

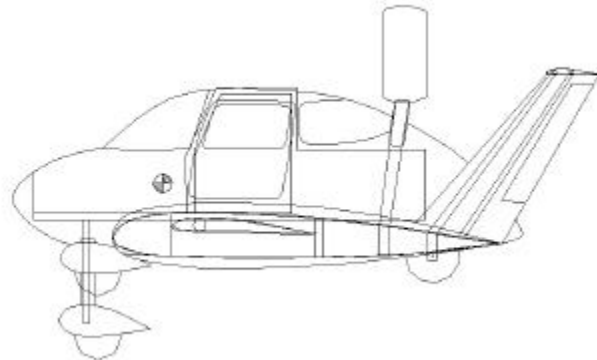


Roadable Aircraft

Final Semester Report

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Introduction

A roadable aircraft could provide a means for the revitalization of the general aviation industry. This international, interdisciplinary team is developing a detailed design for such a vehicle. It will be marketed towards small businesses and, eventually, families. It will provide an innovative means of transportation to and from the airport as well as in the air. Inside, many new technologies will be used for control and, possibly, navigation. Designing a completely new craft from scratch provides the team with some liberties that are not available when a craft is just modified from a previously existing plane designed 30 years ago.

AGATE

The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and the Air Force Research Laboratory sponsor the National General Aviation Design Competition. The purpose of the competition is to revitalize the general aviation industry by involving the academic community in real-world design experiences.

Short term application of Advanced General Aviation Transport Experiments, or AGATE, is needed for the successful revitalization of the general aviation industry. The major design focus is on technologies with an immediate and cost effective impact.

The AGATE consortium includes members from government, industry, and universities. It is developing “best practice” engineering design guidelines and industry standards for aircraft, training, and infrastructure. The main goal in revitalizing the general aviation industry includes the development of advanced technologies in new designs and retrofit products.

Other objectives include making flying safer by providing more information to the pilot, automating flight as much as possible, developing innovative propulsion systems for low emissions and noise, and developing low-cost manufacturing methods.

General aviation design initiatives include:

- Making general aviation appealing for business as well as personal use
- Making general aviation flight easier and more convenient by applying new technologies to training and certification methods
- Improving air traffic control accessibility, reliability, dependability, safety, and comfort

History

Attempts at roadable aircraft have been made since the advent of the airplane itself. Only fourteen years after the Wright brothers first flew, Glenn Curtiss tried to develop a flying automobile. His design was exhibited at the 1917 Pan-American Aeronautic Exposition in New York. This vehicle was abandoned after the flight characteristics were deemed unacceptable.¹ George Spratt built the first flying roadable aircraft by using an existing aircraft and adding a pivoting wing. This simply allowed the existing aircraft to maneuver down the road without side obstruction. Waldo Waterman was the first person ever to be granted a patent on a roadable aircraft, the “Arrowbile” in 1937.² The Arrowbile was the first vehicle designed as a roadable aircraft that actually flew. This gave other inventors hope in being recognized for roadable aircraft designs. A few other designs were attempted afterward, but no real progress came until after World War II.

The huge success of airpower and confidence from WWII helped forward the advancement of roadable aircraft. A milestone came in 1946, when Robert E. Fulton designed a

new concept. His FA-3-101 “Airphibian” was the first to gain certification by an organized flight agency, the Civil Aviation Administration. This opened the door for additional roadable aircraft since it had been shown that a flying car could acquire certification. One of these new innovators was Ted Hall, who became the closest to producing a marketable roadable aircraft. He produced the Hall Flying Car, which flew and was featured in Popular Science. He was on the verge of production when funding fell through and the project fell to the wayside. Following this came another strong contender in the field, the Convair Aircar, in 1947, which had the support of a large corporation.³



Figure 1: Convair Aircar⁴

When the cost of this project was determined to be uneconomical, the project was abandoned and the future of roadable aircraft looked dim. Many people thought that if a large company like Convair could not produce a viable solution, then no one else would be able to, either.

Another attempt at developing a roadable aircraft was made in the 1950s. In 1956, Molt Taylor designed and built the Aerocar I. This was the first roadable aircraft to be certified by the Federal Aviation Administration. This led the way for others because it dispelled the misconception that a flying car would not be able to operate in the United States. This reinvigorated the roadable aircraft industry and helped to push future ideas. But, the interest waned after these failures, and a long dry period in the design of roadable aircraft followed.⁵

Other steps in the design of roadable aircraft did occur after 1956. In 1965, Technik Wagner took an entirely new approach and came up with the first roadable helicopter. Also, during this period, many associations were formed including The Roadable Aircraft Association by Ken Fox, the Flying Car Association by John Olander and the Roadable Aircraft Magazine started by Ron Borovec. These organizations helped to maintain awareness in the attempts to merge flight and driving. But still, a design rush similar to the one after World War II was not existent.⁶

Paul Moller’s continuing studies and the introduction of his Skycar brought the idea of roadable aircraft into the future. Moller’s is an idea that leads into the future of roadable aircraft by harnessing new technologies. His work and the works of university classes like those at California Polytechnic Institute, Florida Institute of Technology and Virginia Polytechnic Institute & State University will help to push the idea of a publicly available roadable aircraft into reality.⁷



