRS) is needed, which exists of solid-state sensors to measure the airspeed, altitude, vertical speed, outside air temperature, attitude, rate of turn and slip and skid [24]. A magnetometer is used as a digital version of a traditional compass and the engine sensor kit should give all turbine engine parameters which are [25] :

- oil pressure
- exhaust gas temperature (EGT)
- turbine inlet temperature (TIT)
- engine pressure ratio (EPR)
- fuel quantity
- fuel pressure, fuel flow
- tachometer
- torquemeter

Barco offers the MOSArt sophisticated system that provides displays and an air computer, which is fully certified and widely used [26]. The beauty of this product is that the displays have multiple connection options, that the customer can develop internally proprietary and closed applications without any involvement from Barco [27] and that it is compatible with multiple other systems. As this vehicle will be one of a kind, it is important that every system can be custom made for this product, and so a product like the Barco MOSArt offers a lot of possibilities for customizing. By 2025, this product will probably be outdated, and a lot less expensive since the costs for a system of two displays, a flight computer and a navigation system will give a cost of around 50.000 to 75.000 euros. It is assumed that in 2025 this will be a lot less and that for buying 500 of these systems, the costs will drop to approximately 30.000 euros. In the cost estimation in Chapter 26 75.000 euros is used as an indication for the complete avionics system, including the ADAHRS, engine sensor kit, etc.

The Barco system is used as an indication for location, space and layout with the PU-2000 as flight computer and the FDU-2109 as displays. Cobham offers separate instrument systems such as the ADAHRS with magnetometer and outside air temperature probe [28]. This system is also used as an indication for the dimensions in the cockpit.

10.5.1.2 Autopilot

To reduce the pilot's workload in order to give him more time to relax, to perform some phone calls or read his e-mails, an autopilot system is implemented in the car. The autopilot will work on a three-axis basis, controlling the ailerons for roll and the elevator for pitch, as is done in most autopilot systems, but now without the rudder for yaw. In Section 10.3 the different modes for this yaw control are explained. This system is implemented in the flight computer, which computes controlled turns using all three axis. Hence, the pilot does not need rudder pedals, but they are implemented for redundancy.

10.5.1.3 Communication system

The aircraft does not only need the instrument systems, but it also needs a communication system with which the outside world can be contacted. The aircraft should possess an aircraft communications addressing and reporting system (ACARS), with which it can exchange data messages via a network of automated ground stations. A Very High Frequency (VHF) Digital Link Mode 2 (VDL-2) should be on board as well, for air traffic control communications [29] and air-to-air communication between aircraft [25] .

Cobham does not only provide a good ADAHRS, but it has very high quality communication systems as well. The VHF Communication System - CVC-151 is a transceiver that provides both requirements, using the VHF COM Control Display - CVC-152 as the interface for the pilot [30]. Again, this system is used as an indication for the systems specifications. It also has a connection for the pilot's headset, which consists of a small band with in-ear headphones and a small microphone.

10.5.1.4 Backup system

To ensure a safe flight, a backup avionics system needs to be included in the cockpit in case something goes wrong with the main displays such as a loss of power. In general aviation, a standard and analog backup system is used called the integrated standby instrument system (ISIS) [31]. It combines the functions of an altimeter, an airspeed indicator, an attitude indicator and a magnetic compass. However, the maintenance of this mechanical instrument is of very high cost compared to a digital version, and a digital instrument is more reliable. One additional important matter for choosing a digital system over a mechanical one, is the panel space. Since the space in the cockpit is very limited, you want the backup system to take as little place as possible, and an ISIS takes a lot of place. Nowadays, it becomes more common to use a digital backup system, and a lot of manufactures offer different solutions [32]. For these digital backups, also a backup power system should be provided. A built-in battery is often used by these systems.

The company 'Innovative Solutions & Support' has developed the Integrated Standby Unit (ISU), which is a small standby system with its own battery, that includes an accelerometer, a gyro and a magnetometer. It shows the altitude, airspeed, Mach number and Slip/Skid. It also has a standby radio management unit (RMU). The ISU uses a PFD format to enhance situational awareness and reduce pilot workload [33]. Also this system is used as an indication. All the indication systems specifications are listed in Table 10.5 .

Table 10.5: Specifications of indication avionics systems

Part	**PU-2000**	**FDU-2108**	**ISU**
nr. of parts used	1	2	1
Weight [kg]	4,50	2,10	0,86
Size w x h x d [mm]	193,5 x 235,2 x 222,5	254 x 203,2 x 101,6	82,6 x 109, x 129,5
Power supply [V DC]	28	28	28
Power consumption [W]	60	55	9,8
Resistant to	20g	20g	-
Operable up to altitude [m]	15.240	13.716	-
Part	**ADAHRS + MSU + OAT**	**Comm display CVC-152**	**Comm system CVC-151**
nr. of parts used	1	1	1
Weight [kg]	0,68	0,35	1,70
Size w x h x d [mm]	50,8 x 63,5 x 99,1	63,5 x 80,01 x 108,97	60,96 x 101,6 x 328,83
Power supply [V DC]	14 to 28	5 & 28	28
Power consumption [W]	-	280 mA	0,5
Resistant to	10g	-	-
Operable up to altitude [m]	>15.100	-	-

10.5.2 Car electronic systems

As the final product should be a modern, luxurious flying car, suited for business men with tight schedules used to efficiency and luxury, a lot of electronic systems are involved. This chapter gives a summary of all electronic systems in the car, what components they are made of and how they are connected with respect to each other.

10.5.2.1 Basic electronic system

Each electronic system exists of three main components: the sensors which take care of the inputs that are necessary for every system, the microprocessor which gathers all data from the sensors and computes the outputs that are sent to the actuators, which perform the eventual task. Now in a modern car, a lot of these systems can be found, which means that if every system has its own sensors, microprocessor and actuators, a lot of weight is added to the car. To avoid this, several sensors and actuators are used for multiple systems. Important actuators are the two displays that are for flight, that will be used for driving as well. Instead of using one microprocessor for each subsystem, a few microprocessors are incorporated that can process all inputs and outputs for several systems. Some systems are incorporated to replace heavy mechanical systems, such that weight is saved.

The different electronic systems can be divided in different categories. These are the engine electronics, chassis electronics, safety systems, driver assistance, passenger comfort, sustainability and infotainment systems. Some systems belong to several of these categories. An overview of all systems with their sensors, actuators and way of data communication can be found in Table F.1 in Appendix F. There you can find the electonic block diagrams as well. There are more safety systems than just the electronic safety systems. These are discussed in Chapter 12. Lighting is discussed as a separate system, since it is used for multiple other systems.

10.5.2.2 Engine electronics

Most of the engine systems are developed such that the engine works more efficiently and therefore uses less fuel. This means that all engine electronic systems also fall into the category sustainability.

Engine control module The ECM basically determines where to set the throttle, how much fuel to inject into the cylinders, and when to fire the spark plugs, such that the motor works as efficient as possible [34]. As can be seen in Table F.1 , this is a very extensive system using a big number of sensors and actuators. Therefore, this system is the most powerful system in the car, employing the most powerful microprocessor.

Electronic valve timing control EVC optimises the valve timing, that allows fuel-mixture in and exhaust gasses out of the cylinder, for all speeds of the car, such that the engine performance and efficiency is optimised. For this to work, electro-hydraulic valves (EHV) will be used, as is done in all new BMW cars [34].

Electronic throttle control ETC is the replacement of the traditional mechanical system that connected the accelerator pedal with the engine. Nowadays, this system is electronic, such that is easily connected to the engine control module. What is also very important for the design of the Volucrem, is that this also is a more lightweight solution [34].

10.5.2.3 Chassis electronics

Chassis electronic systems are mostly implemented for an easier, more efficient and safer ride. So they also belong to the driver assistance and safety systems.

Anti-lock braking system ABS prevents slipping and skidding by wheel lockup by modulating the braking pressure. It is closely related to the electronic stability control and traction control systems, to provide a fully stable and safe ride [34]. For the Volucrem, a three channel, thre sensor ABS is used for maximum braking force, controlling each wheel individually.

Electronic stability control system The ESC system improves the handling performance of the vehicle and prevents possible accidents during severe manoeuvres. By individually putting a braking force on each wheel, the car is stabilised using a yaw moment and the sideslip angle is regulated based on a comparison between the car's state and the driver's demand [34] .

10.5.2.4 Safety electronics

Some of the safety systems are not only just for safety, but driving would probably not be possible without them. Not all of them are for a safe drive, but also for keeping your car save from theft, so the car security system is categorised as safety electronics as well.

Windshield wipers The wipers take care of the driver's view during rainy days, such that he can drive safely in all weather conditions. These wipers can be switched on manually by a switch, or a rain sensor can activate them.

Tire pressure monitoring system This is a mandatory system on all US and European cars. It measures the tire pressure and internal temperature and warns the driver when there is a leakage or if it is under-inflated. This way, failure in the form of a blowout is prevented [34].

Pre-crash safety Since the vehicle is not designed for being a car and having the same safe structure, it can use extra safety systems. One of these systems is the precrash safety system. It warns the driver of a possible crash ahead and takes various actions, trying to keep the driver and passengers safe during the crash if the driver does not react on time [34]. This means that it will pull up the slack in seat belts and increases the brake pressure for better braking performance.

Airbag deployment This is a common system found in cars, also implemented in the Volucrem, which is used when a crash happens. An elaborate explanation of this system can be found in Chapter 12.

Security systems These systems are used for preventing theft and vandalism of the car. When the car is touched roughly, a door or windows opened without the key, the car will use its horn and indicator lights to draw attention. These are the warning devices. An immobiliser is present as well, that disables the fuel and steering such that it cannot get away, and using the GPS of the navigation system, there is a vehicle tracking system [34] .

10.5.2.5 Driver assistance

Driver assistance systems make the driver's life easier, but they also make the ride more safe, monitoring vehicles ahead and keeping the vehicle on track. This means that most of these systems also fall under the category of safety systems.

Adaptive cruise control An ACC system does not only allow you to set a certain speed at which you drive constantly or which is your maximum speed, it also monitors the distance between the car and the vehicle ahead using a headway sensor and makes you keep a safe distance by automatically braking [34].

Dedicated short range communications DSRC is a data-only communication protocol, in two broad categories: vehicle-to-vehicle (V2V) communication, and vehicle-to-infrastructure (V2I) communication. This includes electronic toll collection, intersection collision avoidance, electronic parking payments etc. [34]. As can be seen this is a very multifunctional system that is not only in the category of driving assistance, but also in safety and passenger comfort.

Instrument cluster This system provides the basic information that a driver needs during the ride: vehicle speed, fuel level and status of various vehicular systems [34]. This information will be visualized on a display which acts as the PFD during flight mode. More information about this can be found in Section 10.5.1.

Lane keeping assist This system steers the car back when drifting out of its lane due to heedless driving. It uses the cars brakes and applies a torque to the steering column to do that [34].

Rear-view camera With a camera mounted on the rear of car, it is easier to park the car and not touch anything in the back. The driver can look at the display in the dashboard when parking.

10.5.2.6 Passenger comfort

These systems are purely for the drivers and passengers comfort. They do not add anything to the other system categories

Active cabin noise suppression Driving gives a lot of noise, outside of the vehicle as well as in the cabin. To make the ride more comfortable, a noise cancellation system is implemented in the car. Integrated speakers will make 'contra noise', cancelling out the noise of the engine and the tires, such that the passenger can enjoy the music from the entertainment system, or can have Bluetooth phone calls without any problems [34] .

Remote keyless entry The car needs to be able to get unlocked by using a button on the key. For that, a radio frequency system is used for the communication between the car key and the door and trunk latches [34].

Cabin environment control Riding the Volucrem should be as comfortable as possible. This also includes being able to ride with a comfortable temperature. On a cold winter day the system should be able to heat the car (including heated seats), on a hot summer day the car should be cooled. For extra comfort, there is scent-enhanced air-conditioning. Heating the car does however bring the problem of a fogged windshield, which is solved by knobs present in the dashboard for defogging [34]. The system is connected to the displays used in the avionics system, such that the driver can give his preferences.

Seat position control In order to easily adjust the position of the driver seat, an electronic seat control system is implemented [34]. This not only makes it able to position your seat such that the ride is most comfortable, it can also save the preferences in the driver's Volucrem, such that when it is driven by another person, with one push on the button the seat adjusts to your own preferences again.

10.5.2.7 Infotainment systems

These systems are a combination of the entertainment systems and navigation systems. As they provide more information for the driver, they can also be categorised as driver assistance systems, and as the entertainment system is purely for luxury, it can also be categorised as a passenger comfort system.

Navigation A navigation system is almost essential in the design of a new car. It takes the driver wherever he needs to go, is always up to date, warns the driver in case of upcoming traffic jams and computes alternative routes in order to minimise the travel time [34] . The system will use the displays that are used for the avionics as well.

Communication system Having a communication system in the car is again very essential, especially for the type of customer this product will be designed for. Business men that have a busy life need to be able to make phone calls all the time, wherever they are. However, the communication system is also used in case of emergencies, with automatic crash response, emergency services etc [34].

Entertainment system A luxurious vehicle needs an entertainment system. The most important part of this system is the audio for listening music in the car. A high quality surround sound system is implemented, and music can be chosen from an uploaded list in the computer, displayed on one of the two avionics screens, or the driver's phone can be put in a docking station, which supplies power to the phone, such that music that is stored on this phone can be played as well. Next to this, in-car and in-flight wifi is provided such that it is always possible to check e-mails, read the news, visit websites etc [35] [36] . Again, the displays of the avionics systems will be used as the entertainment interface.

10.5.2.8 Sustainability systems

Sustainability is an important part in the design of a new, modern car. Section 27 discusses all the steps taken for a sustainable approach, this section simply discusses the electrical systems that are implemented because of these steps.

Regenerative braking To reduce the engine load and thus the fuel consumption and CO_2-emissions, regenerative braking is used to recapture some of the vehicle's kinetic energy when the brakes are applied. For a non-electric vehicle as the Volucrem a clutch is added to the alternator, which helps the engine slow down as it charges the battery [34] .

Idle stop-start This systems turns off the engine when stopping at a stop light or during stop and go traffic, such that the CO_2-emissions are decreased. This is a very efficient, low cost method for decreasing the fuel consumption with almost 3.5% [34].

On-board diagnostic systems This system is a mandatory system that refers to a vehicle's built-in capability to monitor its own vital functions and record/report that information to the vehicle operator or repair technician [34] . The integrated OBD-II system has a standard diagnostic connector such that most technicians can access the information stored. The driver is informed that something is wrong with his engine through his 'check engine light' displayed on the dashboard, then using a scanner the technician can find out what is wrong exactly. As the OBD-II system checks the entire engine, oil system, watercoolant etcetera a lot of sensors are used as can be seen in Table F.1 .

10.5.2.9 Lighting

Standard on a motorcycle, you can find a main and a low headlight, a rear headlight, four indicators, a brake light, a license plate light and a parking light [12]. Since the flying car will not be a motorcycle but an enclosed three-wheeled carver-type of car, a centre high mount stop lamp (CHMSL) is needed as well, and two front and rear headlights are used instead of one. Since the car will be able to drive into reverse, which a motorcycle is not able to do, two reverse lights will be added. Furthermore, interior lightning is needed as well. One dome light will be used to light the entire car when opening the door, and some additional lights are a map light above the dashboard, dashboard lights to light up the most important buttons and meters that are used during the ride, and a glove box light.

A research was performed on the type of lights that will be used. For most of the lights LEDS (Light Emitting Diodes) will be used, because they proved to be the most efficient, least power consuming, most durable and have the longest range compared to all other convenient light bulbs [34] . However, for the headlights, BMW has developed a Laser headlight that is almost 30% more efficient than the LEDs, has twice the range, and half the energy consumption [37] . This Laser headlight will find its first use in a car in the summer of 2014, so the assumption is made that this technology will be widely used in 2025. Therefore, the choice is made to use a Laser headlight for the car.

10.5.3 Car conversion

The systems mentioned in the previous section are used in a roadable vehicle, but the Volucrem is also going to fly. There needs to be a conversion between driving mode and flight mode. This conversion mainly includes switching from the car computer to the flight computer. However, a lot of the systems used in the car are also used during flight, such as the climate control, the entertainment and communication system, the engine electronics since the engine powers the pressurisation system during flight, the windshield wipers and the tire pressure monitoring system. A solution is found such that these systems can still work during flight.

The car computer is not one computer as is the flight computer that gathers all data necessary. It consists of multiple microprocessors that via a CAN bus data communication system is connected to the sensors and the actuators. This system is then connected to the displays of the avionics and is always active. During drive mode, the PFD shows the speedometer, the tachometer and the instrument cluster with all the warning and control lights such as [38]:

- Turn signal control lights
- Alternator indicator light
- Brake fluid warning light
- Door open warning light
- Odometer (total kilometres counter)
- Trip odometer (trip-kilometres counter)
- Fuel gauge
- Oil pressure gauge
- Cooling fluid warning light
- High-beam control light
- Engine warning light

The MFD is used for all other systems in the car that need a display with touchscreen: the entertainment system, the cabin environment control, the navigation, the communication system and the seat position control.

During driving mode, the flight computer is not active and does not interfere with the system. On the MFD the application for flight is non-active, meaning you cannot access it. When switching to flight mode, this application is activated and takes over the main screen. During flight, you can go back to the other applications as well. The flight computer then completely takes over the PFD, substituting the car's main gauges by the aircraft's main instruments. Both the car computer and the flight computer are always connected to the displays, such that no further conversion or attaching is needed in order to minimise the conversion time. The conversion from car to flight mode is done using the knob described in Section 10.7. In drive, neutral, park and reverse, the flight system is not active. When switched to taxi or flight mode, the flight computer is activated.

10.5.4 Battery and alternator

Different subsystems of the vehicle need energy to perform. This energy must come from the battery which is charged by the engine through an alternator. To choose the right battery the power needed by the subsystems need to be defined. When looking at the fuel pump, it is found that two separate batteries are needed. This is one battery for the main fuel pump and a separate battery for the emergency pump [39]. The power needed per fuel pump is approximate 48W. Other subsystems which need power from the battery are the avionics (200W) and all car electronics (850W). This gives a total power needed from the battery of 1098W. The battery which can generate this amount of power is the Duralast CB14L-A2FP [40]. This battery weighs 3.4kg and the dimensions are 166x134x89mm. A battery of this sort can be used in the design. The extra battery which is only needed for the emergency fuel pump will be like the Antigravity Battery AG802 6VOL. This battery has a weight of 0.7kg and the dimensions are 110x57x95mm [41]. With a car battery also an alternator is needed to charge the battery and to power the electrical systems when the engine is running. The alternator used is going to be like the Duralast Alternator 12857. This alternator has a weight of 6.77kg with a diameter of 118mm [42].

10.6 Systems and luggage allocation

The fuel tanks are located in the rear part of the carver. This design choice has been carried out in order to reduce the risk of fire and or explosion in case of frontal collision.

The engine of the carver will be located in its rear part. The main reasons for this choice are:

- Enough space behind the passenger seat
- Lower weight of the mechanical transmission from the engine to the rear wheels due to their proximity
- Lower weight of the fuel system due to the proximity between the engine and the fuel tank

The reserve battery has been located in the front part of the carver. However, the main battery has been placed inside the roll cage at the back of the carver.

The electronic systems are placed all over the car, but since these are mostly very small sensors and microprocessors, they can be placed anywhere is needed while not influencing the location of the centre of gravity. In the dashboard the displays and knobs and switches are found, as are most other actuators. A lot of the actuators are implemented in other systems such as the engine. The avionics systems do however take more space and are implemented in the front of the car

The figure below depicts the exact location of the engine, fuel tank, main and reserve battery and the hand luggage:

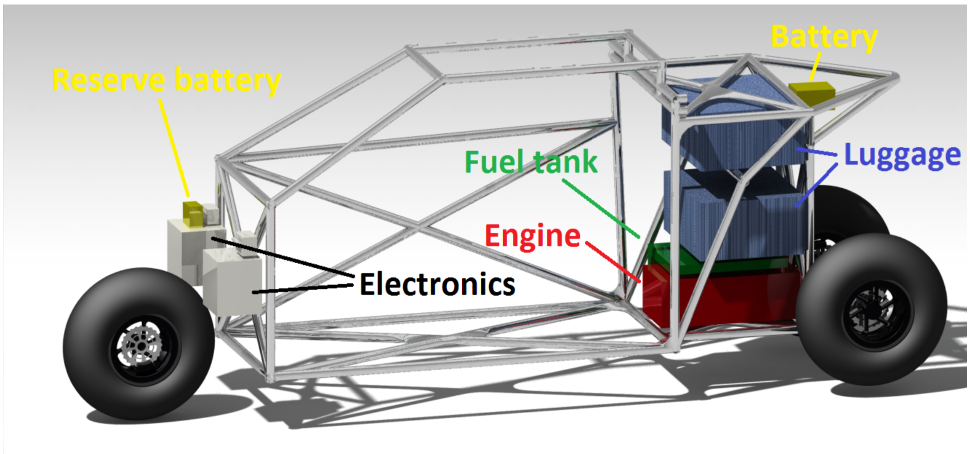

Figure 10.6: Location of the batteries, hand luggage, fuel tank, engine and electronics

10.7 Cockpit/dashboard layout

Knowing all essential parts needed for the driver, the layout of the cockpit/dashboard could be determined. This layout can be viewed in Figure 10.7. In the figure it can be seen that two big screens are used for the indication meters. The left screen is a normal screen with the meters and the right screen is a touchscreen which has various purposes as mentioned in Section 10.5. Most of the flight systems are placed on the left side of the dashboard and the car systems on the right side. The flight systems on the left side are the back-up meters in case there is something wrong with the big screens, the communication system, the landing gear/suspension settings, the flap deployment and the handle for the deployment of the ballistic parachute. On the right side of the dashboard is the red button to activate all indication lights for warning other drivers, the power button to turn on all car systems, a shift for the flight and drive lights, a cigarette lighter/power outlet, a CD slot, a cup holder, a mobile phone holder and the shifting wheel for the different modes (park, neutral, drive, reverse, taxi and flight). There are also two ventilation vents on both sides and right of the M-yoke is the optional placement of the throttle of the flight engine if not implemented in the yoke, which is an option that can be chosen by the customer.

Figure 10.7: Layout of the cockpit/dashboard (not to scale)

Chapter 11: Ground mobility

In order to provide ground mobility and the capability to land, landing gear is required. This function could either be fulfilled by the same wheels that provide ground mobility for the vehicle as well as by a separate system only used for flying. It was selected that the wheels used for driving will also perform the landing capabilities. From the design so far, a few parameters important for the landing gear were attained. These are given in Table 11.1.

Table 11.1: Important parameters for the landing gear design

Parameter	Value	Unit
x_m	0.66	[m]
x_n	2.4	[m]
X_{cg}/MAC	0.25	[-]
H_{cg}	0.75	[m]
X_{LEMAC}	2.7	[m]
W/S	904.4	[N/m^2]
MTOW	1213.25	[kg]

With these parameters, the design process can be started. First of all, the selected tires will be described. Next, the brakes and the shock dampers will be discussed. Finally, a check was performed and some takeoff calculations were performed.

11.1 Tire selection

For the selection of the tires to be used on the vehicle, an investigation into the loads during flight was performed. The loads experienced by each tire are described in Table 11.2. A safety factor of 1.25 to allow for aircraft weight growth is taken into account here. For the dynamic loads, an anti-skid braking system was assumed.

Table 11.2: Tire loads

Load	[N]	[lbf]
Main gear static	6759	1520
Nose gear static	2675	601
Nose gear dynamic	3878	872

The critical speed for the tire will be during driving. The tire is rated for speeds over 250 kilometers per hour. This is sufficient for both driving and flight operations. Next to this, the tire pressure has also been investigated. Normal tricycle configurations use a highly inflated front tire (±35 psi) and a lower tire pressure (±25 psi) in the back [43]. This is to prevent so called ”head shake phenomena” and to improve riding qualities. Aircraft tires however use higher pressures; the nose gear tire is often pressurised up to 50 psi and the main gear around 35 psi. Since this is a requirement for the flight part of the operations, aircraft tires will be used on the vehicle. To prevent thermal expansion and contraction during flight, the tires should be filled with nitrogen.

With these requirements and the desires for the driving system, the final tires could be selected. These will be similar to Goodyear Aviation Flight Custom III tires size 8.50-10. These tires are capable of carrying far higher loads than the aircraft would normally encounter during landing. This is due to the size of the tires. Relatively larger tires than normally used on general aviation aircraft of this size were however required to improve the driving properties. Besides this, the Goodyear Flight Custom III tires are known for their durability, traction and relatively low rolling drag [44].

11.2 Braking

The combination needs to have brakes in order to correctly decelerate. This is required for both the flight part of the mission and the driving part. Motorcycle requirements stipulate that there should be brakes on all three tires with sufficient strength [45]. Next to this, the European Union recently decided that all motorcycles should have an anti-skid braking system per 2016 [46]. This must therefore be incorporated in the design. The braking regulations for three-wheeled motor vehicles also state that a deceleration of at least 4.5 m/s^2 should be achieved. On motorcycles, stronger brakes are often used to allow for better handling. The airworthiness requirements do not specify the required deceleration, this is determined by the landing distance. A quick back of the envelope calculation proves that for a landing speed of 80 knots, the motorcycle requirement would provide enough deceleration to stop within 275 meters. This is well within the requirements so the motorcycle brakes are enough to be used by the aircraft as well.

For comfort a combined braking system will be installed. This is due to the fact that the tricycle configuration will need brakes both on the front and the rear wheel. It is more comfortable when driving if there is no need to brake the front and back wheels separately since this feels more like a car. Disc brakes will be used, as these have the highest braking capabilities.

11.3 Shock damping

For passenger comfort and for correct load transfer during landing, shock dampers will be used in the system. These shock dampers will also prove useful for driving as they can be used to absorb bumps in the road. Since a tricycle configuration is used, the main gear will carry the largest part of the loads during landing. The nose gear will also have to deal with dynamic loads. In this set-up of the car, the nose gear will have a vertical oleo-pneumatic shock damper to deal with the loads. For the rear tires a swingarm will be used as is common on motorcycles for rear tire suspension. This however means that a longer shock absorber has to be used as the loads are relatively larger due to the shorter arm of the shock damper compared to the tire to the hinge. The oleo-pneumatic shock absorber itself will be mounted vertically on the swingarm so that it can be attached on the roll cage which is reinforced there for the attachment system. Incorporating these design considerations gave sizes for the shock absorber, given in Table 11.3. The sizing method described in reference [47] was used to determine these values.

Table 11.3: Shock damper sizes

Length	[cm]
Nose shock absorber stroke	13.2
Nose shock absorber diameter	6.3
Nose tire deflection	4.1
Main shock absorber stroke	16.8
Main shock absorber diameter	4.4
Main tire deflection	4.1
Swingarm length	73
Shock absorber location on swingarm	64

As mentioned before, the tires are rather heavily inflated for driving comfort. This is felt by the occupants when a bump in the road appears. This is not an issue for aircraft since the tarmac on airports is often well-maintained and flat. For this reason the shock damping system shall have a variable damping system. This is a relatively common system on cars and motorcycles. Since oleo-pneumatic shock dampers will be used, a bleed valve can be installed that allows a part of the oil to bypass the damper so that the damping is lighter. Another advantage of this system is that the wheels can be "retracted" and "extended" with this bleed valve by letting some of the oil in the system. In this way, the distance from the ground to the bottom of the vehicle can be varied during driving for more sportive behaviour and during flight the wheels can be retracted in the wheel wells to prevent drag. During landing the wheels should be fully extended to provide the maximum shock absorber stroke. Therefore, the shock dampers should have at least three settings: flight (fully retracted), driving (approximately halfway extended) and landing (fully extended). These modes will also be used when attaching the flight module to the vehicle, as you can see in Chapter 21.

11.4 Final check

Now that most of the parameters of the landing gear are known, a final check can be made whether the design fulfils the requirements. First of all, there is no risk of spray ingestion by the engine since it is above the vehicle. Next to this, in the current design the propeller has enough ground clearance. The final design provided a tail strike angle of 20.9deg. This is sufficient to account for the angled approach during landing. The range of centre of gravity locations which comes from the loading diagrams (Figure 17.3) was investigated as well. For all possibilities there is no tip-over risk. This means that all geometric clearances are met.

The rotation speed was also investigated. This was done using Equation 11.1. The equation gives the load on the nose gear (R_N) as a result of the forces and moments balance in the vehicle around the nose wheel. This analysis was done for a range of velocities and the resultant lift by the wing and tail and the thrust of the propeller. This resulted in a rotation speed of 36 m/s. In order to achieve this rotation speed, the horizontal tail had to be resized. The size based upon stability was not sufficient to provide the negative lift required for rotation. The new tail surface area will therefore be 2.5 m^2.

$$R_N = \frac{T * y_T + (W + L_H - L) * (x_M - \mu * H_{cg}) + L * x_W - L_h * x_{HT} - M_W}{x_N + x_M - 2\mu * H_{CG}} \quad (11.1)$$

Chapter 12: Safety systems

In case of accident, various systems are needed to provide the highest protection for the passengers. These are safety systems and items used in flight and on the road. One large safety system of the road vehicle is the roll cage, which is described in Section 8.1. Other safety systems and items which are obligatory need to be identified and the size and weight determined for the placement inside the vehicle.

When flying over water, a life jacket is obligatory by the flight regulations. This doesn't have to be the large life jackets used on a boat, but normal floating devices. The life jackets used in most aircraft systems are in small packages which fit under a seat and are inflatable. These life jackets are also the ones used in the design. The dimensions of such a life jacket uninflated are 100x200x65mm and its mass is 454g [48].

In most aircraft, oxygen masks can be found. When looking at the FAA certification it was found that aircraft flying below flight level 250 do not need oxygen masks [49]. The cruise altitude of the flying carver is 7000m. When the pressurisation system fails, the pilot can descend fast enough from this altitude to an altitude of 2500m were the oxygen level is high enough for normal breathing. Thus an oxygen mask in the roadable aircraft is not obligatory and therefore not implemented in the vehicle.

When the vehicle has an accident and the doors cannot be opened, a life hammer is needed to smash the windows. The common dimensions of a life hammer are 20.3x7.6x5.1cm with a mass of 181g [50]. The life hammer can easily be placed at a favourable position within reach of the driver.

If the road vehicle fails, it has to be placed at the side of the road with a safety triangle placed at 30m from the road vehicle. This safety triangle has a size of 41x41x25cm, but can be folded to a small package and when making of plastic, is very light weight [51].

In case of fire, a fire extinguisher is necessary. For this reason, a small fire extinguisher will be placed inside the vehicle. The dimensions of a car fire extinguisher are 27.9x10.4x8.9cm with a mass of 1kg [52].

With respect to visibility lights, for the road module a white light in the front is required. This light must have different brightness orders (fog, short and high beams). Furthermore, orange turning lights are needed at the front, the back and both sides of the ground module. At the rear of the car, normal red lights are mandatory as well as a red braking light and red parking light. A small light to lit the registration plate is also required. Lighting for flight on the wings is described in Section 16.7.

Other small safety items needed are seat belts, head restrains, padded surfaces (dashboard, roof, inside frame), a rear camera (for safe parking and ground procedures with the flight module), side mirrors, wind shield wipers, safety glass, safety vests and a first aid kit. The first aid kit can be bought in various weights and sizes. A small first aid kit with some basic products has a mass of 140 grammes with dimensions 17x12x4cm.

The number of doors and the use of an emergency hatch were considered. First, CS-23 regulations were studied. This regulations state that "Each closed cabin with passenger accommodations must have at least one adequate and easily accessible external door" [3]. The vehicle has only one closed accommodation so one door can be used from were the front and rear seat can be accessed (the rear seat potential when folding the front seat). When looking at road regulations there are little requirements for the doors. Looking at reference vehicles like the carver one, it can be seen that one door is sufficient. In case of emergency, the front passenger can use the life hammer to smash the windows and the back passenger can fold the seat to have access to the outside. If however, the driver is unconscious, the back passenger cannot fold the seat. This is why an emergency hatch is located at the roof of the car.

One of the most important safety systems in a car is the airbag. The airbag system consists of an electronic control unit (ECU), an electronic front and side impact sensor as well as the airbag itself. The overview of the airbag system in a normal car can be viewed in Figure 12.1. The electronic sensors detect the collision and send a signal to the electronic control unit. This unit determines the severity of the collision and gives the optimal deployment of the airbags [53]. The size of an electronic control unit is 90x50x34mm with a mass of 100g [54]. The size on the electronic front sensor is 6.6x5.1x3.8cm with a mass of 45g [55]. Finally, the size of the side impact sensor is 8.6x7x2.8cm with a mass of 48g [56].

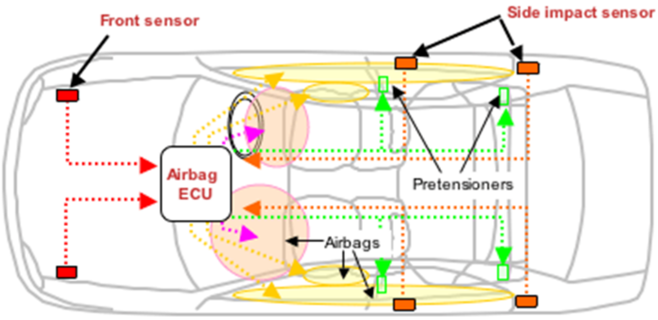

Figure 12.1: Airbag system in a normal car [53]

Ballistic parachute

In case of emergency during flight. A ballistic parachute is employed. A well known company which produces ballistic parachutes is Ballistic Recovery Systems (BRS). A ballistic recovery system contains a parachute, a rocket that ensures a fast extension of the parachute and an activation mechanism which triggers the ignition of the rocket.

There are different types of systems which can be placed inside the aircraft. These systems are the canister, the soft pack and the VLS. They can be seen in Figure 12.2. For the canister, the parachute is folded into a sleeve. This sleeve is put into a plastic liner with the hydraulic assistance placed in a steel jig. This is put into an aluminium can, closed at one end and sealed with a plastic cap at the other end. The system is sealed, so it can be mounted on the outside of the vehicle. However, it is heavier then a soft pack. In the soft pack, the parachute is folded in a fabric container. The soft packs are not weather resistant and can be placed inside the vehicle easier. It is however the lightest system to use. The VLS (Vertical Launch System) is a light weight soft pack sealed within a climate resistance container. It has a low profile and can be placed externally. The VLS can only be mounted horizontally while it fires the chute vertically. It is best when the parachute is located directly in the airflow over the aircraft wings. [57]

Figure 12.2: Ballistic parachute systems from left to right: the canister, the soft pack and the VLS [57]

One big ballistic parachute is chosen to decelerate the descent during a crash. A division of the system in the flight module and road vehicle during a crash was also considered. This would be beneficial if something is damaged on the flight module which cause the design to spin. However, a complex system would have to destroy the attachment system. This option was discarded due to its complexity.

The weight of the road vehicle is 678kg including payload, the weight of the flight module including maximum fuel is 508kg and the attachment system weighs 20kg. This gives the maximum weight of the total design of 1206kg. With this maximum weight, the BSR-172 parachute is the best option nowadays. This is a soft pack system and should be mounted inside the design so it is protected against the weather. The weight of the BSR-172 is 35.8kg and the dimensions are 46x28x91cm. Since the cruise speed is 392km/h, the pilot has to shut down its engine before deploying the ballistic parachute.

When looking at the placing of the ballistic parachute, the operations, the passenger safety, the weight and balance, the structure and the direction the rocket is pointing at need to be taken into account [57]. Since the attachment is a new and critical part. It can cause catastrophic situations if it fails. Thus, the ballistic parachute is placed inside the road vehicle to ensure passenger safety even without the flight module attached. When looking for a place of the parachute inside the vehicle, it was found that the parachute system was too voluminous. However, the design is going into production in 2025, what implies future developments are expected. When considering a ballistic parachute for aircraft with maximum weight slightly above 800kg, the dimensions of the parachutes are almost the half. This will fit in the design. Assuming the BRS company would keep on developing their products, a parachute with this dimensions for heavier weights would be on the market in 2025. Assuming the smaller dimensions and taking the other parameters into account, the best place to fit the parachute is inside the nose of the vehicle. The soft pack can be mounted at the front cross of the safety cage which can carry the loads. The parachute will then be deployed through the hood of the car. The hood of the car is not a load bearing structure, so this could be a frangible cover. Furthermore, the harness is attached to the safety cage. The harness contains three kevlar straps which connect the parachute with the structure.

