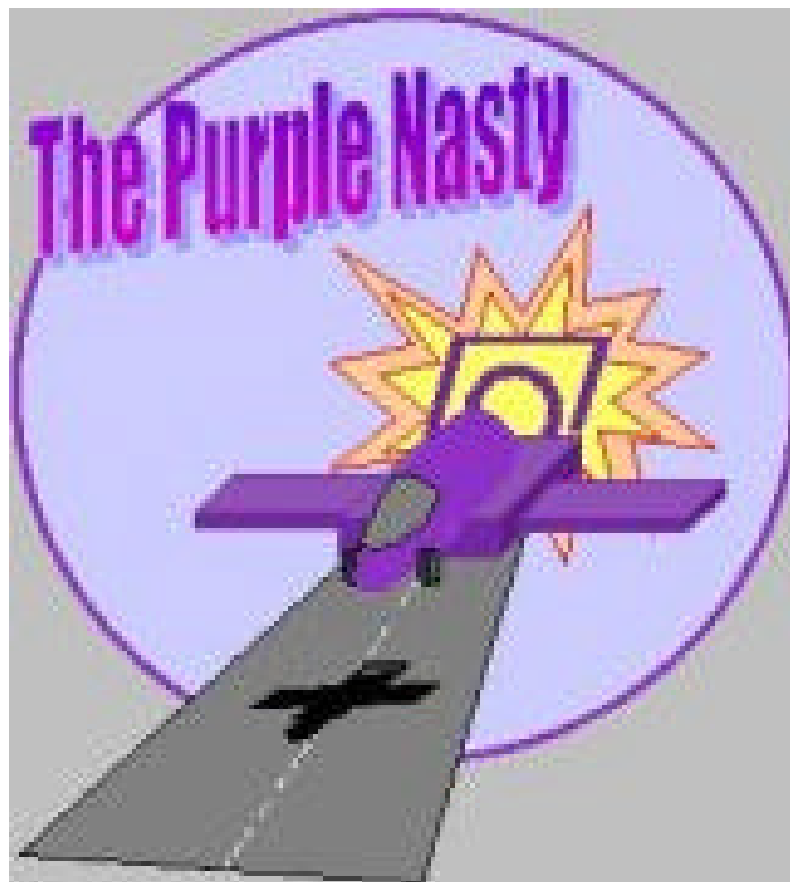




Aircraft Design Baseline Report



Written by the 1999-2000 Loughborough University
and Virginia Tech
AGATE Roadable Aircraft Design Teams

Summary

This document identifies the main design criteria of the Roadable Aircraft concept currently being developed by students from Loughborough University and Virginia Tech.

The detail in this document is the baseline design for the Roadable Aircraft and any further changes that are made to the vehicle should be modifications with reference to this document.

This document has been produced by the Loughborough University Team, with the collaboration and agreement of the team from Virginia Tech, in order to meet the assessment requirements of the Aircraft Project Design Module.

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1 Introduction

The aim of this document is to provide a common baseline from which both the Loughborough Team and the Virginia Tech Team can work from to progress, the development of the Roadable Aircraft. If both teams use this document as a reference source for dimensions and weights etc. then we should at least both be starting from the same design and using the same figures in the developments that the teams make.

Before defining the Baseline for the vehicle as it currently stands it is important to fully analyse the requirements and ensure that the baseline design does fulfil these so that any modifications and improvements simply improve an already feasible solution to the original specification. The two teams have improvised the requirements, which had been set out in the initial specification, during the Virginia Tech visit to Loughborough. This was in order that we could produce a vehicle that is both an adequate automobile and aircraft and also has a viable market so that the vehicle could be sold and hence become commercially successful, a feat that has yet to be fulfilled by existing Roadable Aircraft to date.

For completeness these requirements have been included in this document with explanation where necessary. The main design criteria relate to the performance of the vehicle and the dimensions into which the design must fit. The performance criteria is heavily rated towards the flying characteristics of the vehicle whereas the dimensions have been limited by legal on road requirements for a standard driving licence holder. These details are listed below:

Car width	2.15m (7 feet 2 inches)
Car Height	2.7m (9 feet)
Car Length	6m (20 feet)
Range (as a car)	200 miles
Cruise Speed (as a car)	65 miles per hour
Desired Total Mass	1500kg (3300 lbs)
Take off and Landing Distance	500m (approx. 1650 feet)
Cruise Speed	150 Knots
Range	500 – 800 Nautical Miles
Operating Altitude	Up to 3600m (12000 feet)
Stall Speed	55 Knots (maximum)
Climb Rate	210 m/min (700 fpm)

The final considerations that were made with respect to the requirements were the market to which this vehicle would be aimed. Due to the nature of the vehicle and the initial development costs that would undoubtedly be encountered we decided to make the vehicle a four-seater that would be affordable for businesspeople and families. Clearly the vehicle would have to be able to be driven by a holder of a standard driving licence and likewise flown by a standard single engine PPL holder. This in effect decided the type of propulsion system that needed to be used. From these decisions the following requirements were obtained:

Capacity	4 Adults and luggage (400kg Total)
Propulsion source	Internal Combustion Engine (Petrol or diesel)

Finally as the vehicle is highly unconventional as an aircraft and an automobile particular attention will have to be paid to the handling characteristics on the road and the sky. This becomes even more important when it is considered that a fairly novice driver or pilot could be using this vehicle. Most importantly will be stall characteristics and the possibility of recovery and the inclusion of safety devices in the case of a stall going unrecognised.

2 Critical Technical Issues and Design Philosophy

In a project of this size there are many issues that will have to be resolved to produce a vehicle that can operate as an aircraft and as an automobile. In this section these issues are introduced and the approach adopted to produce solutions to them is explained.

Fundamentally the main issues revolve around combining the automobile and aircraft characteristics to create a vehicle that can fulfil both roles. As far as possible it is desirable to duplicate as few common components as possible. This means utilising a single engine and transmission that will be able to provide drive to the vehicles wheels and a rear-mounted propeller. It also means optimising a suspension system that provides good handling qualities on the road and will also act as an undercarriage when the vehicle is in aircraft mode.

Due to the size limitations and the lack of storage space we will also have to ensure that the vehicle can produce enough lift and also give the pilot some authority when flying the aircraft in order that stall recovery is possible. It is also important that the control surfaces are large enough and can travel far enough to provide the necessary moments required in order that the vehicle can be controlled as an aircraft.

Another problem that we will have to resolve is the stowage of the flight surfaces. In the air the overall dimensions of the aircraft are not too critical, however on the road there are set width, height and length restrictions that we have to conform to. It is therefore necessary to retract the wings for use on the road. From terms of selling the vehicle it will be preferable to make this an automated procedure to minimise the effort required by the user to change the mode of the vehicle from aircraft to automobile.

The final large consideration will be the human factors of the vehicle, which includes both the usability and the maintainability. The vehicle will require controls and displays that allow it to be easily driven as an automobile and flown as an aircraft without cluttering the cockpit interior or intimidating the driver/pilot.

Obviously there will be other issues that will have to be resolved regarding the aerodynamics, the structure that makes up the vehicle, the systems inside it and the resulting stability and performance considerations. In order to successfully solve these problems and evolve a vehicle that fulfils the requirements we have broken the project into specific groups each containing at least one person that can oversee the development and integration of their area into the final design. These include Aircraft Layout, Structures, Aerodynamics, Propulsion, Stability, Human Factors and Systems groups in both Loughborough and Virginia Tech.

By ensuring that all of these groups work in conjunction with one another to cover all of the critical issues and the subsequent design work that is necessary to implement the proposed solutions, it will be possible to produce a suitable solution to the Roadable Aircraft problem.

3 Key Design Criteria

This section of the report identifies the key decisions that have been taken in the evolution of this vehicle design. It covers the early design criteria used to obtain the initial aircraft parameters. It then explains the evolution of this design to the baseline vehicle that is described in the following section.