Figure 2: Moller Skycar⁸

Marketability

Understanding what people want to purchase is important in the design of the final concept. The AGATE organization has an extensive market survey available on their web page.⁹ The survey was given to current, former, and potential pilots. Relevant information pertaining to our design indicates that a large majority of respondents currently:

- Travel 3 – 5 hours away
- Take 50% or more trips by car (more than 2 hours away but less than 1000 miles)
- Travel 5 or less days per month for business
- Travel 5 or less days per month for personal travel
- Travel on an irregular schedule
- Are not full owners of aircraft

The survey also addressed the most important benefits of a general aviation aircraft. The top three benefits indicated by the respondents are affordability, reliability, and increased safety. Almost 50% of the respondents to the survey would increase travel to more than 10 days per month if traveling were faster and cheaper. In comparison to commercial flights, the convenience the roadable aircraft has in driving to and from a local airport and not dealing with tickets and checking baggage could reduce travel time, while not reducing actual flight time. Increased travel would also increase the usage of the smaller airports around the country. One focus for AGATE is the revitalization of these smaller airports, which are disappearing at a rate of almost one a day.

According to 123 potential pilots that responded to the survey 21% indicated that the reason to fly was for transportation. Another ten percent said convenience or business was a reason to learn to fly. The majority of respondents indicated that it was a lifelong dream. Also, a majority of the respondents indicated that a desired key feature was a graphical pilot interface.

There are three main market groups that the design may accommodate. One is the group of pilots that mainly use the craft as a conventional aircraft, and then on occasion have the need to drive the craft home on the highway due to an emergency such as weather. Another potential market is the group of non-traditional pilots that will use the craft instead of the more commonly used car. This type of person would look for a more luxurious vehicle, comparable to what is now found in the mid- to high-end automobile. Lastly, the group of business executives that utilize private jet service time-sharing or helicopters for business travel are candidates for this design. After weighing and discussing different options, the market decided upon by the team is oriented towards small business travelers and families. The family market creates an important focus in safety and the business side of the market will require a cost-effective solution.

Mission

It is imperative to begin the design process with a specific mission geared towards the type of vehicle desired. For this particular competition, no specific mission requirements were given. Therefore, the team first had to decide on a mission for this project. The main focus of the project is the design of a vehicle with both flight and road capabilities. The differing requirements of the two functions could be balanced either toward the air or the ground needs. There are constraints to be met with any configuration, as well as reasons to focus on one function over the other.

A roadable aircraft can be defined as a private plane that meets only the most basic requirements to drive on the road. This configuration would tend to be more stable in the air; however, it would be less than high performance on the highway.

A flying car, on the other hand, is a vehicle primarily used as an automobile that also has flight capabilities. A craft such as this could possibly allow portal-to-portal travel. Given that a high enough degree of automation can be achieved, it is assumed that many more people would be interested in this concept. However, current pilots surveyed by AGATE are extremely leery of both the lack of control with automated flight and having untrained pilots in the air.

The entire team consisting of Virginia Tech and Loughborough University students decided on the primary objective for this design. It was determined that the market drivers affect the objective for the mission. After a lengthy debate, the team decided that a roadable aircraft design would have the broadest application in our chosen market—small businesses and family.

The passenger capacity was established at four to coincide with the family-oriented market. Other factors defined in the mission include:

Table 1: Mission Requirements

Range - Air	Cruise	T/O Landing Distance	Climb Rate	Max Payload
926,000 m	77.22 m/s	500 meters	3.556 m/s	400 kg
500-800 nm	150 knots	1500 ft	700 ft/min	800 lb
Range - Land	Max Speed	Max Length	Max Width	Max Height
321,860 m	31.3 m/s	6.8 m	2.44 m	2.13 m
200 miles	70 mph	20 ft	8 ft	7 ft

The Design Team

The team consists of a combination of twenty-five students from Virginia Tech and Loughborough University in England. Strong team dynamics is vital to the success of the project, especially with a group this large. In any group it is important to establish a common goal and maintain communication. Early in the first semester the Virginia Tech team was divided into subgroups for the development of six initial concepts. Each subgroup then selected an initial concept to improve into an intermediate concept. The Loughborough team, having only just begun classes, only required each student to develop an initial concept.

The team structure includes a group leader from both universities and other positions such as report and web editors. The structure of the team is shown in Figure 3. To facilitate effective communication between the groups, each team maintains a web page containing information pertinent to the design of the concept. It is important to maintain contact by posting progress reports, agendas and minutes from meetings on the web, as there are only two weeks the entire year that the schools have face to face collaboration.

The two teams met for the first time in England the week of November 22 – 26, 1999. This trip provided time for the teams from each school to present initial and intermediate concepts. The Virginia Tech team presented the three intermediate concepts and the students from Loughborough each presented individual concepts. Due to similar individual designs, the Loughborough team selected three concepts for comparison. After the presentations both groups

met to determine the mission, since prior to meeting, the different schools had set some different requirements for the vehicle.