A picture of the location of the parachute and the harness with respect to the safety cage can be seen in Figure 12.3, harness connections are represented by the red dots and the blue square represents the ballistic parachute. With the ballistic parachute at this position, the deployment can be simulated. First, the rocket shoots the parachute through the hood of the car. Then, the parachute is blown to the back of the car because of the airstream. Because the parachute goes to the back of the car, it must be guaranteed that the wires would not get tangled with the engine propellers. Taking into account the inclination of the windshield and the distance to the propeller, it is calculated that there is a space of 0.24m between the propeller and the wires if the vehicle stays parallel to the free-stream. After a second, the rear of the car will drop, what increases the distance between the wires and the propeller. The parachute will begin with a partial deployment to finally deploy completely. It will be suspended above the nose of the car. The passengers will descend in a lying position until it lands safely.

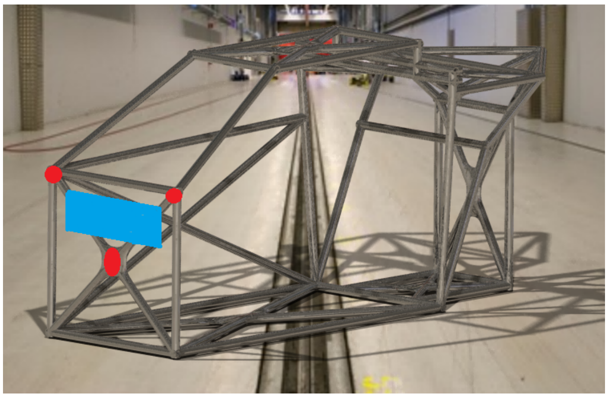

Figure 12.3: The position of the BRS-172 and the harness connection on the safety cage

Subpart B

Flight module

Chapter 13: Airfoil planform

In this chapter the airfoil and the planform of the main lift generating surface will be discussed. After the main lift generating surface the winglet design is given. The chapter ends with the airfoil for the tail surfaces.

13.1 Lift generating surface

For the main lift generating surface, the Joukovsky (f=1% t=17%) is used. The trade off for the airfoils can be found in the midterm report [12]. This airfoil is chosen because the drag is minimal and it has a stall lift coefficient in clean condition of over 1.5. It also offers a lot of fuel space due to the thickness. The airfoil characteristics at the cruise Reynolds number can be found in Figure 13.1.

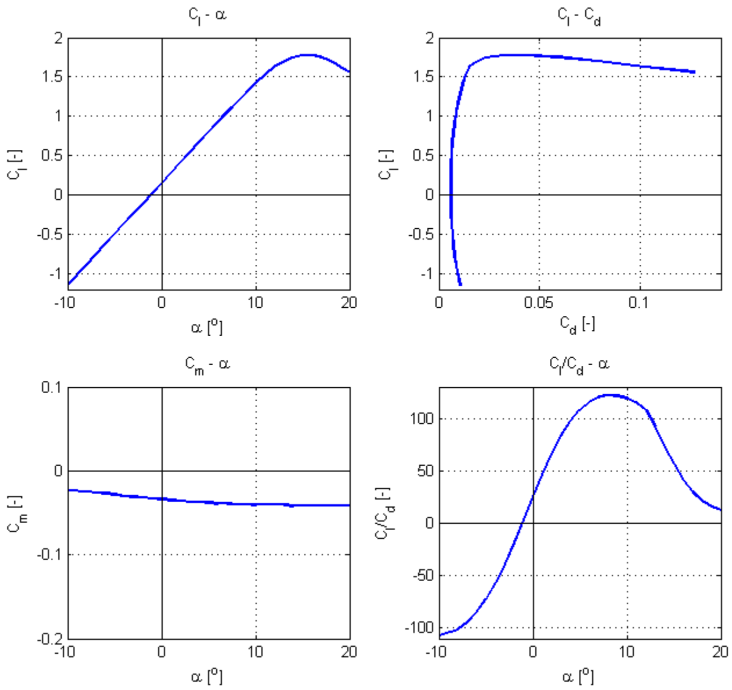

Figure 13.1: Airfoil characteristics at $Re = 5.13 \cdot 10^6$

As stated in Chapter 7 the wing area will be 13.08m^2. The aspect ratio will be 7.4, as this will be optimal (with respect to weight and power required) for the cruise conditions of this design. With this aspect ratio the wing will have a span of 9.87 m.

For an approximately elliptical lift distribution it is required to have a taper ratio between 0.4 and 0.5. Therefore it is chosen to have a taper ratio of 0.45. With this taper ratio, the wing will have a root chord of 1.84 m and a tip chord of 0.83 m. The complete flight module can be found in Figure 13.2.

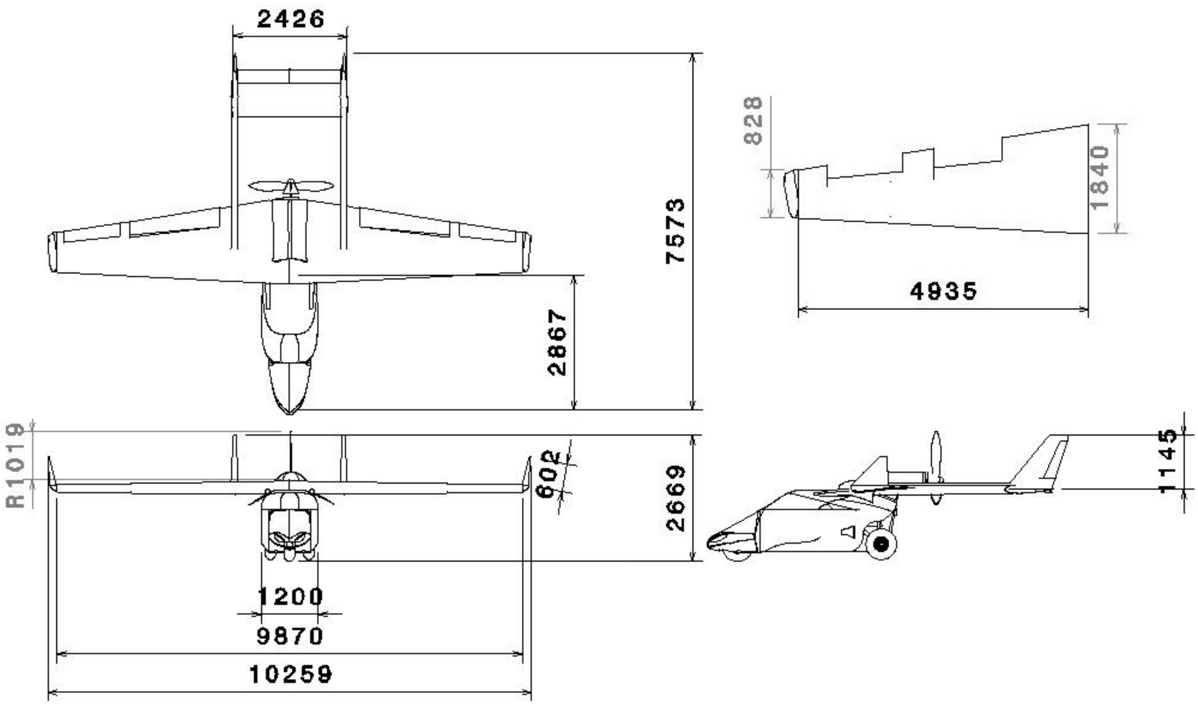

Figure 13.2: Complete flight module with dimensions in mm

13.2 Winglet

The winglet is often used in aircraft to reduce the induced drag. To see whether a winglet is efficient in this design the induced drag with and without winglet has to be estimated. This can be approximated by using the winglet as an extension of the wing such that it increases the aspect ratio. The drag coefficient for an aircraft is calculated by Equation (13.1). Here C_{D_0} is the skin friction which will increase by adding the winglets. The other term will decrease due to the higher aspect ratio.

$$C_D = C_{D_0} + \frac{C_L^2}{\pi A e} \tag{13.1}$$

To find the optimum with respect to the power which is required in cruise condition, the winglet length is plotted versus the power required, as seen in Figure 13.3. From this figure the optimum size can be found, which is 0.6 meter. The taper ratio of the winglet itself is determined from the sharklet taper ratio of the new Airbus A320 aircraft model [58], and equals 0.166. The winglet root chord is equal to the tip chord of the main wing, and the tip chord than is equal to 0.134 m. The winglet will have the same airfoil as the main wing, namely the Joukovsky (f=1% t=17%).

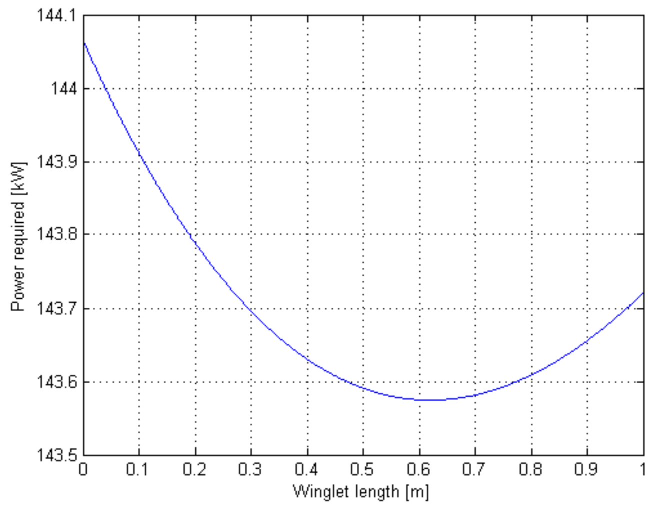

Figure 13.3: Power required versus winglet length

13.3 Tail surfaces

Tail surfaces in general require a symmetric, low drag airfoil. It is preferred for stall that the elevator has a higher stall angle than the main wing of the aircraft, such that the aircraft will get a correcting nose down moment when it enters a stall. This is achieved with the NACA0016 airfoil. The characteristics of this airfoil are found in Figure 13.4

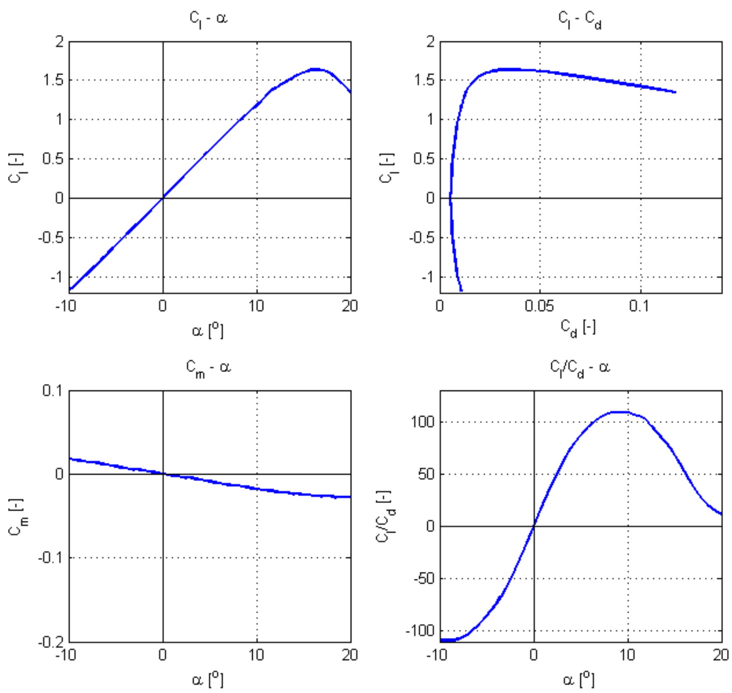

Figure 13.4: Airfoil characteristics at $Re = 5.13 \cdot 10^6$

13.4 High lift devices

As the lift coefficient of the wing is not sufficient for takeoff and landing, high lift devices are required. For this design plain flaps are the solution, as these are relatively lightweight and can generate enough change in the lift coefficient. The high lift device is sized according to Equation (13.2). Plain flaps deliver a $\Delta C_{l_{max}}$ of 0.9. As for landing a $\Delta C_{L_{max}}$ of 0.317 is desired, the wetted area of the flaps can be determined and therefor also the size of the flaps. The flaps will be 25% of the chord with the hinge line at 80%. With these flap characteristics the flaps need to span from 30 to 69 % of the half wing span. The flap dimensions can be found in Table 13.1

$$\Delta C_{L_{max}} = 0.9 \cdot \Delta C_{l_{max}} \cdot \frac{S_{wf}}{S} \cdot cos(\Lambda_{hingeline}) \tag{13.2}$$

Table 13.1: Dimensions of one single flap

Inner chord [m]	0.384
Outer chord [m]	0.285
Width [m]	1.92
$S_{wf} [m^2]$	2.58
$S_f [m^2]$	0.644

Chapter 14: Structures

14.1 Wing

For the structure of the wing a stress analysis should be performed. From this stress analysis the complete structure of the wing can be determined. At first the load carrying structure is designed. This is done with a wing box, which is beneficial for loads and torsion, as well as for fuel storage. The wing box is placed from 10 to 60 % of the local chord length. This location is often used, as it offers space for both leading edge and trailing edge control surfaces.

When selecting a material for the wing and the wing box, the specific density of the material is one important parameter, the costs are also to be taken into account. For the complete wing configuration two materials were selected to do a trade-off. In Appendix D the specific densities of the material can be found. From this the aluminium alloys 2024T3 and 7075T6 have been chosen, as the 7000 series are much more expensive than the 2000 series, the best material of both series will be evaluated with respect to weight and costs.

For the wing, a model had to be created for a double tapered wing box. Both the width and the height of the wing box section vary along the span. The model therefore is discretised in span wise direction. Each section is then also split into subsections to evaluate both the shear and normal stress for each subsection in the wing box.

The forces on the wing are then to be determined. The main force is the lift generated by the wing itself. The other forces are wing weight, fuel weight and the force which is introduced into the wing because of the H-tail configuration. For these forces a worst case scenario has been assumed, the lift of the wing equals the MTOW, with a load factor of 8. This load factor is chosen because the highest load factor for manoeuvring, landing and takeoff is 5. So with a load factor of 8 there is a small safety factor for the stress concentrations at for example, the attachment point. The tail is also introducing an upward force with the same load factor such that the forces amplify one another. The weights for the wing and fuel are set to zero, such that it does not relieve the wing.

The thicknesses and the stringers are then optimised such that the wing will have minimum weight. The alloys selected gave the results as presented in Table 14.1. In this table it can be seen that the weight does not differ that much, where the costs for the material is much lower for the AL 2024 T3 alloy. As the weight of the wing is also lower than in the class II weight estimation for the AL 2024 T3 alloy, it is therefore chosen to make the wing box from this aluminium alloy. The stress analysis for the wing is found in Figure 14.1. Due to the symmetry in the wing the wing is also designed for a load factor of -7, as the weight then acts in the same direction as the forces.

Table 14.1: Trade-off wing box material and characteristics structural analysis

Material	AL 2024 T3	AL 7075 T6
$t_{front}[mm]$	2	2
$t_{back}[mm]$	2	2
$t_{bottom}[mm]$	1	1
$t_{top}[mm]$	1	1
$t_{skin}[mm]$	0.5	0.5
$stringers_{top}$	3	1
$stringers_{bottom}$	3	1
Stringer length [mm]	1: 839 2: 1184 3: 839 4: 839 5: 1184 6: 839	1: 296 2: 296
$A_{stringer}[mm^2]$	140	140
$\sigma_{yield}[MPa]$	345	503
$\sigma_{max_{vonmises}}[MPa]$	308	450
wing mass [kg]	95.5	92.4
cost material [$ / ton]	800 [59]	4260 [60]
cost per wing [$]	76.40	393.62

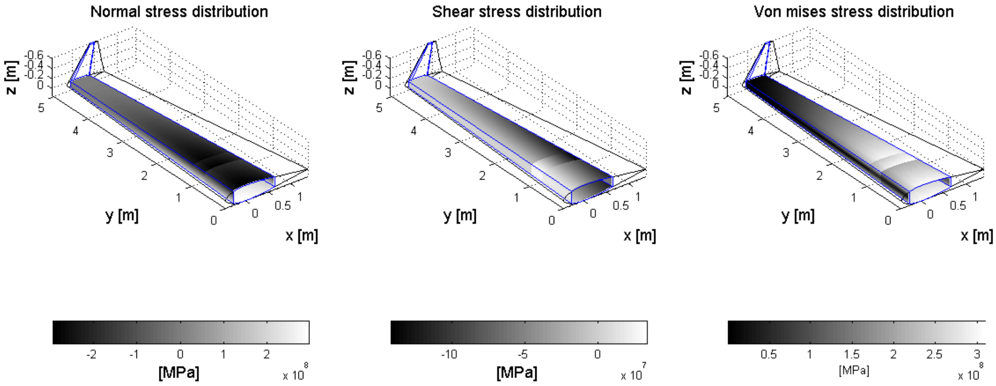

Figure 14.1: Stress analysis for the wing

The wing also needs to be designed to withstand buckling. For column buckling ribs need to be placed in the wing. There are already two ribs in the wing which are important for load carrying. The first rib is placed at the root, as the engine is attached to the wing at this location. The second rib will be placed at the point where the attachment system is placed. The wing is a closed section, so the third rib is at the tip of the wing. Then the column buckling analysis is done according to Equation (14.1). The length (L) may never be larger than the square root given in this equation as buckling will occur. Therefore there is a safety factor such that the yield stress is not exceeded during all operations. In Equation (14.1) K represents the buckling constant, which is determined by the clamping method. The K factor for this design is set to be 2, which represents one end fixed, and the other end free to move laterally.

$$L < \sqrt{\frac{\pi^2 * E_{alu} * I}{F * K^2}} * \text{safetyfactor} \tag{14.1}$$

From the column buckling analysis, it was found an additional rib was needed. This rib is placed at 3.4 m from the root. So the rib locations are as found in Table 14.2. The ribs have a 1mm thickness.

Table 14.2: Rib locations

Rib number	Rib location (mm from root)
1	0
2	641.5
3	3405.1
4	4935

14.2 Vibrational analysis

In order to ensure safety during operation not only the loads must be accounted for, but the wing must also be able to cope with the vibrations induced by both external and internal factors. The wing and its stiffening elements have been analysed. The moving surfaces and internal structure have not been analysed and only flutter in the z-direction is considered since this is the direction of lowest inertia and therefore the lowest frequency. As long as the frequency of the wing, the flight engine and the tail do not correspond to the natural frequency of the attachment system, the expected induced frequencies will not cause resonation. The wing side of the attachment system (specifications of which can be found in Subpart C) has a natural frequency of 1163 Hz. The ground vehicle side has a natural frequency of 1816 Hz, therefore it is assumed no vibrations are transferred between the ground vehicle and the flight module.

Aerodynamic frequencies are generally below 20 Hz [7]. The nominal frequency of the flight engine is 36 Hz (see Section 15.1). The first natural frequency of the wing is 13.3 Hz. The wing movables will increase the moment of inertia slightly but the frequency is still very low. This can result in dangerous situations; therefore the stiffness should either be increased which leads to a significant weight increase or the vibrations should be actively damped by the wing movables [61]. This is to be decided in future iterations.

14.3 Empennage

In the following section the structure of the empennage is discussed. The empennage will consist out of the following components: The tail booms, which caries all the loads applied to the horizontal and vertical stabilisers, the horizontal stabiliser, responsible for pitch control and the vertical stabiliser, responsible for yaw control.

14.3.1 Tail booms

For the sizing of the tail booms, the different forces applied to the booms need to be identified first. Both the horizontal and vertical surfaces will introduce a lift forces according to Equation (14.2) which will result in two bending moments and two torsion forces applied in the two corresponding planes. A graphical interpretation of the forces applied to the tail is shown in Figure 14.2.

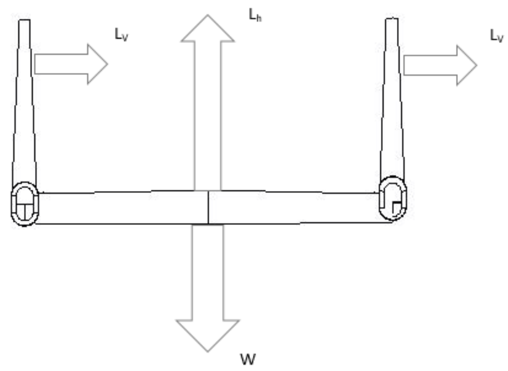

Figure 14.2: Forces on the tail applied

$$L = \frac{1}{2}\rho_{air}V^2 C_{L_{tail}} S \tag{14.2}$$

When looking at failure of the tail booms, three different failure modes are considered: tensile strength, shear strength and yield strength of the material. First the tensile strength will be considered using Equation (14.3).

$$\sigma = -\frac{My}{I} \tag{14.3}$$

Here moments induced along the two different axis introduce the forces and the cross section of the booms will determine its moment of inertia in that corresponding axis. Due to the fact the horizontal tail surface is over two times higher than the vertical tail surfaces, the lift force corresponding with the horizontal tail will introduce a much higher load than the vertical tail surface. Therefore the moment along this axis is the leading design requirement and therefore require a higher moment of inertia in that axis. To cope with the additional torsional forces according to Equation (14.4) an extended closed semi circular cross section is chosen which is shown in Figure 14.3.

$$\tau = \frac{T}{2At} \tag{14.4}$$

To be able to choose the right material and cross section dimensions of the tail booms the yield strength is also considered using Equation (14.5) with the σ_h and σ_v representing the tensile stress in both vertical and horizontal direction and τ_{tot} representing the total tensile stress.

$$Y = \sqrt{\frac{1}{2}\sigma_h^2 + \frac{1}{2}\sigma_v^2 + 3\tau_{tot}^2} \quad (14.5)$$

As a starting point the cross section at the root was sized with the wing airfoil thickness as on of the constraints to keep the tail booms aerodynamically well shaped. A small trade-off was performed between the two aluminium alloys 2024T3 and 7075T6 varying the thickness of the skin within a 2-4 millimetre range. This trade-off can be found in Appendix E. For the final design the aluminium alloy 7075T6 with a thickness of 2.5 millimetres is chosen to be the most suitable for the loads applied to the empennage, when also taking the weight into account. However the 2024T3 alloy is less expensive, but the weight is here considered being more critical. The final design of the tail booms is shown in Figure 14.3. Both a front an rear cross section is presented with the front view connected to the wing and rear connected to the tail. Both struts have a thickness of 2.5 mm along the whole assembly. Furthermore a small taper is applied to decrease the weight of the tail booms when moving to the horizontal and vertical stabilisers.

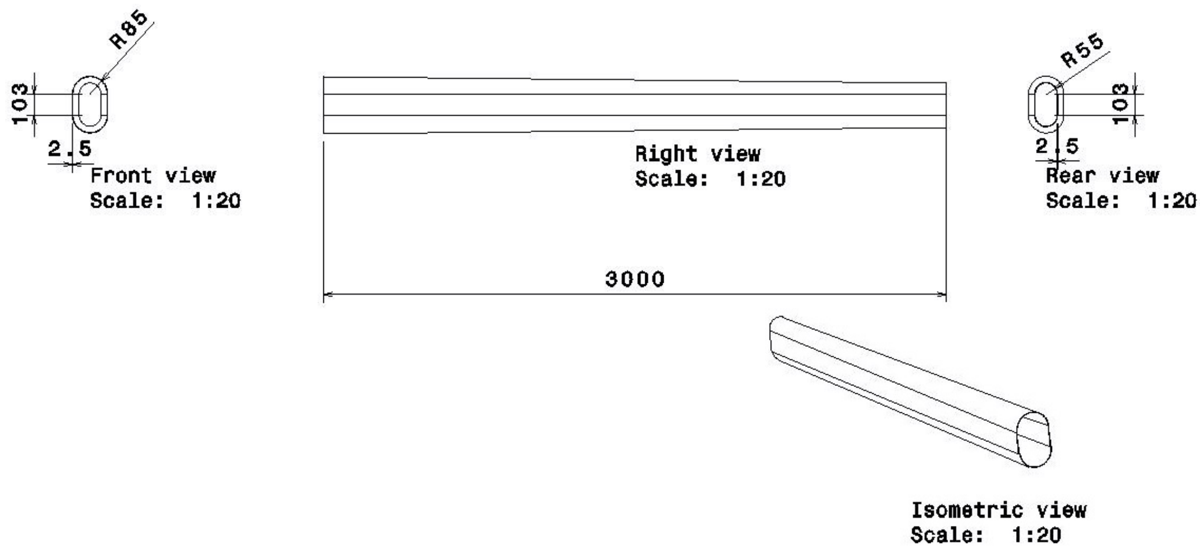

Figure 14.3: Final Tail Booms

14.3.2 Horizontal stabiliser

For the horizontal tail the same method is used as for the wing, the structure is sized for the maximum loads which are expected on the horizontal tail, which will be during rotation at takeoff and at manoeuvres. The same aluminium alloy is used as for the wing structure. The dimensions of the horizontal tail structure can be found in Table 14.3. The stress analysis is found in Figure 14.4.

Table 14.3: Structural characteristics horizontal tail

Property	Value
Material	AL 2024 T3
$t_{front}[mm]$	1
$t_{back}[mm]$	1
$t_{bottom}[mm]$	0.5
$t_{top}[mm]$	0.5
$t_{skin}[mm]$	0.5
$stringers_{top}$	3
$stringers_{bottom}$	3

Stringer length [mm]	1: 328 2: 559 3: 328 4: 328 5: 559 6: 328
$A_{stringer}[mm^2]$	120
$\sigma_{yield}[MPa]$	345
$\sigma_{max_{vonmises}}[MPa]$	309
horizontal tail mass [kg]	11.4

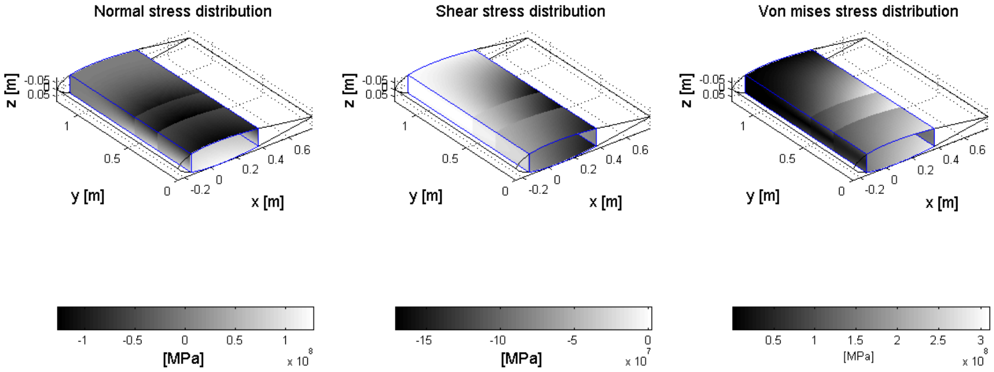

Figure 14.4: Stress analysis of the horizontal tail

14.3.3 Vertical stabilisers

The vertical tail is designed the same way as the horizontal tail, except now the crosswind landing loads and side-slip manoeuvres are most critical. The AL 2024 T3 alluminium alloy is used for the vertical tail as well. The dimensions of the vertical tail structure can be found in Table 14.4. The stress analysis is found in Figure 14.5.

Table 14.4: Structural characteristics vertical tail

Property	Value	$t_{skin}[mm]$	0.5
Material	AL 2024 T3	$stringers_{left-side}$	0
$t_{front}[mm]$	0.5	$stringers_{right-side}$	0
$t_{back}[mm]$	0.5	$\sigma_{yield}[MPa]$	345
$t_{bottom}[mm]$	0.5	$\sigma_{max_{vonmises}}[MPa]$	114
$t_{top}[mm]$	0.5	horizontal tail mass [kg]	5.8

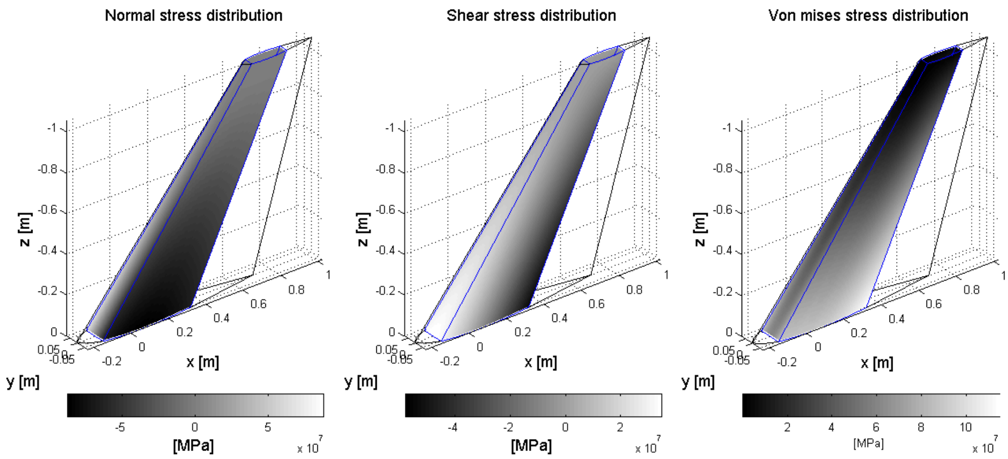

Figure 14.5: Stress analysis of the vertical tail

14.4 Fatigue

As the Volucrem experiences many load and unload cycles a fatigue analysis should be performed on the main load carrying structures. First the wing and tails are considered, which have the same material, then the tail booms and finally also the fuselage as it has to withstand the pressure forces. The number of cycles which is expected during the vehicle's lifetime is set to 10000, as the vehicle is build to fly 3 days a week, twice a day for 25 years. With an average flight time of 2 hours the 20000 flight hours which the design is made for is reached.

14.4.1 Wing and tail sections

The wing is made of the aluminium alloy 2024 T3. This alloy has a fatigue stress of 138 MPa for 500 million cycles [62]. Using Equation (14.6) with the ultimate stress (US) of 483 MPa the slope ($\frac{-1}{m}$) of the S-N curve can be determined. From this it is found that m should equal 16. Using the equation again with N equal to 10000, the maximum fatigue stress found equals 271 MPa. This is lower than the maximum stress found in the wing and tail sections, which is 309 MPa. But still it can be stated that there will not be fatigue during the lifetime of the vehicle, as the maximum stress does not occur once every flight. As there are large safety factors included (and larger load factors than expected are used) and the difference between the maximum stress and the fatigue stress is small, so this statement is justified.

$$\log S = \log US - \frac{1}{m} \log N \tag{14.6}$$

14.4.2 Tail booms

The tail booms are made of a different alloy, the alumunium 7075 T6. This alloy has an ultimate stress of 572 MPa, and a fatigue stress of 159 MPa at 500 million cycles. From Equation (14.6) the slope is determined again, which equals 15.6. The stress at which fatigue occurs for 10000 cycles then equals 318MPa. This is lower than the maximum stress for the tail booms, which equals 477 MPa, again the maximum stress is not expected to occur once every flight, but the difference between the maximum stress and the fatigue limit stress is so high that this should be re-iterated in the future.

14.4.3 Fuselage

The fuselage is loaded and unloaded once every flight. The stress which is present in the fuselage due to the pressurisation is calculated with Equation (14.7). This formula is the maximum stress in the fuselage as the cylindrical part is most critical. The maximum radius of the cylinder is 0.6m. The fuselage will be made of the aluminium 2024 T3 alloy. The required thickness is than calculated. This should be 0.12 mm. This cannot be manufactured, as it is not impact though and for this thickness no safety factor is included, so the thickness is set to 0.5mm, which is the minimal thickness needed for manufactering aluminium sheets of this alloy.

$$\sigma = \frac{\Delta P r}{t} \tag{14.7}$$

Chapter 15: Flight engine

15.1 Flight engine specifications

The power required for the flight engine depends on cruise velocity, required runway length, available fuel, cruise altitude and sustainability restrictions. The best and weight optimal solution for the flying car is the use of a turboprop engine for the flight system. A turboprop "is a gas turbine engine designed to primarily drive a propeller as the thrust generator" [63].

The use of a turboprop was selected due to a multitude of reasons. The first reason being the cruise altitude at 7000 m, at this altitude the turboprop becomes an efficient system for propulsion when compared to reciprocating engines. A reciprocating engine experiences an efficiency drop at high altitudes, even when turbocharged. The turboprop engine is able to deliver the required power at a reduced engine weight. The power-to-weight ratio of turboprops is approximately within $0.386 - 0.453\frac{kW}{N}$ for modern turbines and the piston engine delivers approximately $0.084 - 0.168\frac{kW}{N}$ [63]. Another great benefit of the turboprop engine is the ability to fly above disruptive weather conditions, adding favourable operational windows for the roadable aircraft.

The high power to weight ratio of turboprop engines is the main reason for its selection. Currently, commercial turboprop engines can be selected that meet the requirements imposed previously. A viable engine is an engine similar to the Diemech TP100 turboprop engine, the engine is able to deliver $180kW$ of power and has a dry mass of $57kg$. Furthermore, when a propeller similar to the Avia AV723 is used the engine is able to deliver $5394N$ of thrust at a propeller velocity of 2158 RPM. The required maximum engine power to cruise at an 80% power setting at 200 knots is $155kW$. Since the engine is able to deliver a maximum power of $180kW$, a cruise airspeed of 212 knots is achievable, further reducing door-to-door travel times. The relationship between airspeed and power required is shown in Figure 15.2.

Another parameter of interest is the specific fuel consumption which is rated at $0.5\frac{kg}{kWh}$. This will be used in Section 15.2 to determine the amount of fuel required along with the amount of CO_2 emitted. The engine is fitted with an autonomous oil system, a digital control unit, low voltage ignition source, a propeller speed governor and speed limiter [64]. Furthermore, the engine has an electric starter generator that requires $750W$ for starting. To provide this power, the car engine ($58kW$) is used to start the flight engine. The dimensions are defined by an engine length of $870mm$, a width (without exhaust) of $330mm$ and height of $390mm$. Given the engine dimensions the nacelle for the engine can be designed. For the design of the engine nacelle it is important that the nacelle is strong enough to transfer the engine loads to the airframe and vice versa. Furthermore, the engine nacelle must allow the engine to have sufficient air intake. The design of the nacelle can be seen in Figure 15.1.

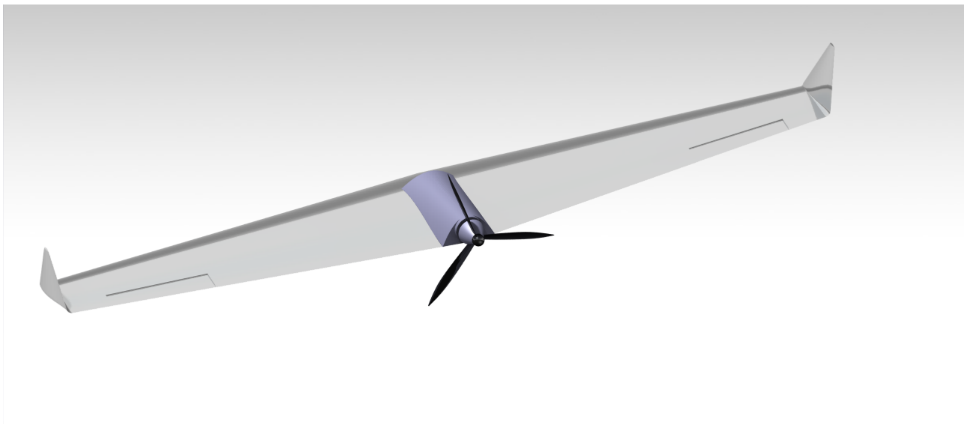

Figure 15.1: Engine nacelle design

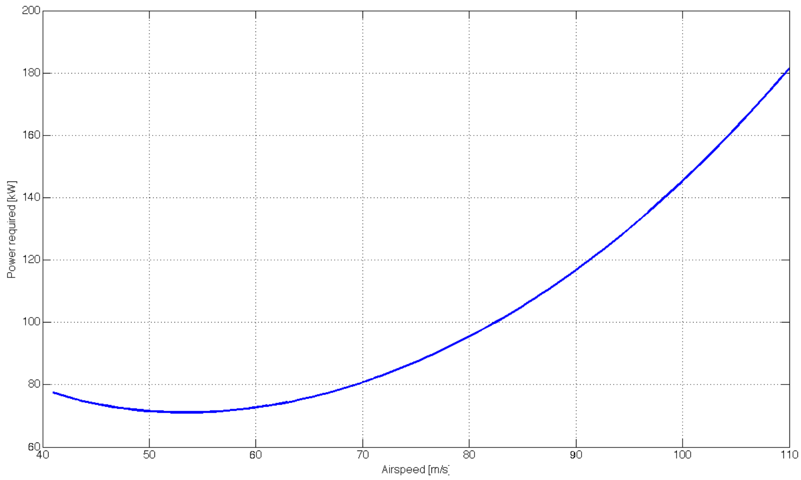

Figure 15.2: Power required versus cruise airspeed

15.1.1 Engine placement

When considering the placement of the engine the options are limited. The flight engine must remain on the flight module which restricts the configuration options. The optimal solution, as long as there is enough propeller clearance, is the use of a push propeller located on the trailing edge of the wing. In this manner, the propeller blades are out of the way of the passengers in case of malfunction during flight. However since the engine will be placed above the wing, it is required to have stiffening elements capable of transferring the engine loads to the rest of the vehicle. The stiffening element will be a rib placed at the root of the wing. Not only will the rib provide the stiffness, but also separate the two fuel tanks in the wing. The placement of the rib is also stated in Section 14.1.