3.1 Constraint Analysis

The constraint analysis is designed to give an approximate thrust loading and wing loading. By using predefined performance characteristics that will have to be complied with, a range of suitable thrust and wing loading can be determined. The performance goals that the roadable aircraft will have to comply to are:

- 1 Take off from a 500m long runway
- 2 Land on a 500m long runway
- 3 Cruise at 150 knots at sea level
- 4 Climb at 700 feet/min from sea level

The master equation, shown in Appendix A, has been developed into appropriate forms so that performance requirements for each of the above cases can be estimated.

3.1.1 Take off criteria

Making the assumption that the aircraft is taking off at maximum take off weight then the variable β , which is W/W_{TO} will equal 1. It is also standard practice to use a value for K of 1.2 during take off. When approximating C_L , typical values for other aircraft were used for reference. For a single slotted flap a C_L of about 1.6 is common, this could be improved by utilizing a more efficient flap system. The next variable is α , this value is given by T/T_{SL} . For a jet engine taking off at sea level this value would be 1. However the plane in question in this case uses a propeller to provide propulsion, so the thrust produced at take off will not be maximum due to the losses associated with the forward speed of the aircraft. Using a basic approximation of propeller thrust compared to air density and the aircraft's velocity it was found that α is approximately 0.8. It was also decided that by using wing loading values in a range of 300 to 2000, comparable values of thrust loading could be found and then plotted in a constraints diagram.

3.1.2 Landing Criteria

As in the take off scenario the landing maneuver is assumed to be at sea level and the value of K is given as 1.3. As this example does not consider such factors as air brakes and advanced car braking systems using a coefficient of friction stated for a dry paved runway should mean that the aircraft will not have a problem landing in the wet. As to make sure that the coefficient of friction " μ " is not underestimated a value of 0.2 has been chosen. This analysis has been carried out for a standard mission for this type of aircraft, and so it will be assumed that the aircraft is landing after using up all of its fuel apart from emergency reserves. This will mean that the ratio of weight to maximum take off weight will be 0.8. As in the take off example a value of C_L was

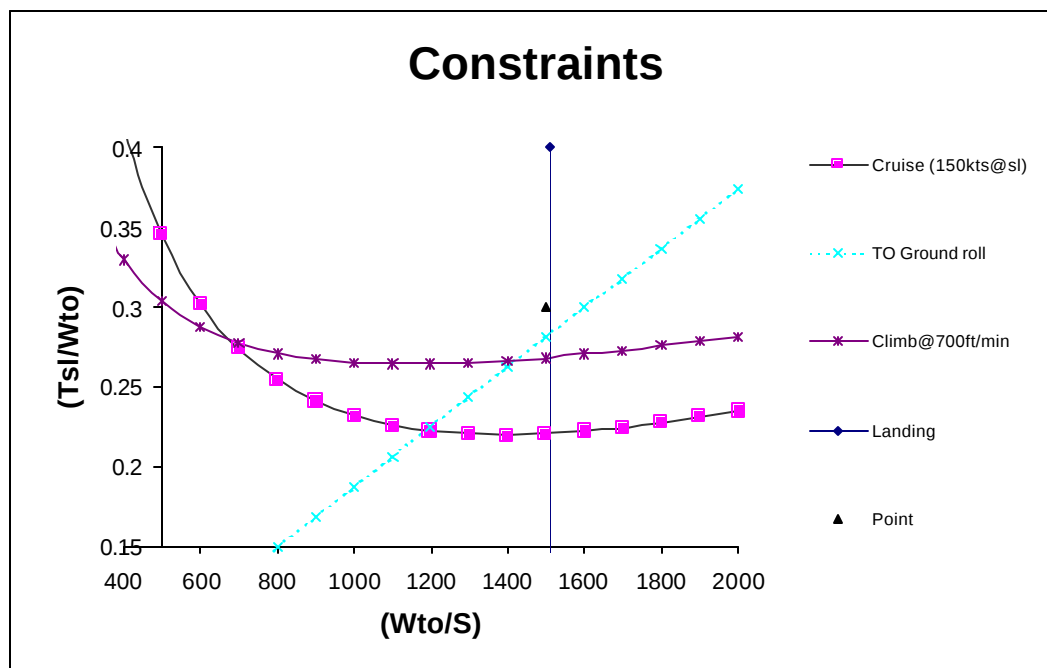
found assuming that single slotted flaps are being implemented, the average C_L for this arrangement is 1.7.

3.1.3 Cruise and Climb conditions

Using assumptions from comparable aircraft it was decided that a C_{D0} of 0.025 was standard for an aircraft of this type. Also for both conditions K_1 can be found to be approximately 0.08. The values for α , β and q will not be the same for both the climb and cruise. When in climb it has been assumed that the aircraft is performing this climb immediately after take off. Looking at other GA aircraft it was also decided that a take off velocity of 34 m/s (66 knots), which is 1.2 times the stall speed would be assumed. Using this velocity q was found to be approximately 2000 and α will be the same as for take off at 0.8. Due to the aircraft having only just taken off with a full fuel load a suitable value for β would be 0.98, as this takes into consideration the amount of fuel used in taxiing and take off. In the cruise condition the predefined velocity was 77 m/s(150 knots), as this aircraft will fly mainly at low level the cruise calculations were performed for sea level conditions. Which is perceived to be the worst case condition. After the aircraft has completed its take off and climb it will have a β of around 0.95, and when it lands this value will be 0.85. Because of this a suitable β at mid flight has been taken as 0.9.

3.1.4 Design Point Decision

When choosing a design point the thrust loading and wing loading have both got to be optimized. For the thrust loading the smallest value obtainable is desirable as this will give the minimum amount of thrust and hence the smallest possible engine. The opposite is true for the wing loading however, as the largest possible value will give the smallest wing area which is good. Taking these considerations into account and allowing for a small amount of clearance a point has been picked at a thrust loading of 0.3 and a wing loading of 1500 N/m². This will give a power of about 147KW (198 hp) and a wing area of 10m². Figure 1 shows the constraint plot that was obtained for the four flight conditions.



3.1.5 Drag Estimation

Throughout the initial design stage the value of the profile drag coefficient was taken to be 0.025. This value is typical of single engine piston propeller aircraft, but it was anticipated that the need for car conversion would add to this value.

In order to provide a more realistic value of the profile drag coefficient in the different configurations for the baseline design, the drag estimation methods indicated in Raymer were employed, with some additional information from Torenbeek. Using these methods the major differences between the roadable aircraft and a conventional GA aircraft, in terms of profile drag, can be seen to be the wheels and the outboard wing roots. The telescoping outboard wing section cannot be filleted into the inboard section wing tip, which will increase the interference factor for the wings.

With the exception of the flaps in landing configuration, the wheels produced the largest single contribution to the profile drag. In the cruise configuration the undercarriage contributed over 35% of the total, and although this can only be an estimate with the suspension design as yet not finalised, it clearly shows the penalties of not having a fully retractable undercarriage. The values of profile drag for the aircraft were found to be:

At stall speed, sea level,

Cruise configuration	0.0272
Take off configuration	0.0418
Landing configuration	0.0906

At 70m/s, 3000m altitude,

Cruise configuration	0.0254
Take off configuration	0.0448
Landing configuration	0.0935

These values have been used, together with values for Oswalds efficiency factor and lift coefficient to plot a graph of the variation of drag coefficient with air speed, as shown above. This graph is for straight and level flight only, but it does give an indication of the drag over a wide range of velocities and configurations. Figure 2 below shows the graph generated. The spreadsheet for this graph can be found on the Loughborough Team website.