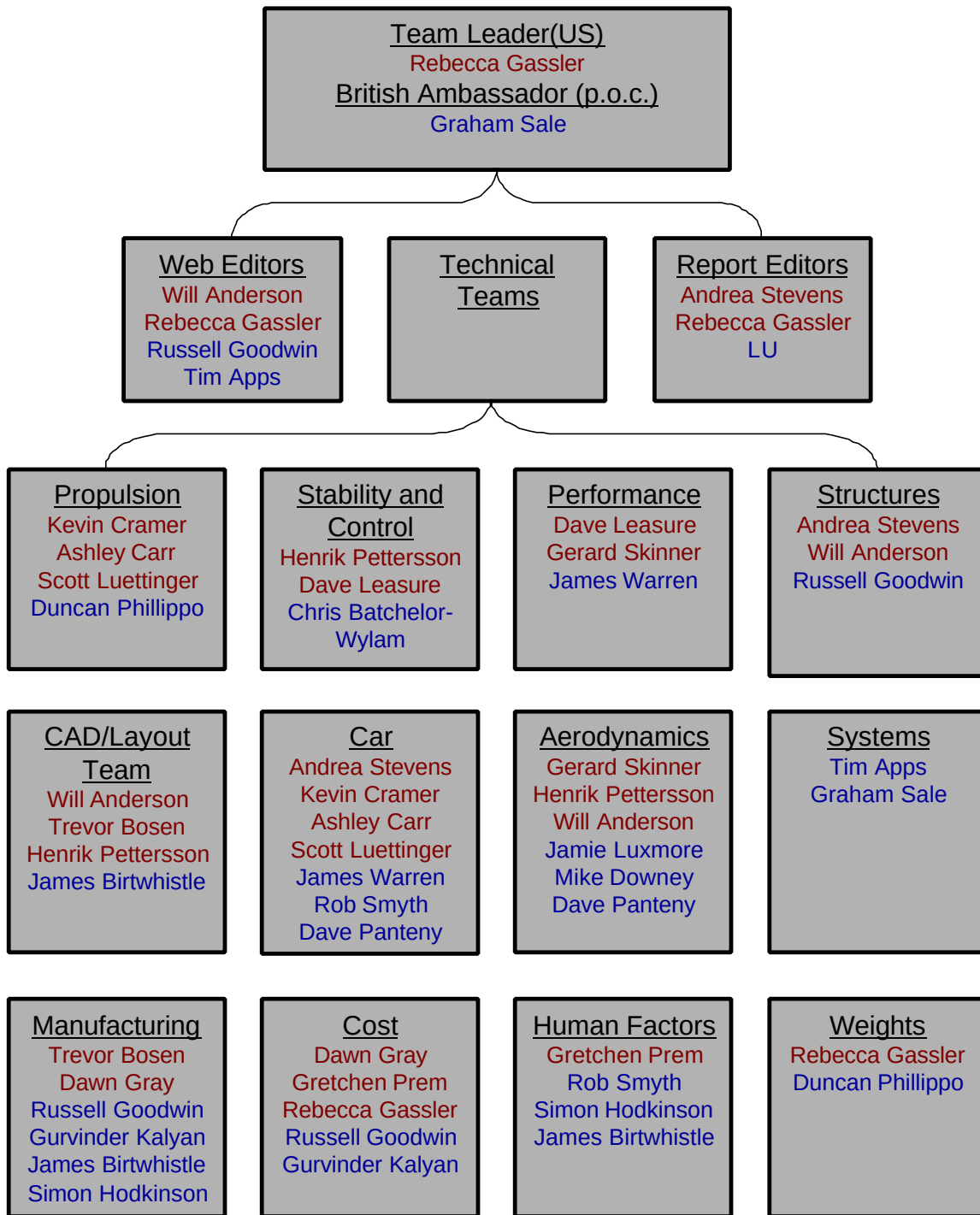


Figure 3: Team Structure Composed of Students from Virginia Tech and Loughborough University

Initial Concepts

The six initial Virginia Tech concepts are shown in Figure 4. These sketches show each craft in the roadable configuration. Each of these concepts was presented in an informal presentation to the rest of the Virginia Tech team and their merits and faults were discussed. From these discussions, the intermediate concepts were developed.

Initial Concept #1

Initial Concept #1 shown in Figure 4 (1) follows the flying car approach. It is meant to be used equally as a car and a plane. It has a relatively short fuselage with a length of 5.18 m (17 ft) and the tail telescopes in .61 m (2 ft) when in a roadable configuration. This enables the craft to be more maneuverable on the street. It has a wingspan of 8.53 m (28 ft) and a wing area of 7.80 m² (84 ft²). To make the craft fit in a lane on a typical road, the wings fold over once, pivot along the spar ninety degrees, then fold up against the body. This makes the craft 1.83 m (6 ft) wide. Having the wings fold against the body will also aid in crash protection since airplane fuselage skins are typically thin and would not withstand a crash at highway speeds.

The landing gear for the plane is traditional tricycle gear. For the roadable configuration, the front wheel folds up and two additional front wheels extend downward. The rear wheels rotate towards the rear to lower the plane and the center of gravity for road operation. Control surfaces on the plane include flaps and ailerons with elevators and a rudder on the empennage. The bench seat in the back, allowing a maximum of five passengers, enhances seating capacity for the craft. Baggage is stored behind this rear seat. Ingress and egress through the raised canopy is further assisted by a fold-down step.

Initial Concept #2

Initial Concept #2, shown in Figure 4 (2), is primarily a general aviation plane meant for road use only in inclement weather and emergency situations. The main unique feature of this design is the placement of the wheel and transmission. These are both located in the end of the wing. When the wing folds, there is a drive shaft protruding from the side of the fuselage that will fit into a hole in the transmission apparatus. There is one engine that drives both the wheels and the propeller. The engine is mounted aft of the cockpit and is connected to the drive shaft and the propeller through the use of the shafts and universal joints. Instead of a rear horizontal stabilizer, all-flying canards are present. This concept became Intermediate Concept #1 and more details and dimensions are presented later in the report.