15.2 Fuel

One of the downsides of the use of a turboprop engine is the larger fuel consumption compared to a reciprocating engine. Therefore it is important to ensure that the fuel tanks are sized to cope with the fuel required. Additionally it is of importance to ensure that the emitted CO_2 does not exceed $150\frac{kg}{h}$. To size the fuel tanks the required amount of fuel has to be determined, which is done by investigating the amount of fuel the engine consumes during the mission.

The required fuel will be determined based on the required range which the vehicle aims to obtain. Since a range of 1000km is required we can assume an average mission velocity to be $V_{ave} = 370.4\frac{km}{h}$ which is 5.5% lower than the cruise velocity of $V_{cruise} = 392\frac{km}{h}$.

$$E = \frac{R}{V_{ave}} = \frac{1000km}{370.4\frac{km}{h}} = 2.699h$$

The total time which the aircraft has to remain in the air is the total time required to obtain the desired range and a holding time of 15 minutes. This makes the total endurance $E = 2.949h$. Then the next step is to determine how much fuel the TP100 engine burns in cruise conditions. Since the engine processes $0.5\frac{kg}{kW \cdot h}$ of fuel and the power required to cruise is $P_{req} = 141.75kW$ the total amount of fuel consumed per hour can be determined.

$$\dot{m} = SFC \cdot P_{req} = 0.5\frac{kg}{kW \cdot h} \cdot 141.75kW = 70.88\frac{kg}{h}$$

Then, to determine the total fuel utilised during the mission, the product between the fuel flow and the total endurance plus holding time is taken, which results in a fuel mass of $M_{fuel} = 209.0kg$. Given the density of the fuel to be $\rho_{fuel} = 780\frac{kg}{m^3}$, this results in a fuel volume of $V_{fuel} = 268.0L$.

With the current fuel flow of $\dot{m} = 70.88\frac{kg}{h} = 90.87\frac{L}{h}$ we note that the fuel flow would result in too much CO_2 released as the requirement was that $61\frac{L}{h}$ of Jet A-1 fuel could be burned [65]. Therefore a solution is required to minimise the CO_2 emissions without decreasing the power plant performance. The solution is the use of a 50/50 blend of Jet A-1 fuel with Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK). The biofuel solution lowers the overall emissions of CO_2 in the overall cycle of the fuel considering how the fuel is made and used. It emits approximately 1.9% less CO_2 than the conventional Jet A-1 fuel[66]. Biofuels can be made from different biological sources such as algea, camelina and Jatropha [67]. The cultivation of these fuel sources requires CO_2 for photosynthesis, thereby reducing the overall fuel life cycle's emissions. Some calculations of the CO_2 amount that is saved with the use of Bio-SPK are described in Section 27.5.1.

Bio-SPK has a approximately 1% higher energy density per unit mass than Jet A-1 fuel, this justifies the specific performance properties of the fuel [67]. An advantage of using this biofuel is that the engine will not require alterations. Furthermore, while currently not being readily available at every airport, by 2025 the use of these biofuels could become more widespread with the aviation community placing special attention to sustainable fuels. Currently, the use of biofuels is also more costly than the use of solely petroleum based fuels. This is due to the longer and more intricate system to process the fuel. The difference in the fuel process is shown in Figure 15.3. Further information on the fuel properties of both Jet A-1 and Bio-SPK is shown in Appendix B.

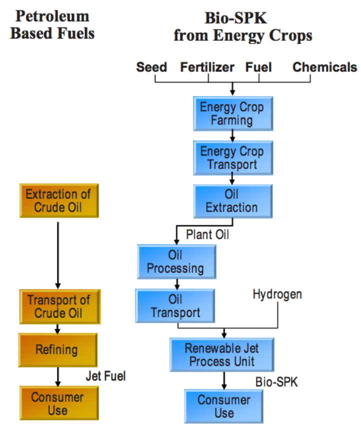

Figure 15.3: Fuel processing flow diagram [67]

15.3 Noise levels

As stated in the requirements, the flying car should have noise levels under 65 dB within a 200m radius during takeoff and landing. As the flight engine is fairly new and there are no reference aircraft to extract data from, similar turboprop data has been sought for. Most comparable turboprops have noise levels between 57.0 dBA to 78.3 dBA [68], taking into account that the turboprop used in flight is rather small, it can be argued that its noise will be closer to the lower limit. To reduce the noise of the tip vortices of the propeller winglets are added to the propeller. However, the exact effect of these winglets have to be investigated by model testing. Furthermore, it has been researched what noise limits are implied by small airfields where general aviation is often found. Antwerpen airport has a noise limit of 76dBA for aircraft under 2000kg MTOW [69]. As the Volucrem will takeoff from similar small airfields it will not be necessary to comply with the requirement of <65dB as the surroundings are already used to higher noise levels. So in this stage of the design it can be assumed that the Volucrem will not have noise issues due to the subjects just discussed. On top of that the assumption can be made that turboprops will be improved and intensively investigated on noise properties as this is an important subject for airfields and the environment such that in ten years, by 2025, noise levels of the Volucrem are further reduced.

15.4 Flight module fuel system

The flight module utilises a different fuel type than the car module, thereby making an independent fuel system essential for a successful flying car. The fuel system plan has to be generated. Since the engine is located above the tank, a pump driven system will be implemented. Some important subsystems of the fuel system will be described in detail.

15.4.1 Fuel transfer system & engine feed system

The engine feed system is an essential element of the fuel system as it is responsible for boosting the pressure to "avoid cavitation in the engine system" [70]. There is a necessity for transfer and boost pumps to pump the fuel from the tanks within the airframe to the engine interface.

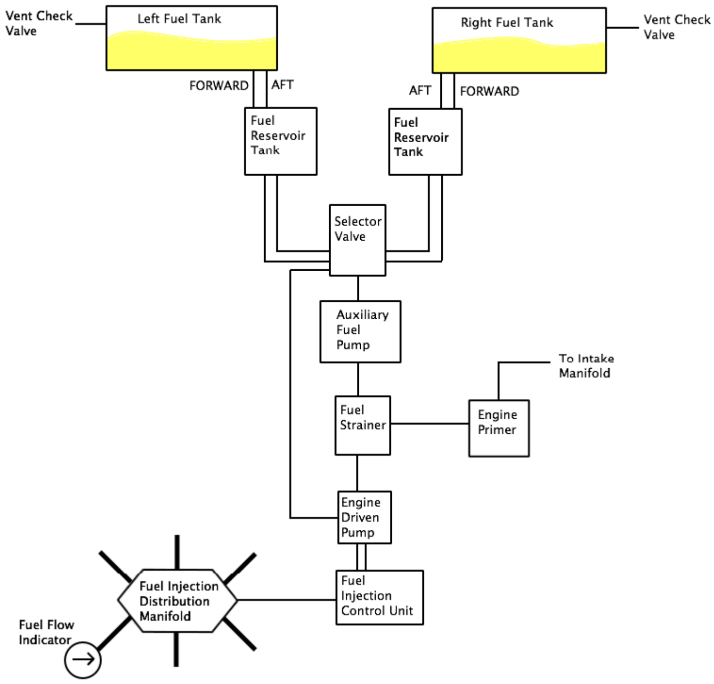

Figure 15.4: Pump driven fuel system for the flight module

The fuel transfer system is the mechanism of pumping the fuel from the source tank to the collector tank before it is further transported to the engine. The overall fuel system is depicted in Figure 15.4.

15.4.2 Fuel tanks

The fuel tanks must be fitted with vent check valves in order to ensure one-way drainage of fuel to vent the fuel. The fuel tanks must be sized to the fuel required for the mission, since $268L$ of fuel is required and the most convenient would be to place two fuel tanks of $134L$. However since the tanks have to account for fuel expansion the tank must be made 5% larger. This will make the tanks $141L$ each. It was chosen to set the fuel tanks to $180L$, in order to be able to get some more range if required.

Since the main fuel tanks are located in the wing of the aircraft, roll manoeuvres can affect the fuel distribution from root to tip. This causes non constant fuel pressure which is detrimental for the fuel transfer system. Furthermore, the effect can cause fluctuations in the centre of gravity and can induce errors in the fuel quantity measurements. To prevent this from happening anti slosh baffles must be implemented in the tanks. These ribs serve to reduce the slosh and if the flap check valves are closed the fuel can be contained to a specific wing section.

At an altitude of $7000m$ the ambient air temperature according to the international standard atmosphere model is $T_{air} = -30.55°C$. The 50/50 blend of Bio-SPK with Jet A-1 has a freeze point of $T_{freeze} \approx -55°C$, therefore it is not necessary to heat treat the fuel such that it does not freeze [67].

To determine the fuel level remaining in the fuel tanks, the use of ultrasonic probes located on the bottom of the tank can be utilised. With knowledge of the fuel tank shape the system is able to determine the amount of fuel remaining in the tank by transmitting ultrasonic pulse from the bottom of the tank and when the pulse reaches the fuel air interface the pulse will be reflected and the pulse will return to the probe with a time delay which relates to a certain amount of fuel.

Chapter 16: Subsystems

16.1 Power-by-Wire (PBW) flight control system

The flight control system is the subsystem that is responsible for deflecting the control surfaces to give the aircraft the necessary forces to change the attitude and manoeuvre. The aircraft has three primary flight controls, lateral, longitudinal and directional controls. The primary flight control surfaces are responsible for a change in the pitch, yaw and roll. Furthermore the aircraft should have secondary flight controls that operate the trim tabs. The vehicle will operate via a fly-by-wire (FBW) system, this means that electronic or hydraulic actuators must be used to ensure that the flight control system provides the necessary actuation movement. The optimum solution for the flight control system would be to implement electromechanical actuators (EMA) or electrohydrostatic actuators (EHA) for the primary and secondary moving flight controls. The primary benefit of departing from a classical hydraulic system approach is the weight reduction. Additionally an electric actuation system further offers advantages such as no chance for leakage in the system, the capability to remove components without having to disassemble hydraulic lines and the ease of physically separating the system.

16.1.1 EHA versus EMA

After opting for a power-by-wire solution for the irreversible flight control systems actuator selection can be performed. Currently there are two actuator technologies that can be implemented and provide significant benefits when compared to the classical centralised hydraulic system. These two actuator systems are EHA and EMA. EMA and EHA provide an increase in efficiency when compared to hydraulic systems. The operating principle of EMA is the use of an electric motor to provide torque which is mechanically transmitted to the control surface. EHA is a hydraulic actuator incorporating a pump driven by an electric motor all within one system [71]. A schematic depicting the operation of the EHA and EMA system can be seen from Figure 16.1 and Figure 16.2 respectively.

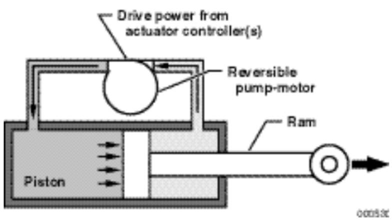

Figure 16.1: Electrohydrostatic Actuator[72]

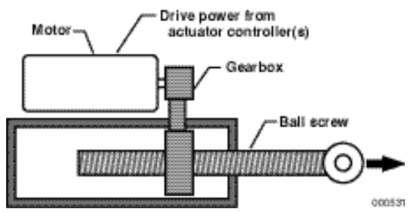

Figure 16.2: Electromechanical Actuator[72]

The EHA technology has a high efficiency and easy setup. The drawback of EHA is that installation and maintenance requires fixtures[73]. The EMA technology has a high efficiency along with an easy setup and easy maintenance. Furthermore the complexity, weight and reliability of the EMA system is preferred over EHA [72]. However the use of an electro motor means that there has to be a system which transfers the rotational motion into a translational motion. This introduces certain problems such as backlash, gear wear and jamming. The jamming characteristics are difficult to predict for EMA systems due to the hundreds of gear teeth [72]. EMA systems are also more prone to wear, this is an issue as the wear in mechanical transmission could lead to control surface freeplay or non-linearity in control surface actuation [72]. EHA can be easily made reversible in stand-by mode unlike the EMA system. Finally the EMA system also requires a backup battery for failsafe operations. [73] With the associated benefits and drawbacks the EHA was selected for the design.

16.2 Layout of irreversible flight control system

The next step in the design process is to develop the overall layout of the flight control system. The actuators require two input commands, the power required to operate the actuator and the information giving the instruction of how much the actuator should move. Thereby the electrical signal layout will also be presented. The actuators have two ends, the fixed and moving ends. The moving ends must be connected to the control surfaces which they control, this restricts the placement options of the actuators. For the main wing the optimal placement of the actuators is to attach the fixed ends to the rear spar. The spar structure is stiff enough to ensure that the servo-elasticity is reduced. The installation of an actuator is shown in Figure 16.3. Furthermore the overall flight control schematic is shown in Figure 16.4.

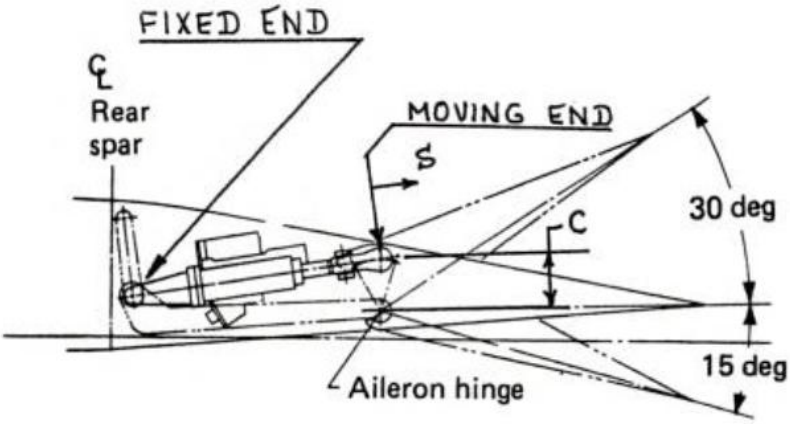

Figure 16.3: Typical actuator-to-surface installation [47]

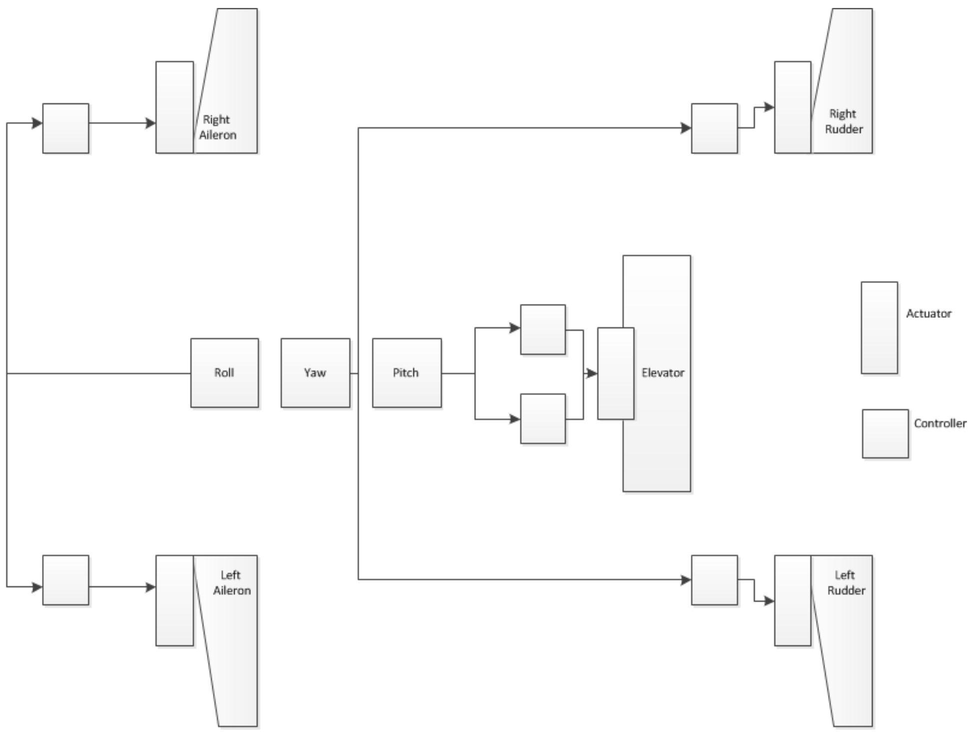

Figure 16.4: Flight Control Schematic

One requirement that has to be considered in the design of a safe system is redundancy in case of actuator failure. Since the electrohydrostatic actuator can fail and the vehicle must be able to operate its control surfaces to ensure safe flight the only option is to place redundancy on such a flight critical element of the design. This means that for every control surface two EHA units will be placed. This means that also two sets of electrical wire to transmit the power and command will be required for redundancy. Even with the redundancy the removal of the central hydraulic system with the accompanying piping results in a lower weight system. The redundant systems should be independent from each other to ensure that the failure of one system is independent of the redundant back-up, thereby imposing a limit on the placement options of the electric wiring. The wiring should follow different physical paths to ensure that the magnetic field generated in one wire does not influences the other. The layout of the flight control system can be seen in Figure 16.5.

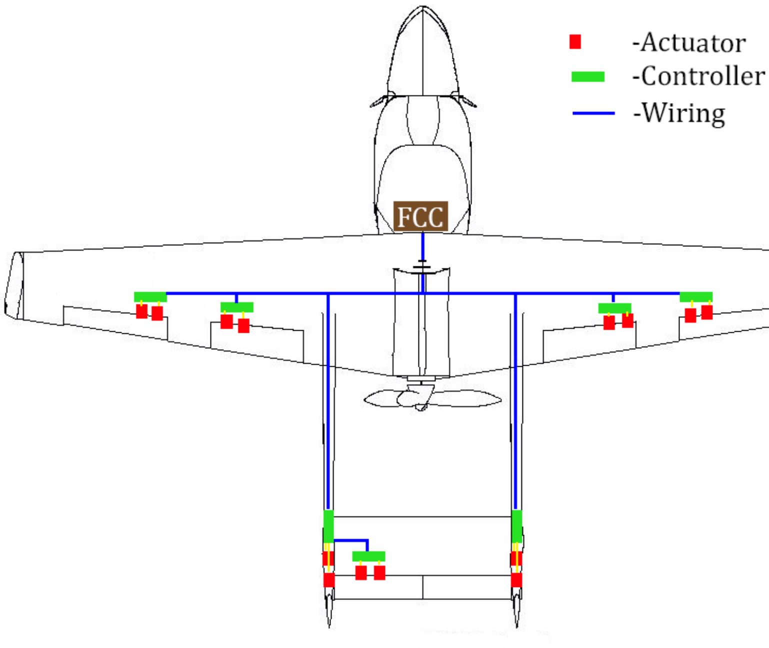

Figure 16.5: Flight control system layout

16.3 Flight control computer (FCC)

For a FBW or more specifically PBW system there is a need to instruct the actuators on the amount of motion they must produce. This function is carried out by the FCC. A very useful feature of a FCC is the notion that it can be programmed such that it evaluates inputs and sensory parameters to place operational limits for the aircraft. For the success of the flying car it must be easy to operate and 'fool proof', thereby placing operating limits will ensure that the vehicle is not unnecessarily strained. The importance of the FCC is crucial thus the system should be made triple redundant.

The FCC is responsible for reducing the pilot workload in order to ensure that the vehicle becomes more user friendly. This can be achieved by the use of coordinated turns by coupling the yaw and roll controls. Additionally, the computer can ensure that the aircraft does not operate outside of the operational limit of the vehicle ensuring passenger safety. The flight controller will permit the flying car to be more accessible to the public. A basic communications flow diagram of the flight system including the flight control computer can be found in Appendix G.

16.4 Stall warning

One of the requirements for safe flight is sufficient warning before stalling. Stall occurs when the angle of attack is too high, though in general this is related to velocity. A stall warning system will be implemented which warns the pilot from flying too slowly by a sound signal. Furthermore an angle of attack limiter is optional, either mechanically by means of a stick pusher or by electronically by programming it into the flight computer. It is expected that avionics packages will include software for measuring the angle of attack from standard sensors by 2025. This way an angle of attack indicator or even limiter can be implemented for ease of operation.

16.5 Pitot static system

The avionics within the aircraft require sensors to measure the unaffected and affected air pressure. The pitot static system measures these pressures in order to determine the airspeed, altitude, mach number and vertical speed. Knowing the various flight parameters of the aircraft is essential to operate the vehicle safely. Therefore the pitot tube and static port must be located on the flight module such that the flight critical component remains safely stored in the airport.

The measuring of the static pressure is limited in locations for placement as the static port must be situated in aerodynamically neutral locations. The vents will be situated on the tail booms near the trailing edge of the wing. The vents feed into the same tube to reduce errors due to poor aerodynamic positioning [74].To further minimise error, the system requires accurate calibration.

The placement of the pitot tube has to be parallel to the flight direction, this limits the placement possibilities. The optimum pitot tube placement is therefore under the main wing. For redundancy two independent systems should be implemented, thereby installing two pitot tubes equidistant from the root chord.

16.6 Anti-icing solution

Deciding to cruise at 7000 metres means most of the flight is carried out above the icing altitude. However, some measures still need to be implemented to prevent accumulation of ice on the wing. Since a significant portion of the wing lies directly in front of the engine and propeller, an inflatable de-icing boot cannot be used. Bleed-air systems are being used in the aircraft industries which duct heated air from an engine compressor to the wing in order to melt the ice. However, this is a costly system and it is not possible to use the car engine to power this due to the modularity of the ground vehicle. A more suitable option could be a de-icing or anti-icing fluid. These are fluids which temporarily prevent the accumulation of ice on the wing until diluted or contaminated to lose their function. Several types of fluids are available and more ecologically friendly solutions are expected to be available in 2025.
Not only the wing need to be protected but also the forward window should be de-iced in case of freezing in order to provide visibility for the pilot during flight. The standard solution for small aircraft is an alcohol-based spray which removes icing from the forward window. Similar options are available in cars and therefore this can provide a freeze protection solution for the modular flying car.

16.7 Lighting

When flying at night or in bad weather, the visibility of the vehicle decreases. To maintain the visibility of the vehicle to other pilots and avoid collisions, lighting of the vehicle is required. The lighting must indicate the maximum width and length and the position of the aircraft. According to the CS-23 regulations, the left and right position lights must consist of a red and a green light spaced laterally as far apart as practicable and installed on the aircraft such that, with the aircraft in the normal flying position, the red light is on the left side and the green light is on the right side. The rear position light must be a white light mounted as far aft as practicable on the tail or on each wing tip [3]. LED lights will be used due their being the most efficient, least power consuming, most durable and have the longest range compared to all other convenient light bulbs as discussed for the car module, see Section 10.5.2.9. The head lights of the car module will be used for flight. A visualisation of the Volucrem during night showing the lighting during flight is shown in Figure 16.6.

Figure 16.6: Volucrem during night showing flight lighting

Chapter 17: Stability and control

In order to obtain stability and controllability both the horizontal and vertical tail need to be sized properly. First the longitudinal stability and controllability is considered with the creation of a scissor plot and loading diagram during normal operations. With this loading diagram a centre of gravity range can be set. Next, both the centre of gravity range and scissor plot are used to size the optimal horizontal tail and the relative position of wing. Furthermore the vertical tail is sized. Finally, the control surfaces (ailerons, elevator and rudders) have been correctly sized.

17.1 Longitudinal stability and controllability

Starting with the stability analysis all forces and moments for the aircraft should be considered. After simplifications and when only considering the longitudinal moment and force contributions the forces can be simplified as seen in Figure 17.1.

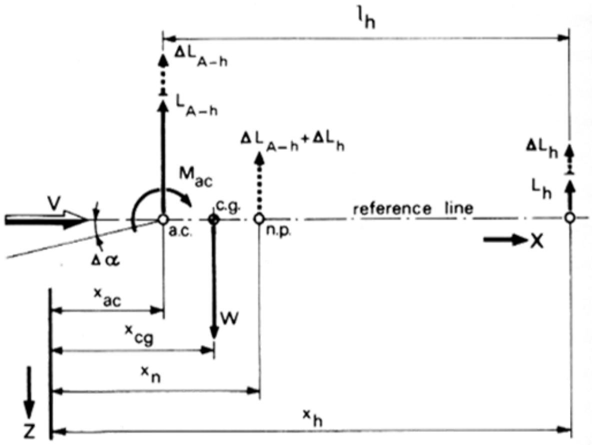

Figure 17.1: Forces and moments for longitudinal stability [75]

17.1.1 Scissor plot

Stability is achieved when the change in moment due to a disturbance in the angle of attack is smaller than zero, a condition illustrated by Inequality 17.1.

$$\frac{dC_m}{d\alpha} < 0 \tag{17.1}$$

The changes in forces due to this disturbance occur at the neutral point. In other words, at the neutral point the change in moment due to a disturbance is equal to zero. Thus both the moment contribution due to the change in lift of the aircraft minus tail and the horizontal tail should be equal as seen in Equation (17.2). In this equation the contribution of the aircraft minus tail (A-h) is given as Equation (17.3) and the tail (h) contribution as Equation (17.4)

$$\Delta L_{A-h}(\bar{x}_{np} - \bar{x}_{ac}) - \Delta L_h(\bar{x}_h - \bar{x}_{np}) = 0 \tag{17.2}$$

$$\Delta L_{A-h} = C_{L_{\alpha_{A-h}}} \Delta\alpha \frac{1}{2}\rho V^2 S \tag{17.3}$$

$$\Delta L_h = C_{L_{\alpha_h}}(\Delta\alpha - \Delta\epsilon)\frac{1}{2}\rho V_h^2 S_h \tag{17.4}$$

Using Equations (17.2) to (17.4) and the assumption that the neutral point is very close to the aerodynamic center of the main wing ($x_h - x_{np} \cong l_h$), Equation (17.5) is obtained. Rearranging the terms gives Equation (17.6) where $C_{L_\alpha} = C_{L_{\alpha_{A-h}}}$ and adding the stability margin ($\bar{x}_{np} - \bar{x}_{cg} = S.M.$) gives the final results as in Equation (17.7)

$$C_{L_{\alpha_{A-h}}}\Delta\alpha\frac{1}{2}\rho V^2 S(\bar{x}_{np}-\bar{x}_{ac})-C_{L_{\alpha_h}}(\Delta\alpha-\Delta\epsilon)\frac{1}{2}\rho V_h^2 S_h l_h = 0 \tag{17.5}$$

$$\bar{x}_{np} = \bar{x}_{ac}+\frac{C_{L_{\alpha_h}}}{C_{L_\alpha}}\left(1-\frac{d\epsilon}{d\alpha}\right)\frac{S_h l_h}{S\bar{x}}\left(\frac{V_h}{V}\right)^2 \tag{17.6}$$

$$\bar{x}_{cg} = \bar{x}_{ac}+\frac{C_{L_{\alpha_h}}}{C_{L_\alpha}}\left(1-\frac{d\epsilon}{d\alpha}\right)\frac{S_h l_h}{S\bar{x}}\left(\frac{V_h}{V}\right)^2 - S.M. \tag{17.7}$$

When the longitudinal stability has been determined the controllability of the aircraft will be examined. As a starting point the force and moment equilibrium around the aerodynamic center will be taken. As seen in Figure 17.1 Equations (17.8) and (17.9) were obtained.

$$L = L_{A-h}+L_h = W \tag{17.8}$$

$$M = M_{ac}+W(x_{cg}-x_{ac})-L_h l_h \tag{17.9}$$

Using dimensionless coefficients and by assuming that $L_h << L_{A-h}$ and therefore $W \approx L_{A-h}$ Equation (17.10) is obtained. Rearranging the terms and trimming the aircraft ($C_m = 0$) results in Equation (17.11).

$$C_m = C_{m_{ac}}+C_{L_{A-h}}\left(\frac{x_{cg}-x_{ac}}{\bar{c}}\right)-\frac{C_{L_h}S_h l_h}{S\bar{c}}\left(\frac{V_h}{V}\right)^2 \tag{17.10}$$

$$\bar{x}_{cg} = \bar{x}_a c-\frac{C_{m_{ac}}}{C_{L_{A-h}}}+\frac{C_{L_h}}{C_{L_{A-h}}}\frac{S_h l_h}{S\bar{c}}\left(\frac{V_h}{V}\right)^2 \tag{17.11}$$

Using Equations (17.7) and (17.11) the diagram in Figure 17.2 is obtained which shows the tail design area. Only the stability curve including the stability margin(SM) is presented.

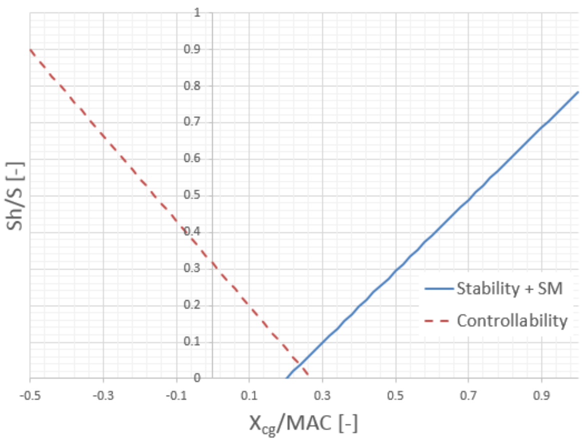

Figure 17.2: Scissor plot

17.1.2 Center of gravity range

To determine the centre of gravity (c.g.) range, first the operating empty weight (OEW) and its c.g. location needs to be determined. During the Class II weight estimation all the different components of the OEW were estimated. Next, a detailed weight estimation of several components is performed where components as the wing and engines are given a detailed weight estimation. To determine the c.g. location of the OEW an estimate of component c.g. is taken which is shown in Table 17.1. These values are based on the detailed design phase and the class II estimation which is component is based on which estimation is displayed in the last column.

Table 17.1: *Assumed mass and centre of gravity location of all major components*

Component	mass [kg]	x front [m]	Design stage
Wing	120	3.19	Detailed
nacelle engine	25	3.98	Detailed
engine flight	57	3.98	Detailed
engine car	94	3.18	Detailed
tail	43	5.46	Detailed
fuselage	80	2.03	Detailed
main lg	65	3.58	Class II
nose lg	11	0.2	Class II
Cockpit systems	63	0.39	Class II
electronic systems	67	3.58	Class II
Attachement	20	3.1	Detailed
Parachute	35	0.2	Detailed
Furnishing	40	2.03	Class II
Airco	22	2.03	Class II
OEW	742	2.83	

This results in a OEW of 742 kilograms with a c.g. of 2.83 meters from the nose of the car which is at 0.25 % of the mean aerodynamic chord (MAC). This point will be used as starting point in the loading diagram of the vehicle. Next, the luggage and passengers will give the maximum zero fuel weight(MZFW). Finally fuel is added until the maximum takeoff weight(MTOW) of 1206 kg is reached with its c.g. position which will provide the cg range during operations, also called the loading diagram. This loading diagram is presented in Figure 17.3.

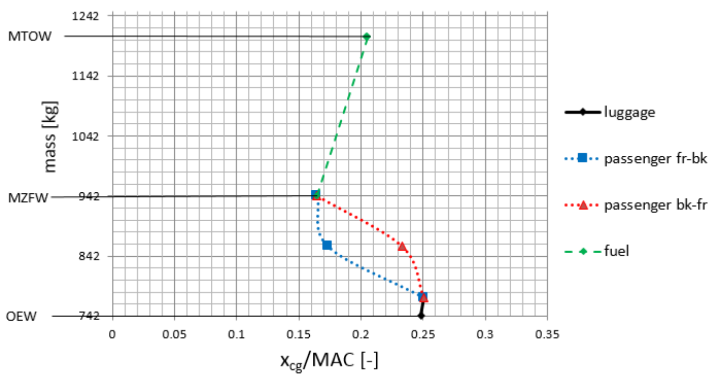

Figure 17.3: Loading Diagram

To study how the c.g. ranges will change with a shift of the longitudinal location of the wing both a forward and backward shift is performed. These shifts are performed in x location of leading edge mean aerodynamic chord with respect to the fuselage length (X_{LEMAC}/l_{fus}) and can be seen in Figure 17.4. The starting X_{LEMAC}/l_{fus} will be 0.62 with a range of 0.52-0.72.

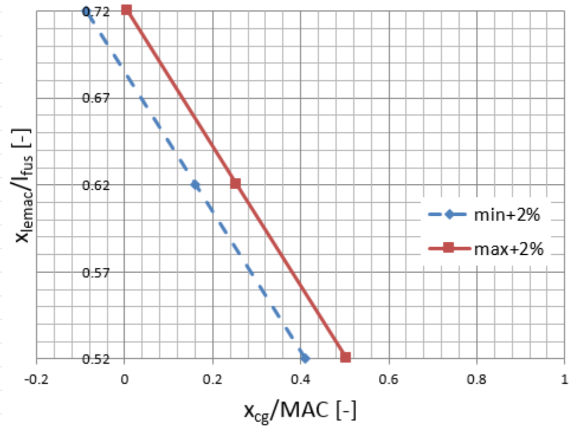

Figure 17.4: c.g. range

17.1.3 Horizontal tail sizing

After both the c.g. range plot and scissor plot are generated both plots can be overlapped to determine the optimal horizontal tail surface ratio and location of the wing with respect to the fuselage length. The optimal S_h/S will be 0.08 with a X_{LEMAC}/l_{fus} of 0.62.

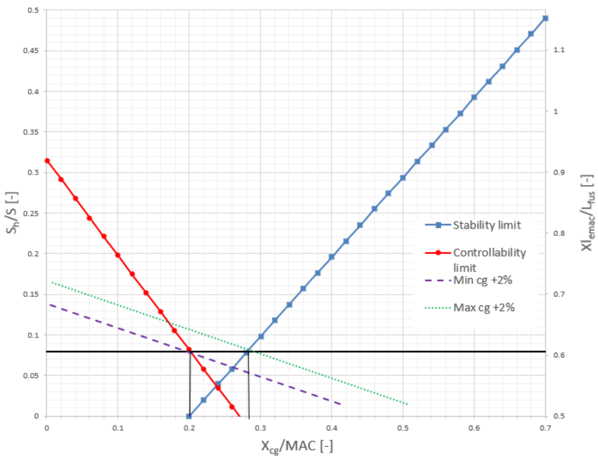

Figure 17.5: Projection of scissor plot and c.g. range

However, these optimal values are only with respect to the longitudinal stability and controllability of the aircraft and do not correspond with the required horizontal tail surface needed to meet the takeoff requirement. This takeoff requirement states that the aircraft needs to be able to rotate at a reasonable takeoff speed, see also Section 11.4. The final horizontail tail dimensions are then presented in Table 17.2.