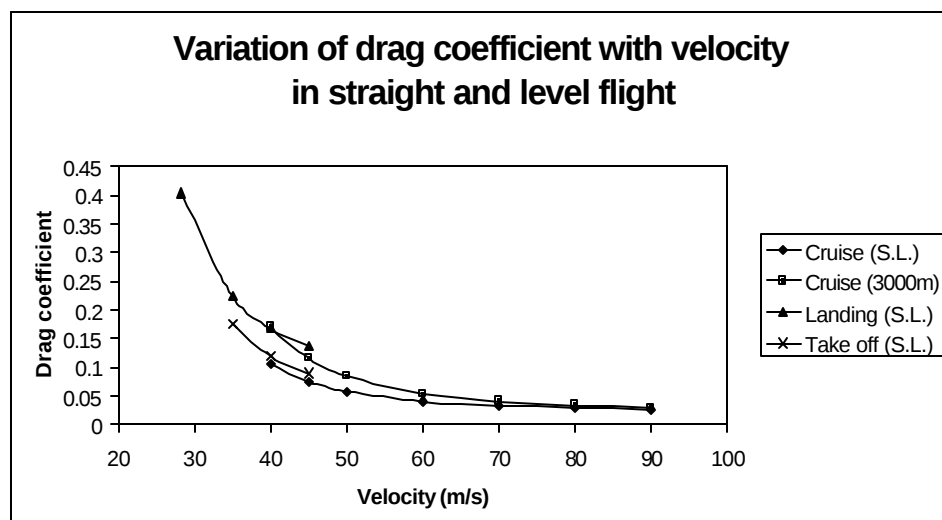


Figure 2 Graph to show drag coefficient against speed

3.2 Evolution of Design

After the week of discussions with our American counterparts a baseline model was agreed on. This was a combination of the highest ranking Loughborough design and the equivalent VT design. This initial concept is shown in Section 5. Since then though, there have been numerous changes as the concept has evolved into what is presented at the end of this document.

Probably the first changes came from a detailed analysis of the wing planform. It was evident that the design using winglets that came out of the centre section was inadequate in terms of gross wing area. In order to achieve any sort of realistic flying qualities the outboard sections had to be doubled in area. This gave rise to some complex stowage issues. The simple solution was to stow the wings one on top of the other and have them on a simple sliding mechanism. This did however mean that the wings would be slightly offset when viewed from the front or rear of the vehicle. Although this offset was not great and had a negligible affect on the aircraft performance it was not a superb solution, as its appearance would not inspire confidence in the user. A better solution was to utilise telescoping wings, which can be stored on either side of the vehicle in road mode and then deployed to give adequate wing area in aircraft mode. It is also now easier to put some dihedral in the wing to aid stability and fit the necessary wing mechanisms (Deployment and Control Surfaces) into the gap between the two stowed wings.

Early on it also became apparent that twin pusher ducted fan units might be inadequate in size for the application. Subsequent investigation showed a very high disc loading and in order to keep the width of the vehicle within 2.15m the model adopted a single propeller unit. This had the additional knock-on effect of changing the tail section. The vertical stabilisers had to be repositioned from behind the centre of the fans to the edge of the propeller shroud. This created a new 'box' tail, the design of which remains unchanged on the developed models. The twin boom on the rear had obvious advantages on the ground in crash situations as well as enhanced protection of the propeller unit. The lower sections of the boom also evolved to house the undercarriage and rear drive train.

The propulsive mechanism for the wheels was an issue, which took a great deal of thinking to resolve. There were two main design ideas; front or rear wheel drive. These options were also linked to the engine position selection that is discussed shortly. An idea dismissed early on in the evolution was to drive the rear wheels with an electrical motor, which used electricity produced by running a dynamo off the engine. This incurred several weight penalties and, it was agreed, did not make sensible use of the engine that was available. The differential has been housed in the wing body in order to create independent suspension for the rear wheels. The wheel can then be driven with a chain/belt and hence all these moving parts could be outsourced from motorcycle applications and hence the research and development costs could be decreased. The complexity of the undercarriage was not really appreciated until a physical model was produced. Initially the drive was towards a fully retractable undercarriage but weight penalties and increasing complexities drove the design toward fixed and faired front wheels and a slightly moveable rear swing arm configuration.

The engine position itself also caused controversy between the two groups. The baseline model, as agreed on during late November, utilised a mid-engined design. This idea was included in developments made by the Loughborough Team although the VT team considered the effects of moving the engine to the front of the vehicle in order to fit in with standard car structure design. Both teams rejected this modification, when the analysis showed a poor centre of mass position, which produced an excessive nose down pitching moment. After further analysis it was found that the existing tail surfaces would not be able to produce a sufficient opposing pitching moment to allow for rotation on take off.

There was also the issue of crash protection. If the volume in front of the crew were filled with a massive body such as the engine then the nose would have to be lengthened in order to provide crumple zones to meet stringent US and UK road-worthiness certification laws. These could of course be built into the modular Audi Space Frame construction technique currently being researched to produce the vehicle structure.

At present, the final design stands with the engine positioned behind the cockpit, 0.23m behind the centre of mass of the total aircraft. The weight of the engine is yet to be confirmed following a decision on specific model. The 300kg total propulsion system mass estimate is a reasonable approximation for the selection being considered.

Finally the construction techniques to be used have been considerably refined following further research. At the start of the project the 'buzz' word was Carbon Fibre. This was used extensively and with very little justification. A more cost-effective solution has been to use a range of materials, specialised to their local environment and the loads applied to them. Glass fibre has now become the leading material with aluminium forming many of the features (centre load bearing sections of the fuselage, cockpit braces etc). Carbon Fibre still has its uses in sections of the wing where weight and strength is of optimum importance. Using glass fibre as the primary material now has enabled a more 'modular' approach behind the design. This in effect has enabled the groups to work more efficiently by allowing several design processes to carry on in parallel.

4 Description of Baseline Design

This section of the report outlines the baseline aircraft layout and then concentrates on the individual components of the aircraft that combine to produce this overall layout.

4.1 Aircraft Layout

The aircraft that is described here as the baseline design has a relatively standard layout when it is in the aircraft mode. The General Arrangement drawing is included in Section 5.2 at the rear of this document. The main body of the aircraft is surrounded by a thick inner wing, which houses the telescoping outer wings. These are in three extending segments each of 1m in length and extend with 5 degrees of dihedral to aid stability. Included in the outer wings are full-length Flaperons, which provide additional lift for take off and roll control during flight. At the rear of the vehicle are twin vertical tails containing rudders and a high horizontal tail containing the elevator. Also included at the rear are two low tail mounted, all moving horizontal tail surfaces that can act in both the pitching plane when moved together or the rolling plane when moved differentially. The vehicle is powered by the ducted propeller at the rear of the aircraft, which provides more thrust than an un-ducted propeller of the same diameter.

In the automobile mode the vehicle is powered by the two rear wheels and is steered using the two front wheels. The retractable wings are stowed in the fuselage and the all moving tail surface folds into the fin. In order to conform with road regulations the vehicle has “pop-up” lights both front and rear.

4.2 Structure

The construction of our roadable aircraft will need to consider both automotive and aeronautical requirements and design philosophies. It is possible to break down the construction into several elements; materials, structure and manufacture, the first two of which will be considered here.

4.2.1 Materials

There are many materials available but, as always, careful consideration must be given to what is most appropriate. The main materials to be considered are steel, aluminum, titanium, glass reinforced plastic and carbon reinforced plastic. The main factors affecting our decision will be strength, stiffness and density. These are summarised in table 1 in appendix A.

Other factors which are harder to quantify, but still important, are durability (fatigue), damage tolerance (fracture toughness/crack growth) and corrosion resistance.

Finally, cost will always be a factor, and this breaks down into material cost, manufacturing cost and maintenance cost.

Most cars are constructed using steel, but for the aeronautical industry the higher strength/weight and stiffness/weight ratios of aluminium and titanium are preferred.

Recently composite materials have become more popular, with weight savings of up to 40%

4.2.2 Structure

The type of structure is also extremely important. Previous attempts to design a viable flying car or roadable aircraft have failed, so it is reasonable to assume that modern construction methods are more likely to succeed than older techniques which have already been tried and failed.

Part of the problem of designing a roadable aircraft is the need to meet the loading requirements for flight and road conditions. The essential difference is that aircraft are designed for strength, while cars are designed for stiffness to improve handling and to enable the suspension to work properly.

4.2.3 Main Fuselage

It is easy to rule out a separate chassis and body type structure, and the clear way forward is an integral structure. Since integral construction first came onto the scene it has taken over the small car manufacture. Integral construction was adopted even earlier in aeronautical construction for many World War II aircraft.