Initial Concept #3

The third initial concept seen in Figure 4 (3) is a car body fuselage with standard, or even sporty, flight characteristics. The concept features a pair of Williams-Rolls FJ44 turbofans selected because of the available thrust (8.45-10.23 kN (1900-2300 lbs)) and small size (1.02 m (40.2 in)) in length with a diameter of 0.60 m (23.7 in)). A high thrust turbofan is necessary to balance the additional weight of the separate car engine and for vectored thrust applications. Thrust vectoring has potential for vertical take-off and landing and stability and control in this design.

This concept features a telescoping high wing with the turbofans mounted underneath. The wing area is maximized at 16.37 m² (176 ft²) to reduce the wing loading to that of

comparable telescoping wing designs. The wing loading of this concept was determined to be approximately 128.4 kg/m^2 (26.3 lbs/ft^2). The tail surfaces also telescope for transformation to the car configuration.

The design has fixed gear with front wheel drive and front wheel steering. The car engine is forward mounted with fuel storage aft of the cabin space. This concept was not selected due to the expense associated with using turbofan propulsion.

Initial Concept #4

The fourth initial concept seen in Figure 4 (4) is mainly an airplane fuselage that can also cruise down the highway. This vision was then combined with Kenneth Wernicke's podded Burnelli lifting fuselage. The Burnelli lifting wing has an area of 7.69 m^2 (82.7 ft^2) and produces an aspect ratio of 0.774. This design also features telescoping wing extensions with an area of 6.41 m^2 (21 ft^2) to provide the additional lift in the airplane configuration.

The fixed gear with forward steering and rear wheel drive propels the vehicle on the road. The aircraft configuration has a forward mounted engine with a forward-mounted propeller. Fuel storage is located in the wing. This concept moved onto the intermediate design stage with few changes. More detailed information presented on this concept can be found in the Intermediate Concept #2 section.

Initial Concept #5

Initial concept #5, shown in Figure 4 (5), is designed to be a 2 passenger flying car. The premise of this initial concept is a vehicle that easily converts from an automobile to a general aviation configuration. Basically, this concept originates from a car body with attached wings and tail.

The major features of this design include bi-fold wings and a retractable tail boom. The 7.93 m (26 ft) span wings fold under twice to become the side panels on the automobile. The tips fold under first and then the wing folds under again and is manually locked into place. Double hinges on the wing surface itself allow the folding of the wings. Using the wings as side panels on the car provides extra material that protects the vehicle in the event of a crash on the highway. For extra support, the wings are manually secured to the body of the vehicle by struts. When not in plane mode, these struts are secured inside the vehicle. The tail boom includes a V-tail that folds into the boom extension. The entire boom becomes the hatchback of the automobile.

A 1.83 m (6 ft) diameter propeller placed on the front of the vehicle powers the vehicle. Originally, it was thought to design the propeller shaft so it could be retracted under the hood. This would entail placing all engine equipment in the rear of the vehicle. Upon further reflection, it was determined to be better to leave the propeller in place and to manually lock it when in driving mode. This allows the engine and transmission to be placed under the hood of the vehicle. The entire vehicle is driven by a car engine in conjunction with a continuously variable transmission that provides power during flight. When in driving mode, the car has a short drive train that powers the front wheels.

This initial concept was not chosen to become an intermediate concept for several reasons. For one thing, the body style is not aerodynamic. Separated flow from the roof of the vehicle would likely interfere with the control of the v-tail. Another initial problem is the lack of a rotation angle for take off.

Initial Concept #6

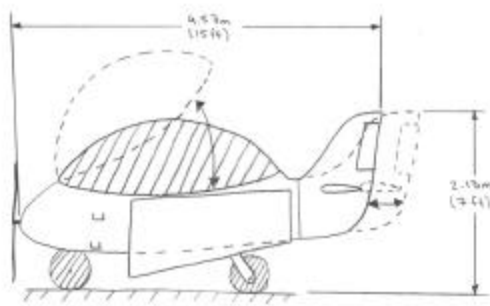
Initial concept #6 depicted in Figure 4 (6) is designed as a four passenger roadable aircraft. This concept features a unique pivot and hinge system for folding the wings. A pusher propeller is also part of the design.

The 9.15 m (30 ft) span wings folds onto the top of the vehicle for the driving configuration. The lower portions of the wings first pivot underneath the upper portions. Then, the upper portion rotates onto the top of the vehicle. The entire wing configuration is then folded over a set of hinges and locked in place with latches. The horizontal stabilizers in the rear fold against the side of the body using hinges. Vertical fins remain in place during both flying and driving modes. They are small enough to prevent any height restrictions while in driving mode.

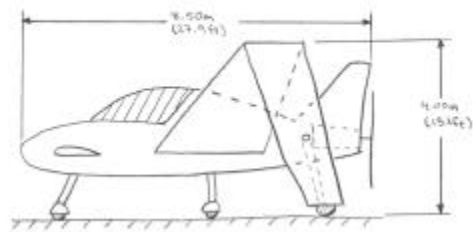
A rear-mounted 1.83 m (6 ft) diameter propeller propels the flying vehicle. The propeller will be locked in place to prevent unwanted movement during driving mode. The propeller in the rear provides safer driving conditions than a forward-mounted propeller would.