Table 17.2: Horizontail tail dimensions

Parameter	Value
Total surface area (S_h)	2.5 m^2
Span (b_h)	1.22 m
Root chord (C_h)	1.04 m
Tip chord (C_h)	1.02 m

17.2 Vertical tail sizing

For the vertical tail sizing Torenbeek's method as stated in [76] is used. First the yaw moment due to the sideslip angle by the fuselage, wing configuration and propeller is determined. This is done using Equations (17.12) to (17.15), the parameters implemented in these equations can be found in Figure 17.6. Adding these equations result in a sum which is used to determine the vertical tail volume coefficient as found in Figure 17.7.

$$C_{n_{\beta_f}} = -k_\beta \frac{S_{fs} l_f}{Sb} \left(\frac{h_{f_1}}{h_{f_2}}\right)^{\frac{1}{2}} \left(\frac{b_{f_2}}{b_{f_1}}\right)^{\frac{1}{3}} \tag{17.12}$$

$$k_\beta = 0.3\frac{l_{cg}}{l_f} + 0.75\frac{h_{f_{max}}}{l_f} - 0.105 \tag{17.13}$$

$$C_{n_{\beta_p}} = -0.053 B_p \sum \frac{l_p D_p^2}{Sb} \tag{17.14}$$

$$C_{n_{\beta_i}} = -0.017\& + 0.012\& + 0.024 \tag{17.15}$$

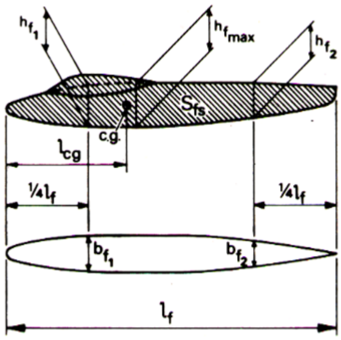

Figure 17.6: Parameters used for determination yaw moment contributions [76]

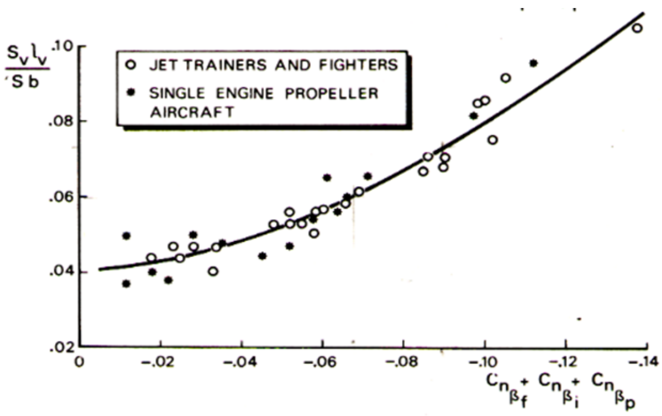

Figure 17.7: Vertical tail sizing jet trainers, fighters and single engine propeller aircraft [76]

The results for the yawing moment contribution and the vertical tail volume coefficients are found in Table 17.3

Table 17.3: Yawing moment contribution and vertical tail volume coefficients

$C_{n_{\beta_f}} + C_{n_{\beta_p}} + C_{n_{\beta_i}}$	Vertical tail volume coefficient
-0.168	0.042

After the vertical tail volume coefficient is determined the required dimensions can be calculated. Due to the h-tail configuration the total surface is simply divided over both surfaces at the end of the horizontal tails [77, p.126]. The aspect ratio of the tail is chosen to be 1.6, the sweep at 25% of the chord ($\Lambda_{\frac{1}{4}c}$) will equal 35° and the taper ratio for the vertical tail is chosen to be 0.40, all of which are regularly used in general aviation. The dimensions of the h-tail can be found in Table 17.4.

Table 17.4: Vertical tail dimensions

Parameter	Value
Total surface area (S_v)	1.64 m^2
Span (b_v)	1.15 m
Root chord (C_r)	1.02 m
Tip chord (C_t)	0.41 m

17.3 Aileron sizing

For the aileron sizing the helix angle for the aircraft is considered. According to [77, p. 274] pilots consider an helix angle of 0.07 as preferable. The helix angle is represented by Equation (17.16).

$$\frac{pb}{2V} > 0.07 \tag{17.16}$$

According to [78] a preferable helix angle for cargo and heavy lift aircraft should be larger than 0.07 and for fighter aircraft larger than 0.09. Thus the flying car ailerons are designed to be larger than 0.07. The equation for the helix angle depends on the rolling moment initiated by the ailerons, the roll damping of the aircraft and the aileron angle. The ailerons are assumed to have a maximum deflection of 25°. The type of ailerons used is chosen to be plain, as these are the least complex and cheap to produce and can be used without significant modifications to the wing. The ailerons are designed such that they have the same length (along the chord of the wing) as the flaps; 25% of the local chord and the hinge at 80% of the chord. Now only the location and the width have to be determined. The ailerons should not interfere with the flaps, which are located between 30%-69% of the half wing span as calculated in Section 13.4. That is done according to [78], the derivation is found in Equations (17.17) to (17.21).

$$\frac{pb}{2V} = -\frac{C_{l_{\delta a}}}{C_{l_p}}\delta_a \tag{17.17}$$

$$C_{l_{\delta_a}} = \frac{c_{l_{\delta a}} C_R}{Sb}\left[b_2^2 - b_1^2 + \frac{4(\lambda-1}{3b}(b_2^3 - b_1^3)\right] \tag{17.18}$$

$$C_{l_p} = -\frac{(c_{l_\alpha} + c_{d0})C_R b}{24S}[1+3\lambda] \tag{17.19}$$

$$\frac{pb}{2V}\frac{1}{\delta_a} = \frac{24c_{l_{\delta a}}\left[b_2^2 - b_1^2 + \frac{4(\lambda-1}{3b}(b_2^3 - b_1^3)\right]}{b^2(c_{l_\alpha} + c_{d0})[1+3\lambda]} \tag{17.20}$$

$$\frac{pb}{2V}\frac{1}{\delta_a} = \frac{24c_{l_{\delta a}}\left[\frac{y_2}{2}^2 - \frac{y_1}{2}^2 + \frac{4(\lambda-1)}{3}(\frac{y_2}{2}^3 - \frac{y_1}{2}^3)\right]}{(c_{l_\alpha} + c_{d0})[1+3\lambda]} \quad \text{since} \quad b_1 = y_1\frac{b}{2}, b_2 = y_2\frac{b}{2} \tag{17.21}$$

In Equation (17.21) the final expression is given and the location and width of the aileron is expressed in percentage of half span. The y_1 parameter is the inner side of the aileron and y_2 the outer part. The coefficients used are determined by the airfoil design, as elaborated in Section 13.1. One parameter which is not determined in Section 13.1 is $c_{l_{\delta a}}$. This is estimated using [79] using the change in c_l for a plain flap, which equals 0.9. Using this data the location and width of the ailerons is found after several iterations, and equals 0.73 to 0.97 of the half wing span. In Table 17.5 the final parameters per aileron are presented.

Table 17.5: Dimensions of the two ailerons

Aileron parameters	Value
Surface area (S_A)	0.290 m^2
Span (b_A)	1.184 m
Root chord ($C_{A_{root}}$)	0.275 m
Tip chord ($C_{A_{tip}}$)	0.215 m
Max. deflection ($\delta_{A_{max}}$)	$\pm$25°

17.4 Elevator sizing

The primary function of the elevator is to provide longitudinal control of the flying car. This requires a specific elevator deflection range and dimensions of the elevator which will provide the lift needed to ensure controllability. Rotation during takeoff is the most critical requirement for the elevator design during the flight envelope due to the high pitch angle needed. Detailed design based on aircraft derivatives is not reliable in this stage of the design. Hence a different approach will be used for the design of the elevator. The horizontal tail is based on a symmetric airfoil which will produce no lift during the ground run of the takeoff. However, a ΔC_L of 0.5985 is needed for the horizontal tail during takeoff based on Equation (17.22).

$$\Delta C_L = -0.35 A_h^{\frac{1}{3}} \tag{17.22}$$

To reach this ΔC_L a plain flap, which is modelled as the elevator, is designed using Equation (17.23). The assumption is made that there is no sweep in the elevator and the Δ_{clmax} of a plain flap is 0.9 which gives a $\frac{S_{wf}}{S}$ ratio of 0.739 which complies to a wetted elevator surface of $1.85 m^2$. The elevator span will be 90% of the horizontal tail tail span which is the maximum span usage and the elevator chord will be 30% of the horizontal tail chord which is conventional for plain flaps. The compliant elevator dimensions are given in Table 17.6. Furthermore, an elevator deflection of 22° down to 25° up is chosen based on statistics.

$$\Delta C_{Lmax} = 0.9 \Delta C_{lmax} \frac{S_{wf}}{S} cos(\Lambda_{hingeline}) \tag{17.23}$$

Table 17.6: Dimensions of the elevator design

Elevator paramater	Value
Wetted area (S_{wf})	1.85 m^2
Surface area (S_E)	0.68 m^2
Span (b_E)	2.19 m
Mean chord (C_E)	0.31 m
Max. deflection ($\delta_{E_{max}}$)	$-22°$ to 25°

17.5 Rudder sizing

To provide directional yaw control to the Volucrem a rudder is needed. The flying car has two vertical tails which implies that two rudders will be sized which act simultaneously such that they have the effect of one rudder. Effects of the wake flow of the propellers are not taken into account for the rudder sizing. This will imply some errors, but the effects are unknown at this stage of design.
The rudder design has to comply with the (CS-23) regulations which state that an aircraft must be able to be directional controllable during a cross-wind up to 90° of 25 knots while flying at the minimum airspeed [80]. Of the various scenarios in which the rudder is needed such as cross-wind landing, turn coordination, spin recovery, and adverse yaw, the cross-wind landing is the most critical in the case of the flying car. However, due to a lack of specific details of the vehicle's geometry, which are not available at this stage of the design, the rudder will be sized based on similar aircraft during a cross-wind landing. The rudder area to the vertical tail area ratio is 0.38, the rudder chord is 0.42 of the vertical tail chord meaning the rudder is swept as the vertical tail has some sweep. The rudder design surface area will be split upon the two actual rudders such that they have the effect of the one rudder design required. The wing span of the rudders will be 2.19 metres and maximum deflection is 24° in both directions. The rudder dimensions are summarised in Table 17.7.

Table 17.7: Dimensions of the two identical rudders

Rudder parameter	**Value**
Surface area (S_R)	0.32 m^2
Span (b_R)	1.04 m
Root chord ($C_{R_{root}}$)	0.43 m
Tip chord ($C_{R_{tip}}$)	0.17 m
Max. deflection ($\delta_{R_{max}}$)	$\pm 24°$

Chapter 18: Performance analysis

In this chapter the performance of the aircraft is analysed. The first section will calculate the achieved rate of climb, the second and third will discuss the field length of the aircraft at takeoff and landing respectively and the fourth section will calculate the range of the aircraft. The final section concerns the fuel usage. The calculations in this chapter are based on the final dimensions of the vehicle, which are summarised in Table 18.1.

Table 18.1: Dimensions of the aircraft

Dimension	Value		
$A[-]$	7.4	$OEW[kg]$	742.8
$C_{D_0}[-]$	0.0198	$P[kW]$	180
$C_{L_{TO}}[-]$	1.67	$\rho_0[\frac{kg}{m^3}]$	1.225
$C_{L_{Landing}}$	1.892	$\rho_{cruise}[\frac{kg}{m^3}]$	0.5895
$e[-]$	0.816	$\sigma[-]$	1
$f[-]$	0.9	$S[m^2]$	13.08
$\eta_p[-]$	0.8	$sfc[kg/kW/h]$	0.5
$MTOW[kg]$	1206.1	$W[kN]$	11.8

18.1 Rate of climb

The minimum rate of climb requirement is 500 ft/min. The design conditions for the flying car impose that this requirement is not critical. Therefore it is analysed what the vehicle can achieve. The rate of climb is calculated according to Equation (18.1)[81]. In this equation the “c" is the rate of climb and this aircraft can achieve a rate of climb of 9.39 m/s at sea level and 8.16 m/s at cruise altitude. This equals 1848 and 1606 ft/min respectively, so the rate of climb requirement is met. Moreover, at these climb rates the pressure system can no longer adapt quickly enough. This is therefore a limit which will not be achieved during regular operation.

$$c = \frac{\eta_p P_{br}}{W} - \frac{\sqrt{2\frac{W}{S}}}{\frac{(3*C_{D_0}\pi Ae)^{\frac{3}{4}}}{4C_{D_0}}\sqrt{\rho}} \tag{18.1}$$

18.2 Takeoff field length

The takeoff field length is the horizontal distance between the start of the takeoff roll and the point where the aircraft clears a 35 feet obstacle. The flying car is required to have a field length of less than 500 meters. The field length is initially calculated using Equation (18.2) [82]. The field length is then calculated using Equation (18.3). Using the numbers provided in Table 18.1, the TOP parameter equals 35.6, which gives a field length of 382 meters.

$$TOP_{prop} = \left(\frac{W}{S}\right)_{TO}\left(\frac{W}{P}\right)_{TO}\frac{1}{C_{L_{TO}}}\frac{1}{\sigma} \tag{18.2}$$

$$s_{TO} = 0.0577TOP_{prop}^2 + 8.6726TOP_{prop} \tag{18.3}$$

18.3 Landing field length

For the landing field length the distance from 50 feet above the ground until complete stop has to be calculated. The field length is calculated using Equation (18.4) [82]. The field length is then equal to 415 meters, which is again within the requirement of 500 meters. In this calculation the effect of the relatively strong motorcycle brakes is not accounted for. The true landing field length can therefore be shorter.

$$s_{land} = \frac{1.183f\left(\frac{W}{S}\right)_{TO}}{C_{L_{landing}}\rho} \tag{18.4}$$

18.4 Range

To calculate the range it is important to know the zero fuel weight, the maximum takeoff weight, the specific fuel consumption and the power required to fly at cruise speed. It is assumed that the aircraft has a climb flight path angle of 8° and a descend flight of 4°. With these angles the aircraft travels 150 km to climb to and descend from cruise altitude. Climb is performed using 90% of the maximum power, descend is done at a much lower power setting, depending on the descend angle. The maximum design payload is 200 kg. The minimum is 85kg. Of course there are pilots who weigh less, thus the maximum range can be slightly higher. The payload to range diagram is shown in Figure 18.1. When flying at maximum cruise speed, the range decreases, as shown in Figure 18.2. The exact ranges are found in Table 18.2, in this table it can be seen that the range requirement of 1000 km is achieved.

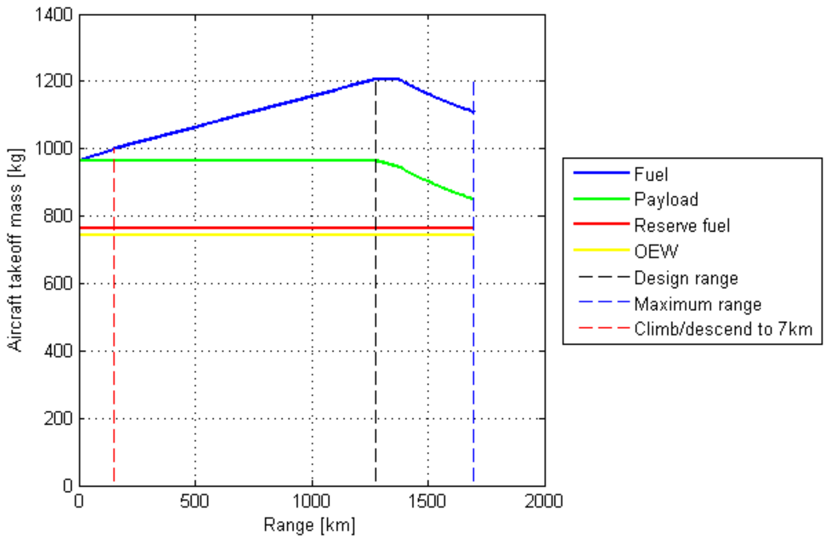

Figure 18.1: Payload range diagram at cruise speed

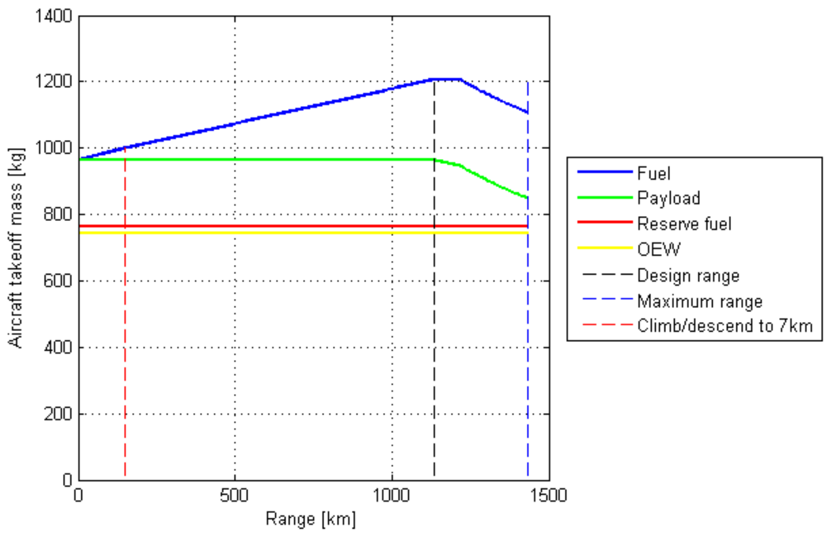

Figure 18.2: Payload range diagram at maximum speed

Table 18.2: Ranges for different conditions

Condition	Range cruise speed [km]	Range maximum speed [km]
Climb and descend to cruise altitude (7km)	150	150
Design payload	1278	1133
Minimum payload (max range)	1698	1431

18.5 Fuel usage

The fuel use for the different flight conditions is dependent on the power setting of the engine. The fuel use per flight segment is shown in table Table 18.3.

Table 18.3: Fuel usage for different flight conditions

Flight Condition	Mass Flow [$\frac{kg}{h}$]
Takeoff	90
Climb	81
Cruise	72
Holding	45
Descent	18

Subpart C

Attachment system

Chapter 19: Attachment concepts

In order to protect flight critical elements from outside influences and possible hazards, the flight module should be detachable and be able to be left behind at the airport. This will be a major challenge. The attachment system will have to carry all the loads during manoeuvres, during turbulence and landing. In addition to being reliable and providing redundancy it should be easy to use and maintain, and effort should be put into making it certifiable as well. As always the ease of use both during expected use and when something fails is one of the most important aspects to be considered. Finally it can not be forgotten that not only the loads but also the electronic systems need to be connected for the fly by wire system and to use the ground vehicle system to power the lights, EHAs and other subsystems.

First and foremost the mechanical loads need to be transferred between the ground vehicle (or fuselage when in flight mode) and the flight module. As observed from the fuselage and under normal circumstances the wings will be pulling it upward and pushing it forward using the flight engine. During other circumstances such as turbulent flight and violent manoeuvres the loads will be less predictable and all six degrees of freedom must be sufficiently constrained. The dimension restrictions of the attachment system based on the safety cage and the wing box dimensions are visualised in Figure 19.1. Also the axis system used is shown in the figure. Figure 19.2 gives the placement restrictions of the attachment system with respect to the ground vehicle.

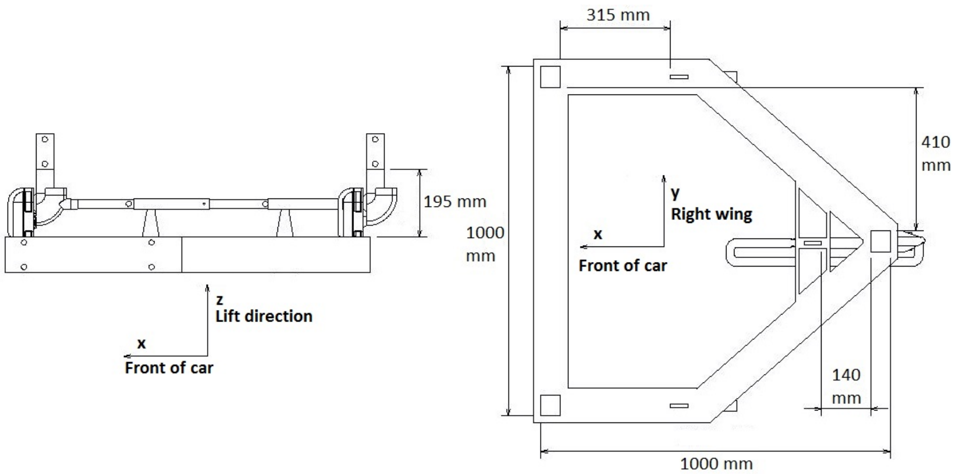

Figure 19.1: Left: Side view of the attachment system. Right: Bottom view of the attachment system

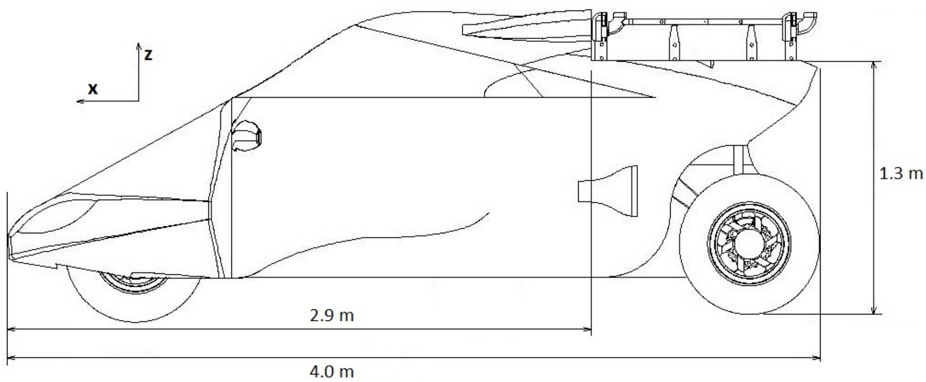

Figure 19.2: Side view of the attachment system with respect to the car dimensions

19.1 Concept generation

During the conceptual design phase, three different attachment systems were conceived. Two of them are based on direct mechanical attachment and one is based on magnetism. The automation of the attachment systems is a requirement as ease of attachment is a primary need. Preferably the driver would not be required to exit the ground vehicle to connect the modules.

19.1.1 Ball joint system

When temporarily connecting systems which carry substantial loads, a ball joint system comes to mind rather early in research. The ball joint principle is widely used, strong and most importantly low in complexity. Furthermore it would be possible to use off the shelf products which is always a preferable quality. The concept consists of a set number of ball joints with the female sockets connected to the ground vehicle safety cage, directly transmitting the loads from the attachment system into the load bearing structure of the ground vehicle. If connected to the wing box of the flight module this connection would likely minimise the weight penalties of modularity. Depending on the design load factors and redundancy either, 3, 4 or 6 ball and socket couples could be implemented. At first, the system will be sized for three attachment points using aluminium as material. This saves weight and aluminium has favourable fatigue properties even though the maximum allowable stress given geometric constraints is lower than steel for example.

19.1.2 Close fit pin system

The close fit pin system is characterised by the near perfect fit of stiffening elements mounted both on top of the ground vehicle and under the wing. Constraining elements would have to match up perfectly allowing pins to connect wing box and safety cage protrusions. The connection of aligned stringers would allow restriction of all degrees of freedom as well as simple implementation of redundancy by adding stringers or connection pins. Additionally it would be easy to automate the securing system after alignment. The attachment itself would be based on existing motorcycle lock systems where the connection between the stringers would be made by sliding metal bars. These bars would however experience shear forces and vibrations. Lift and thrust forces would be transferred in different ways, lift acting through shear in the sliding bars whereas the thrust forces are transferred through the bending resistance of the stringers. This was one of the preliminary ideas to attach both modules, and sail planes use a similar lightweight method to connect wings to the fuselage.

19.1.3 Magnetic attachment

The principle of the magnetic attachment is that permanent magnets would keep the modules together while the magnets can be disabled by switching on equally powerful electromagnets with a field in the reversed direction. Some disadvantages are evident since the cabin would need to be shielded from the magnetic field, certification would be hard and the materials are not sustainable. It is possibly a lightweight solution and shows more promise in the future.

19.2 Attachment system trade-off

Three concepts have been generated at this point. A trade-off is made between the concepts using a scale of one to five, worst to best design choice respectively. It can be seen from Table 19.1 that the ball joint concept design is preferred over the other concepts. This is mainly due to the simplicity of the system. The magnetic attachment is not preferred, primarily because it is not a proven concept and still needs a lot of development. The names used for the specific parts of the attachment joints are given in Figure 19.3.

Table 19.1: Attachment system concepts trade-off

Field	Weight	Concepts		
		Ball joint	Close fit pin	Magnetic attachment
Axial loads	11	5	3	5
Shear loads	11	3	5	2
Moment loads	11	4	4	2
Vibrations	11	5	3	4
Ease of use	9	5	3	4
Maintenance	9	5	4	2
Redundancy	9	4	5	4
Design complexity	8	5	3	2
Manufacturing	7	4	3	3
Sustainability	5	5	5	2
Certification	4	5	4	1
Cost	5	4	4	3
Total	**100**	**4.46**	3.79	2.99

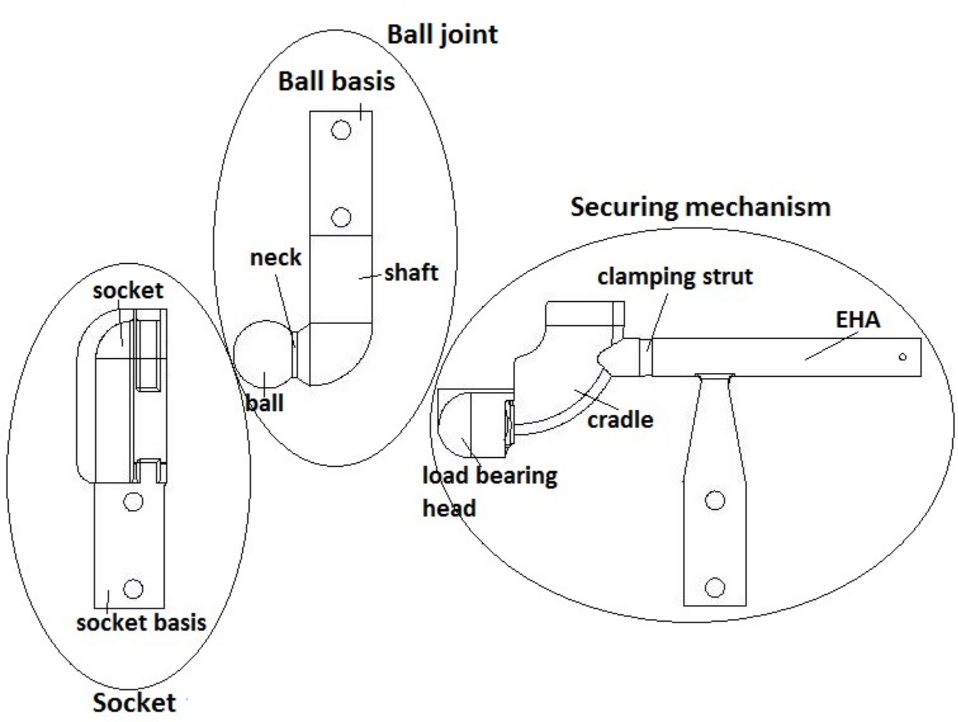

Figure 19.3: Specific names of the attachment joints

19.3 Electronics attachment

The attachment system for the electronic system is a more straightforward design than the mechanical attachment system such that no trade-off between several concepts is needed. The connection of the fly-by-wire is done by attaching a cable from the flight module to the ground vehicle. To be redundant the backup fly-by-wire system will use a second independent cable system. These two cables form the electric attachment system. Existing 13-pin connections should be able to transmit enough information and power while easily fastened and secured. In practice this would translate to a hatch in the back of the ground vehicle. After attaching the wings mechanically, the driver would open the hatch, take both 13-pin plugs and attach them to sockets in the car. Then the hatch can be closed leaving only the plug attachments in the cabin.

Chapter 20: Structural analysis

In order for the attachment system to be sized and certified the stresses during its operational life have to be considered and sized for. Since the ball joint system was selected after the trade-off, the stresses were calculated for this system. Ideally only three ball-joint connections are required and this was the initial configuration for calculations. The plan of approach will be explained first. Then load cases, initial sizing and stress concentrations will be investigated upon.

20.1 Calculation method

In order to size the load bearing elements of the attachment system, several steps should be taken. First the loads which will act on the attachment system will be investigated. The load in each of the three axis will be given a maximum value after which roll, pitch and yaw loads will add final values of the forces. This is an iterative process since the roll, pitch and yaw forces can be restricted in order to keep the system safe. Ball joints only restrain the three translational motions but do not fully constrain any rotation. This allows the determination of stresses whenever any force in any direction is applied. After the load limits for each of the components had been determined the load applied during the lifespan of the vehicle was determined by applying forces and moments in each of the six degrees of freedom and distributing these over the load bearing elements keeping in mind an unequal distribution of loads. After the loads have been identified the sizing for the bases, bolts and ball hook dimensions can be carried out. A CATIA model FEM analysis will be used to verify these sizes and to size the more complex socket. The latter is presented in section 20.3.

Assumptions used:

- When all three load bearing components are involved in transmitting loads, each component is sized to carry 50% of the total load
- When two load bearing components are involved in transmitting the same load each component is sized to carry 60% of the total load
- The largest load factors in each degree of freedom are isolated
- Combined load cases require the use of non-ultimate loads
- The fore-aft motion is restricted to 'wing forward' direction only
- Fore-aft motion in 'wing backward' direction occurs only due to gusts and these loads are significantly smaller than other critical load cases
- The wing box and safety cage of the ground vehicle are assumed to suffice in transferring loads
- Pure yaw forces are very small since a coordinated roll-yaw motion is implemented; yaw forces are assumed to be covered by lateral shear (gust) loads
- The load transfer between the ball and socket is perfect but does induce a moment with an arm of half the socket radius
- The material fatigue yield stress of 348 MPa is used in all calculations
- It is assumed the fore-aft security clamp does not carry critical loads
- The mass of the vehicle used for calculations is 1350 kg

In order to size the simple parts of the attachment system, the system can be simplified to be fully defined by the following equations:

$$\sigma = \frac{P}{A} \tag{20.1}$$

$$\sigma_{\tau} = \frac{V}{A} \tag{20.2}$$

$$\sigma = \frac{M \cdot y}{I} \tag{20.3}$$

$$\Sigma F_x = \Sigma F_y = \Sigma F_z = 0 \quad (20.4)$$

$$\Sigma M_x = \Sigma M_y = \Sigma M_z = 0 \quad (20.5)$$

20.2 Design load cases and preliminary sizing

Previous analysis of the load cases during normal operation revealed a maximum load factor of 3.2. This was due to manoeuvring loads as the gust loads are rather small in the intended range of flight velocity. A safety factor of 1.5 then leads to a maximum load factor of 4.8, rounded up to 5. The roll cage and wing have been designed to withstand a load factor of 8, therefore the attachment system is designed for this same load. The attachment system does not carry the loads of the entire vehicle at any time during operation. For example, when the wing generates a lift force equivalent to eight times the total weight of the vehicle part of this lift is used to accelerate the flight module and this force is not transferred to the modular ground vehicle through the attachment system. The maximum load case therefore is a pull-up under a load factor of 8. This results, depending on the weight distribution and loading case of the cabin, in a force equivalent to five times the total vehicle weight. Because of this a maximum load case in the z-direction of 66.2 kN has been used. Since the gust loads did not exceed 1.8 the maximum load factors used for the lateral and fore-aft direction are taken to be 2. Note that even though this adds only a small safety margin, the gust load will not be carried completely by the attachment system since the ground vehicle module is assumed to fly in a similar airflow to the wing module. Furthermore the 'wing backward' loading is assumed to be much smaller than the 'wing forward' loading since the engine is located in the wing module and the fuselage causes most of the drag. Using the assumptions listed in section 20.1 this results in the loads per joint per direction as shown in Table 20.1

Table 20.1: Limit loads from translational load factors

	x-direction	y-direction	z-direction
positive limit [kN]	13.3	13.3	33.1
negative limit [kN]	6.7	13.3	33.1

Moment load cases were added to the loads from Table 20.1. Due to the coordinated roll-yaw motion the yaw forces are assumed to be much smaller than the pitch and roll forces. The maximum loads from roll and pitch motions are shown below together with the EAS, ΔC_L and surface area S in Table 20.2. The load factor adds a tensile force to the simulate rough flight conditions. As can be seen in this table the stresses do not exceed $40kN$ which is set as the design load. In the x direction the 'wing forward' design load is $25kN$ due to the thrust, and $12kN$ is the 'wing backward' direction. The lateral y-loads are designed for $15kN$ as normally no loads should be present and only yaw and gust loads should affect loads in this direction. The safety factors used are rather generous in order to satisfy possible issues with certification.

Table 20.2: Additional limit loads from manoeuvres

	EAS	ΔC_L	S	load factor	axial force
Roll	80 $\frac{m}{s}$	0.7	1.35 m^2	2	38 kN
Pitch up	60 $\frac{m}{s}$	-0.6	2.5 m^2	2	27 kN
Pitch down	60 $\frac{m}{s}$	1.2	2.5 m^2	2	34 kN

From these limit loads the dimensions of the basis and hook have been determined, these are very low complexity parts and designed to fail last since the basis cannot be inspected visually from the outside. Finally these dimensions define limits used during the next step; adjusting the socket design until it it safe. Dimensions obtained are shown in section 20.4.

20.3 Finite element method

After calculating the necessary dimensions of several elements as described in section 20.2 the built-in Finite Element Method (FEM) from CATIA was used to identify the locations of stress concentrations in the ball and socket system connection. Six load cases were defined and are summarised in Table 20.3 which are the ultimate loads acting on the attachment joints.

Table 20.3: *Load cases of the attachment joints*

		Direction (kN)		
Load case	*Figure*	*z*	*x*	*y*
1	20.1	40	0	0
2	20.2	-40	0	0
3	20.3	0	25	0
4	20.4	0	-12	0
5	20.5	0	0	15
6	20.6	30	5	5

The first two load cases concern pure axial loading of the attachment joints. Figure 20.1 shows the tensile case. As can partly be seen in the figure the critical cross sections such as the largest socket cut-out are stressed to up to 308MPa. The highest stress found in this tensile case occurred in the inside of the socket; this is due to a CATIA error which removes the stress concentration when fixed. Therefore the attachment joint can carry the 40 kN tensile load.

Figure 20.2 shows the stresses during the maximum design landing case. Disregarding the pin which has a high stress due to CATIA clamping simulation the stress goes up to 100MPa. This is expected to be higher in reality due to CATIA FEM constraints since the securing mechanism strut is designed to bend elastically while its head transfers the loads from the ball joint into the socket base. Since the stresses do not surpass the limit the attachment joint passes this load case.

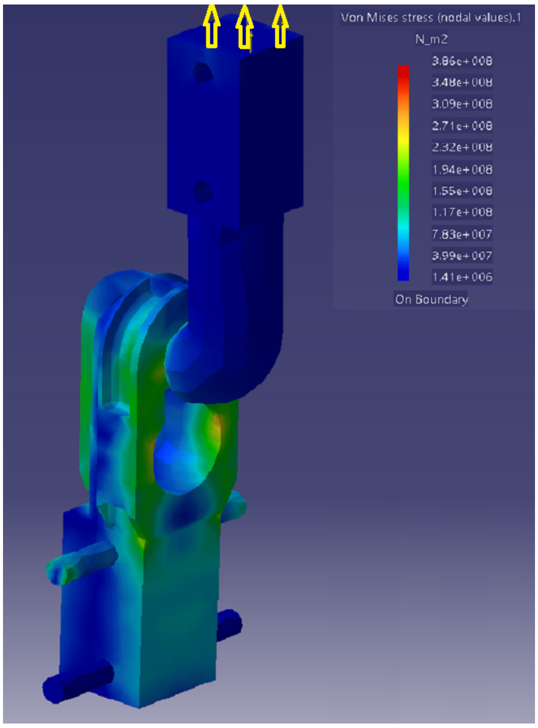

Figure 20.1: FEM z=40 kN (tension)

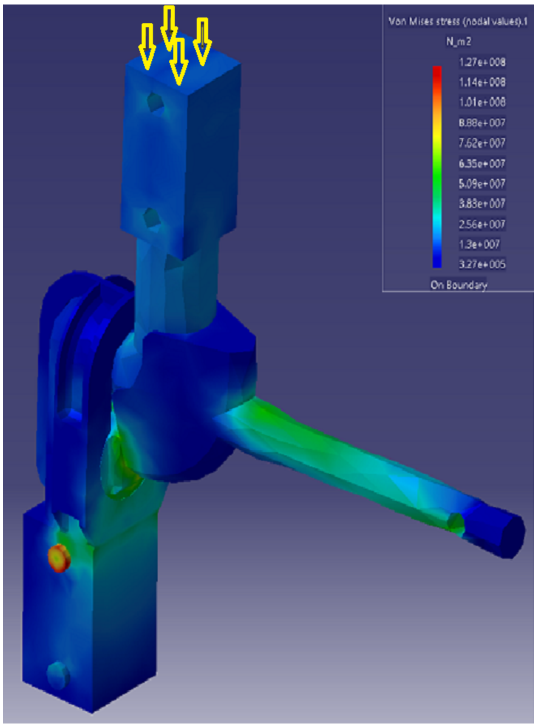

Figure 20.2: FEM z=-40 kN (compression)

The FEM stress calculations of the 'wing forward' loading of 25 kN is shown in Figure 20.3. The highest stress concentrations occur in the socket tip at the same location as in the previous tensile load case. When disregarding this concentration which will not occur for a smooth socket the maximum stress is 415MPa in the widest part of the socket opening as well as on the forward stiffener. This stress is slightly too high. However, the socket neck can be shortened by 20% which will reduce the bending loads by 20% without inhibiting any other function. With this adjustment the attachment joint will pass this load case as well.