Steel is the most common material found on modern cars, with the car body constructed from overlapping sheet metal fastened with thousands of spot welds. The framework is constructed from thin walled box sections. Where reinforcement is necessary longitudinal sections and flanged members are used. Much of the strength is still found in the underframe assembly, which is usually reinforced.

A better solution is the Audi space frame construction. This differs from the above in that instead of pressed steel assemblies, an aluminium-silicon alloy is used. This takes the form of extruded box sections, cast components and sheet panelling. Using curved extrusions reduces the number of spot welds necessary, so there is less strength reduction. Wall thickness can easily be varied according to requirements at a location, optimising material use. High strength vacuum castings are used, and the sheet panelling is formed from thin gauge aluminium stampings.

The advantages of this method of construction are

- Further savings in weight over conventional monocoque construction, which also means;
 - ◆ Other components, for example suspension, can also be lighter
 - ◆ Power to weight ratio is improved, giving better performance and lower emissions
- The vehicle will be stiffer, therefore reducing vibration and helping noise control
- Improved structural stability means the vehicle is safer for passengers
- Weight and stiffness improvements combined improve handling of the vehicle
- Finally aluminium is an environmentally friendly alternative compared to steel

It is anticipated that engine, fan and gearbox will be located towards the rear of the vehicle, so a subframe will probably be necessary for mounting these. Once again

aluminium is the most likely material for this. The telescopic wings will also be mounted in this region, so this frame will likely be combined with the wing mounting.

4.2.4 Wings

The use of telescopic wings for the roadable aircraft was considered from an early stage, but decided upon late in the design process. Quite simply, they offer the most compact method of storage when on the road, and also offer a larger wing area compared to other designs considered, where the wing was stored unfolded and uncompressed inside the aircraft, with one on top of the other. The telescopic wings we are utilizing are being developed from a design in an AIAA/SAE paper by Czajkowski, Clausen and Sarh. A more conventionally structured inboard wing will complement the outboard telescopic wings.

4.2.5 Safety

Safety is a very important part of the structural design of the aircraft, including such things as crumple zones and material energy absorption. This is being covered in a separate section.

4.3 Aerodynamics

The wing sections to be used will be of a General Aviation (Whitcomb) design. These wing sections are relatively new and few general aviation aircraft use them at present. They give benefits with the maximum lift of about 30% over the more conventional four and five series airfoils.

With the original wing stowage system the wings were staggered, the wing section for the outboard wings was required to have a small thickness to chord ratio so that the two outboard wings could fit inside the inboard wing. It was decided upon a GA(W)-2 (NASA LS(1)-0413) section for the outer wing, which has a thickness to chord ratio of 13%. This resulted in a thickness to chord ratio requirement of 21% for the inner wing in order that the outboard wings could be satisfactorily stowed.

For the new design with telescoping wings, it was decided that the outboard wing section could be changed for one with a higher thickness to chord ratio. The main benefit of doing this is to ensure that leading edge stall is less likely to occur.

The wing section to be used for the telescoping wing is a GA(W)-1 (NASA LS(1)-0417), which has a thickness to chord ratio of 17%, and a design lift coefficient of 0.4. The inner wing may also have this section, as now only one wing thickness will be stowed inside it.

The inner wing may be faired into the outboard wing to reduce drag losses and minimise vortex formation at the join between the two wings. If the inboard wing is faired in, and as there is not a large difference between the two chords of the wing (2.5m and 1.75m) the wings could be treated as one wing with a chord of 1.75 metres.

One of the requirements is for a stall speed of 55knots, which equates to 28.3 m/s. This means that for an aircraft weight of 1500kg, and a wing area of 13.5 m² at the stall speed and at sea level the C_{Lmax} value required is 2.2. This should be easily obtainable if flaps are used to complement the wings. In order to obtain this value of

C_{Lmax} the possibility is being looked at to use single slotted flaps, in the landing configuration.

With the original staggered wing design there was the possibility of using leading edge slats on the wings to increase the maximum lift when landing and taking off. However, it has now been seen that the new design with the increased wing area should not need this extra augmentation and flaps should suffice in providing the lift required at or near stall conditions.

The aircraft in cruise, at a height of 3000m, and a speed of 77 m/s (150 knots), will have a C_L of 0.4. This value is the design lift coefficient for the wing section being used, however the aspect ratio of the wing is low, being roughly 5. This may mean that the induced drag is a little high. To reduce this induced drag, winglets may be used on the tips of each wing. It is still undecided at this point whether the winglets would be beneficial enough to warrant their use. The information required by some other groups is the $dC_L/d\alpha$ value and the C_{Lmax} value for configurations with and without flaps. To obtain this information, 2-D values must first be found. We have found this data hard to come by for the wing sections that we are using, however the following data was found:

The 2-D values are:

$$\begin{aligned}dC_L/d\alpha &= 5.9 \\ C_{Lmax} &= 2.2\end{aligned}$$

This gives the following 3-D values:

$$\begin{aligned}dC_L/d\alpha &= 5.7 \\ C_{Lmax} &= 1.5 \text{ (without flaps)}\end{aligned}$$

These 3-D values were calculated using theory as suggested by Raymer for initial design studies. The C_{Lmax} value with flaps will be calculated later when the extent to which they can be used on the wing has been decided.

The tail and fin sections still have to be decided upon, although the fin will have a symmetrical section i.e. it will be a NACA 00XX section, so the only thing still to be decided for the fin is its thickness to chord ratio.

4.4 Propulsion

The propulsion system consists of four main components, the power source (engine), transmission (gearbox), drive for road (wheels), and drive for air (propeller). Obviously these are all interconnected and the choice of one has an effect on the selection of the others, they will however be looked at separately here. Firstly however the performance required needs to be looked at, the specification gives preferred cruise speed and altitude. As all the data regarding other aspects of the craft are not yet available in their final form approximations and estimates need to be used. From this though we can estimate the performance required from the engine and the most suitable propeller to use with it. From the constraints diagram a thrust loading

was chosen of 0.3, from this and the estimation of vehicle weight a desired thrust can be calculated, which then leads to an engine sea level power of 210hp.

4.4.1 Engine

Considering the dual nature of the vehicle one of the engine's primary objectives must be its suitability to both air and road use. The key factors here are the type of fuel, its availability and the performance requirements in both environments. While not affecting the versatility, the cost is also an important consideration. Looking at the first point, fuel, the two main contenders here are the diesel (aero or auto), and the gas turbine. Both of these types can run on diesel, and AVTUR (Aviation Turbine Fuel, kerosene), enabling refuelling at airfields and on the road. On the basis of cost and current availability of an appropriate performance powerplant the gas turbine option has to be ruled out. This leaves a choice between an aviation diesel and an automotive diesel, the choice between these comes down to the preferred operation of the engine. Aviation engines tend to run at constant revs, whereas auto engines rev much higher and move around the rev range almost continuously. The choice is helped by looking at how each type of engine can be adapted to perform both roles. By using an aero engine combined with a continuously variable transmission suitable driving performance can be obtained, in fact this approach has been looked at by the automotive industry to improve efficiency. This of course forces the decision on the choice of transmission type as discussed in the following.