The four wheels on this concept are similar to car tires. They extend for take-off and landing conditions. For driving, the wheels retract into wheel wells. The motor used to power this concept will be hybrid electric. A gas generator charges fuel cells that are present under the hood. The batteries then power an electric motor in the rear of the vehicle. The electric motor has the ability to drive both the propeller as well as the drive train.

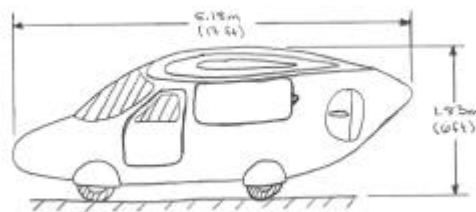
One major flaw with this concept is getting free stream air to reach the propeller. The propeller is directly behind the vehicle structure with only a small portion above the roof. It would be very difficult getting any free stream air to the propeller at all.



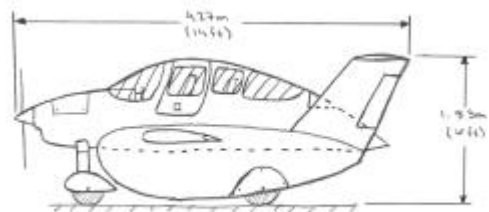
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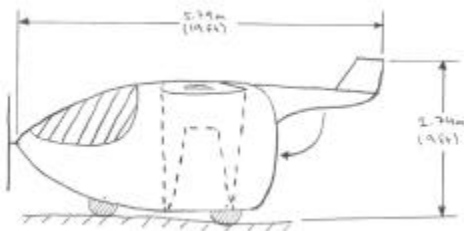
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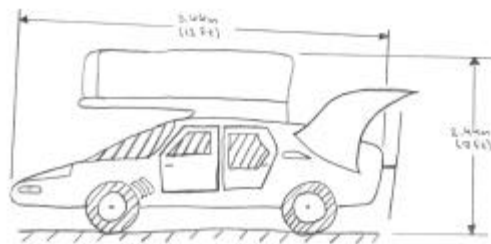
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(4)



(5)



(6)

Figure 4: Initial Concepts #1-#6

Intermediate Concepts

The Virginia Tech team, prior to visiting England, developed the first three intermediate concepts in this section. These concepts as well as pro/cons for each were presented in a midterm presentation. The second group of three intermediate concepts was developed by the Loughborough University team. The team had not conducted a pro/cons study for their concepts, nor did they have detailed, dimensioned drawings. The six concepts presented below were the ones evaluated by the entire team in order to develop the final concept.

Intermediate Concept #1

This concept is an example of a vehicle that is primarily an aircraft and occasionally a car. The car conversion is only to be used in emergency situations such as to avoid inclement flying weather. The aircraft configuration is a canard with a swept main wing and vertical tail. When the roadable configuration is needed, the wings are folded at their joints and the drive transmissions are connected therein. The wheels in the wing tips take the power from this transmission and push the vehicle on the road.

The cruise range is 805.2 km (500 miles) with a loiter period of 30 minutes for reserve fuel. The land range of the vehicle is 322.1 km (200 miles), though with the same engine being used for the flight and land configuration, this range is likely to be closer to that of the flight configuration, if not larger. The ground range is not as crucial as the flight range because gas stations abound along highways. A flight cruise speed of 241.6 km/hr (150 mph) and a land cruise speed of 112.7 km/hr (70 mph) are estimated. A takeoff distance of 488 m (1600 ft), a landing distance of 335.5 m (1100 ft), and a climb rate of 183 m/min (600 fpm) are estimated for the configuration. Four passengers and their cargo are envisioned as the useful load, estimated to weigh 1760 kg (800 lbs). A take-off gross weight of 6600 kg (3000 lbs) is estimated from charts and historical trends described by Nikolai.¹⁰

Baggage is stored in the nose of the craft. Fuel is stowed in a tank under the cabin and the baggage storage area. Because the wings fold for stowage, the fuel cannot be stored in them. Fixed tricycle landing gear is used in the aircraft configuration. The rear wheels have variable stroke, facilitated by telescoping wheel posts. The variable stroke is required to transfer the vehicle weight to the drive wheels in the wings during the road phase. So that the center of gravity position is maintained fore of the neutral point, the engine is placed slightly ahead of the center of gravity. A long horizontal driveshaft transfers power from the engine to the pusher prop in the rear.

No horizontal tail is included in the design. Rather, a flying canard is located near the nose. The canard area is about 20% of the total lifting surface area while the rest is devoted to the wings. The wing area is 14.94m² (160.8 ft²) with a root chord of 2.13 m (7.00 ft) and a taper ratio of 0.5. The wing is swept back 45° at the leading edge and has positive dihedral. The wing must be swept to facilitate the drive shaft wing intersection. Ingress and egress is accomplished through a canopy that raises 50°. The fuselage is 10.37 m (34 ft) long.

When on the ground, the airplane converts into a car by folding its wings. The wings fold upwards at the wing-fuselage intersection, and a further joint in the interior wing folds the outboard panel down, such that the wheel touches the ground. Extended from the wing tips are the aforementioned small auto wheels, which take the load of the aircraft when the rear gear are raised. The transmission components and braking systems are located in the outboard wing panels. A strap is attached over the fuselage and between the two mid-wing joints during

conversion from aircraft to car – either a geared manual jack or an electric motor then tightens this strap. The wings are retracted with deflated tires so that there is no problem with the wheels dragging and preventing full retract. These tires are subsequently inflated. After the wings are folded and the tires inflated, the rear landing gear are retracted by removing a lock pin and telescoping the post in until the wheels are within a highway lane width. They are subsequently re-locked.