Figure 20.4 shows the 'wing backward' load case. Disregarding known anomalous stress concentrations the highest stresses occur at the base of the socket which is a concentration which will be removed by making the lines smoother. The critical cross sections show maximum stresses of 410MPa which is slightly over the stress limit. This possible safety hazard will however be removed by shortening the socket neck as suggested for the 'wing forward' load case. This adjustment will provide a solution for both loads.

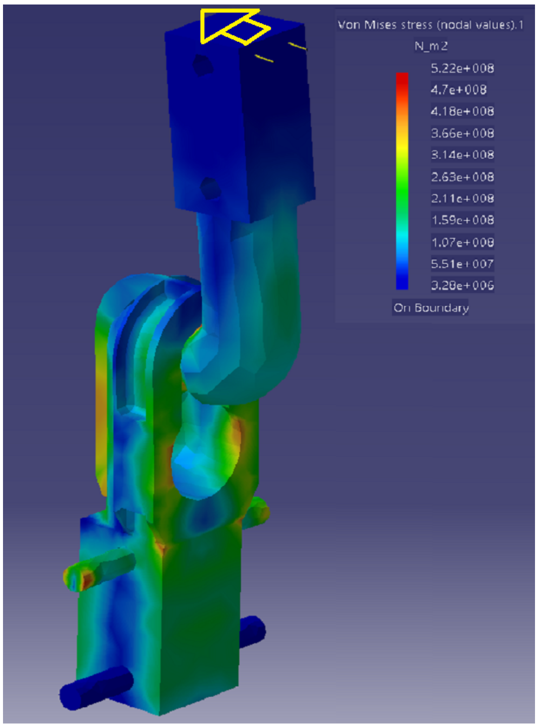

Figure 20.3: FEM x=25 kN (wing forward)

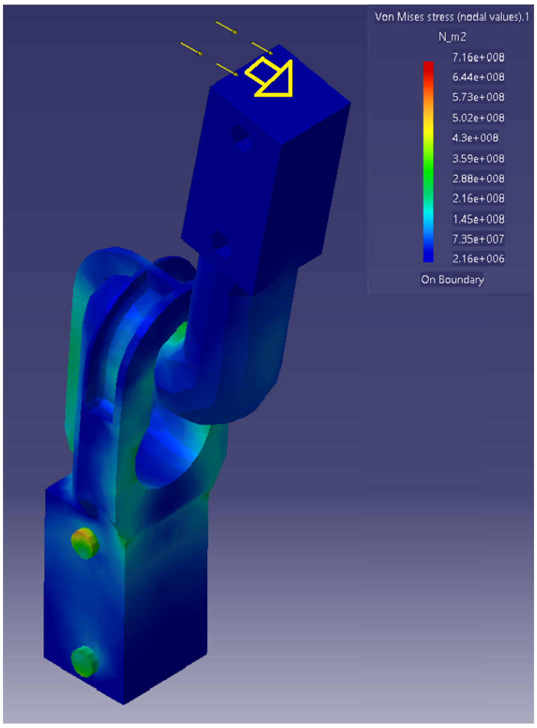

Figure 20.4: FEM x=-12 kN (wing backward)

Figure 20.5 depicts a lateral load of 15 kN. The highest stress aside from known anomalous stress concentrations is 330MPa. This lies below the maximum stress and this will further decrease with a shorter socket neck. Therefore the joint will sustain these loads.
Figure 20.6 shows the combined load case as described in Table 20.3. The maximum stresses are 334MPa which is just below the limit. Again, this stress will be reduced with a reduction in socket neck length. Therefore the joint is safe for the combined load case as well.

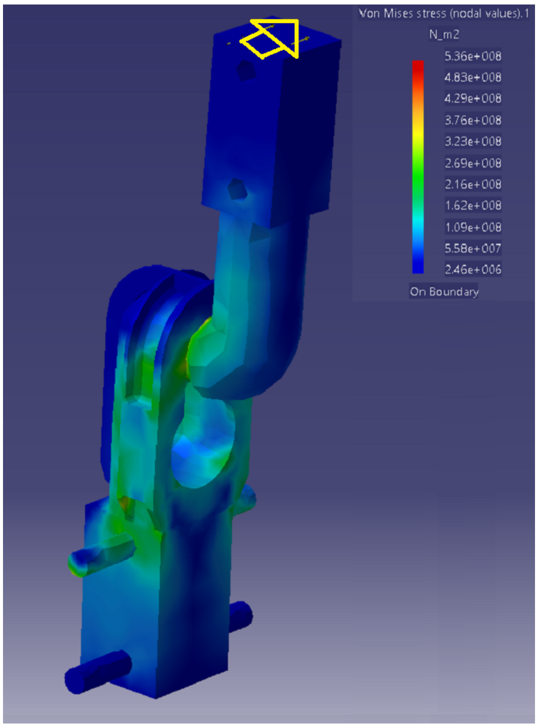

Figure 20.5: FEM y=15 kN

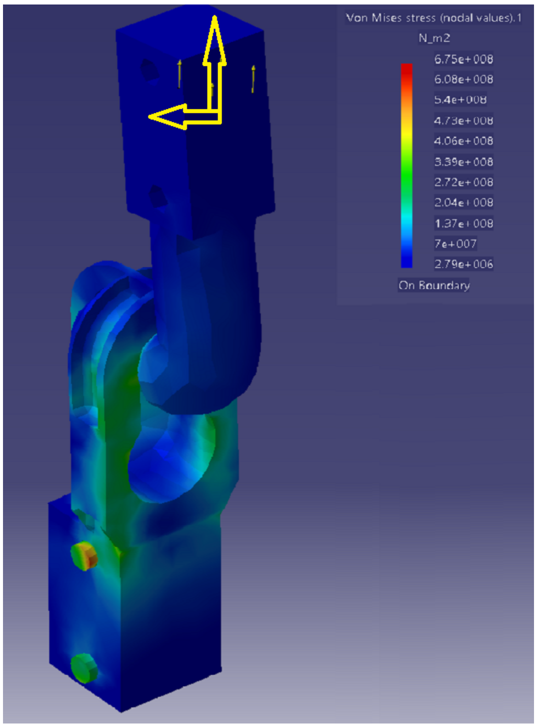

Figure 20.6: FEM x=5 , y=5, z=30 kN (tension)

20.4 Attachment system dimensions

This section focusses on defining the final dimensions of the ball and socket system geometry. The ball joint will be focussed specifically; the securing mechanism is not designed to carry loads and is sized by FEM. Additionally it is a noncritical component which is easy to inspect and replace and therefore its dimensions are not as critical as the dimensions of the rest of the attachment system. Table 20.4 lists the necessary dimensions for the attachment system. Figure 20.7 and Figure 20.8 visually depict the corresponding elements listed in Table 20.4.

Table 20.4: Dimensions obtained from preliminary analysis

Element nr.	Size [mm]	Element nr.	Size [mm]	Element nr.	Size [mm]	Element nr.	Size [mm]
1	50	9	95	17	22	25	5
2	50	10	60	18	36	26	70
3	100	11	6	19	80	27	24
4	5	12	18	20	140	28	102
5	15	13	25	21	54	29	10
6	15	14	60	22	54	30	44
7	70	15	100	23	56	31	3
8	25	16	13	24	10	32	15

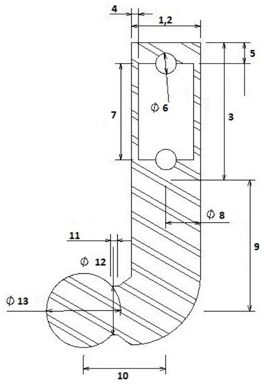

Figure 20.7: Dimension numbering of the ball hook, side view

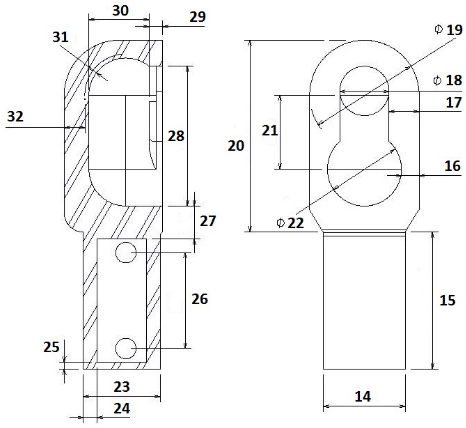

Figure 20.8: Dimension numbering of the socket, left side view, right front view

Chapter 21: Attachment operation

This chapter explains the use of the attachment system. The method of attachment is described first, then a short section will deal with emergency and safety measures on the attachment system outside of regular maintenance.

21.1 Positioning

To position the flight module above the ground vehicle for attaching purposes a positioning system is needed. The system must be designed such that the flight module can be lifted $1.675m$ above the ground from the module storage in the hangar to the ground vehicle. This should all be done with maximum ease of operation for one pilot. Three struts are designed to carry the wing module, each can carry all the flight module weight on its own. The flight module including fuel has a mass of $435kg$ meaning the struts have to be designed for at least $4300N$ using a gravitational acceleration of $9.81\frac{m}{s^2}$. Using a safety factor the force at which the individual struts will be designed for is $6000N$. The following formula is used to calculate the moment of inertia needed for one strut.

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{21.1}$$

Using a Young's modulus of $69GPa$ of Aluminium and a K of 2 gives a moment of inertia of $9.88 \cdot 10^{-8} m^4$. Using Equation (21.2) and a preset thickness of $2mm$ results in a radius needed of $26mm$. The resulting strut design is shown in Figure 21.1.

$$I = \frac{\pi}{4}r^4 - \frac{\pi}{4}(r-t)^4 \tag{21.2}$$

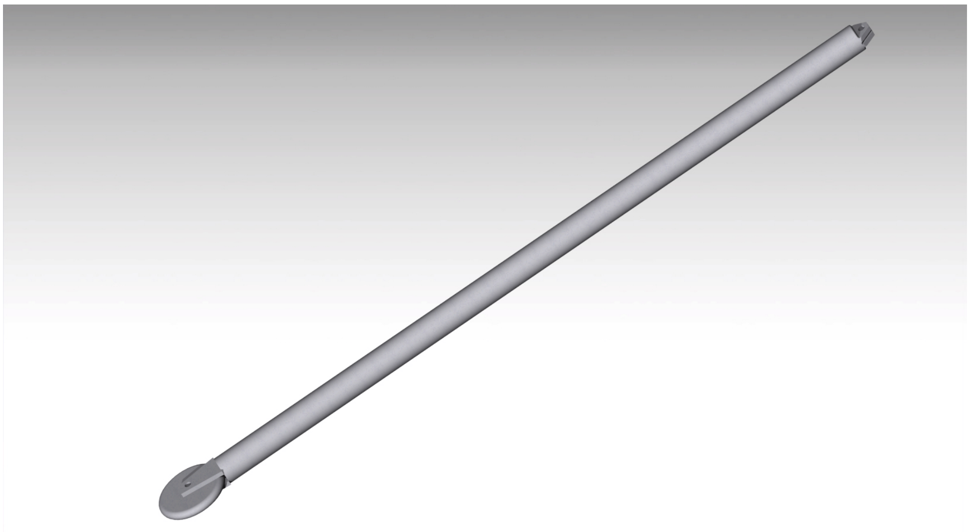

Figure 21.1: Attachment strut

Two struts are placed in front of the centre of gravity of the flight module and one strut is placed at the horizontal stabiliser for stability and ease of control of the flight module positioning. The top view of the positioning stage including the three struts is visualised in Figure 21.2 and the side view is given in Figure 21.3. The struts are attached to extended parts of the wing box ribs using two horizontal placed pins per strut to transfer the forces optimally. When the flight module is attached to the ground vehicle the struts are removed and stored in the wing, since plenty of space is still available. Ideally the struts would be left behind which is possible if a new set is available at the destination location. For detaching purposes of the flight module the struts can be re-attached and the module is stored in the module storage facility.

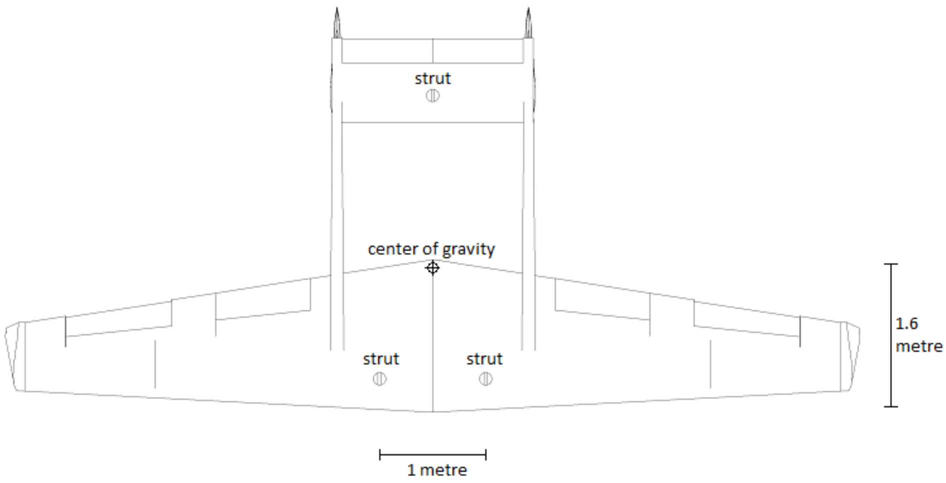

Figure 21.2: Top view of the flight module positioning stage

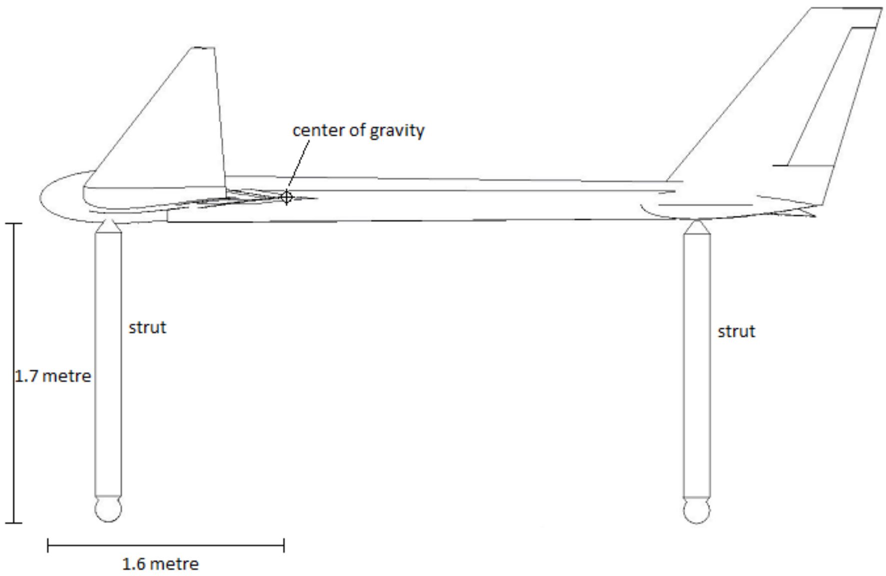

Figure 21.3: Side view of the flight module positioning stage

21.2 Connecting

The designed attachment system consists of three ball socket joints as decided in the trade-off. The joint, just before the ground vehicle and flight module are to be attached, is shown in Figure 21.4. The socket can be seen which is attached to the load bearing structure of the ground vehicle, and the ball joint is shown which is attached to the wing box. Furthermore a clamping system which involves an actuator is placed on the structure of the ground vehicle. Six steps are needed to perform the attaching which can be fully automatised. First the flight module must be moved forward to position the ball joint in between the socket and clamp. Then the hydraulic suspension of the ground vehicle must be moved upward. The flight module is then moved further forward such that the ball joint slides in the bottom of the socket. The ground vehicle is lowered using the hydraulic suspension such that the ball joint slides upward in the socket. The movement of the attachment system is now lowered because the gap of the socket is lowered to the neck dimensions of the ball joint. Then the clamp is moved in the lower part of the socket using the actuator, minimising movement of the ball joint and socket attachment. Finally a visual inspection can be performed and a pin is to be placed in the actuator making the EHA system redundant. The final state of the joint, when attached, is shown in Figure 21.5 including a gap in the actuator for the securing pin.

The shown joint geometry will be used twice in the front of the attachment system. The third joint is placed in the rear of the system such that the space between the front and rear sockets is one metre. Due to restrictions in the attachment system dimensions, the clamp of the rear component must be placed on the other side of the socket. The principle of the mechanism does not change and keeping in mind that the clamp does not bear critical loads the rear component is redesigned and visualised in Figure 21.6 when opened and attached in Figure 21.7.

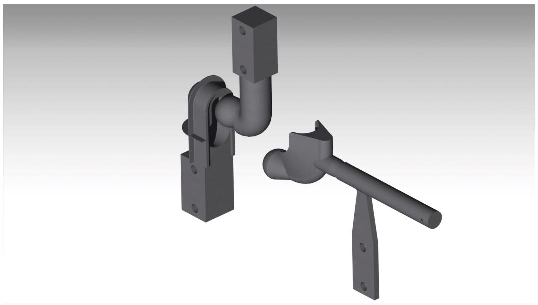

Figure 21.4: Front joint when open

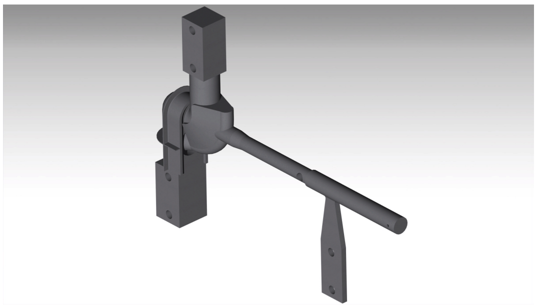

Figure 21.5: Front joint when attached

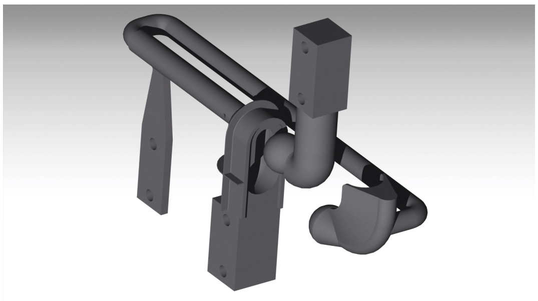

Figure 21.6: Rear joint when open

Figure 21.7: Rear joint when attached

The full model of the attachment system is shown in Figure 21.8. The three joints are shown, two in the front and one in the rear, without the wing box on top of the attachment system to which the joints are attached. Also a small part of the load bearing structure of the ground vehicle is shown in the bottom of the figure in which the sockets and clamps are attached. The attachment system is connected to these frames by 18 pins. The five-sided frame below the attachment joints is part of the safety cell as described in Section 8.1 and is sized as the safety cage. As seen from the figure there is enough space to position the cables for the electrical attachment and the EHA system.

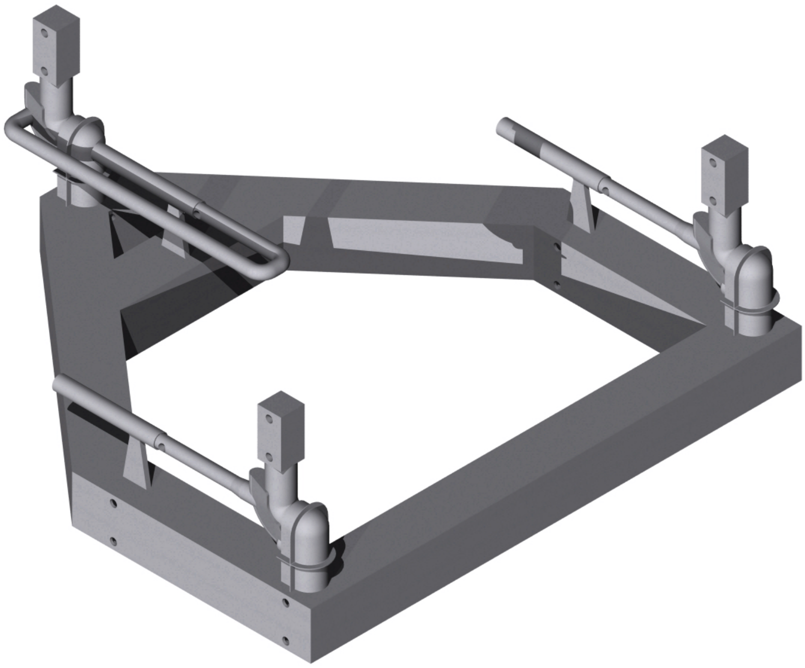

Figure 21.8: Attachment system including parts of the safety cage

21.3 Emergency and safety

Safety factors incorporated in the design include increasing the manoeuvring load factors to 5 times the gravity. Furthermore an unequal distribution of loads has been incorporated such that each joint is able to carry more loads than necessary. Additionally the entire load is assumed to be held by the attachment system whereas part of the forces will be used to accelerate either the wing or the ground vehicle. Finally a higher mass has been assumed such that the customer is safe if he or she chooses to overload the vehicle.

In case of critical failure of one of the components of the attachment system a backup is required to be available. This can be a simple cable hanging from the bottom of the wing and connected to the ground vehicle safety cell. To prevent retraction case of failure of the EHA of the noncritical securing mechanism a mechanical pin is inserted in its strut, preventing it from retracting during operation.

In order to promote transmission between socket and ball joint the fit is required to be close. Additionally lining the contacting surfaces with a simple elastomer or polymer will promote contact surface and load transmission, thereby reducing stress concentrations. Another advantage of coating the contacting surfaces is the maintainability. The coating will wear before the load bearing metals and this is easier to inspect and replace. Finally a polymer coating can help reduce noise and vibrations.

Subpart D

Operations

Chapter 22: Manufacturing, assembly and integration plan

The manufacturing, assembly and integration plan (MAI) shows the steps necessary to reach the complex end product starting from the production of basic parts. In the following chapter, the MAI will be described according to the chronological steps often seen when building aircraft. The system can be subdivided into the major components fuselage, the wings and empennage, the engines and the electronics.
In this design the concept of 'just in time' will be used. This means that the MAI is not based on fixed time constraints, but based on parts or assemblies which are finished just before they are needed. The reason for this is that this will improve a business' return on investment by reducing waste with respect to time, storage and material. Aside from this, the MAI presented here is based on the assumption that the Volucrem has been certified prior to mass production. The summarised process can be seen in Figure 22.1.

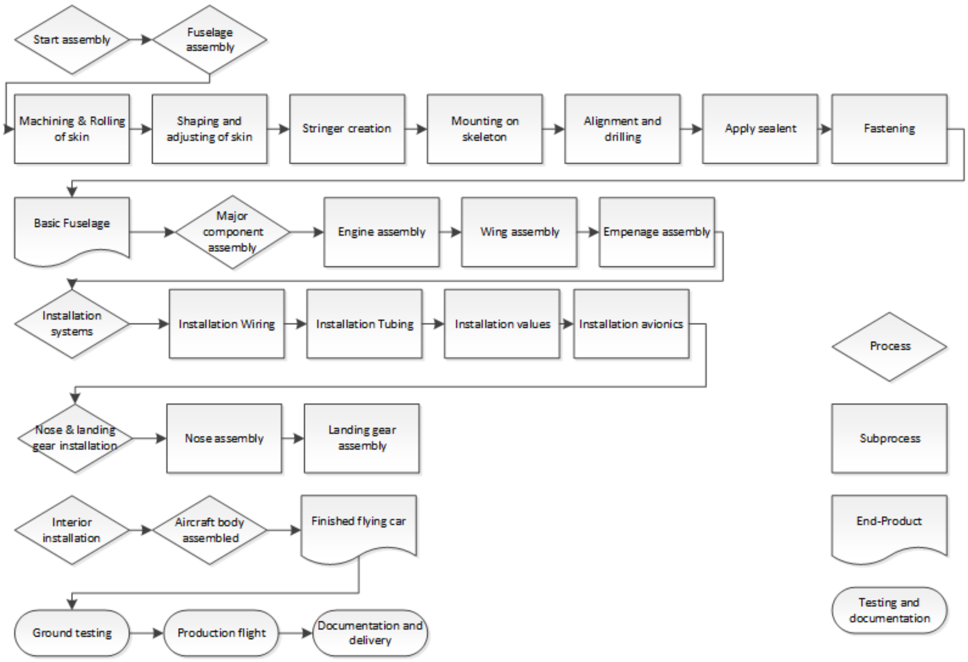

Figure 22.1: Manufacturing, assembly and integration plan

Fuselage assembly

The fuselage assembly consists of subparts which will be discussed chronologically. The skin is first machined and rolled out, after which shaping is carried out and the adjustments are performed onto a frame mould. Simultaneously the fuselage stringers will be created and positioned on the frame. Next the holes where rivets and bolts will be placed are drilled to ensure perfect alignment of the connection. The skin is then taken off as to make room for the application of a sealant over the frame. Before this sealant dries out, the skin is repositioned and riveted and bolted in to place, creating a near airtight system. This finished fuselage structure will then be held to be combined to the other major components.

Major component assembly

During the same time as the construction of the fuselage structure, the major components of the flight module are assembled. The engine will be put in the specifically manufactured nacelle after which the propeller will be attached. The wing and empennage will follow approximately the same process as the fuselage with the exception of the sealant. Additionally the fuel tanks will be placed in the wing.

Landing gear assembly

During the fuselage assembly stage, the landing gear parts will be put together as much as possible. This will mainly consist of attaching tires and brakes to the struts and assembling the suspension. These parts will then be attached to the fuselage during the major component assembly stage. Preferably the landing gear should be able to hold the fuselage after assembly as it would ease moving the product in further manufacturing.

Combining major components

After the fuselage and major components are ready, they will be combined. As this is a flying car and not a conventional aircraft, the fuselage will not undergo much in this stage. The wing, empennage and engine on the other hand will be combined to create the flight module. Here the focus will lie on mechanically joining the structures to each other, in a later stage the tubing and electrical systems are applied.

Installation systems

In this phase of the MAI, the avionics, hydraulics, flight control, tubing and electrical systems will be built into both flight and driving modules. The electric wiring will be bundled as much as possible to ensure optimal use of space and kept away from sensors as much as possible to ensure that there will be no interference. Systems that are both found in the pressurised cabin as well as outside the cabin will need to be sealed properly to ensure a minimum amount of cabin leakage. Furthermore areas where fuel tubing will be present will have to be coated with fire retardants.

Interior installation

During the last part of the MAI, the interior of the flying car will be inserted. The parts that will be placed are for example the seats, the seatbelts, lifevests, dashboard and steering wheel. All parts should be fastened safely, as during flight it is op the utmost importance that objects can not move around in the cockpit.

Painting

After all parts have been assembled to form the finished structure, the flying car will be painted in the colours that the customer prefers. This paint will not only benefit the Volucrem with respect to market appeal but will also help prevent damage due to moisture and light.

Ground testing

After all systems have been assembled non-destructive ground tests will be the first tests the Volucrem will undergo. These include general tests of the electrical systems, the hydraulic systems, on board computer and the landing gear. The fuel tanks are checked for leakage [83]. Furthermore the driving module will go through a track test to ensure that all driving systems work accordingly. As a last ground test, the attachment system will be tested by hanging the complete system on a jig and apply extra forces to see if the attachment holds.

Production flight

If ground test are passed without any deficiencies the pre-delivery flight tests will be performed. Flight systems will be closely watched to check if any faults arise, and simultaneously the engine temperature will be checked to prevent sudden overheating. These tests will only be done in perfect weather conditions to make flight as safe as possible. Certification will already have happened before the production phase, so if flight and ground tests are completed sufficiently the aircraft can be considered safe.

Documentation and delivery

In the final step of the MAI, the flying car will receive its registration numbers and chassis numbers with which the customer will be eligible to fly and drive the Volcurem. The flying car will then be delivered to the customer at a desired location.

Chapter 23: Logistics

23.1 Regulation and certification

When considering both motorcycle and aircraft (CS-23) regulations some guidelines are present for the certification of a specific vehicle. First the aircraft part is considered due to the fact that this is a more critical vehicle. Then the regulation set for a motorcycle is considered. To make the conversion between driving and flying, a multi purpose cockpit should be a good solution. Switching between the flight and drive mode would ideally be done by pressing one button. The same screen inside the cabin will show driving or flying parameters when applicable.

23.1.1 Aircraft

The CS-23 regulations are applicable to the following general configurations: airplanes in the normal, utility and aerobatic categories that have a seating configuration of nine seats or fewer excluding the pilot seat(s), and a maximum certified takeoff weight of 5,670 kg (12,500 lb) and propeller driven twin engined airplanes in the commuter category that have a seating configuration of nineteen seats or fewer, excluding the pilot seat(s), and a maximum certificated takeoff weight of 8,618 kg (19,000 lb) or less. The normal category is limited to non-aerobatic operations.[3]

According to the regulations, the aircraft requires a minimum number of instruments to be able to safely operate a light aircraft. These instruments are also referred to as the 'six pack' and are stated below and shown in an analog matter in Figure 23.2. [3] [84]

1. An airspeed indicator
2. A non-stabilised magnetic director (also called heading indicator)
3. An attitude indicator
4. Vertical speed indicator
5. Turn Coordinator
6. Altimeter

Next to these six basic indicators three navigation indicators were commonly used to enable the pilot to determine its trajectory. However, nowadays the use of analog instruments is outdated. Modern aircraft use a glass cockpit with most of the time a dual-display electric integrated flight instrument system which shows all the essentials on two digital screens without the use of analog instruments. An analog and digital display is shown in Figure 23.1 and Figure 23.2. For redundancy an integrated standby instrument system(ISIS) should be used in case of electrical breakdown. In Figure 23.1 an ISIS is present at the left hand side of the cockpit.

Figure 23.1: Digital cockpit layout[85]

Figure 23.2: Analog cockpit layout [86]

When considering the instruments needed regarding power plant setting the following list is the absolute minimum.

1. A fuel quantity indicator for each fuel tank
2. An oil pressure indicator for each engine.
3. An oil temperature indicator for each engine.
4. An oil quantity measuring device for each oil tank
5. A fire warning system

23.1.2 Road vehicle

For transportation on the road, the choice was made to use a three wheeled Carver-type vehicle as opposed to an enclosed motorcycle. One of the reasons for that is that the regulations are the same but the design complexity is limited due to the inherent low speed stability of three-wheeled vehicles. Safety systems such as a roll cage or airbags are not required but this does not mean that they will not be implemented in the final design. The requirements which have to be fulfilled to get the vehicle certified as a motorcycle are the following:

- Lights
  - Front
    - One headlight (White/Yellow)
    - One dipped headlight (White/Yellow)
    - Indicators (Orange)
  - Back
    - One headlight (Red)
    - Brake light (Red)
    - License plate light (white)
    - One reflector (Red)
    - Indicators (Orange)
    - One parking light (Orange)
- Interior
  - Speedometer
  - Horn
  - RPM meter
- Body works
  - Left and right mirror
  - Interior mirror
  - Dimensions
    - $< 4m$ in length
    - $< 2m$ in width
    - $< 2.5m$ in height

23.1.3 Licenses

23.1.3.1 Pilot

To be allowed to fly an aircraft, a pilot licence is needed. These pilot licences are granted by the Civil Aviation Authority of each country. On these licences extra rating can be obtained in special cases. The three main pilot licences are the recreational license, the private pilot license and the commercial license. In America also a sports pilot licence exists. The licence needed for the roadable aircraft will be a private pilot licence. This licence allows the pilot to fly relatively light aircraft with passengers without commercial gain.

In order to fly IFR an instrument rating on the licence is needed. With this rating the pilot can fly in IMC (Instrument Meteorological Conditions) like fog and clouds. However the rating is rather expensive. A less expensive version of this rating is the enroute instrumentation rating. With this rating the pilot can fly under IMC during cruise, but is not allowed to fly IFR during take-off and landing. For some specific systems the pilot needs an instructors endorsement. The endorsements however do not require any flight tests with a representative. The systems for which an endorsement is needed are: tail wheels, complex aircraft (like variable pitch propellers, flaps and retractable landing gear), performance aircraft with more than 200 horsepower per engine and pressurised aircraft operating at high altitudes. Since the Volucrem features a pressurised cabin and a turboprop flight engine additional qualifications are needed to be allowed to fly this vehicle.

23.1.3.2 Road vehicle

As indicated earlier, the roadable part of the the flying car will be certified as a motorcycle or tricycle. Therefore a motorcycle license will need to be obtained in the country of use. In the Netherlands, a motorcycle licence can be obtained by taking several tests at the 'Rijksdienst voor het wegverkeer'. These licenses are split into the following categories [87]:

- A1; motorcycles with a maximum cylinder capacity of 125 cm^3, a maximum power of 11 kW and a power/weight ratio of less than 0.1 kW per kg; all-electric motorcycles with a maximum power of 11 kW and a power/weight ratio of less than 0.1 kW per kg and motorised tricycles with a maximum power of 15kW.
- A2; motorcycles with a maximum power of 35 kW and a power to weight ratio of less than 0.2 kW per kg and not derived from a vehicle of more than double its power.
- A; motorcycles and motorised tricycles with a power of over 15 kW.

In order to be allowed to operate the road able vehicle it is expected that the full license A will be needed.

23.2 Module storage

The flight modules will be stored together in hangars at different airports. To ensure optimal use of space it has been decided to stack the flight modules in a similar manner to stacking cars. To accommodate this, a basic design of the stacker has been made which can been seen in figure 23.3. The system will work as follows:

1. Request flight module at stacker
2. Stacker lowers flight module
3. Client prepares positioning system
4. Client rolls out flight module and attaches it to the road vehicle

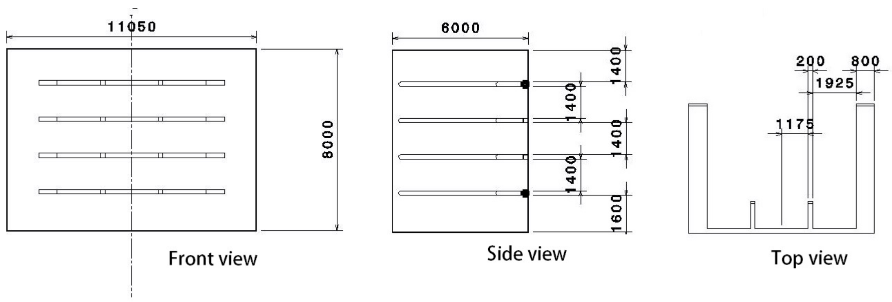

Figure 23.3: Stacker storage drawing

On return, the same process will be done but then in reverse order.
The stacking system accommodates four flight modules per stacker while having a maximum height of 8m which was assumed to be the maximum height able to fit inside a standard airport hangar. It will depend on the airport and the amount of clients to decide how many stackers are needed in the hangar.
Of course the possibility exists that the flying car will be flown to airports where this system is not available. Here the flight module will be stored as conventional planes on the positioning struts.

23.3 Refuelling

The refuelling system will be incorporated in the flight module stacker. Every flight module that is put into the stacker will be connected to a fuel tube, which will fuel the aircraft automatically when told to do so. A system which has been thought of for example, is that the customer can login to a server and define the range that will be flown and the weight taken on board, after which the system will automatically calculate how much fuel should be tanked into the wing. This means that at arrival, the customer will not have to worry about fuelling his aircraft which reduces conversion time. Again the possibility exists that the airport where the flying car is stored does not have this system. Here the conventional method for wing fuelling will be used.

23.4 Conversion

The conversion of the car to an aircraft is one of the most important activities which will have to occur. According to the given requirements the conversion should be able to be done within thirty minutes. In Table 23.1 the estimated conversion time can be found.

Table 23.1: Conversion time

Task	Time [mins]
Retrieve Flight module	5
Refuel	5
Attach to car module	5
Remove and stow poisitioning system	2
Convert interior systems	3
Pre-flight checks & taxiing	10
Total	30

As can be seen, the conversion can be done within thirty minutes. Refuel is in bold as it is not always applicable, if the stacker system is present refuelling will have taken place automatically. It is however advisable to refuel the car tank before flight, as to ensure the car engine has enough fuel to power the flight systems and pressurisation systems during flight. This will take a maximum of three minutes.
The conversion of the interior systems has also been conservatively estimated to ensure that no rush is needed. As explained in section 10.3 the electronics and control modes are switched from drive to taxi to flight mode by means of a turning knob which is considered easy on the operator. Pre-flight checks have two components, the visual manual checks and the electronic flight checks performed during taxi mode using the electronic displays. The manual checks are explained in section 23.5 and the electronic checks include checking the fuel indicator, electronic connection between car & flight module and flight display checks. The rest of the tasks are assumed self-explanatory. When converting from flight to car mode the reverse will have to be done. However as refuelling the flight engine is not needed and flight checks are not necessary, this will most likely only cost 15 to 20 minutes.
When flying IFR a flight plan is required. According to a recently graduated pilot flight plans can be submitted starting a day before flight and will need approximately half and hour to be processed. Furthermore this can be done using internet which increases the flexibility to changes and can be done from anywhere. As the trend of digitalisation is visible in all sectors, it can be assumed that this process will become more and more automated. A flight plan will therefore in the future take next to no time to create and submit.