4.4.2 Transmission

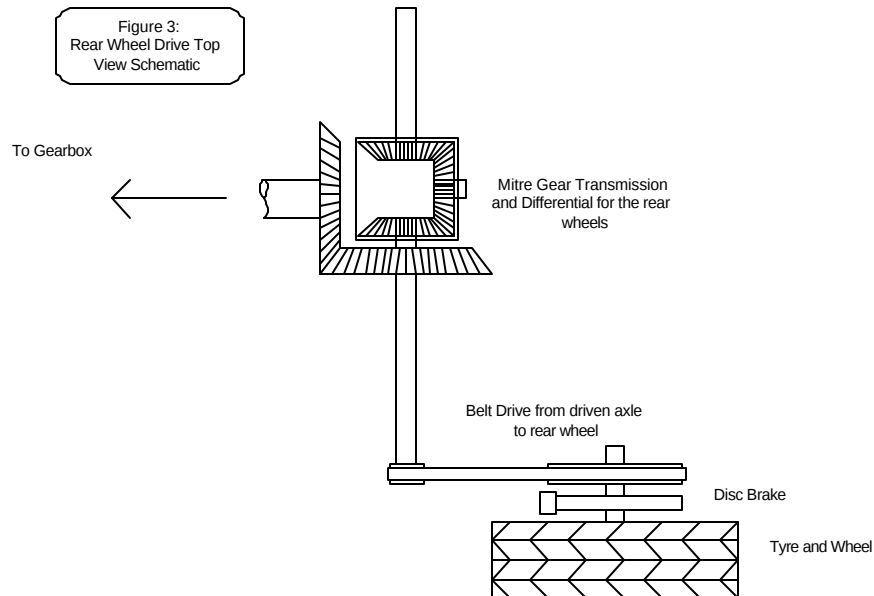
This can be split into two sections the drive to the propeller unit, and the drive to the wheels. That for the propeller can take the form of a conventional light aircraft, a direct drive, or simple reduction gear. This depending on the revolution speed of the engine and that required for the propeller, these usually being designed to match at optimum efficiency for a particular flight phase, such as cruise. The drive to the wheels is a little more complicated, because during normal driving the speed varies considerably. As previously discussed a virtually constant engine speed will be used, this will necessitate the use of a continuously variable transmission (CVT). These can come in many forms and the type to be used still needs consideration. Also includeable in this section is the need for a clutch system to engage and disengage the two forms of propulsion at the appropriate times.

4.4.3 Propeller unit

Here the original design called for a ducted fan, this was for several reasons including safety. The fans performance is also greater than that of a conventional propeller, or put another way it has the same performance as a larger diameter propeller of similar characteristics. The fan also has greater efficiency over its design speed range. The actual propeller inside the duct will be of fixed pitch, this is due to its simpler construction and maintenance. The characteristics will be optimised for cruise, or climb, or some compromise of the two depending on the rest of the system. While it is preferable to purchase a unit 'off the shelf' and adapt it to our requirements the lack of ducted fans available makes this unlikely. The size of the unit is limited by the maximum diameter of the duct, this being 2m, it can then be designed backwards from here.

4.4.4 Drive to the wheels

On leaving the gearbox the drive is transmitted to a differential gearbox that provides drive to the rear wheels. The drive is transmitted from the differential drive shaft to the rear wheels using a toothed belt drive directly linking the wheels axle to the differential axle. This can be seen in Figure 3.



This mechanism is stored within the trailing edge of the lifting body wing with the wheels situated under the vertical tail surfaces at the rear of the vehicle.

4.5 Stability

The intended use of this aircraft as a simple, easy to fly vehicle implies that it needs good natural static and dynamic stability and safe stall characteristics. This can be created through having large tail surfaces with a long tail arm. The maximum length we decided on to fit the requirements of American Road Laws and for drivability means that either the tail boom is extendable or the tail has a very large surface area. The current design uses the latter option with two fin surfaces and a large horizontal surface with two extra folding out sections. While this method creates more weight and drag, it means there does not have to be some tail boom storage inside the fuselage. While the current design uses a very large tail with a short tail arm, this may be changed to an extending tail boom at a later stage.

The effect of the flaps, ailerons and propeller wake must be considered and can be reduced by increasing the tail arm. The initial values for the horizontal and vertical surface areas were calculated using the formula suggested in Design for Flying Design for flying by David B. Thurston McGraw-Hill, 1978.

Horizontal Tail Volume Coefficient > 0.5 (all-moving tail)

Vertical Tail Volume Coefficient > 0.3

These values are a useful estimate based on empirical results that can be used as a starting point for later calculations.

4.5.1 Dihedral

The effect of dihedral is to increase roll stability and this could be useful due to our low wing. The low wing means that the fuselage has a negative effect on stability. As it is difficult to estimate the inertia and other variables at this point the initial value has been set at 5 degrees. On the downside, the dihedral does increase the complexity of the telescoping system and the structure though it should not pose too much of a problem.

4.5.2 Design considerations

The rudder needs to be able to overcome the adverse yaw moment created by the different drag on each aileron as a turn is initiated. Usually this is not a major problem as differential ailerons can be used. Also in our case there is a short moment arm for the ailerons and so this is a relatively small problem. Crosswind landings require a sideslip angle to be maintained to align the aircraft with the runway. The requirement for transport aircraft is to be able to land in a crosswind of 15.5m/s. Spin recovery was mentioned earlier and is obviously important. The rudder is used to overcome the spin rotation and so one of the requirements is that the rudder surface should not be in separated flow either from the horizontal tail surface or from the wing. There are the FAR requirements, which set a minimum roll and pitch rate. The rudder trim should be large enough to fly the plane should the primary rudder controls fail and similarly for the elevator. There are other requirements to ensure acceptable handling characteristics. The computer system on board could be used to improve the stability of the vehicle though the stability must still be reasonable without it to meet safety standards.

4.6 Roadability

The objective for the Roadability Team is to design those components necessary for travel on the road. Specifically these components include the steering, suspension and braking systems and miscellaneous equipment such as mirrors, lights, wipers, etc. The vehicle performance requirements pertinent to travel on the road are:

Cruise Speed: = not less than 65mph
Range: = not less than 200 miles.

In addition the vehicle must be safe and legal for travel on the road, conforming to current regulations.

4.6.1 Regulations

The Roadable Aircraft is classified as a Motor Car, according to UK construction & Use Regulations, and is categorised as an M1 type vehicle according to the EEC Classification, whereby:

Category M: Motor vehicles having at least four wheels, or having three wheels when the maximum weight exceeds one metric ton, and used for the carriage of passengers.

Category M1: Category M vehicles used for the carriage of passengers having not more than eight seats in addition to the drivers seat.

The Construction & Use Regulations are summarised in three categories: dimensions, performance, and required equipment and can be found in Appendix B. The regulations are taken from Toyne (1982) and Bosch Automotive Handbook 4th Ed. (1996), and are not necessarily the most current (see Loughborough Web Site for full automotive regulations).

4.6.2 Tyres and Wheels

The roadable aircraft shall use standard passenger car tyres and following industry practice all shall be of radial construction. To reduce weight alloy wheels shall be fitted, attached to the hub by four wheel nuts. The tyres must be large enough to support the weight of the vehicle and its load. The section width of the tyre relates directly to the tyres load capacity. With a maximum loaded mass of approx. 1500kg and a design load distribution of 50/50 (front/rear), the load supported by each tyre is 375kg (825lb). Ellinger & Hathaway (1989) present the load-carrying capacities of a number of popular American tyre sizes, showing that a section width of 175mm is more than sufficient (@ 24psi). Tyre aspect ratio is selected as 70% to provide a good ride comfort combined with reasonable handling. A rim diameter of 13" is selected, giving the following tyre choice:

Tyre Choice	= P 175/70 R13
Overall Wheel Diameter	= 575 mm
Overall Wheel Width	= 175 mm

4.6.3 Steering

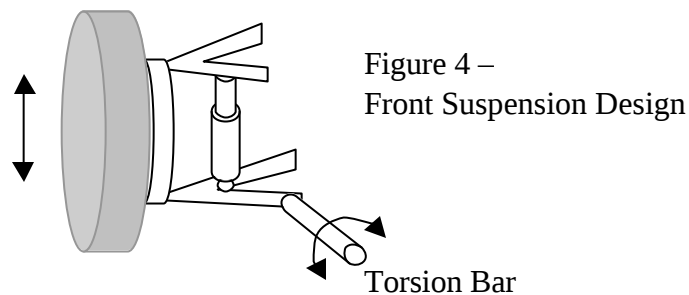
The baseline design for the steering system has not yet been resolved. The problems lie in the need to implement a system without mechanical linkages between the control and the actuators, in order that the controls may be reconfigured for road and flight modes. However, in the event of system failure the vehicle will be without steering control, which is unacceptable. Further research is required into drive-by-wire systems currently being developed by companies such as Mercedes.

4.6.4 Suspension System

The independent front suspension has three modes – take-off, flight and road. In the take-off mode the wheels are lowered to provide a greater incidence on the wing. In the flight mode the wheels are partially retracted to reduce drag. In the road mode the wheels are locked in a central position.