The propeller in the rear of the aircraft remains in place and is locked whenever the plane operates as a car. This location is ideal because it minimizes hazards to other cars. The diameter of the propeller is 1.98 m (6.50 ft). This vehicle will have a 149.1 kW (200-hp) engine, used both on the road and in flight. The driveshaft supplying power to the transmissions within the wings is branched off of the propeller driveshaft with a universal joint. The shaft protrudes from the side of the fuselage and is connected to the gearing through a hole in the wing. When the wings are folded up, the driveshaft aligns with the hole in the wing. The driveshaft is not engaged when the aircraft is in flight. During flight a fiberglass sleeve cloaks the driveshaft.

FOLDOUT OF INT CONCEPT #1 HERE

Figure 5: Intermediate Concept #1

Intermediate Concept #2

This “roadable aircraft” concept is a podded Burnelli lifting fuselage with telescoping wings shown in Figure 6. The low aspect ratio wing enables this vehicle to fly and to drive on streets without impeding traffic, as it is 2.44m (8ft) wide. The endplates are necessary to keep the high-pressure air on the bottom of the wing from escaping around the wing tip to the top of the wing and creating induced drag. The telescopic wings provide greater lift as well as roll stability and control when extended. Fully telescoped, the wings have a span of 4.33m (14ft 2in) and give the aircraft an overall aspect ratio of 0.964. The large horizontal tail gives pitch stability and control over an otherwise pitch-unstable vehicle. The large Burnelli wing is a NACA 4415 or 4418. The telescoping wing is a NACA 2412 set at an incidence angle of 3°. These airfoil shapes and angle of attack generate sufficient lift for the aircraft to takeoff without rotation. This allows the rear wheels to be set further back, producing greater stability on the road. The vehicle is 4.97m (16ft 3in) long and 1.83m (6ft) in height in both the roadable and flying modes.

The design proposal for the telescoping sections is modeled closely after the MAK-10, a Russian design built in France in 1931 that flew and functioned well. On this craft, the inner section consists of upper and lower panels that carry the load. Two girders will join these sections, one running along the leading edge and the other forming a false spar. This forms a tube, inside which a metal box-spar is placed. The outer section is made of strong, lightweight material. These slide in and out of the inner sections using rollers at the extremities to transmit the load. Telescoping the wings manually allows for maximal wing span.

The propulsion system consists of two separate engines, one for ground usage and one for aircraft usage. Two engines have been selected for simplicity as an airplane engine does not function well at the variable speeds required for road travel and the car engine is not made for the endurance necessary in flight. When on the ground, the vehicle is powered by a car engine located in the aft of the fuselage. A standard automatic transmission will be mounted on the engine. The crankshaft will propel an axle on the same level, forward of the engine. This axle will turn ninety degrees down with bevel gears in order to drop down the side supports and move the rear drive wheels. The car engine inlets are located at the aft of the fuselage and are covered when the vehicle is in flight. When flying, the propeller engine is utilized and this inlet is located at the bow of the fuselage. The aircraft engine is a Tectron Avco Lycoming O-540 series with 186.4 kW (250 hp). It is already approved by the FAA to be used with ordinary gasoline. This will simplify fuel issues, including fuel flow, fuel tanks and fuel lines. When on the road, the propeller is locked in place. There are access panels over both engines for easy access. Fuel for the engines is stored in the Burnelli wing.

The steering will consist of a dual rack and pinion system in the front wheels, which will have a shaft with a pivot on it connected to a pinion. When the pinion is in the down position it will be connected to the automobile rack. This rack will connect to a gear on the side that will rotate a downward shaft. This shaft will go directly down the front struts to the wheel housing. While in flight, the front wheels lock in the forward position. When the pinion rotates up, it will engage the aircraft rack. The ends of this rack will be connected to standard aircraft cables and pulleys. As well as moving laterally, this rack will move forward and backward in order to control pitch. The gas and brake pedals will be shrouded by the rudder pedals. The rudder pedals will pivot on their supports. These supports will connect on the top and bottom only and will completely surround the automobile pedals. The movement of these pedals will not

interfere with the gas or brake. The brakes for the automobile and aircraft will be separate so that the aircraft brakes will only engage the rear wheels, while the automotive brakes will engage both the forward and rear wheels.

The large hatches swing up along the centerline, providing a means to ingress and egress. A step is located on the front gear supports to get into the plane. The wheels are not retractable, so they are covered to reduce drag. They are easily accessed for repair or maintenance through the panels shown on Figure 6. The cabin seats four people with a baggage area behind the two rear seats, which is easily accessed from the cockpit.

Figure 6: Intermediate Concept #2

Intermediate Concept #3

Intermediate concept #3, as seen in Figure 7, is designed to be a four passenger roadable aircraft with a storage compartment located near the front of the vehicle. Key features of the design include a lifting-body, scooped out rear fuselage shape, twin vertical tails, a rear pusher prop, an aircraft engine with a single reciprocating, continuously variable transmission, semi-retractable landing gear, and a unique wing and stabilizer stowage for driving configuration.