23.5 Pre-flight checks

When looking at pre-flight one of the key requirements here is the conversion time of less than 30 minutes. To assure a low door-to-door time both the attachment and the pre-flight checks should not require that much time. Usually the pre-flight checks will last around 10 minutes to perform which leaves about 20 minutes to assure the attachment is fitted properly beforehand.

When looking at pre-flight checks it is preferable to use a pre-flight checklist due to the risk of missing fail-safe system checks. When considering a modular system this will be of even greater importance. In the following enumeration a list of the pre-flight checks of light aircraft is given. When looking at a modular aircraft additional steps should be made, these steps are made italic to emphasise their importance.

1. Begin the pre-flight in the cockpit, since before flying it is necessary to ensure all cockpit equipment is operating, the pitot tube heating is functional and the fuel tanks have sufficient fuel for the flight. *Check for any warning lights of attachment of electrical wiring and mechanical bonding of the flight module.*
2. Exit the aircraft. Check for the internal structural failures by looking at the smooth movement of the door.
3. *Remove the side mirrors and place them within the cabin.*
4. Walk around the aircraft, looking for damage caused by impacts or cracks and seams separating from airframe fatigue, hard landings or other mishaps.
5. *Assure that the mechanical connection of the flight module is fitted properly by inspection.*
6. Begin at the right wing, after exiting the aircraft, and look at the forward wing surface for nicks, loose fasteners, dents, or other damage. Inspect the pitot tube for blocking.
7. Check the fuel for contaminants by draining some fuel, pay specific attention for water, particulates and microbial growth.
8. Move to the tail assembly.
9. Visually inspect the antennae assembly and the pitot static ports.
10. Move to the opposite side of the aircraft, continuing to look over the aircraft skin to the wing and inspect the second pitot tube.
11. Move to the front of the aircraft and look at the exhaust; looking for oil blow-out and other damage.
12. Check the engine oil, the ignition wires, magneto electrical connections, and the fuel lines and other hoses to be sure they are seated properly and tightly clamped.
13. *Check if the electrical backbone is properly connected by inspection.*
14. Move to the propeller and look at the propeller itself, to be sure the blades are not cracked, bent, delaminated, or damaged in other ways.
15. Check for fuel or lubricant leaks around the engine compartment, cowling, and fuel tank locations.
16. Visually inspect the wheels and landing gear for irregularities.

These pre-flight checks increase the mission door-to-door time therefore these checks only have to be carried out when no existing airport infrastructure is present to perform these checks before the user arrives at the airport. Having an automated system which prepares the flight module in advance would minimise the conversion time. However, when the Volucrem is first introduced the specialised infrastructure will be minimal making these pre-flight checks essential.

Chapter 24: Maintenance

24.1 Ground vehicle maintenance

In general cars undergo a maintenance check once every year. Even though the flying car is classified as a motorcycle, it is advisable to go into maintenance once per year. The yearly check should include the inspection of on-board electronics, the engine, dynamic vehicle control and the pressurisation system as additions to the standard maintenance procedure.

24.2 Flight module maintenance

In Table 24.1 a maintenance cycle is presented form the Light Aircraft Maintenance Programme (LAMP) presented by the UK Civil Aviation Authority(CAA). The programme addresses the scheduled maintenance requirements for airplanes with less than 2730 kg MTOW, regulated by the EASA [88].

Table 24.1: Example Maintenance Check Cycle [88]

Check title	Content	Period
Pilot pre-flight	Refer to airplane flight manual	Prior to every flight
Check A	Check A items	Prior to first flight of the day
50 hour check	50 hour check items	Not exceeding 50 flying hours or 6 months, whichever is sooner
150 hour	Check 50 and 150 hour check items	Not exceeding 150 flying hours
Annual check	50, 150 hour and annual check items	Not exceeding 12 months

The 50 and 150 hour checks should be performed within a 10% offset of the actual deadline and the annual check could have an maximum offset of 1 month. Essentially all flight critical elements, with the exception of the board computer, are present in the flight module. Therefore the flight module can be inspected in relative isolation from the ground vehicle module during the 50 and 150 hour checks and the CS23 [3] regulations can be followed.

24.3 Attachment system maintenance

The attachment system was designed to be easy to maintain. Since the ball joint and socket basis are bolted to the roll cage and wing box they can be removed entirely during yearly checks to be inspected for cracks and wear on surfaces normally covered. A defective ball joint or socket can be completely removed and replaced by a new insert in case cracks or dangerous wear is detected by simply unbolting and removing the insert. This scheme ensures that the attachment system is always suitable for operation.

24.4 Maintenance logistics

The flying car is a new product, therefore several adjustments will have to be made to existing infrastructure. For example, car mechanics should be available with knowledge of the DVC, attachment and pressurisation systems. Additionally, regular flight module checks should be specified for an aircraft which is missing the fuselage and cannot move on its own. This will require the use of a location as well as personnel qualified to perform maintenance on the flying car.

Chapter 25: Sensitivity analysis

A sensitivity analysis can be carried out on the design to investigate the robustness of design options to changes in the design to determine the design feasibility. This analysis will therefore focus on altering different inputs and investigating the change in output. The parameters which are changed are cruise speed, payload mass and the range. The effects are explained in Sections 25.1 to 25.3. These parameters are useful design parameters that affect the mission of the Volucrem vehicle.

25.1 Cruise speed

When the cruise speed is altered there are various parameters of interest that should be investigated, namely the power required, the fuel weight, range and mission duration. The power required is dependent on the drag generated and the velocity at which the vehicle travels. Therefore increasing the cruise velocity results in an increased power required. Since the drag depends quadratically on the velocity, the power required has a cubic relationship with velocity. Since the power required increases, this means that the total fuel mass changes as well, and therefore also the aircraft takeoff mass. If there is a change to the mass of the aircraft the amount of lift and thus also drag depends on the weight, thereby again changing the power required. Furthermore, the change in required power changes the optimal engine selection which could result in a different engine mass again affecting the entire aircraft mass.

Another effect of altering the cruise speed is the time to complete the mission. Increased cruise speed results in a reduction in the time to cover the mission range and vice versa. Therefore the cruise speed has a large influence on the door-to-door time, which is a large selling point of the design and has to be carefully considered. Furthermore, the fuel tanks are sized depending on the power required and the time it takes to complete the mission. This means that the aircraft mass is sensitive to change to a different cruise speeds.

25.2 Payload mass

Another parameter of interest to investigate the sensitivity properties is the payload mass. Changing the amount of payload is of interest for the mission as changing the number of passengers and the amount of luggage that the passengers can carry affects the market success of Volucrem.

Changing the payload mass increases the overall aircraft mass, this results in increased fuel mass and drag which in turn increases the power required. This could affect the engine selection which could further alter the overall weight. Furthermore, changing the payload mass affects the centre of gravity location, this imposes certain stability constraints that have to be considered. Moreover, the fuselage will have to be redesigned to account for more passengers or luggage space. This would have an influence on the pressurisation system design. The pressurisation system is driven by the drive engine, thereby this would have to be re-investigated to determine whether the drive engine can still drive the pressurisation system.

25.3 Range

The range is another parameter which affects the design greatly. The range has an influence on the amount of fuel that is required to obtain that particular range. However, the snowball effect plays a predominant roll in the analysis of range. If the range of the aircraft is lowered, the amount of fuel required is also decreased. This would lower the weight of the aircraft which reduces the power required. Having a lower required power means that a smaller engine can be selected further lowering the weight and drag. This then again reduces the required fuel and so on. For an increase in range the same snowball applies for increasing weight.

Chapter 26: Business model

In the following section of the operations chapter, the cost analysis and the business model will be portrayed. For the cost analysis the estimation has been performed using the method described in the book 'Airplane cost estimation' by Dr. Jan Roskam [89]. This has been used for the research and development phase, the manufacturing phase and finally for calculating the unit price of the flying cars. The estimations have been based on a production of 566 flying cars during the entire program, for which reasoning will be given in the Section 26.3. The operation costs have also been estimated, taking into account the maintenance costs, the fuel costs, the hangar costs and the insurance costs. Finally, with all costs estimated, a business model has been created which complements the costs in such a way that it will be the most advantageous for the clients.

26.1 Research, development, test and evaluation costs

As mentioned earlier the RDTE costs were estimated using Roskams method [89]. The research and development costs consisted of the following:

- Airframe engineering and design cost
- Development support and testing cost
- Flight test airplanes cost
- Flight test operations cost
- Test and simulation facilities cost
- RDTE profit
- Cost to finance RDTE phase

For this estimation, certain parameters were needed. These parameters included the maximum velocity, engineering costs and number of test vehicles. A complete view on all the parameters can be found in Appendix C.
The total RDTE costs were estimated to be approximately 7.5 million euro, which would be divided over all flying cars sold.

26.2 Manufacturing and acquisition costs

In the following section the manufacturing and acquisition costs that have been estimated are explained. The difference between the manufacturing costs and the acquisition costs is the profit the company makes, nothing more nothing less. For this estimation, the profit was assumed to be 10% of the manufacturing costs. The manufacturing costs consisted of the following:

- Airframe engineering and design costs
- Airplane program production cost
- Production flight test operations cost
- Cost to finance the manufacturing phase

It was estimated that the manufacturing and acquisition costs would total to be 264 million euro for 566 flying cars, and would again be divided over the sales of all aircraft. A complete view on all the parameters can be found in Appendix C.

26.3 Unit costs

In the previous sections it was stated that the production volume would consist of 566 flying cars. This number is deduced by keeping the requirement of a maximum unit price of half a million euros in to account. The more flying cars produced, the lower the unit price becomes as the RDTE costs are spread over all flying cars. It was found that the production of 566 flying cars, at a rate of 5 per month would lead to a unit price of 480.000 euros. The reason

20.000 euros less then the half a million is realised, is as unexpected costs should be able to be coped with. If more flying cars were to be sold, the choice could be made to decrease product price or to make more profit.

The unit price consisted of summing the RDTE costs and the manufacturing and acquisition costs and dividing that by the amount of flying cars sold during the complete product life. A complete view on all the parameters can be found in Appendix C.

26.4 Estimation accuracy

As mentioned before, the cost estimations have been done using the method developed by Roskam. Theses estimation techniques are used to make preliminary cost estimations for newly designed aircraft and that is exactly how it should be treated. The flying car is an unconventional aircraft configuration, especially due to the modular aspect of this design. The estimation itself will not be very accurate, but is suitable in this phase of the design and can therefore be used to give an indication in what values need to be considered.

Costs that have not been accounted for are for example the attachment system of the flying car. This will most likely not have a great effect on the price, as the additional costs will mostly be found in the RDTE phase which are already divided over all sold products. Furthermore, prices for the engine and avionics are now very high, but can be assumed to have decreased by 2025. Additionally buying parts in bulk will drop the price as well, it is therefore hard to estimate by how much this will effect the unit price but for off the shelve parts it can be assumed that parts will most likely be cheaper. Another factor that will effect accuracy of the cost estimation is the fact that depreciation was not taken into account.

26.5 Operations and maintenance costs

To make the use of the flying car sustainable, the operational costs have to be reasonable. For the flying car an estimate was made of the operation and maintenance costs for the mission scenario explained in Section 3.2. The hangar and maintenance information can be found in Table 26.1, the costs for the maintenance are per time that they are done.

Table 26.1: Hangar and Maintenance Information

	Costs [€]	Time [Days]
Hangar rent	300	30
50 Hours maintenance	1000	1
150 Hours maintenance	1500	2
Annual maintenance	2000	7

In the following table a cost estimation is portrayed which shows the operation costs with different customer to flight module ratios. Using this it can be seen how to keep costs as maintenance costs as low as possible.

Table 26.2: Maintenance cost estimation

Number of flight modules [#]	1	2	4	6	7	7	8
Usage per week [Days]	3	3	3	3	3	3	3
Usage per trip [Hours]	3	3	3	3	3	3	3
Customer [#]	1	2	3	7	8	9	10
50 hours every [weeks]	6	6	7	5	5	4	4
150 hours every [weeks]	17	17	22	14	15	13	13
Annual [#]	1	1	1	1	1	1	1
Maintenance costs [per Year per person]	16040	9020	6176	4054	3755	3561	3355
Change in price [%]		-43.8	-31.5	-34.4	-7.4	-5.2	-5.8

As can be seen in Table 26.2 owning a flight module and flying it three hours per flight three days a week will lead to maintenance costs of approximately €16,000 per year. This is a large amount if compared to a situation where seven wings are shared by ten customers, in which situation maintenance costs €3400 per year. It is beneficial to keep this in mind when designing the business plan around the flying car.
Now summing up all costs in one table to portray what it would cost to fly the flying car per month can be found

in Table 26.3. The situation calculated for is again flying three hours per flight, three days a week, while sharing seven flight modules with ten customers.

Table 26.3: Flying costs per month: minimum scenario

Personal Costs	[€]
Hangar	300
Fuel	2930
Maintenance	279
Insurance	100
Total per month	3609

Table 26.4: Flying costs per month: maximum scenario

Personal Costs	[€]
Hangar	300
Fuel	6288
Maintenance	400
Insurance	100
Total per month	7090

This same calculation has been done for the maximum mission scenario, where the customer would fly three times a week with flights of six hours. The difference between pricing between the two situations comes mainly due to the doubling in the amount of fuel needed and thus doubling the fuel price. The results of the maximum mission can bee seen in Table 26.4. Here ten flight modules are shared by ten customers.

26.6 Business model

In the following section the business model that will be followed will be explained, here the previous sections will be incorporated to find the best business solution. Looking at the operational and maintenance costs it can be concluded that sharing flight modules will be the most cost efficient option. Additionally this would have the effect that the customer is not always constrained to one airport, but can choose which airport is most suitable at that time. This leaves the question if the customers will lease the flying car system or buy a flying car and will share the rights to use of flight modules.

26.6.1 Lease

In the car sector, leasing is a very common practice. Leasing in the aircraft sector on the other hand is limited to the business buyer, the reasons being the following. First comparing the lease to a loan, it is often cheaper to get a loan on buying an aircraft. Loans are usually done over a longer period of time, with low monthly payments. Leasing an aircraft on the other hand combines relatively low monthly payments with high 'security deposits' and 'Amounts due at closing'. Furthermore, a lease specifies a maximum amount of flight hours, flying more will add additional costs and flying less will mean having paid for hours not flown. Damage to the aircraft will lead to price depreciation, which will be the clients responsibility to make up for. Aircraft that are not damaged on the other hand hold their value very well, therefore, selling the aircraft in the future will leave the customer with residual value. In the case of the lease this is not the case [90].

26.6.2 Ownership

As a lease system does not sound ideal, the flying car will be sold to the customers as a whole. The sale will not be a conventional one though. The car module will be a personal asset and the flying module will be a shared asset. Besides being cost efficient, the reason for that is that the flight module should be stored and maintained by the company as to ensure safety and quality of the product, a faulty flight module could have disastrous consequences. This also means that the customer will not always use the same the flight module, but the one available and will only pay for fuel and maintenance costs according to use. The flight module maintenance will be done by the company itself, while the car will be maintained or repaired by car repairs appointed by the company to ensure adequate knowledge is available.
The flying car will cost 500,000 euros, 20,000 euros more than the calculated unit price. The reason being that during the usage life of 25 years, the hangar rent will be paid using the difference. Profit for the company has already been incorporated in the unit price estimation, and totalled to be 43,000 euros per flying car.
A small note has to be taken when looking at Table 26.2. Here it can be seen that the amount of customers is not always equal to the amount of flying wings. Wings that are not used, as it would effect optimal cost distribution, will be stored for when usage is at high demand or other flying modules are temporarily out of service. Customers will always have access to a flight module when needed.
When taking the final price of 500,000 euros into account and dividing that by its life span to achieve the price per month over a 25 year period, it was found that the flying car would cost 1666 euros per month. Furthermore operation costs exclusive of fuel would sum up to be approximately 800 euros, leading to a total price for the flying car of approximately 2500 euros. Comparing that to lease prices of cars, it was found that this would be comparable to leasing a Porsche Panamera with a new price of 120,000 euros [91]. Lease contracts usually run

for around five years, this means that five cars of this calibre will be used during the life time of the flying car with no residual value at the end of this period. The most important difference here is that the flying car is owned by the customer and does not depreciate as much as a car. Therefore after the 25 year life period, there will still be a substantial residual value of the flying car. Besides being more useful, the Volucrem will be financially more attractive.

Chapter 27: Sustainability approach

In the following section, the sustainability approach of the entire project will be specified. The approaches will be discussed in the order found in the report. For all major structural components the choice of material is elaborated. For both engines the emission in both gases and noise are discussed. Next, manufacturing of Volucrem is examined. To conclude the chapter the recyclability of product at the end of its life cycle will be examined.

27.1 Roll cage

The material of the roll cage that has been chosen is one that allows the minimum weight and maximum recyclability. The minimised weight leads to results that are beneficial in terms of fuel consumption and CO_2 emissions. With respect to recyclability, aluminium is currently more recyclable than composite materials and it is expected that even whilst composite recyclability will increase the coming years, aluminium will stay superior in this field.

27.2 Car engine

The propulsion system mainly contributes to the sustainability strategy in the form of fuel usage. Biodiesel will be used as much as possible, which reduces greenhouse gasses such as CO_2 significantly in comparison to the CO_2 emission of burned diesel. Furthermore the production of the bio-fuels is done from organic waste and plants which, during their life, convert CO_2 into oxygen. According to U.S. Department of Energy this leads to a total decrease of 52% in greenhouse gases [92]. With respect to noise pollution, it will be the same as smart, nothing better and nothing worse then current technologies.

27.3 Car interior

For the interior, the use of sustainable materials is considered. The seats for instance can be made of recycled fabric, simimlar to KLM seats which are made of previous flight attendants clothing. The ballistic parachute is placed inside the vehicle so it suffers the least of the weather and does not have to be replaced as often, which saves material. The cockpit/dashboard lay-out was kept simple, to minimise the number of buttons and rely mainly on the two displays. This way the material and the production costs of the dashboard is minimised.

In the electronic systems of the car, there are some systems implemented just for a sustainable drive, mostly to decrease the CO_2 emissions. You can read more about these systems in Section 10.5.2.8.

27.4 Ground mobility

For the ground mobility the main challenge lies in the reduction of the rolling friction. Modern tire development trends towards tires with a low rolling friction coefficient. This process will be closely monitored and lower friction tires will be selected when they become available. This reduction of the rolling friction helps save fuel during the operation of the vehicle.

27.5 Flight engine

The propulsion system mainly contributes to the sustainability strategy in the form of fuel usage. Bio-SPK will be used as much as possible, which reduces greenhouse gasses such as CO_2 significantly in comparison to CO_2 emission of burned Jet A-1 fuel. Furthermore the production of the bio-fuels is done from organic waste and plants which, during their life, convert CO_2 into oxygen. As mentioned earlier, Bio-SPK emits approximately 1.9% less CO_2 than the conventional Jet A-1 fuel[66]. With respect to noise pollution, no conclusion can be made. It is expected however that the noise will be comparable to small turboprops.

27.5.1 CO_2 Engine emissions

For the requirements with respect to emissions, the amount and type of fuels used for both drive and fly mode were very important to consider. As explained in Section 15.2 the drive mode will use biodiesel with a maximum amount of ten litres due to tank size. In flight mode, 90.87 litres per hour of a 50/50 blend of Jet-A1 and Bio-SPK will be used. Using these values and combining them with their respective CO_2 emissions in kg/h table 27.1 was made.

Table 27.1: CO_2 *Emissions*

Travel type	Travel time [h]	Fuel type	Usage [L/h]	CO_2 [kg/h]
Flight	6	Jet A1	45.4	112
Flight	6	Bio-SPK	45.4	110
Drive	2.8	Biodiesel	3.6	11
Average	8.8	All	-	155

The flight and drive time used for the calculations are the maximum times that can be achieved. As can be seen in the table, if only flight mode were considered: 222 kg/h of CO_2 would be made, which would exceed the requirement. However, if you take the average over the complete travel time, thus including driving and flying, the average CO_2 emissions equals 155 kg/h which only just does not meet the requirement of staying under 150 kg/h. Additionally what has not been taken into account in the table is that the production of the bio-fuels is done from organic waste and plants. These plants convert the carbon dioxide during there life into oxygen, which means that effectively even less carbon dioxide is actually being produced. Therefore it can be concluded that this requirement is achievable.

27.6 Attachment system

The load attachment system is a purely mechanical system. The sustainability approach in this system is based on the material selection. Using aluminium components increases the recyclability as well as increasing the ease of maintenance. Coating the contacting surfaces with a biodegradable polymer or elastomer further increases the recyclability of the attachment system.

27.7 Manufacturing

As mentioned in section 22, the manufacturing approach will make use of the 'just in time' principle. Parts will thus only be made just before they are needed, which decreases the possibility of building excess parts and thus using excess material. Furthermore, due to the low time between part building and use, delivery directly from manufacturing to the next step is possible without or with minimum storage.

27.8 Recyclability

The Aircraft Fleet Recycling Association (AFRA) is currently the market leader on aircraft recycling [93]. After 25 years of operating the flying car, it can be fully handed over to the AFRA which disassembles the system and recycles the materials. The components which consists of aluminium are the flight module and ground vehicle skin, safety cage, wing box, attachment system, and parts of the engines and landing gear. These components are fully recyclable and already form 40 to 50% of the OEW of the flying car. Other components such as the electronics, furnishing, and engines are designed and picked off the shelf for high recyclability meaning 80 to 85 % of the OEW is recyclable. AFRA aims to achieve a 90% recycling rate for aircraft by the end of 2016 [94] such that the assumption can be made that by 2050 the flying car is at least 90% recyclable. Parts which are hard to recycle form the last 10 % of the OEW. These are materials such as lead, cadmium and beryllium which are found in on-board computers, digital instruments batteries which are hard to dispose of. These parts are categorised as electronic waste and even though a lot of research is done on recycling these type of materials, it can not be assumed that these materials are fully recyclable or environmental friendly disposable by 2050.

Part III

Conclusion

Chapter 28: Budget breakdown

To conclude the design, this chapter presents a short overview of the general characteristics of the Volucrem. The budget breakdown in Table 28.1 also represents the quantified compliance to the previously defined weight and cost budgets. Chapter 29 will elaborate on the design requirements which the Volucrem should have complied to.

Table 28.1: Budget Breakdown of the Volucrem

	Ground vehicle module		Flight module			
Cost [€]	car engine	1,000	engine + nacelle	100,000	budget	500,000
	avionics	75,000	manufact. & acquisition	290,000		
	reserve	20,000				
	R&D	14,000				
	total	110,000	total	390,000	total	500,000
Mass [kg]	structure	80	structure	120	budget	1300
	engine	94	engine + nacelle	82		
	attachment	20	fuel	253		
	avionics & electronics	131	remaining systems	42		
	safety & comfort	99				
	wheels & suspension	75				
	payload	200				
	fuel	10				
	total	709	total	497	total	1206
	power [kW]	74	power[kW]	180		
	range [km]	230	range [km]	1278		
	speed [km/h]	180	speed [km/h]	392		
	unit cost [euro]	500,000				

Chapter 29: Requirements compliance

In the Table 29.1 all the requirements are listed and are checked off when this particular requirement is met. For all the requirements where it was possible a complying value is presented. Furthermore, in the last column a reference of the corresponding section is presented. Here, an explanation is given if the design has met that particular requirement. All requirements which need a further explanation are elaborated in the feasibility analysis.

Table 29.1: Compliance matrix on the requirements

Requirements	Tick	Complying Value	Reference
"Carver" type of vehicle	x	Yes	Chapter 8
Detachable flight module	x	Yes	Chapter 21
Detailed cockpit interface	x	Yes	Section 10.7
2 or 3 seats	x	2	Section 10.1
Standard cabin luggage space	x	150 L	Section 10.1
Range min 1000 km (15 min reserve)	x	1278 km	Section 18.4
Ease of conversion (time $\leq$ 30 min)	x	30 min	Section 23.4
Max safety of operation	x	8g	Section 20.2; Section 14.1; Section 8.1
Cruise speed of 200+ kts (80% max power)	x	212 kts	Section 15.1
Min rate of climb 500 ft/min, 500 field length	x	1606ft/min and 415m	Section 18.1; Section 18.3
Noise levels below <65 dB at 200 m radius	+/-	57- 78.3 dBA	Section 15.3
Easily and secure storability	x	Yes	Section 23.2
CO2 emissions <150 kg/h	+/-	155	Section 27.5.1
>90 % recyclable	x	$\geq$ 90	Section 27.8
Unit cost <500,000 EUR	x	480,000 EUR	Section 26.3
First flight in 2025	?	n/a	n/a
Life span of 25 years	?	n/a	n/a
Design for 20,000 flight hours	x	Yes	Section 14.4
Comply with CS23 regulations	x	Yes	Section 23.1.1

Feasibility analysis

Since four requirements were not certainly met a feasibility analysis has been performed on those requirements. An elaboration is given of all the requirements which needed an extensive explanation.

Noise

The engine used in the design is rather new, no actual noise test data is available at this point. Since most comparable turboprops have noise levels between 57.0 dBA to 78.3 dBA [68], taking into account that the turboprop used in the flying car is rather small, it can be argued that its noise will be closer to the lower limit. Furthermore, small airfields have a noise limit which extended the design requirement, so complying with the <65dB is not essential and noise will not be an issue for the design.

Emissions

Although the originally set requirement has not been met, it can be concluded that the 150 kg/h CO_2 is achievable if technology improves between now and the first flight in 2025. Furthermore, in the CO_2 calculation the effective contribution of the bio-fuel is not taken into account which further improves the engine emissions specifications.

First flight 2025

Even though this is not verifiable at this point of time, the Volucrem was created with this requirement in mind. All technology chosen for the design are available now or available in 2025. So the first flight in 2025 is achievable.

Life span

One of the requirements was that the Volucrem would last for 25 years. The life expectancy of an aircraft is close to this number. The wing is designed to carry loads up to high fatigue factors as was the attachment system. Flight engines are also designed for a 25 year lifetime. Therefore the flight module should be able to last for 25 years, given the regulated proper maintenance. However, ground vehicles are generally designed to last between 100,000 and $200,000$km. Because of this, the modular ground vehicle is assumed to be the limiting factor when it comes to the life expectancy of Volucrem. Properly maintained and thinking about future development in engine performance, the life expectancy of the ground vehicle engine could be assumed to reach up to 15 years, and this is something to be investigated into more detail.

Chapter 30: Verification and validation

30.1 Power systems

Verification of the power required calculation was carried out by independent calculations by different group members, both for drive and flight mode. The ground vehicle engine is normally implemented in a 57% heavier vehicle. Besides, piston engines with a turbocharger can tolerate the altitude at which the Volucrem is designed to fly, which validates the choice of the ground vehicle engine. Comparable aircraft use turboprop engines which validates the type of engine used in flight mode.

30.2 Car module

To verify the different subsystems of the car module, mostly off-the-shelf and reference subsystems are used. The load calculations on the roll cage are verified by a FEM analysis in CATIA to show that the structure and material chosen can withstand the loads. For validation purposes however, the Volucrem is compared with various reference vehicles. All subsystems were also checked with the CS-23 regulations and the regulations for roadable vehicles for validation purposes.

30.3 Wing sizing

The sizing of the wing was done twice: once by hand calculations which was then verified by a previously verified Matlab program. This was verified further by the FEM analysis in CATIA. In order to validate the wing dimensions other aircraft of similar size were investigated. As the wing size and loadings were similar, this was accepted as sufficient validation.

30.4 Empennage sizing

In order to verify the tail boom sizing, the method was reviewed by two independent group members. The tail boom dimensions were compared to aircraft such as the Cessna “Skymaster” and the Adam A-500. The horizontal and vertical tail surfaces were sized according to stability criteria and take-off distance constraints, after which the sizes were compared to existing aircraft for validation purposes.

30.5 Aerodynamics

To verify the different aerodynamic properties that were designed for, all calculations have been performed independently by two different group members. Furthermore, the use of XFLR5 was utilised to investigate different aerodynamic properties. This includes the distribution of the pressure coefficient as can be seen in Figures 30.1 and 30.2 which show the coefficient of pressure for different air speeds at an angle of attack of 7.5 deg. Furthermore the lift distribution was investigated as the wing was designed to produce a near elliptical lift distribution, this is verified by Figure 30.3. To validate the aerodynamic properties however, wind tunnel tests should be performed.

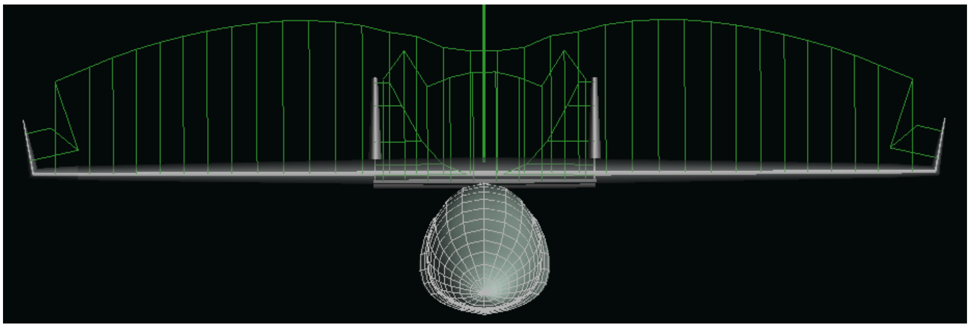

Figure 30.3: Lift distribution of Volucrem in flight

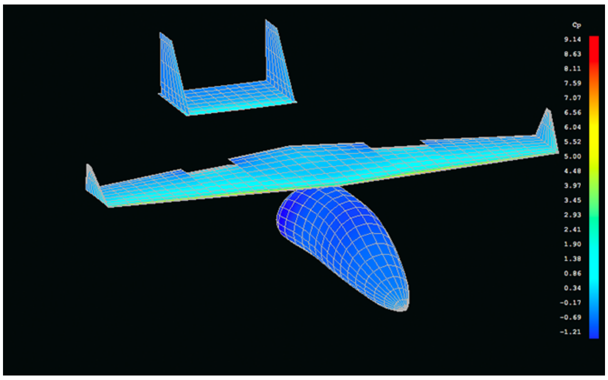

Figure 30.1: Pressure coefficient distribution for an airspeed of 40 $\frac{m}{s}$ and a 7.5 degree angle of attack

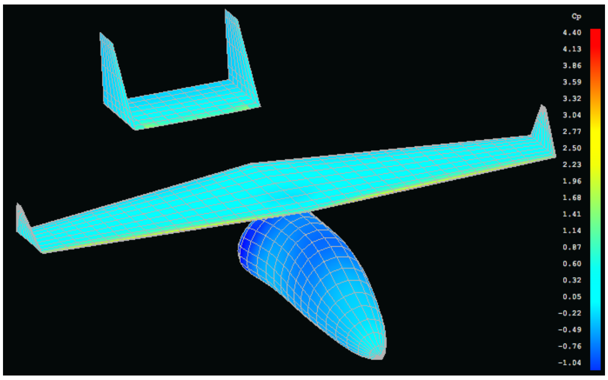

Figure 30.2: Pressure coefficient distribution for an airspeed of 109 $\frac{m}{s}$ and a 7.5 degree angle of attack

30.6 Attachment system

The attachment system calculations have been verified by a review of methods used by experts and rework of the calculations. After this, the FEM of CATIA was used to verify and modify the geometric properties of the more complex elements. Validation needs to be performed by testing the designed geometry, but this is not possible at this stage of the design.

Chapter 31: Future planning

In this chapter the future planning of this project will be described. Here the focus lies on what should be done if the project were to continue after the ten week DSE period. There will be more steps to take than those listed here, but these points are of greatest importance. In Figure 31.1 the project design and development logic diagram is shown to give an overview of logical order of activities to be executed in the post-DSE phases of the project.

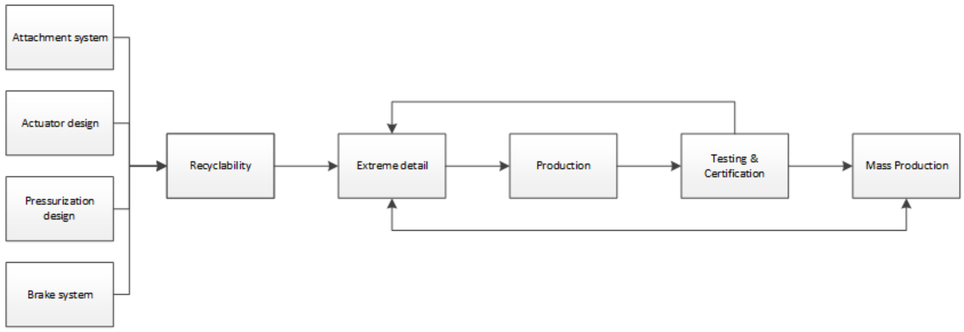

Figure 31.1: Project design and development logic

Actuators During the DSE project, the control surfaces were not sized. The reason for this was that XFLR5 did not create correct C_{m_α} diagrams and there was no wind tunnel data to use for calculations. Therefore, the forces that the actuators would need to be able to produce could not be accurately determined. This should be done in future design.

Pressurisation The pressurisation concept has been worked out during the report with respect to the basic design of the system and the compressor power needed to pressurise the cabin. The air conditioning system that conditions the compressed air coming from the turbocompressor before it is brought into the cabin remains to be designed. Furthermore, the sealing methods should be worked out in more detail and the cabin leakage should be determined.

Brake system The braking system has only been designed in a conceptual way due to the fact that no separate brake systems are available to compare with. It is known that disk brakes will be used, but logically more has to be done on this subject. Post-DSE a breaking system will have to be designed according to motorcycle laws.

Attachment system Many tests should be performed to validate the strength of the attachment system. Additionally future iterations could use different materials as stronger materials become more sustainable. Small adjustments will have to be made to several elements of the attachment system. The ball and socket joint should be manufactured with a slightly shorter socket neck and a smooth inner socket surface. This prototype joint should be tested and if possible the thickness of the skin and the stiffening elements can be increased. Finally the weight can be optimised, possibly by increasing the radius of the socket and ball.

Recyclability As described in section 27.8, the flying cars will be handed over to the AFRA for recycling. More extensive research on the use of non-recyclable materials has to be performed to increase the recyclability of the roadable aircraft.

Extreme detail Thus far, the vehicle has been designed but no decay analysis has been performed. There will be a limiting factor to the total life span of the vehicle. Since aircraft are generally designed to last for 20 to 25 years, it is expected that the limiting factor will lie in the ground vehicle, specifically in the engine. More research is necessary to determine the limiting factors and the final life span such that future iterations of the product have accurate forecasts of the lifespan. Furthermore, the overall vehicle will have to be designed in more detail before production is possible.

Production After all of the phases above have been accomplished, the vehicle will be able to be produced for testing. This test model will show if the design team has managed to design an aircraft capable of flying and driving in a proper manner.

Testing & certification The first produced vehicle will be rigorously tested to see if it complies with current rules and regulations. If flaws are present, these will be taken back to the design team which will redesign the issue. This will be a constant feedback loop up until certification is possible. Once certified, mass production can start.

Mass production During the mass production phase, the flying car will be produced in high quantities. During this phase it will be crucial to see where time and money can be saved in the manufacturing phase and where flaws occur. Again this will have to be corrected for directly by a design team.

Chapter 32: Societal impact

Daily commuting has only had minor changes since the introduction of affordable automobiles and implementation of rapid public transport solutions. The modular flying car is a completely new concept that can drastically reduce door-to-door times with the comfort of having a personal vehicle at all times. The banking road vehicle delivers a comfortable driving experience and with the use of bio-diesel it manages to have a low CO_2 emission. This means of ground travel is an ideal solution for the future of human transport. A rapid vehicle that is capable of comfortable day-to-day driving, has space for luggage and all the necessary safety systems.

The most important mission of the Volucrem is to give its owner the freedom to live wherever desired while commuting to their work. The current paradigm of commuting relies heavily on urbanisation such that the travel distances to the workplace are reduced. However, the Volucrem aims to shift this paradigm. With high airspeed and long range capability, travelling from rural areas to more urban areas becomes viable for daily commutes.