The suspension linkage between wheel hub and the vehicle body consists of upper and lower A-arms (or wishbone), with a damper joined between them. The suspension

is sprung by a torsion bar attached at one end to the lower A-arm, see figure 4. The torsion bar is rotated by an electric motor and is locked in position in each mode.



The independent rear suspension has three modes – road, flight and landing. In the road mode the suspension is in a central position. In the flight mode the suspension is partially retracted to reduce drag. In the landing mode the suspension is lowered to increase rear clearance and to provide greater impact absorption.

The suspension linkage between the wheel hub and the vehicle body is of a trailing arm type. A modified version of Citroen's hydro-pneumatic suspension system is to be used to raise and lower the rear wheels, as shown on the Citroen Zantia in figure 5 below. This system provides considerable wheel movement in a compact and proven design.

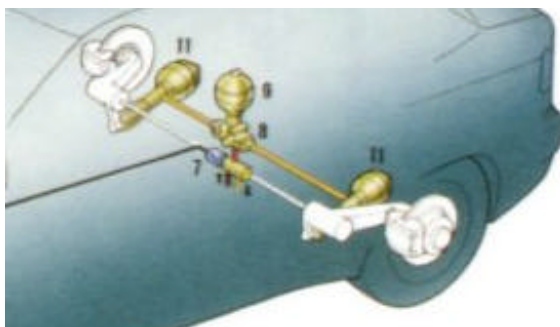


Figure 5 –
Citroen Zantia
Rear Suspension

4.6.5 Braking System

Disc brakes shall be fitted to all wheels, as they are of lower mass and greater performance than drum brakes, with floating calipers. Due to the need to reconfigure the vehicle controls when switching between flight and road modes it is not possible to have a physical linkage from the brake control to the actuators, therefore a power-braking system is required. A two-circuit air braking system is proposed, as employed on many trucks. The design is shown in Figure 6 below:

Figure 6 -
Air Braking System

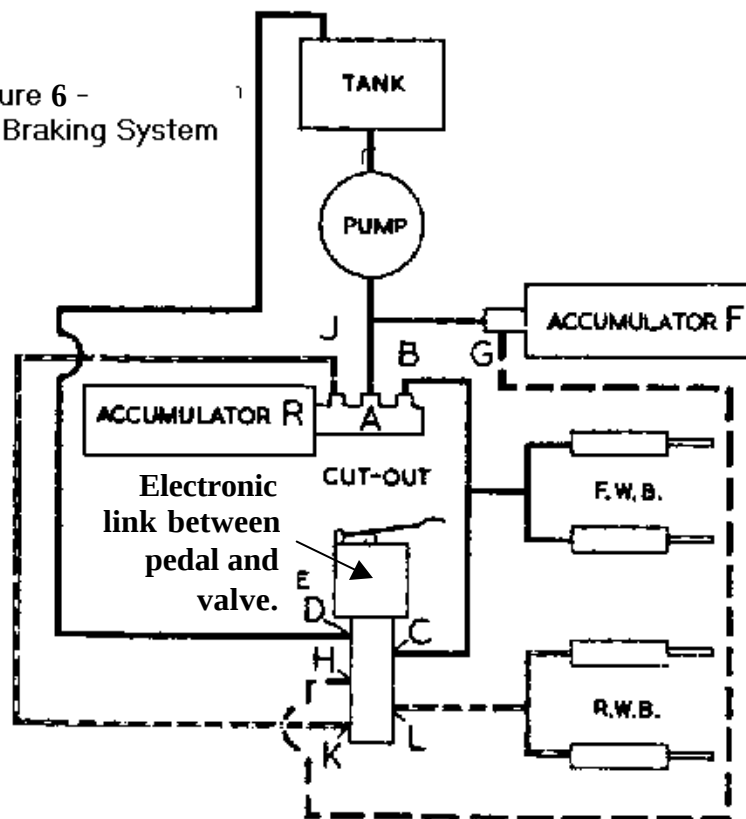


Figure modified from *The Motor Vehicle 12th Ed.* (1986).

The braking system differs from truck systems, in that the mechanical foot valve is replaced by an electronic displacement sensor on the brake pedal linked to a servo that drives the valve. The air braking system constitutes the service braking system. In addition, secondary and parking brake systems are provided via a mechanical linkage from the vehicle handbrake to the rear brakes.

4.6.6 Additional Equipment

A single windscreen wiper and washer is fitted and at rest the unit is embedded within the front cowling. Nearside and offside drivers mirrors are provided which may be removed and stored within the cabin during flight. Rear lights and indicators are placed within the two vertical fins and the rear number plate is held in place by a fitting on the ducted fan, and is stored in the cabin during flight.

4.7 Human Factors

The vehicle cabin has been designed so that it can accommodate 4 average sized or larger adults in a conventional two by two seat layout. The design/selection of seat is still to be made but it will provide the highest possible level of comfort and legroom for all the occupants.

Due to the unconventional nature of this vehicle, the display and controls have been designed to reduce the workload on the operator and therefore make the vehicle easy to operate. In order to achieve this a 'glass' cockpit has been used, where possible and

practical, as it will improve the clarity of the displays and dramatically reduce the amount of clutter.

The majority of the information for the vehicle instruments are displayed currently on 2 LCD's (Liquid Crystal Display) either side of a central MFD (Multi Functional Display). The LCD's provide the operator with the normal instrument displays for each mode, i.e. an artificial horizon, altimeter, compass, etc. for the aircraft mode or a speedometer, rev counter etc. for the car mode. The primary role of the MFD is to provide the operator with a moving map display and navigation information, based on data provided from a GPS (Global Positioning System) system. It will also display a video image from a rear-facing camera whenever reverse gear is engaged in car mode to alleviate the problems of the limited rear view. The other information that can be accessed via the MFD is yet to be decided. In addition to these displays there are CDU's (Control Display Units) for the radio, the transponder and a warning panel.

The whole changeover process is automatic and is initiated by pressing a single guarded switch, provided certain conditions are met, i.e. engine not running and weight on wheels, so that the changeover cannot be activated inadvertently. When the changeover is initiated, the LCD's change to display the appropriate symbology. An example LCD is on the Loughborough website demonstrating the changeover procedure. The MFD changes to display the current status of the changeover and indicate if there are any failures, the control system changes to the relevant method, the wings' and differential tail segments automatically extend or retract and the gearbox switches to whichever mode is required.

The vehicle can be controlled in both modes from either of the front seats however in car mode control will only be provided to one side at a time. It is possible to change which side has control, during car mode, via a guarded switch.

Steering input is via a single yoke/steering wheel device that connects to the relevant steering system as required. This provides the operator with an intuitive control device for both modes. The vehicle only has two pedals that act as the rudder pedals and toe brakes when the vehicle is in aircraft mode and as a brake and accelerator when in the vehicle is in car mode. There is no clutch pedal and as such a conventional automatic or a manual 'tiptronic' style gear selector can be used to control the gearbox for the car mode.

The vehicle is being designed to provide a high level of safety for the occupants and will include many of the standard secondary safety features found in current road vehicles, such as airbags and seat belt pre-tensioners.

All the vehicle access points will be designed to provide the maximum ease of access, this includes entry and exit from the cabin and access to the various systems for maintenance.