The lifting body, scooped out rear fuselage takes on an airfoil shape and is intended to generate lift, reducing the required wing area. A major adversity faced in designing a vehicle that transforms from a plane into a car is stowage of the external aircraft components in driving mode. Thus keeping the wings and control surfaces as small as possible for easy stowage is a driving factor for this concept.

Twin vertical tails on either side of the scooped out rear fuselage provide the vehicle with lateral stability and control during flight. A semi-shrouded, 1.83 m (6 ft) diameter pusher propeller, located on the rear of the vehicle between the twin vertical tails, in the scooped out portion of the fuselage, induces flow over the top of the body further increasing the lift on the body. The added lift from the body along with the aft center of gravity due to the rear-mounted engine and propeller may tend to generate negative pitching moments on the vehicle in flight thus leading to instability. Horizontal stabilizers (elevators) are located on the outer sides of the vertical tails to oppose negative pitching moments and increase vehicle control.

The vehicle is driven by a single 149.1 kW (200hp) rear mounted aircraft engine for both driving and flying. The engine contains a continuously variable transmission which allows the engine gear ratios to change continuously and thus maintain a constant engine speed, providing the engine with the capability to drive both the propeller and the rear wheel drive train. The engine is air cooled, with an intake located on the bottom of the vehicle. The intake contains screens to act as filters to keep debris and water from entering the engine. Fuel for the vehicle is stored in the bottom of the fuselage around the center of gravity. Fuel was kept out of the wings to avoid problems with moving the wings during transformation from flying mode to driving mode.

The landing gear is fully extended for landing and takeoff and is semi-retracted while in flight and driving mode, but can be extended or retracted by the driver as needed. The vehicle is entered with the gear in its semi-retracted configuration.

Transformation from flying to driving mode is performed manually. Electronic transformation was initially considered but it was decided that manual transformation would be more economical since the vehicle will only be driven in extreme cases. Transformation occurs as the wings are manually rotated 90° counter-clockwise along a centerline spar. The wings are then folded back, over hinges, along the side of the vehicle body. As the wings are folded alongside the body, a protective cap is manually placed on the exposed portions of the wing near the wing root, protecting the electronics and mechanics extending from the fuselage into the wing. The horizontal stabilizers are folded down, over hinges, against the outside of the vertical tails. All folded components, i.e. the wings and stabilizers, are then manually latched to prevent unwanted movement in driving mode. A pin is placed into the shaft of the propeller to prevent rotation during driving. The landing gear is then automatically semi-retracted into their driving configuration.

The vehicle is intended to be driven from the right and flown from the left for console simplicity and is equipped with a two point restraining device for each of the four passengers. The vehicle must also meet all federal highway and aircraft safety standards.

Figure 7: Intermediate Concept #3

Pros & Cons

The three Virginia Tech intermediate concepts were compared using several criteria to show the relative strengths and weaknesses of each. Criteria used for refinement included the overall dimensions, weights, propulsive systems, passenger capacity, and performance characteristics. The intermediate concepts compared were the general aviation craft with wheels on the wings, which will be referred to as IC #1, the Burnelli fuselage with telescoping wings, or IC #2, and the scooped out rear fuselage with folding wings, IC #3. The three concepts can be seen in Figures 5, 6, and 7, respectively.

The overall dimensions of the three concepts were compared to find which would be suited to function in automobile traffic. While IC #2 and IC #3 are of reasonable size for driving on roads, IC #1 is too long at 10.36m (34 ft). IC #3 has the smallest width, which makes it more favorable on the road. IC #2 is narrow enough to drive on US roadways, but again IC #1 is excessive in this dimension. IC #2 is the smallest of the three concepts in height, followed by IC #3 and IC #1, respectively.

Using initial sizing programs, the estimated takeoff gross weight of the three concepts were calculated. IC #1 is the lightest of the vehicles followed by IC #3, IC #2 is the heaviest of the three. The aspect ratios of IC #1 and IC #3 were comparable and high, which is favorable for long range flight. IC #2 has a very low aspect ratio around 1. With its long wing span, IC #1 has a low wing loading. IC #3 has the intermediate values while the wing loading of IC #2 is quite high with its low aspect ratio wings.

Passenger comfort is another important factor in deciding on a concept. One aspect of this is ease of ingress and egress. IC #2 has relatively easy ingress involving only one step to a large hatch. IC #1 seems difficult to access as it involves substantial climbing. IC #3 has its hatch well above the ground with no steps or such to access it. All three concepts hold at least 4 passengers, which was the set desired number. Another aspect in passenger comfort is the ease of transformation from flying to driving mode. IC #2 and IC #3 both have relatively simple transformation schemes, making them acceptable choices. The transformation of IC #2 only involves extending or retracting the telescoping wings. The transformation of IC #3 simply involves manually rotating and folding the wings as well as folding the horizontal tail. IC #1 involves a difficult transformation. Here the wing must be manually folded up and attached to the fuselage using the wheels in the wing tips as tires in the driving configuration. This is difficult because wings are extremely heavy. Several mechanical components, including the drive shaft, connecting the wheels to the drive train are in the wings making them very difficult to transform manually or electronically.

IC #2 has a much smaller takeoff distance than IC #1 or IC #3. This short takeoff distance is due to the high angle of attack Burnelli wing and the set angle of incidence of the telescoping wing. The estimated required landing distances for the three concepts are all relatively close, and all acceptable.