The fact that the Volucrem provides private air transport offers benefit from a personal perspective. The owner of a Volucrem will have the freedom to not only live much further from his or her place of employment, but will also be empowered to spend their free time at a much larger distance from their place of residence. Visiting family hundreds of kilometres away, travelling to the mountains or the beach will be much easier since airline waiting times can be avoided and weekend trips can be taken over far longer distances. The Volucrem therefore does not only present a paradigm shift with respect to work related travel but also improves free time mobility drastically.

Some additional societal benefits are present as mass production of the Volucrem will decongest traffic which can solve different environmental hazards such as smog. The fact that the vehicle permits one to live further could in fact reduce the travel times of all commuters. While the roads could free up the increase in air traffic would increase the air traffic control work load, parting from the assumption that airports will function on the same way in 2025 as 2014. However with the modernisation of unmanned solutions the airports could be more efficient at managing flights increasing the functionality of the Volucrem.

The notion of a personal or leased flying car could revolutionise the system of international air travel. Currently commercial air travelling is a hassle due to long waiting times and security checks. The air transportation model that the Volucrem will introduce would result in a reduction of travel related stress. The flying car provides freedom from airline imposed schedules and delays, and the use of a personal vehicle would allow for users to schedule their own departure and arrival times during any time of the day and any day of the week.

For society, the introduction of sustainable technologies that can replace the current unsustainable technologies is of paramount importance. The increase in energy demands and the global oil production reaching a peak means different sustainable solutions have to be implemented. The Volucrem operates on biofuels which on itself is able to reduce the net emissions due to transportation.

Chapter 33: Conclusion

In the beginning of the project, the objective statement was formulated as follows: *The design of a competitive, modular flying carver type vehicle capable of flying within a 1000km range and 200 knots cruise speed by 10 students within 10 weeks time*. Additionally a need statement was formulated: *There is a need for a safe, sustainable, modular and attractive flying carver with minimum difference in operation concept, a minimal door to door time at 200 knots cruise speed for a 1000 km range and is available before 2025 and with a market price below 500,000 euros*. At the end of this project, it can be concluded that the objective statement has been achieved. To reach these achievements, the design was divided in four parts, the car module, the flight module, the attachment system and the operations.

The car module is based on a three wheel vehicle with space for two occupants. It has a banking mechanism for turning. Thi implies a similar handling between the driving and the flight mode. On the road, an engine with 80hp is used to achieve a maximum velocity of 180 km/h. For minimum operation difference, a control column is used with an M-yoke. To prevent confusion, the throttle and brakes for the car are placed on the steering wheel as in a motorcycle and the shifting is done automaticly with a turning knob for park, neutral, reverse, drive, taxi and flight. For easy and modular electronic systems, the MOSArt system designed by Barco is suitable. It contains two screens and a flight computer. One of them is a touch screen and the other has to be operated with buttons, which is more convenient in case of turbulence. These screens can easily be switched to show the required indicators and sensors information. The landing gear must also be usable for both landing and driving modes. Therefore, shock dampers are used. They have at least three settings: flight (fully retracted), drive (approximately halfway extended) and landing (fully extended). With respect to comfort and safety measures, pressurisation, a ballistic parachute, a light weight roll cage and other standard systems are included in the design.

The flight module consists of a wing, engine and an H-tail which is connected to the module by two booms. The main function of the flight module is to get and keep the Volucrem in the air and make sure it is safe and easy to fly. The wing box structure must withstand all loads while accommodating flaps, ailerons, elevators and two rudders on both vertical tail fins. For easy implementation of the modular systems, the Volucrem will be operated emplying Fly By Wire. In addition, flight safety systems are implemented. To minimise the door-to-door time, a similar engine to the Dimech TP100 turboprop is chosen. Keeping in mind the CO_2 emissions, a 50/50 fuel blend is used of Jet A-1 fuel with Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK). FInally, the Volucrem is able to fly more than 1000 km.

To prevent that flight critical elements are damaged on the road, they are removed for road driving. To make this possible, an attachment system for the flight module was designed. The attachment system consists of three ball socket joints and an additional clamping system, which is mounted on the ground vehicle. It is an easy to use system and it is strong enough to carry 8g loads. The connection of the electronics is performed by connecting a 13-pin connector. The backup fly by wire system is connected with a separate cable for redundancy. For operational simplicity of the flight module when not connected to the car, three foldable struts with wheels are mounted on the wing.

To get the product on the market, some operational parameters are defined. The manufacturing, assembly and integration of the Volucrem was planned. Furthermore, research into the licencing needed for the Volucrem has been done and it was found that to operate it, an extended private pilot licence and a motorcycle licence are needed. The storage of the wing module is done employing a stacking system. In addition, the refuelling can also be implemented in this stacking system. The conversion between modes can be performed within 30 minutes. When creating a business model, the unit cost of the Volucrem was estimated to be around 480,000 euro. Using the innovative flight module sharing method, operational costs were drastically reduced. Additionally, the Volucrem was designed using sustainable materials and thus, it is expected to be 90% recyclable in 2050.

The parameters discussed above portray the design of the Volucrem, which is a competitive, modular, safe, sustainable and attractive carver type vehicle. It has a low door-to-door time, it can fly at a speed of 200 knots with a range of over 1000km, and it will be available before 2025 for a price below 500,000 euro. The Volucrem represents the evolution of transport, it is a personal vehicle combining the advantages of an airplane and the convenience of a car.

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Appendix A: Team organisation

This appendix concerns the team organisation and the revision of organisational diagrams from previous reports. First the group division is presented. Next, a revision of the work-flow diagram and the work break-down structure is given. Thirdly, the risk assessment including a risk map is presented. Following, the functional flow diagram, the functional breakdown structure and finally the gantt chart is presented.

A.1 Group division

In the project plan a classification of different project functions was made [95]. Each project member was assigned one of these functions to be able to work more efficiently. During the conceptual design however, another division of the group was carried out into technical design departments. These departments are Aerodynamics, Structures & Materials, Operations, Propulsion, and Stability & Control. For the detailed design the group was separated into subsystems and different design aspects to ensure that every aspect of the design was designed in detail efficiently.

A.2 Risk Assessment

In this section the technical risks for the design are identified and scaled on their probability and consequence. All the risks are mentioned below with sub-risks for the attachment and flight safety. In Table A.1 the risk map can be viewed. The impact of the specific risks is on the horizontal axis increasing to the right. The probability that these events will occur is presented on the vertical axis increasing upwards. The numbers in the table correspond to the numbers in front of the given risks. To avoid the risks in the top right, these should get some extra attention during the design process.

Table A.1: Risk map

Certain	9.1	12	9.2, 6	9
Expected	11	6.3	9.3	
Likely	6.4	6.1	5	
Unlikely	3		1	6.2
Rare		2, 8	4, 7	10
	Negligible	**Marginal**	**Critical**	**Catastrophic**

Risks:

1. AC control
2. Car safety
3. Comfort
4. Communication
5. Car control
6. Attachment
   6.1 Design of attachment system
   6.2 Reliability of attachment system
   6.3 Probability of certification
   6.4 Compatibility with Off-the-shelf materials
7. Ground mobility
8. Instrumentation
9. Flight safety
   9.1 Certification risk
   9.2 Total AC breakdown contingency plan
   9.3 Human error contingency plan
10. Lift generation
11. Storage
12. Combined AC/GV control

A.3 Functional flow diagram

For the design to be carried out efficiently, the functions for which the system must be designed, according to the customer, must be mapped. The functional flow diagram was created in [65]. The functional flow diagram can be seen as a complete overview and in sections below.

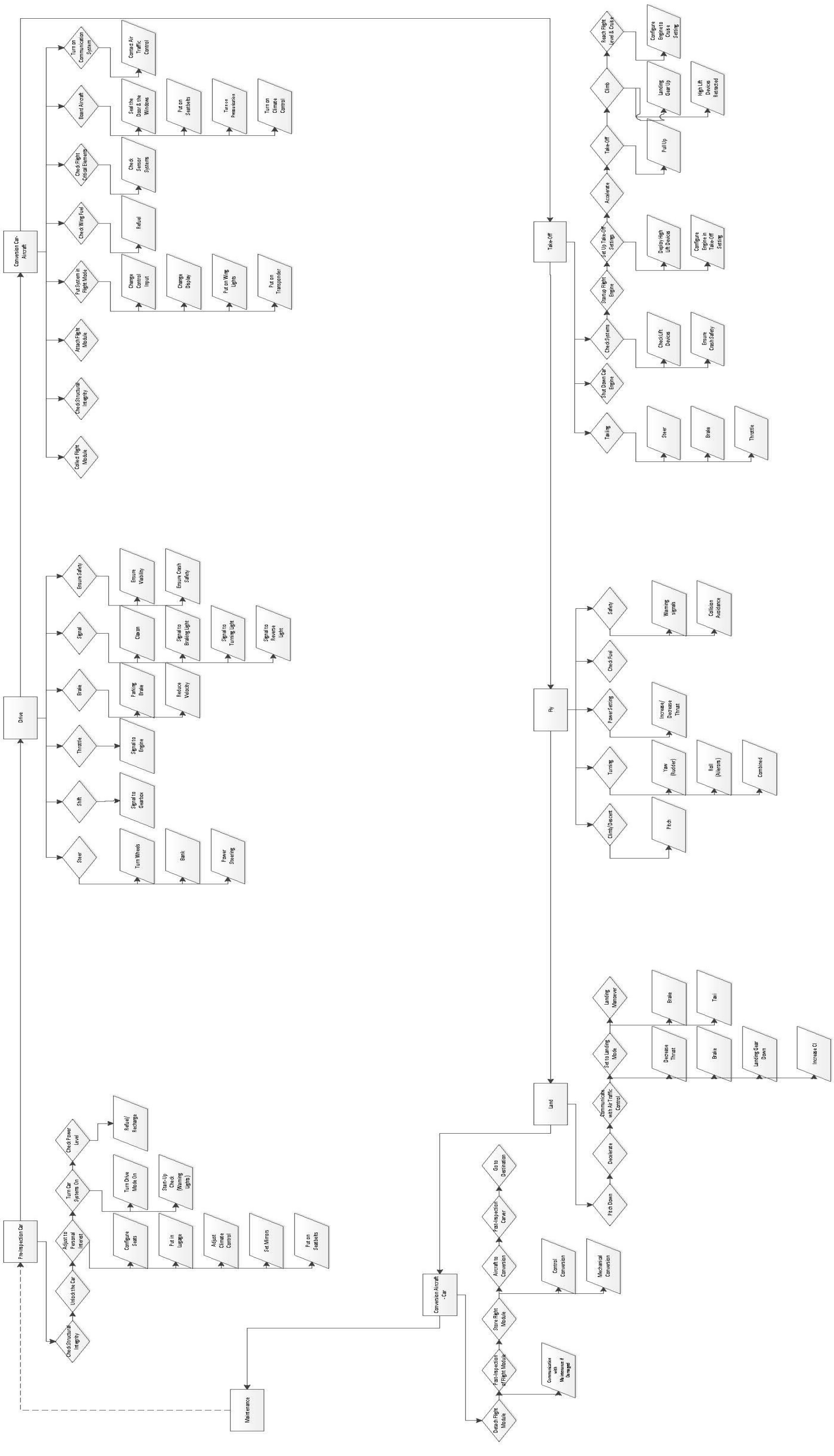


Figure A.1: Functional Flow Diagram - Complete overview

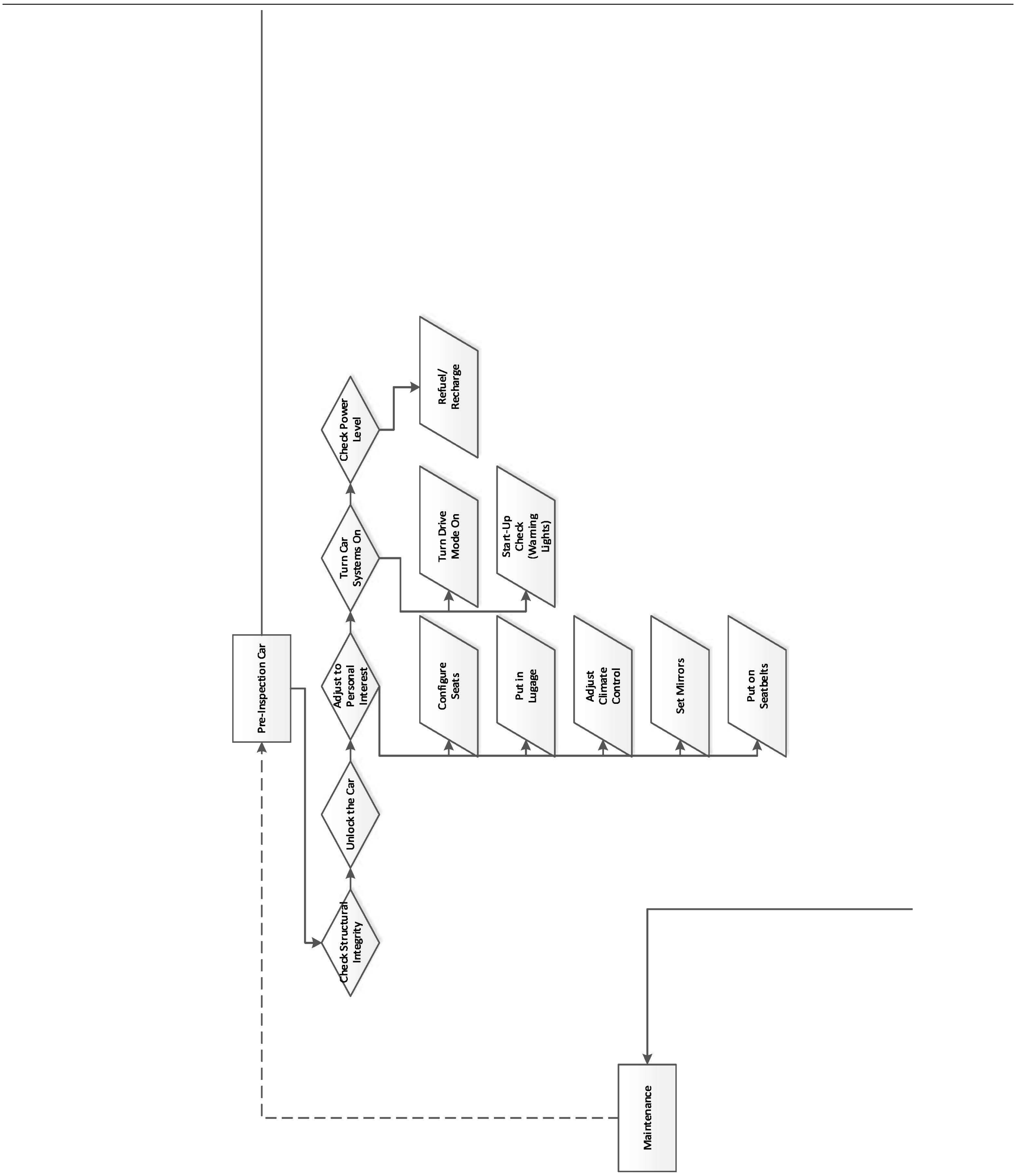


Figure A.2: Functional Flow Diagram - Pre-inspection of the car

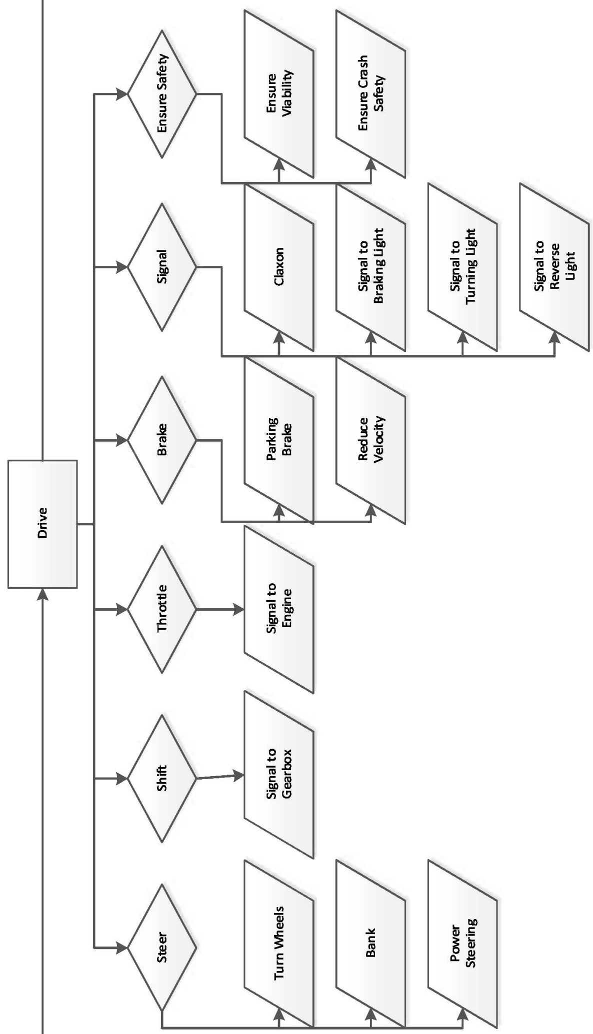


Figure A.3: Functional Flow Diagram - Driving of the car

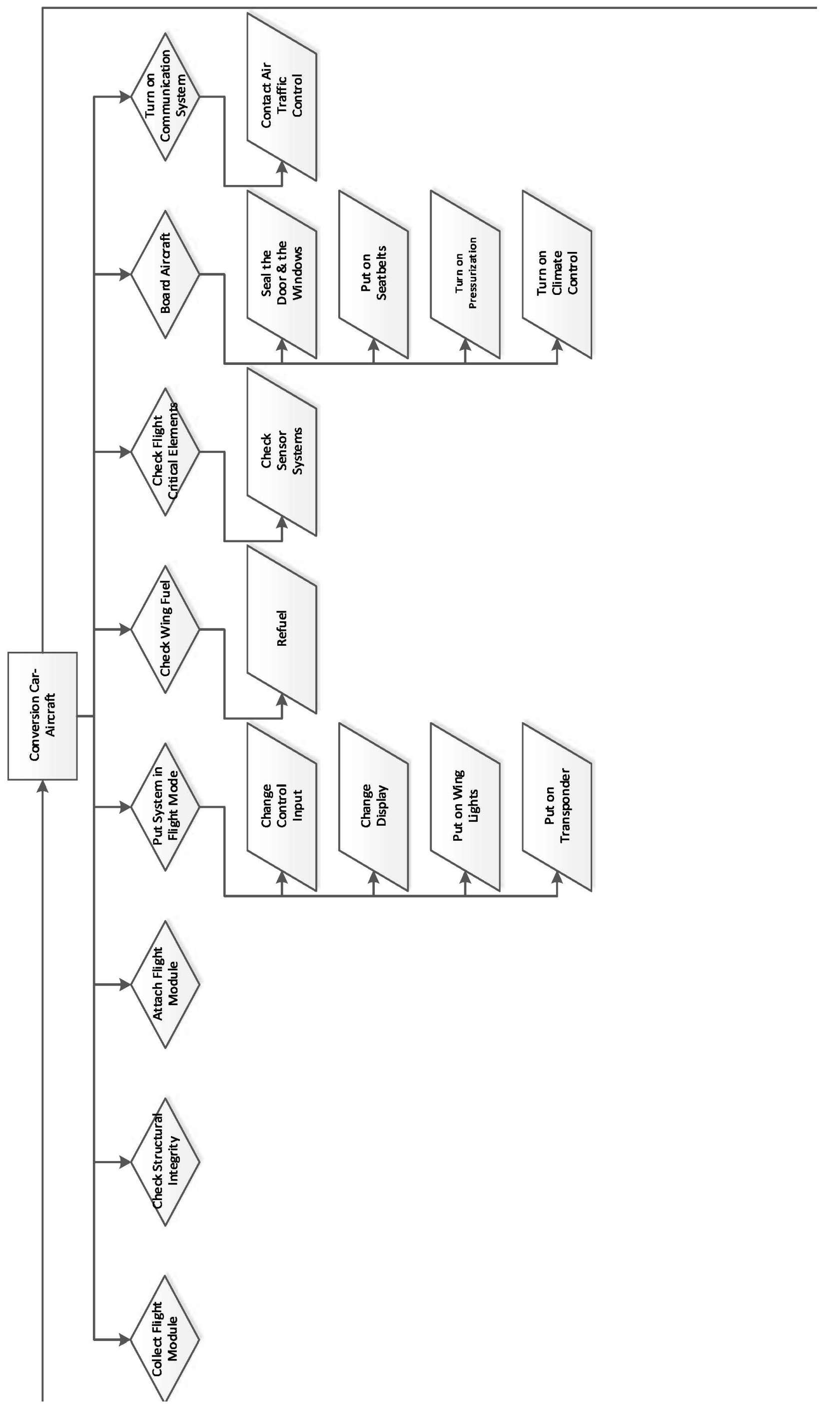


Figure A.4: Functional Flow Diagram - Conversion from car to aircraft

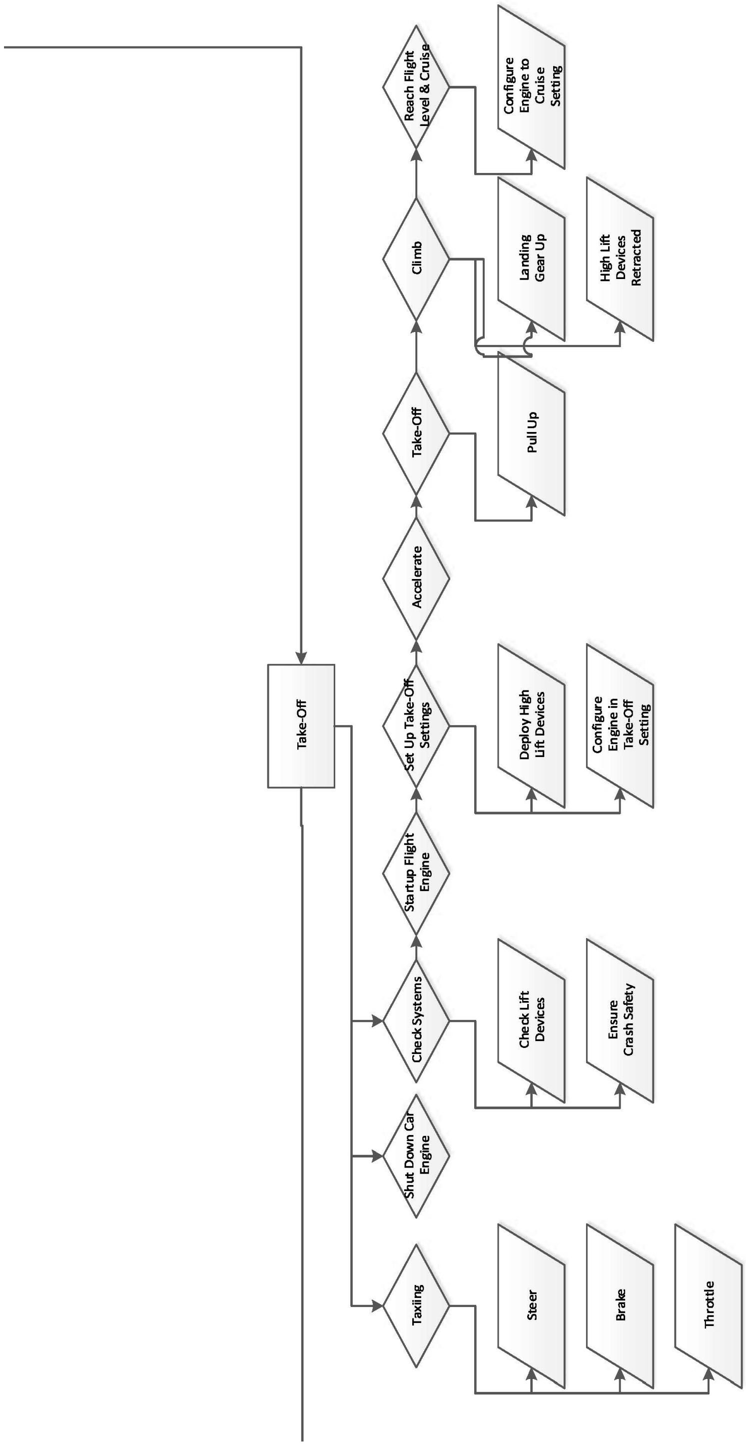


Figure A.5: Functional Flow Diagram - Take-off

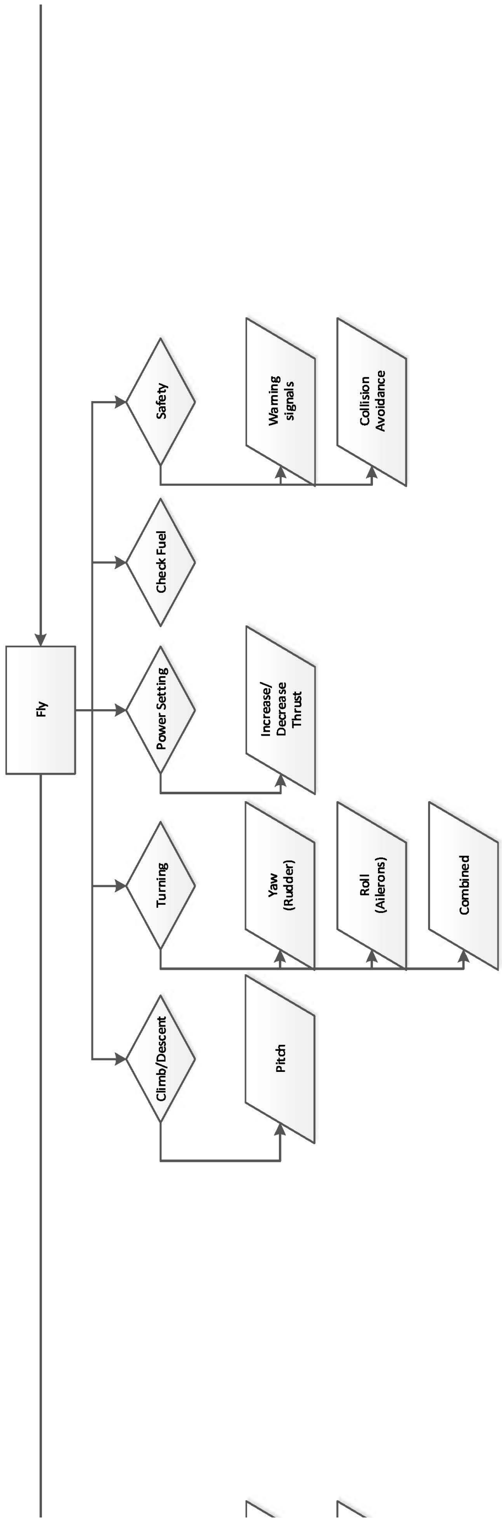


Figure A.6: Functional Flow Diagram - Flight

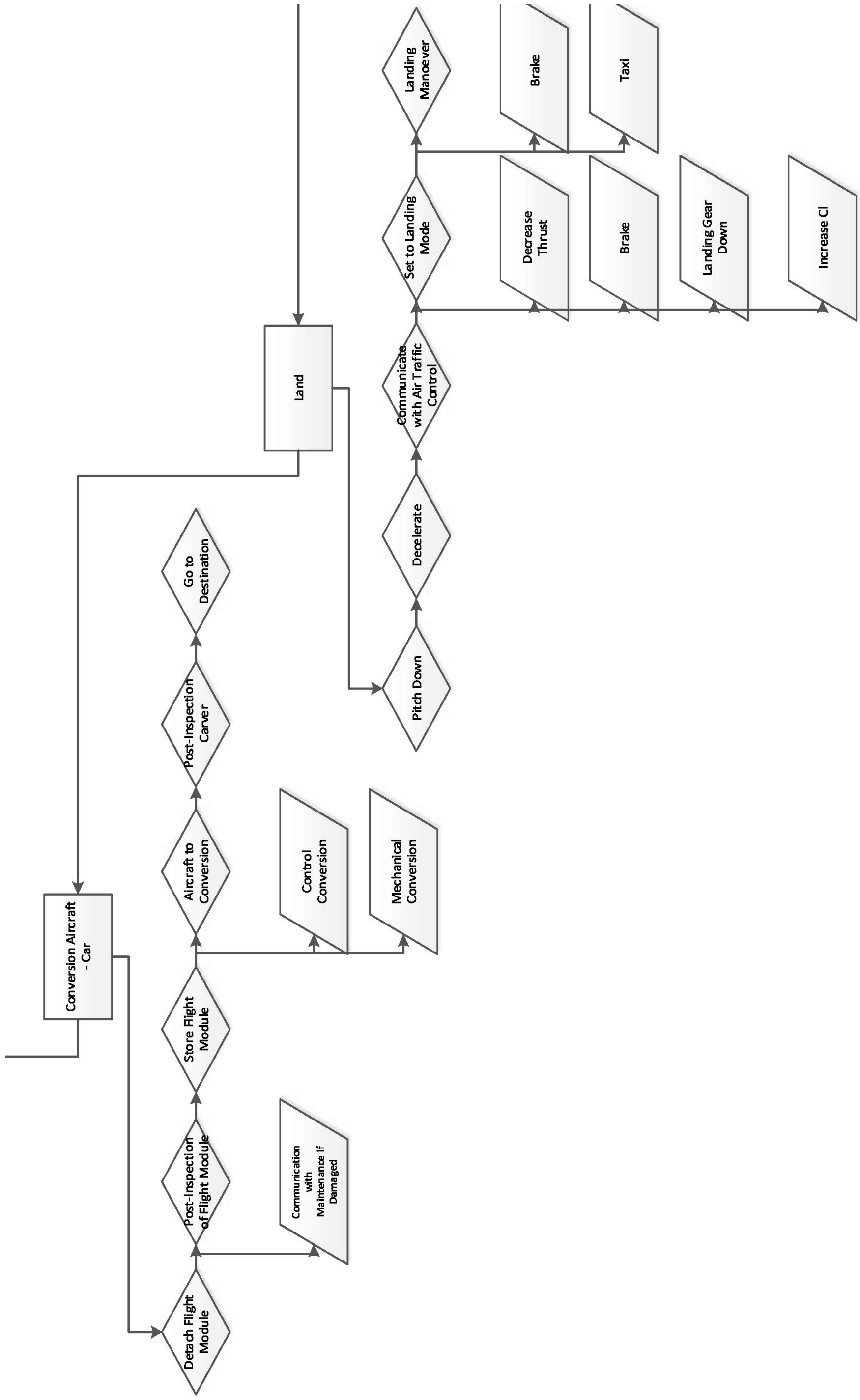


Figure A.7: Functional Flow Diagram - Landing and Conversion from aircraft to car

A.4 Functional breakdown structure

The functional breakdown structure is similar to the functional flow diagram, however all the functions are reported in a tree style diagram. The functional breakdown structure can be seen below.

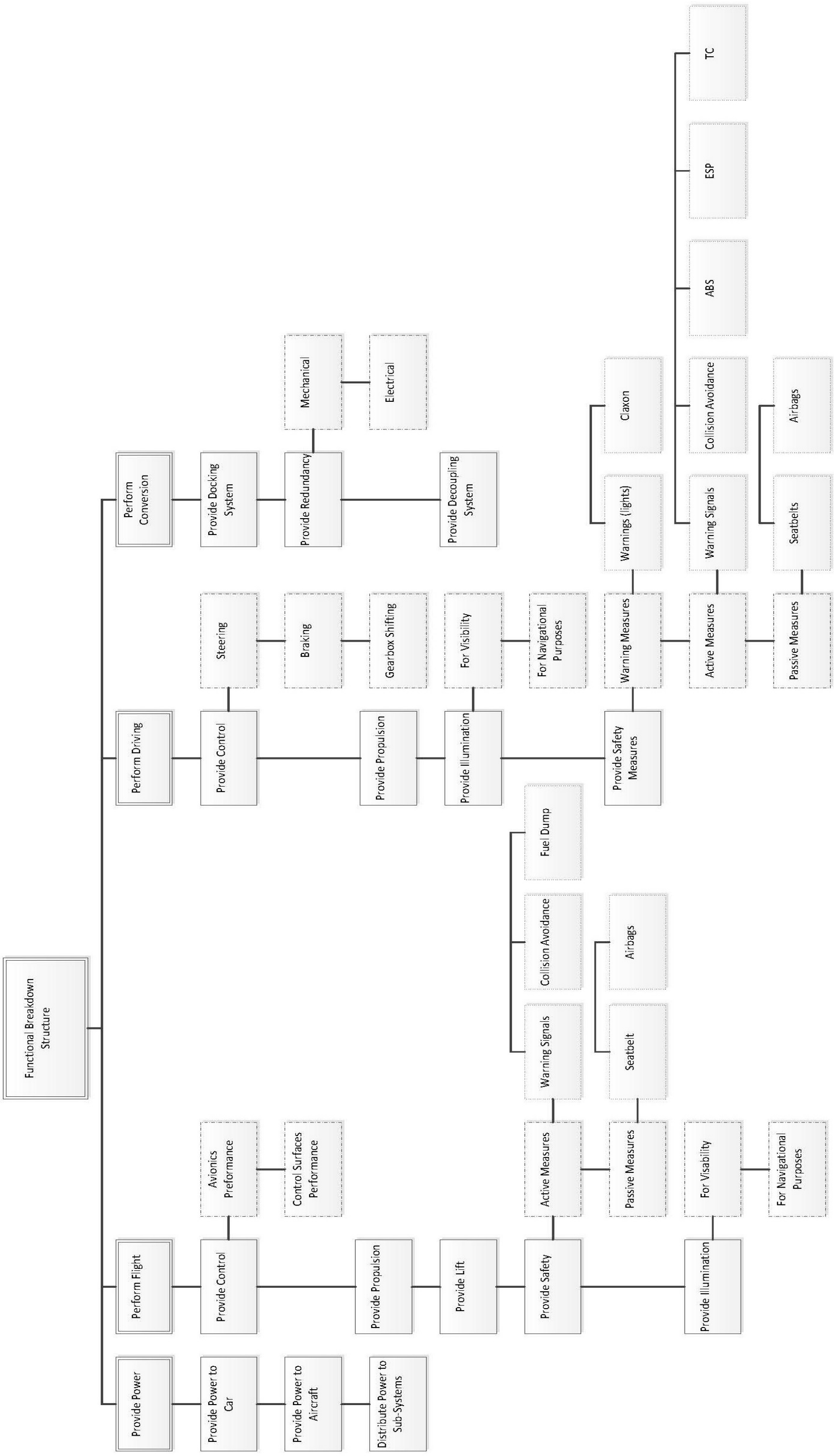


Figure A.8: Functional Breakdown Structure

A.5 Gantt chart

The Gantt chart illustrates the project schedule followed and is shown in figures fig. A.9 through fig. A.11. It has been updated since the midterm report to accurately depict the scheduling that occurred during the detailed design phase.