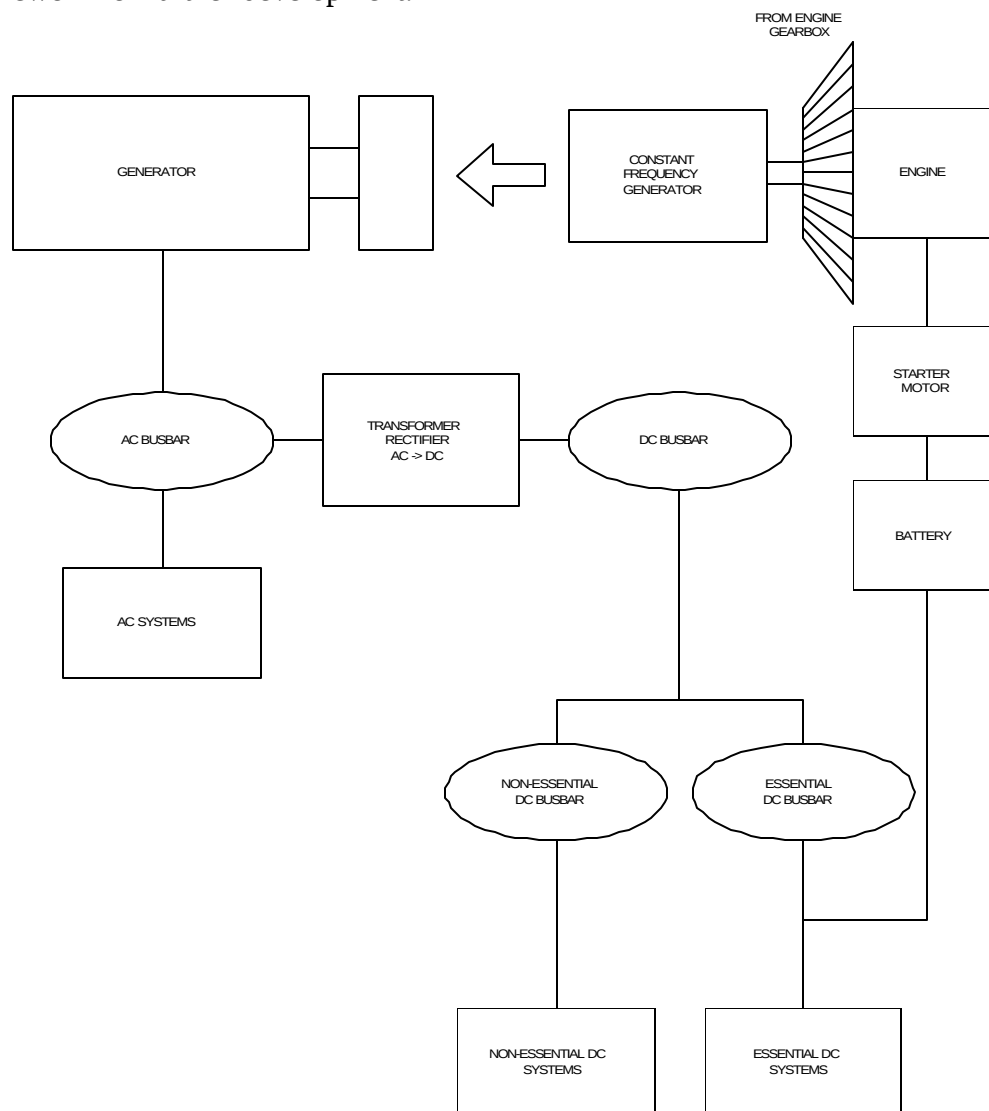
4.8 Systems

The baseline vehicle, as mentioned earlier, will utilise an all electric approach with regards to the control and monitoring of the all on board systems, including those which may have traditionally used hydraulic power. This decision was taken for a

number of reasons, primarily to reduce weight and increase available internal capacity. Secondly it allows us to take advantage of electrical power reliability and relative ease of maintenance. Clearly the main electrical components will be the avionics and displays that are utilised in the cockpit, the mode switching facility necessary to change from an aircraft to an automobile and the transfer of stick inputs to the control surfaces for flight and in road use, via power actuators.

The main disadvantage with this set-up is that each system is entirely dependent on an electrical power supply. This means that a permanent power supply will need to be applied at all times during the use of the vehicle. The constraints of the specification have determined the power distribution architecture that has been adopted. For example the aircraft is required to operate from airfields where ground power units will not be available and hence the vehicle will require a battery in order to start the engine and commence generating power on its own via an engine driven generator.

Complex redundancy features had been considered however it was decided based on cost and weight considerations that the generator will be backed up by a single battery source which can run DC busbars for a limited period of time. The diagram below shows a very simplified layout of the electrical architecture. This will be used as the framework for further development.



Electrical Usage

The baseline design and development has highlighted a number of areas that require electrical power services. Referencing the other design aspects of the vehicle, such as propulsion, human factors and stability a breakdown of their basic power requirements is given in the list below:

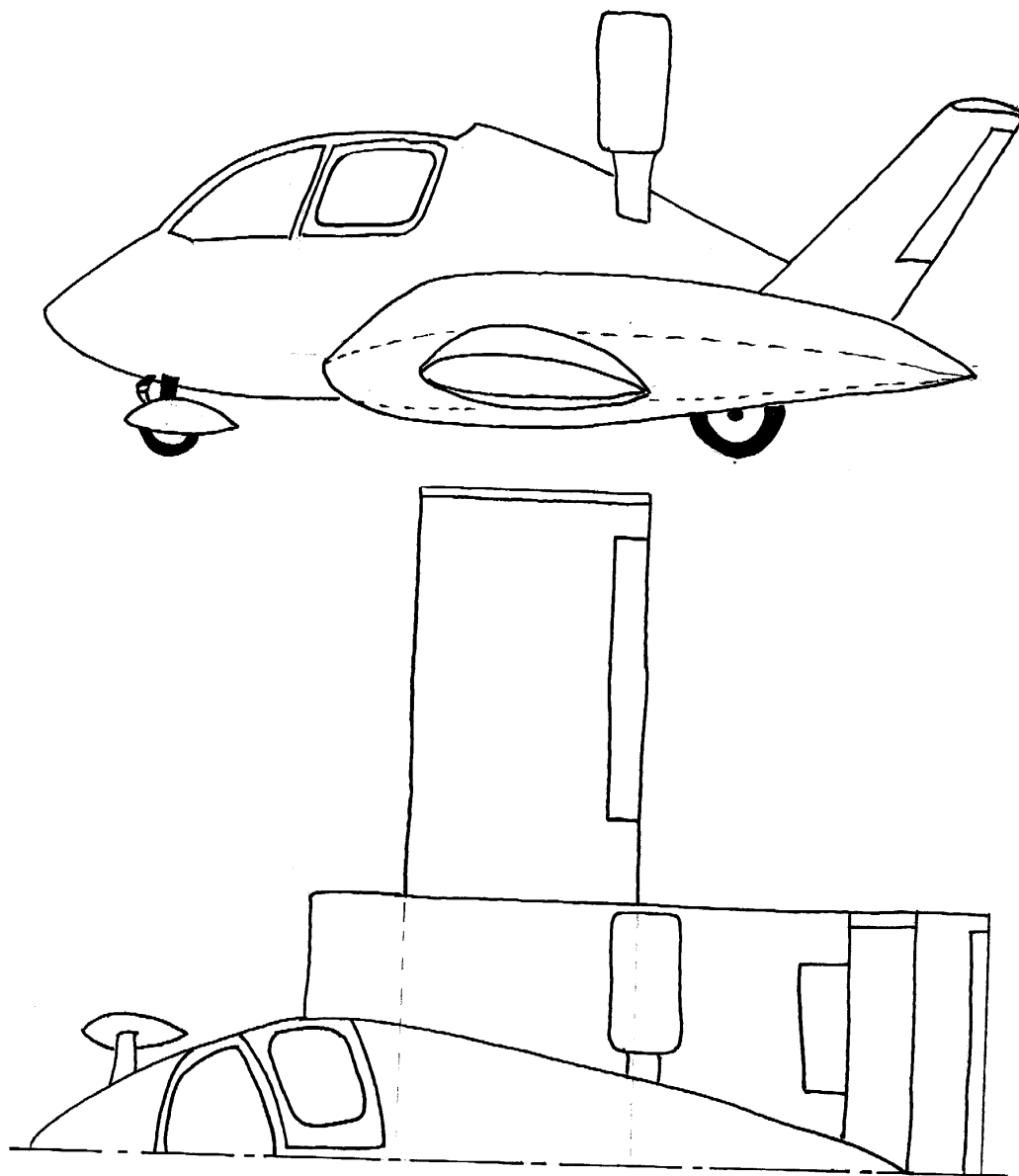
- Human Factors
 - Controls and displays.
 - Internal lighting.
 - In car entertainment
- Stability
 - Control surfaces.
- Roadability
 - Road/Air mode transformation.
 - External lighting
 - Suspension, steering, braking
- Propulsion.
 - Engine control and management.
 - Fuel management.
- Systems
 - Utilities management
 - Avionics
 - Navigation.
 - Communications.
 - Safety Monitoring.
 - Sensors.

Clearly at this stage the necessary systems are still being researched, however as various sub groups start to make firm decisions on layout and components the systems element of the project will start developing to ensure that the various components function correctly and more importantly safely together. Safety is an issue that has currently not been considered in any great detail however it is a very important part of the development of a new vehicle. It will include both onboard devices for the protection of the occupants and to guard against possible accidental decisions (e.g. retracting the wings in flight) as well as external safety features to protect other road users.

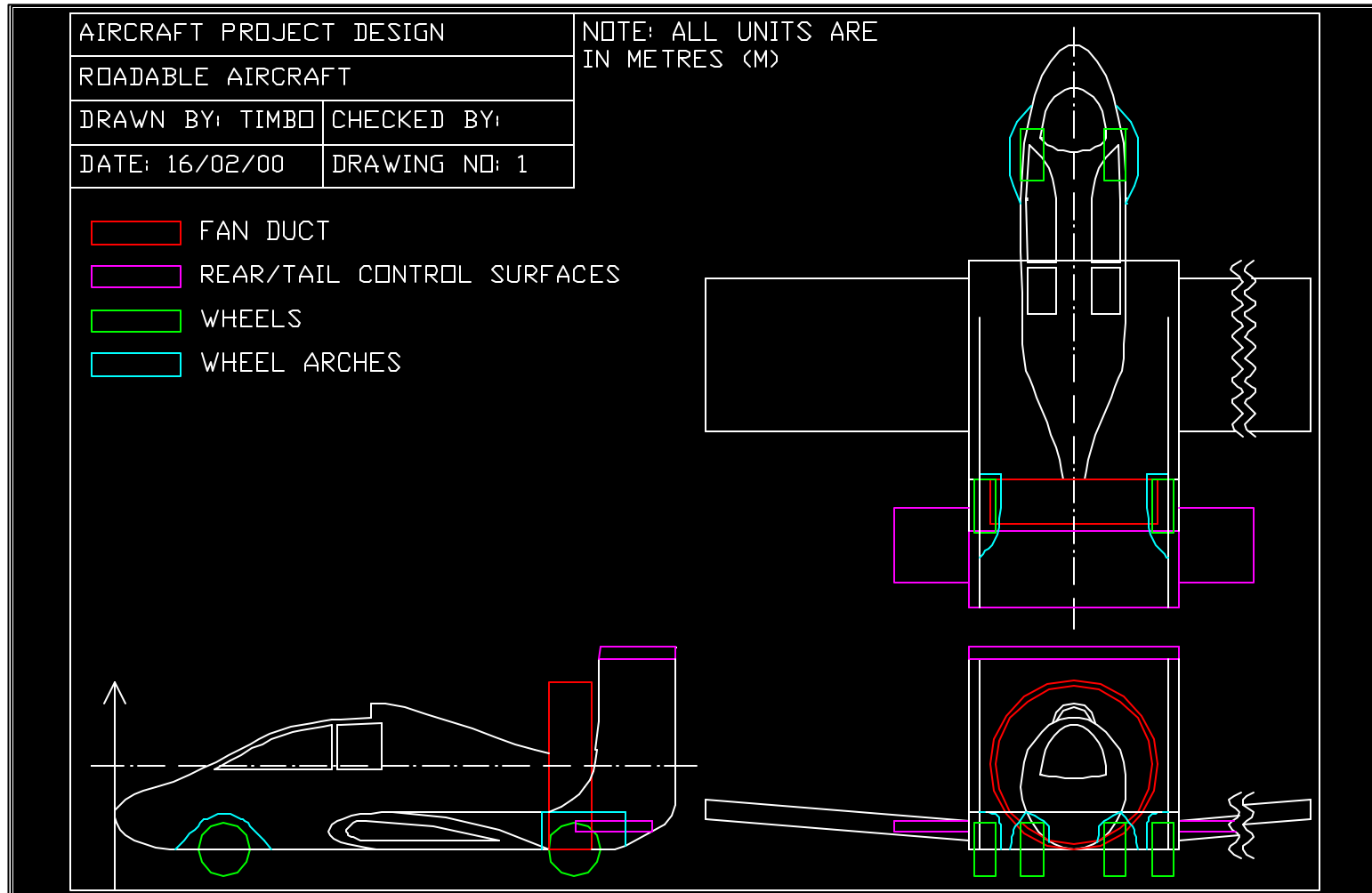
5 General Arrangement Drawings

This section has the two general arrangement drawings that show the original concept that we started with and the final baseline concept that we are currently working with.

5.1 Original concept



5.2 Baseline Design



6 Issues still to clarify

Although this document establishes a baseline design from which modifications can be made there are still a number of points that require some consideration to proceed the design into the detailed design stages of the development process.

In order to improve the aerodynamics of the vehicle and reduce the interference drag the body of the vehicle may have to be blended into the wing. This will almost definitely include fairing the leading edge of the inboard wing into the fuselage of the towards the nose.

Research is still being carried out into using a joystick control for both vehicle modes. As yet these systems are only at the concept stage in cars and so more information is required to make a decision on their suitability and acceptability for the task. There is also a particular issue concerning the safety of a drive-by-wire steering system due to the lack of redundancy in the event of failure.

Ducted Fan or Propeller – A decision will be made based upon a trade-off of the advantages and disadvantages of each. This is currently being investigated in some detail by both propulsion teams.

Following further stability research it may be necessary to have a small extendable tail boom at the rear of the aircraft to increase the tail arm and hence the moments produced by the tail control surfaces.

7 The Future

The main objective in the coming months is to build upon the baseline design described herein, working mainly within the defined sub-groups, to develop the aircraft to a maturity required for a detailed design. Pressing matters include the resolution of the issues described above, and agreeing the way forward with the Americans. The decision making process will shift its emphasis from aircraft configuration decisions made within the full team environment, to decisions at the detailed sub-team level, concentrating upon detailed issues within each area:

- Structures - Define space frame construction, with aluminum sub-frames, and GRP non-structural members.
- Stability - Perform stability calculations, define control surfaces.
- Aerodynamics - Develop aerofoil and fuselage sections to optimise performance.
- Human Factors - Development of final cockpit solution (D&C).
- Systems - Develop avionics capability. Integrate electronic systems throughout the vehicle.
- Roadability - Detailed design and performance calculations for the suspension system.
- Manufacturing - Determine materials and evaluate manufacturing potential.

Decision and problems should initially be decided between British and American sub groups, before passing the desired change to the team leaders who shall disperse the information to any other affected sub-groups.

Appendix A: Supporting Material

Table 1: Material Comparison Table

Material	Density	Youngs Modulus	Tensile Ultimate Stress	Tensile Yield Stress
	G/cm ³	GPa	MPa	MPa
Steel <i>300M</i>	7.8	200	1860	1520
Aluminium <i>7075-T6</i>	2.78	71	538	490
Titanium <i>Ti-6Al-4V</i>	4.46	110	925	869
Glass Reinforced Plastic <i>S2 Glass Epoxy</i>	1.8	43	1700	-
Carbon Reinforced Plastic <i>AS4/3501-6</i>	1.55	140	2100	-

Constraint Diagram Master Equations

Master Equation for take off

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta^2}{\alpha s_G g \rho C_{LMAX}} (W_{TO}/S)$$

Master equation for landing

$$s_L = \frac{\beta}{\mu g \rho C_{LMAX}} (W_{TO}/S)$$

Master Equation for climb

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha} \left[\frac{C_{D0}}{[(\beta/q) (W_{TO}/S)]} + k_1 \frac{\beta}{q} (W_{TO}/S) + \frac{1}{V} \frac{dh}{dt} \right]$$

Master Equation for cruise

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha} \left[\frac{C_{D0}}{[(\beta/q) (W_{TO}/S)]} + k_1 \frac{\beta}{q} (W_{TO}/S) \right]$$

A bibliography for this report will be available on the Loughborough Team web page