ID	WBS	Task Name	Start	Finish
0	0	**Flying Car DSE Planning**	**Tue 22-4-14**	**Thu 3-7-14**
1	1	**Start up**	**Tue 22-4-14**	**Fri 25-4-14**
2	1.1	**Team organization**	**Tue 22-4-14**	**Fri 25-4-14**
3	1.1.1	Resource organization	Tue 22-4-14	Tue 22-4-14
4	1.1.2	Management function distribution	Tue 22-4-14	Tue 22-4-14
5	1.1.3	Organogram	Tue 22-4-14	Tue 22-4-14
6	1.1.4	**Project planning**	**Wed 23-4-14**	**Fri 25-4-14**
7	1.1.4.1	Work Flow Diagram	Wed 23-4-14	Wed 23-4-14
8	1.1.4.2	Work Breakdown Structure	Wed 23-4-14	Wed 23-4-14
9	1.1.4.3	Gantt Chart	Wed 23-4-14	Wed 23-4-14
10	1.1.4.4	Project Logic Diagram	Thu 24-4-14	Thu 24-4-14
11	1.1.5	Data Inventarization	Tue 22-4-14	Fri 25-4-14
12	1.1.6	Project Plan Report	Tue 22-4-14	Fri 25-4-14
13	1.1.7	Project Plan	Fri 25-4-14	Fri 25-4-14
14	2	**Project Definition**	**Tue 22-4-14**	**Tue 6-5-14**
15	2.1	Project Objective Statement	Wed 23-4-14	Wed 23-4-14
16	2.2	Mission Need Statement	Wed 23-4-14	Wed 23-4-14
17	2.3	Risk planning	Thu 1-5-14	Fri 19-12-14
18	2.4	**Mission analysis**	**Wed 23-4-14**	**Thu 24-4-14**
19	2.4.1	Multiple scenarios	Wed 23-4-14	Wed 23-4-14
20	2.4.2	Technical Feasability	Wed 23-4-14	Wed 23-4-14
21	2.4.3	Mission Requirements	Wed 23-4-14	Wed 23-4-14
22	2.4.4	Market Analysis	Fri 25-4-14	Tue 29-4-14
23	2.4.5	Budget Breakdown	Fri 25-4-14	Mon 28-4-14
24	2.5	Functional Requirements Tree	Thu 24-4-14	Thu 24-4-14
25	2.6	**Functional Analysis**	**Mon 28-4-14**	**Wed 30-4-14**
26	2.6.1	Contingency Management	Thu 24-4-14	Fri 25-4-14
27	2.6.2	Functional Breakdown	Thu 24-4-14	Thu 24-4-14
28	2.7	Design Option Tree	Mon 28-4-14	Tue 29-4-14
29	2.7.7	Ground mobility	Mon 28-4-14	Tue 29-4-14
30	2.7.3	Communication	Mon 28-4-14	Tue 29-4-14
31	2.7.4	Control - car	Mon 28-4-14	Tue 29-4-14
32	2.7.5	Control - aircraft	Mon 28-4-14	Tue 29-4-14
33	2.7.6	Attachment system	Mon 28-4-14	Tue 29-4-14

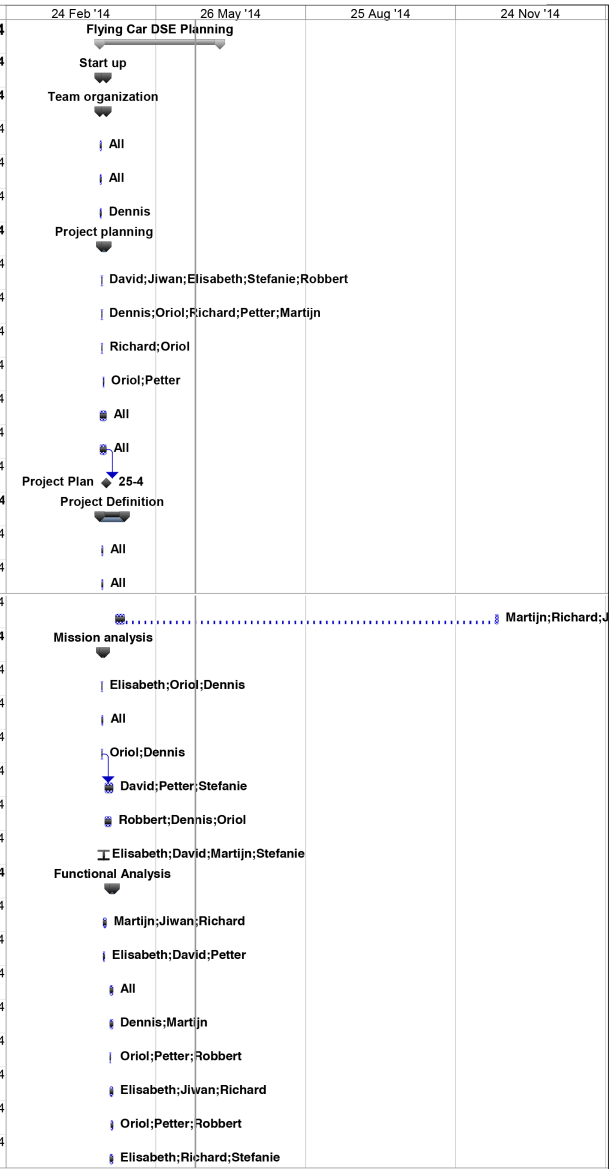


Figure A.9: Update Gantt Chart

ID	WBS	Task Name	Start	Finish
34	2.7.8	Instrumentation	Mon 28-4-14	Tue 29-4-14
35	2.7.9	Safety - aircraft	Mon 28-4-14	Tue 29-4-14
36	2.7.10	Propulsion	Mon 28-4-14	Tue 29-4-14
37	2.7.11	Lift generation	Mon 28-4-14	Tue 29-4-14
38	2.7.12	Storage	Mon 28-4-14	Tue 29-4-14
39	2.7.2	Comfort	Mon 28-4-14	Tue 29-4-14
40	2.8	Baseline reporting	Fri 2-5-14	Tue 6-5-14
41	2.7.1	Car safety	Mon 28-4-14	Tue 29-4-14
42	2.9	Baseline Report	Tue 6-5-14	Tue 6-5-14
43	3	Baseline Review	Tue 6-5-14	Tue 6-5-14
44	**4**	**Conceptual design phase**	**Tue 6-5-14**	**Thu 5-6-14**
45	4.1	Gantt Chart update	Tue 6-5-14	Tue 6-5-14
46	4.2	Risk planning	Tue 6-5-14	Tue 6-5-14
47	4.3	Concept Generation	Wed 7-5-14	Thu 8-5-14
48	**4.4**	**Concept Analysis**	**Thu 8-5-14**	**Wed 14-5-14**
49	4.4.1	N2 Chart	Fri 9-5-14	Fri 9-5-14
50	4.4.2	Design Option Verification	Fri 9-5-14	Fri 9-5-14
51	4.4.3	Communication Flow Diagram	Fri 9-5-14	Fri 9-5-14
52	4.4.4	Risk Identification	Fri 9-5-14	Fri 9-5-14
53	4.4.5	Risk Analysis	Fri 9-5-14	Fri 9-5-14
54	4.4.6	Risk Assesment	Fri 9-5-14	Fri 9-5-14
55	4.4.7	Risk Handling	Fri 9-5-14	Fri 9-5-14
56	4.4.8	SWOT Analysis	Thu 8-5-14	Thu 8-5-14
57	4.4.9	Cost Estimation	Wed 14-5-14	Wed 14-5-14
58	4.4.10	Maintenance	Tue 13-5-14	Tue 13-5-14
59	4.4.11	Configuration/lay-out (structures)	Mon 12-5-14	Wed 21-5-14
60	4.4.12	Performance Analysis	Mon 12-5-14	Wed 21-5-14
61	4.4.13	Operations and logistics concept design	Mon 12-5-14	Wed 21-5-14
62	4.4.14	Aircraft system analysis	Mon 12-5-14	Wed 21-5-14
63	4.4.15	Aerodynamic characteristics	Mon 12-5-14	Wed 21-5-14
64	4.4.16	Verification & Validation Methods	Wed 21-5-14	Wed 21-5-14
65	4.4.17	Sustainability Analysis	Wed 21-5-14	Wed 21-5-14
66	**4.5**	**Design Concept Trade-off**	**Thu 15-5-14**	**Fri 23-5-14**
67	4.5.1	Trade-off Methods	Thu 22-5-14	Thu 22-5-14

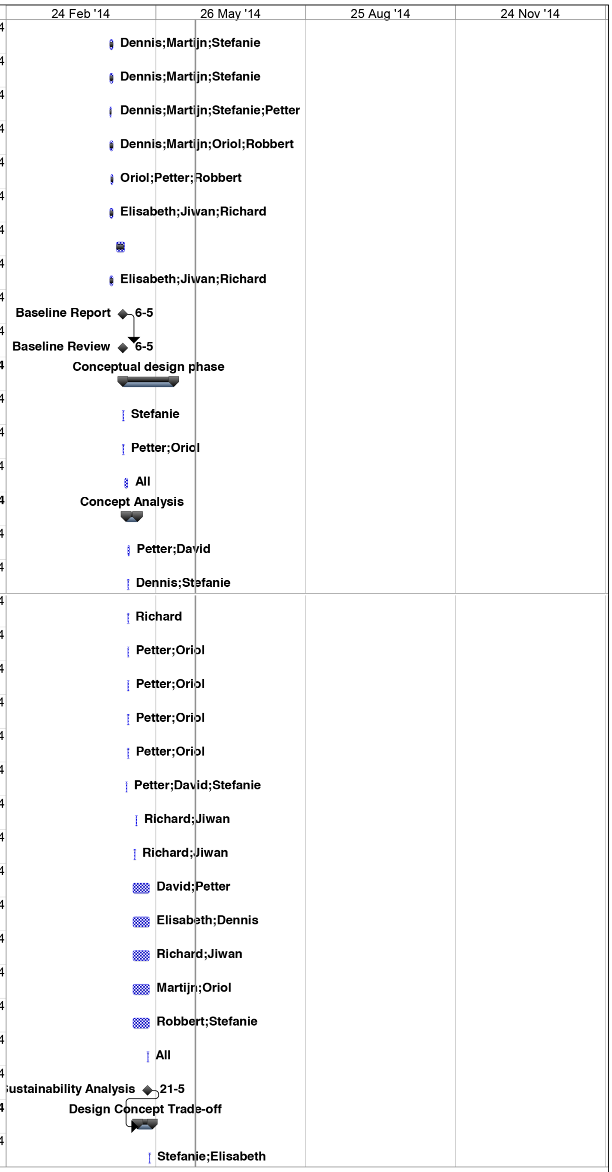
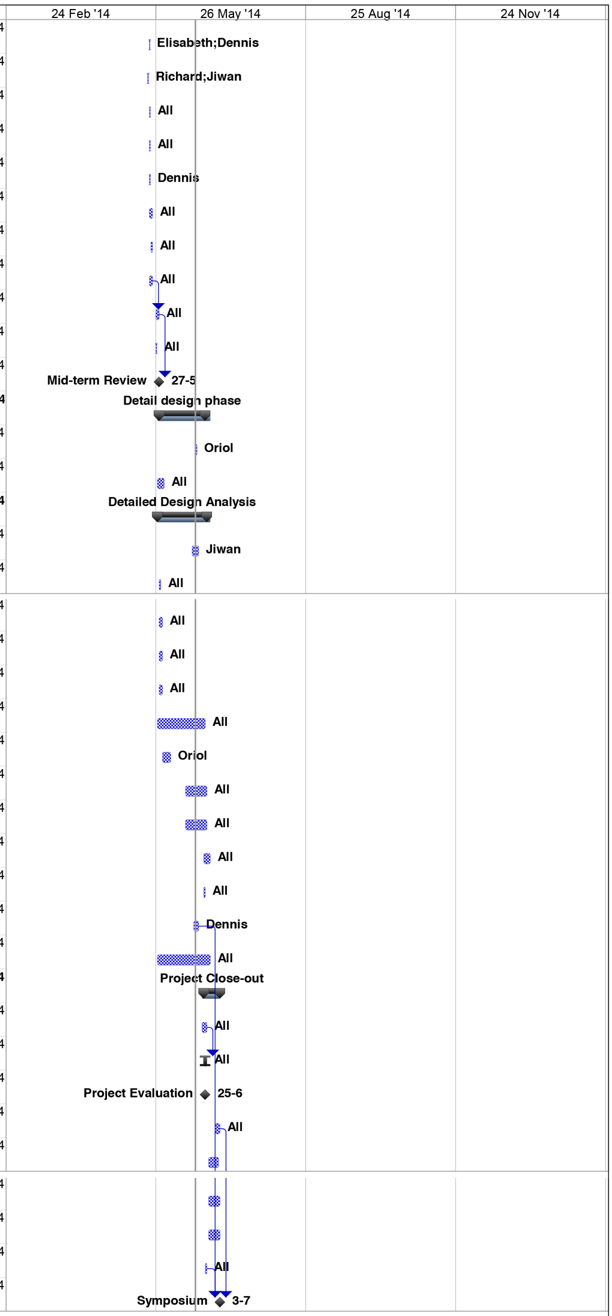


Figure A.10: Update Gantt Chart

ID	WBS	Task Name	Start	Finish
68	4.5.2	Trade-off Criteria	Thu 22-5-14	Thu 22-5-14
69	4.5.3	Certification	Wed 21-5-14	Wed 21-5-14
70	4.5.4	Weighting Assignment	Thu 22-5-14	Thu 22-5-14
71	4.5.5	Summary Table	Thu 22-5-14	Thu 22-5-14
72	4.5.6	Sensitivity Analysis	Thu 22-5-14	Thu 22-5-14
73	4.6	Choose Final Concept	Thu 22-5-14	Fri 23-5-14
74	4.7	Personal Appendix	Fri 23-5-14	Fri 23-5-14
75	4.8	Mid-term Report	Thu 22-5-14	Fri 23-5-14
76	4.9	Prepare Mid-term	Mon 26-5-14	Tue 27-5-14
77	4.10	Practice Mid-term	Mon 26-5-14	Mon 26-5-14
78	5	Mid-term Review	Tue 27-5-14	Tue 27-5-14
79	**6**	**Detail design phase**	**Wed 28-5-14**	**Tue 24-6-14**
80	6.1	Gantt Chart update	Thu 19-6-14	Thu 19-6-14
81	6.2	Risk Planning	Tue 27-5-14	Fri 30-5-14
82	**6.3**	**Detailed Design Analysis**	**Tue 27-5-14**	**Wed 25-6-14**
83	6.3.1	Performance Analysis	Tue 17-6-14	Fri 20-6-14
84	6.3.2	Risk Identification	Wed 28-5-14	Wed 28-5-14
85	6.3.3	Risk Analysis	Wed 28-5-14	Thu 29-5-14
86	6.3.4	Risk Assesment	Wed 28-5-14	Thu 29-5-14
87	6.3.5	Risk Handling	Wed 28-5-14	Thu 29-5-14
88	6.3.6	Technical Performance Management	Tue 27-5-14	Tue 24-6-14
89	6.3.7	Deliverable Block Diagrams	Fri 30-5-14	Tue 3-6-14
90	6.3.8	Verification	Fri 13-6-14	Wed 25-6-14
91	6.3.9	Design Validation & Certification CS23	Fri 13-6-14	Wed 25-6-14
92	6.3.10	Reporting	Tue 24-6-14	Fri 27-6-14
93	6.3.11	Personal Appendix	Tue 24-6-14	Tue 24-6-14
94	6.3.12	Jury Summary	Wed 18-6-14	Fri 20-6-14
95	6.3.13	Final Report	Tue 27-5-14	Fri 27-6-14
96	**7**	**Project Close-out**	**Tue 24-6-14**	**Thu 3-7-14**
97	7.1	Prepare Final Presentation	Mon 23-6-14	Wed 25-6-14
98	7.2	Practice Final Presentation	Tue 24-6-14	Wed 25-6-14
99	7.3	Project Evaluation	Wed 25-6-14	Wed 25-6-14
100	7.4	Poster	Tue 1-7-14	Thu 3-7-14
101	7.5	Excutive Summary	Fri 27-6-14	Wed 2-7-14
102	7.6	Prepare Symposium	Fri 27-6-14	Thu 3-7-14
103	7.7	Practice Symposium	Fri 27-6-14	Thu 3-7-14
104	7.8	Final Presentation	Wed 25-6-14	Wed 25-6-14
105	7.9	Symposium	Thu 3-7-14	Thu 3-7-14



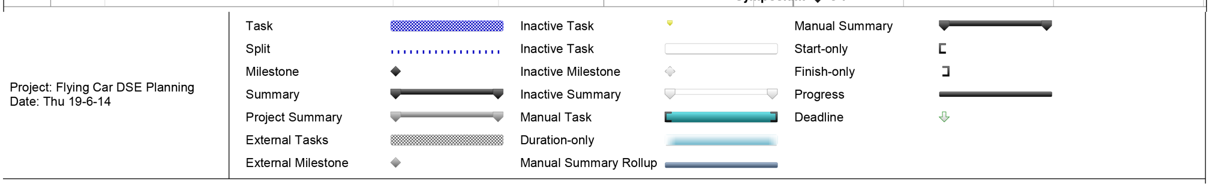


Figure A.11: Updated Gantt Chart

Appendix B: Flight fuel properties

Property		Jet A/Jet A-1	JP-8	ANZ		CAL	JAL	ASTM Test Method
				Jatropha	Camelina	Jatropha/Algae	Camelina/Jatropha/Algae	
COMPOSITION								
Acidity, total mg KOH/g	Max	0.10	0.015	0.002	0.002	0.001	0.003	D3242
Aromatics								
1. Aromatics, volume %	Max	25	25	0.0	0.3	0.0		D1319
2. Aromatics, vol ume%	Max	26.5						D6379
Sulfur, mercaptan, mass %	Max	0.003	0.002	0.0001	<0.0001	<0.0001	<0.0001	D3227
Sulfur, total mass %	Max	0.30	0.30	<0.0001	<0.0001	<0.0001	0.0001	D1266, D2622, D4294 or D5453
VOLATILITY								
Distillation:								
One of the following requirements shall be met:								D2887 or D86
Distillation temperature, °C:								
10 % recovered, temperature (T10)	Max	205	157-205	168	162	164	163	
50 % recovered, temperature (T50)		report	168-229	188	186	187	183	
90 % recovered, temperature (T90)		report	183-262	227	226	233	226.3	
Final boiling point, temperature	Max	300	300	255	251	256	237.7	
Distillation residue, %	Max	1.5	1.5	1.3	1.3	1.2	1.2	
Distillation loss, %	Max	1.5	1.5	0.1	0.2	0.3	0.3	
Final boiling point, temperature (simul)	Max	340						
Flash point, °C	Min	38	38-68	46.5	42.0	41.0	42.0	D56 or D3828
Density at 15°C, kg/L		0.775-0.840	0.775-0.840	0.749	0.753	0.748	0.752	D1298 or D4052
FLUIDITY								
Freezing point, °C	Max	−40 Jet A −47 Jet A-1	-47	-57.0	-63.5	-54.5	-63.5	D5972, D7153, D7154 or D2386
Viscosity −20°C, mm²/s	Max	8.0	8.0	3.663	3.336	3.510	3.353	D445
COMBUSTION								
Net heat of combustion, MJ/kg	Min	42.8	42.8	44.3	44.0	44.2	44.2	D4529, D3338 or D4809
Hydrogen content, mass %	Min		13.4					
One of the following requirements shall be met:								
(1) Smoke point, mm, or	Min	25	25					D1322
(2) Smoke point, mm, and	Min	18	19					D1322
Naphthalenes, volume, %	Max	3.0	3.0	<0.01	<0.01	<0.01	<0.01	D1840
CORROSION								
Copper strip, 2 h at 100°C	Max	No. 1	No. 1					D130
THERMAL STABILITY								
JFTOT (2.5 h at control temperature)								
Temperature, °C	Min	260		340	340	340	300	D3241
Filter pressure drop, mm Hg	Max	25	25					
Tube deposits less than		3	3	1	<1	1	1	
CONTAMINANTS								
Existent gum, mg/100 mL	Max	7	7		<1	<1	<1	D381, IP 540

Figure B.1: Properties summary of neat Bio-SPKs against existing jet fuel specifications [67]

Appendix C: Cost estimation data

Table C.1: Research, development, test and evaluation costs coefficients

Coefficients	Value	Description
v_{max}	233	Maximum velocity
w_{ampr}	485	Weight fuselage & wing
r_{er}	45	Engineering costs per hour in euros [96]
N_{rdte}	1	Number of test vehicles
F_{diff}	1.75	Judgement factor difficulty
F_{cad}	0.8	Experience company with CAD
C_{EF}	6.11	Cost escalation factor [97]
C_e	100000	Cost engines
N_e	1	Number of engines
C_p	0	Cost propeller
N_p	1	Number of propellers
$C_{avionics}$	75000	Costs avionics
N_{stk}	0	Number of stock airplanes
R_m	12.5	Manufacturing labor rate in euros
F_{mat}	1	Correction factor type of material
N_r	0.33	Rdte production rate
R_t	12.5	Tool labour rate in euros
F_{obs}	1.1	Factor for having low observables
F_{tsf}	0.1	Cost adjustment factor due to extra testing facilities
F_{prof}	0.1	Cost adjustment factor due to profit on rdte
F_{fin}	0.1	Cost adjustment due to money interest rate

Table C.2: Manufacturing and acquisition cost coefficients

Coefficients	Value	Description
N_m	566	Production aircraft
$CEF(2014-1900)$	1.81	Cost escalation factor
F_{int}	500	Interior cost factor
N_{pax}	2	Number of passengers
N_{rm}	5	Manufacturing rate per month
C_{ops}	120	Airplane operation cost per hour in euros
t_{pft}	2	Number of flight test hours
F_{ftoh}	0.4	Coefficient due to lacking of overhead data

Appendix D: Material properties

Table D.1: Material properties

Alloy	Tempers	Density [kg/m3]	Modulus of Elasticity [Gpa]	Specific Strength [$\frac{MPa}{kg/m^3}$]	Tensile Strength [Mpa]	Yield Strength [Mpa]	Fatigue [MPa]
6061	0	2700	68.9	0.020	124.1	55.2	62.1
6061	T4	2700	68.9	0.054	241.3	144.8	96.5
6061	T6	2700	68.9	0.102	310.3	275.8	96.5
7075	0	2810	71.7	0.037	227.5	103.4	
7075	T6	2810	71.7	0.179	572.3	503.3	159
2024	0	2780	73.1	0.047	345	131	89.6
2024	T3	2780	73.1	0.124	483	345	138
2024	T4	2780	73.1	0.117	469	324	138
7050	T745	2830	71.7	0.166	469	524	
6063	T4	2700	68.9	0.033	172	89.6	
6063	T6	2700	68.9	0.079	241	214	68.9
5052	H38	2680	70.3	0.095	290	255	138

Appendix E: Tail boom trade-off

Table E.1: Trade-off between several tail booms

Case	2024 t=2	2024 t=2.5	2024 t=3	2024 t=4	7075 t=2	**7075 t=2.5**	7075 t=3	7075 t=4
tensile 483 572.3	sigma_h1 = 596.0035	sigma_h1 = 477.8355	sigma_h1 = 399.0606	sigma_h1 = 300.6004	sigma_h1 = 596.0035	**sigma_h1 = 477.8355**	sigma_h1 = 399.0606	sigma_h1 = 300.6004
tensile 483 572.3	sigma_v1 = 170.3679	sigma_v1 = 136.6433	sigma_v1 = 114.1608	sigma_v1 = 86.0591	sigma_v1 = 170.3679	**sigma_v1 = 136.6433**	sigma_v1 = 114.1608	sigma_v1 = 86.0591
Yield 345 503.4	Y_1 = 455.9199	Y_1 = 365.4762	Y_1 = 305.1831	Y_1 = 229.8227	Y_1 = 455.9199	**Y_1 = 365.4762**	Y_1 = 305.1831	Y_1 = 229.8227
Weight	W_total 24.4792	W_total 30.5334	W_total 36.5615	W_total 48.5391	W_total 24.7433	**W_total= 30.8629**	W_total 36.9561	W_total 49.0629
Costs	C = 19.5833	C = 24.4268	C = 29.2492	C = 38.8313	C = 111.3449	**C = 138.8832**	C = 166.3023	C = 220.783

Appendix F: Electronic systems

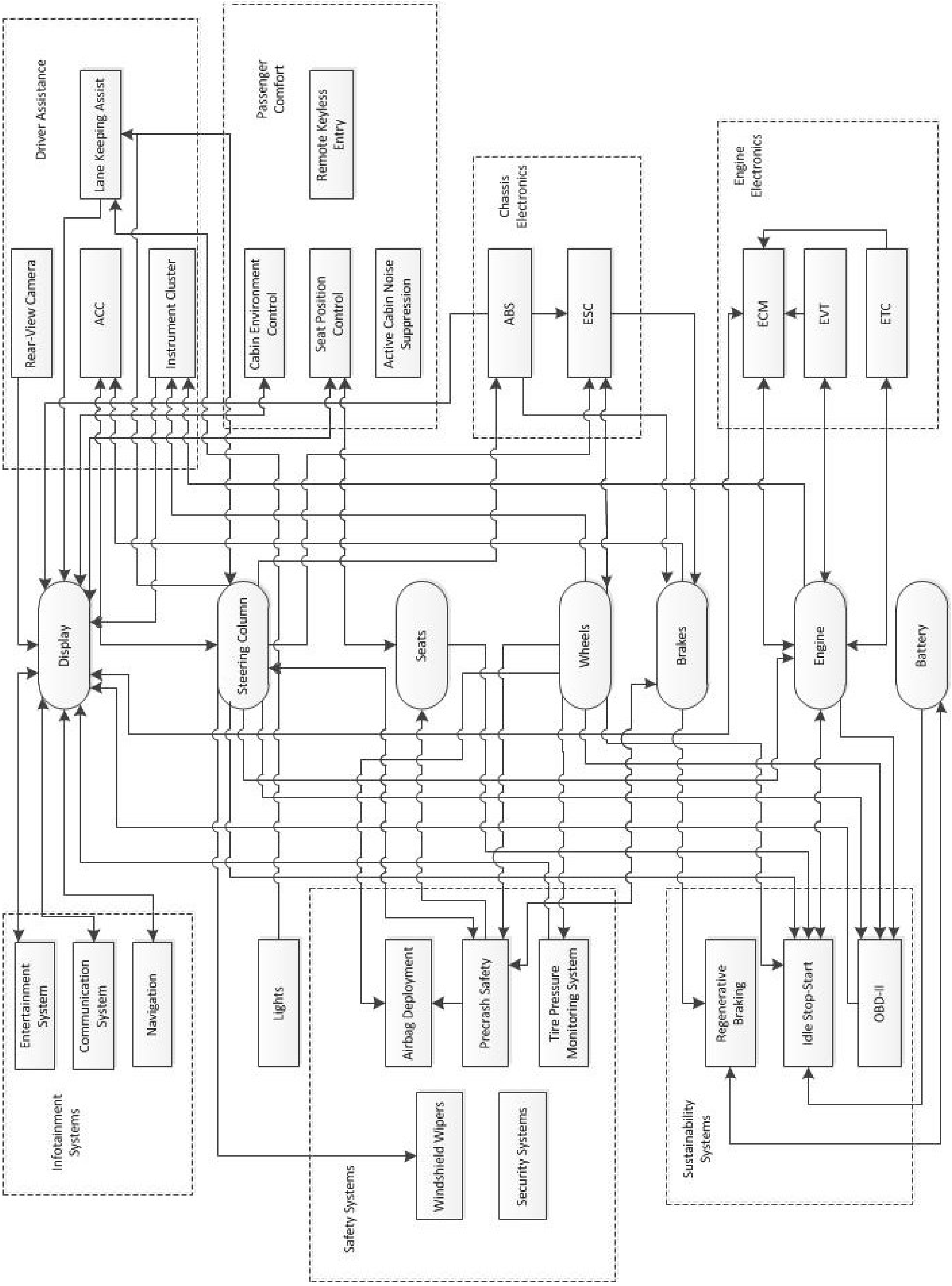


Figure F.1: Electronic block diagram of the car electronic sytems

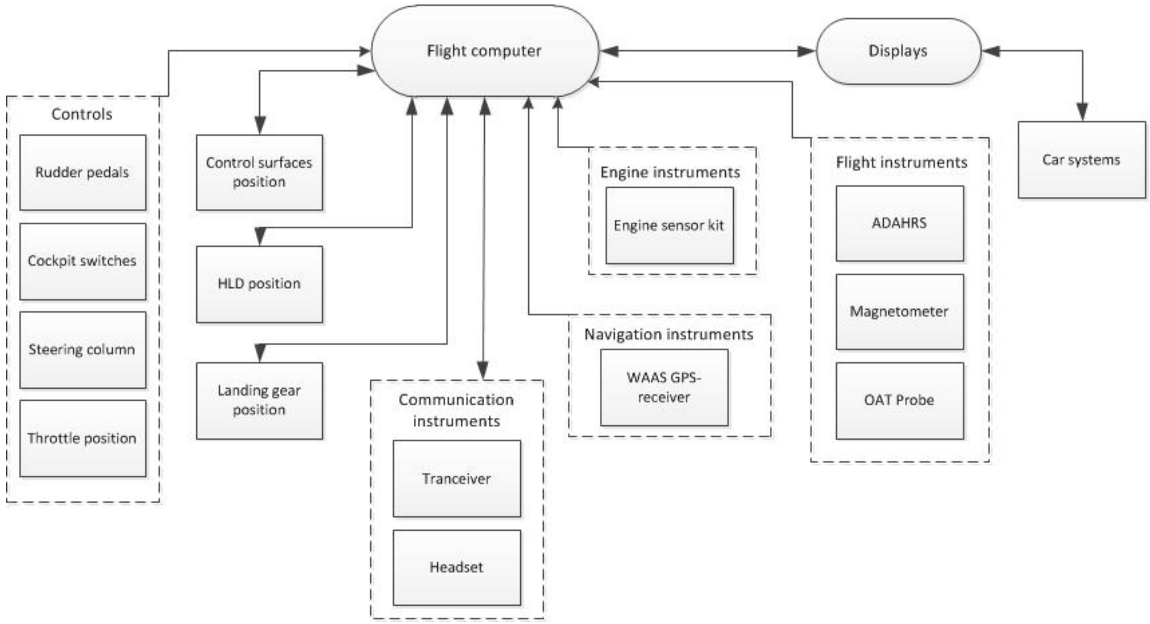


Figure F.2: Electronic block diagram of the aircraft electronic sytems

Table F.1: Sensors, actuators and data communication of all car electronic systems

System	Sensors	Data communication	Actuators
Engine Control Module	- knock sensor - throttle valve position sensor - engine oil temperature sensor - EGR sensor - oxygen sensor - induction air temperature sensor - oil pressure sensor - fuel tank level sensor - wheel speed sensor - torque sensor - airflow sensor - crankshaft position sensor - camshaft position sensor - coolant temperature sensor	CAN (and LIN)	- fuel injectors - spark plugs - EGR valve - fuel tank venting - fans - throttle position monitor - check engine light
Electronic Valve Timing	- crankshaft position sensor - throttle position sensor - fluid pressure sensor	CAN	- hydraulic electromagnetic valve actuator - piezoelectric valve actuator - cramshaft position pin actuator
Electronic Throttle Control	- throttle valve position sensors	CAN	- motor on throttle body
Anti-Lock Braking System	- wheel speed sensors	high-speed CAN	- hydraulic modulator - master cylinder - wheel brake cylinder - warning lights
Electronic Stability Control	- steering wheel angle sensor - lateral acceleration sensor - yaw rate sensor - wheel speed sensor	high-speed CAN	- anti-lock brakes - electronic throttle - fuel injector - spark plugs
Windshield wipers	- wiper switch - rain sensor	LIN	- electric motor
Tire Pressure Monitoring System	- air pressure sensor - temperature sensor - wheel speed sensor	- 315MHz RF between tires and control unit - CAN	- low-tire-pressure display
Precrash Safety	- laser sensor - vehicle speed sensor - yaw sensor - acceleration sensor - accelerator position sensor - brake position sensor	CAN	- brakes - throttle - seatbelt tensioner

Airbag Deployment	- accelerometer - wheel speed sensors - brake pressure sensors - seat occupancy sensors	CAN	- airbag inflation device - passenger airbag ON/OFF indicator
Security Systems	- pressure sensors - switches - microphones - tilt sensors - vibration sensors - acceleration sensors - proximity sensors - GPS position sensor	- 125kHz RF for communication with immobilizer - LIN - 315 MHz or 434/868 MHz RKE	- audible alarms - lights - RF link to telephone
Adaptive Cruise Control	- headway sensor - vehicle speed sensor - accelerator position sensor - brake position sensor	CAN	- throttle - brakes
Dedicated Short Range Communications	/	- IEEE 802,11 - Bluetooth - CALM	/
Instrument Cluster	- wheel speed sensor - engine speed sensor - engine temperature sensor - fuel level	CAN	- digital display - lights
Lane Keeping Assist	- vehicle speed sensor - infrared image sensor - turn signal sensor	- CAN with ECM - AV IN*4 with image sensor - NTSC/I2C with control panel	- audible warning alarm - visual indicator - steering wheel vibrator - electronic power steering - brakes
Rear-View Camera	- optical image sensor	CAN	- image display
Active Cabin Noise Suppression	- microphones	CAN	- speakers
Remote keyless entry	- radio frequency receivers	RF at 315 MHz or 434/868 MHz	- door locks - engine ignition - door motors
Cabin Environment Control	- temerature sensor - pressure sensor - humidity sensor - ambient light sensor - gas analyzers	CAN	- heating pads - AC compressor - dampers - blowers
Seat Position Control	- position sensors	LIN	- electric motors
Navigation	- GPS receiver - gyrocompass - accelerometer - vehicle speed sensor	CAN	- display
Communication system	- GPS reveiver - mobile cellular	- CAN - cellular - GPS - RF - Bluetooth	- speakers - door locks
Entertainment System	- switches - ambient light sensors	- IEEE 1394 - MOST	- displays - speakers

Regenerative Braking	- brake position sensor - vehicle speed - energy storage status	CAN	- brakes - energy storage device
Idle stop-start	- engine temperature sensor - external temperature sensor - cabin temperature sensor - battery status - steering angle sensor - seat belt connection - brake position sensor - accelerator position sensor - gear shift sensor - wheel speed sensor	CAN	- starter motor - valve timing
On-Board Diagnostics	- oxygen sensor - engine coolant temperature sensor - intake air temperature sensor - crankshaft position sensor - map sensor - fuel tank pressure sensor - fuel temperature sensor - oil temperature sensor - wiper washer fluid level sensor - vehicle speed sensor - brake fluid level sensor - wheel speed sensor - accelerometer - yaw rate sensor - master cylinder pressure sensor - steering angle sensor - throttle position sensor - knock sensor - camshaft position sensor - fuel level sensor	CAN	- Malfunction Indication Lamp

Appendix G: Communications flow diagram

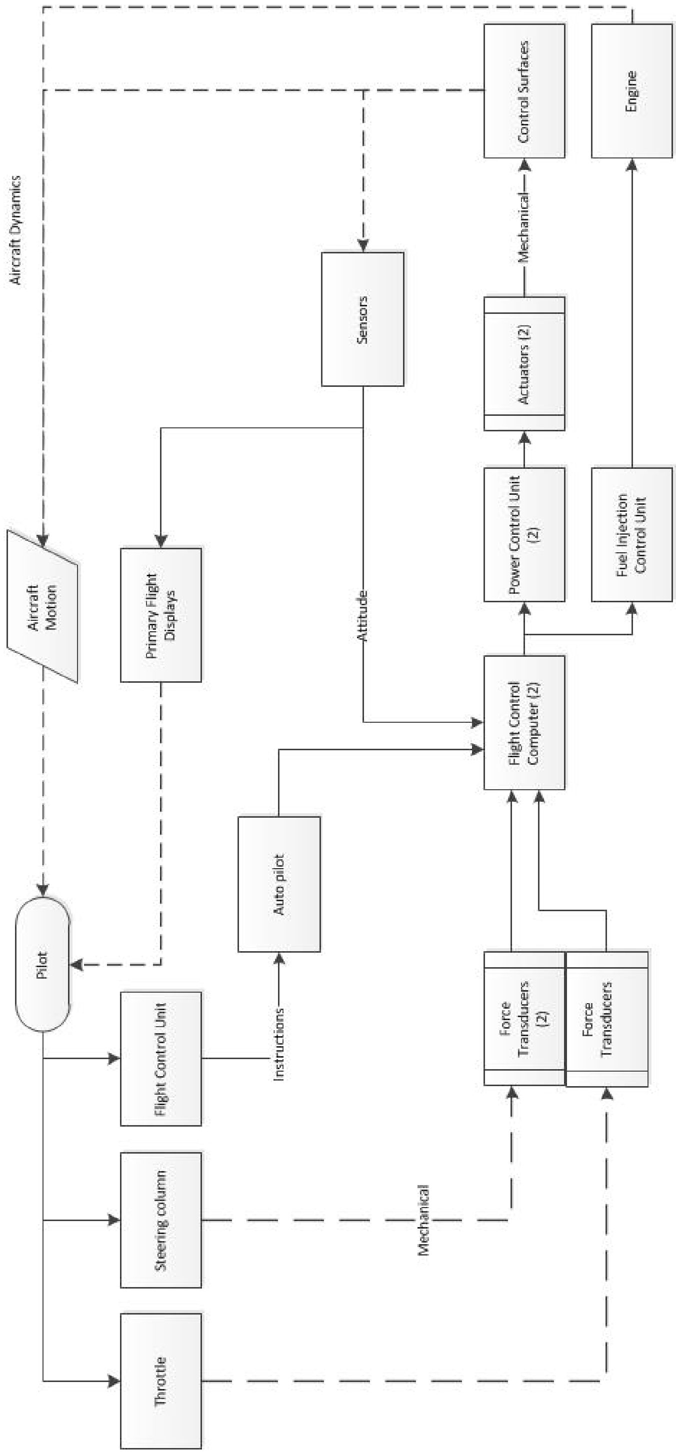


Figure G.1: Communications flow diagram