The power plant is an important aspect of the design, but it is one which can readily be changed. IC #1 proposes a single aircraft engine for use both in the air as well as on the ground, which is acceptable. IC #2 utilizes two engines, one for flying and one for driving. This is undesirable as it adds significant weight to the design. IC #3 uses a single aircraft engine with variable transmission. This is the best of the three power plant proposals.

Intermediate Concept #4*

This concept uses an entirely different approach to the operation and stowage of a roadable aircraft flying surface. This concept is an autogyro, like those of Juan di Cuerva in the 1920's and 30's. An autogyro was the development stage between a fixed wing airplane and a full-fledged helicopter. It flies with an unpowered main rotor that autorotates during the entire flight at an angle of attack. There is a conventional pusher or tractor engine that maintains forward velocity, which in turn, maintains the autorotation. The lift to drag ratio of the autorotating rotor is not competitive with that of a fixed winged aircraft or a full helicopter because the autogyro essentially drags the spinning rotor through the air to generate lift. However, it is a mechanically simple device, quite easily capable of conversion between aerial and roadable configurations.

This concept exploits this advantage to its fullest. In the roadable configuration, the vehicle resembles an existing Ford minivan, with its rotors stowed alongside of the concept and its stub tails fully retracted into the sides of the vehicle. There is a pusher propeller behind the cabin portion, which has questionable flow during flight. However, it stows neatly on the road and would not be especially hazardous to other motorists.

To take off, the rotor is sped up at negligible pitch under power. Then, the rotor pitch is quickly increased and the vehicle 'hops' off of the ground. The pusher motor simultaneously engages, facilitating a fully articulated launch into a climb.

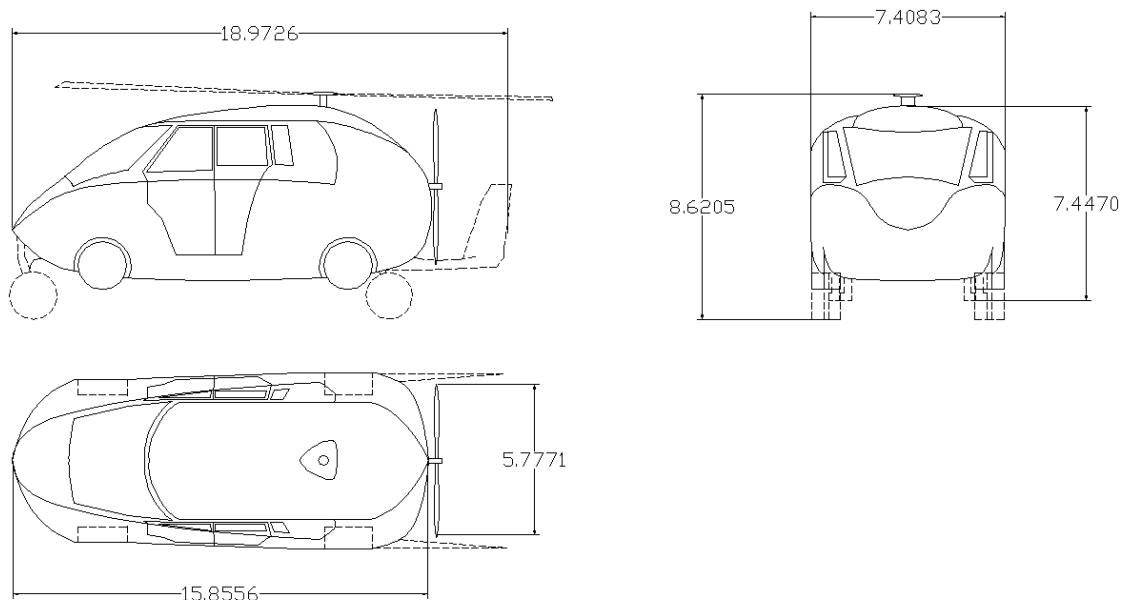


Figure 8: Intermediate Concept #4

Intermediate Concept #5*

Concept #5, seen in Figure 9, is a three passenger roadable aircraft featuring twin ducted fans located on top of the fuselage. The cockpit looks similar to a conventional automobile

* Intermediate Concepts #4, #5, #6 are non-dimensioned initial concepts from Loughborough University

modified for flight. The fuselage is 5.33m (17ft 6in) long, 2.43m (8ft) wide, and 1.83m (6ft) in height. The cockpit is similar to that of the McLaren F1 supercar. This has a central pilot position with the two passengers straddling the driver on either side. A baggage area will be located between the two back seats. Crumple zones located at the front and rear of the fuselage provide increased crashworthiness on the ground. The front wheels are extended in driving mode and retracted into the fuselage and stored flat to minimize drag in flight. The rear wheels are also extended for road travel and retracted without rotation for flight. The wings have a 10m (32ft 10in) span, making it comparable to other general aviation aircraft. These gull wings fold up in two stages along the side of the vehicle for driving.

The propulsion system for this vehicle consists of twin ducted fans. This is based on Stinton's premise that the equivalent area of a ducted fan is 70% of a standard propeller area. An aircraft engine will be used for both flight and driving, using a hybrid gearbox to transfer power to the rear driving wheels. This engine is located behind the three passengers with an air intake just behind the cockpit and exhaust located behind the fan.

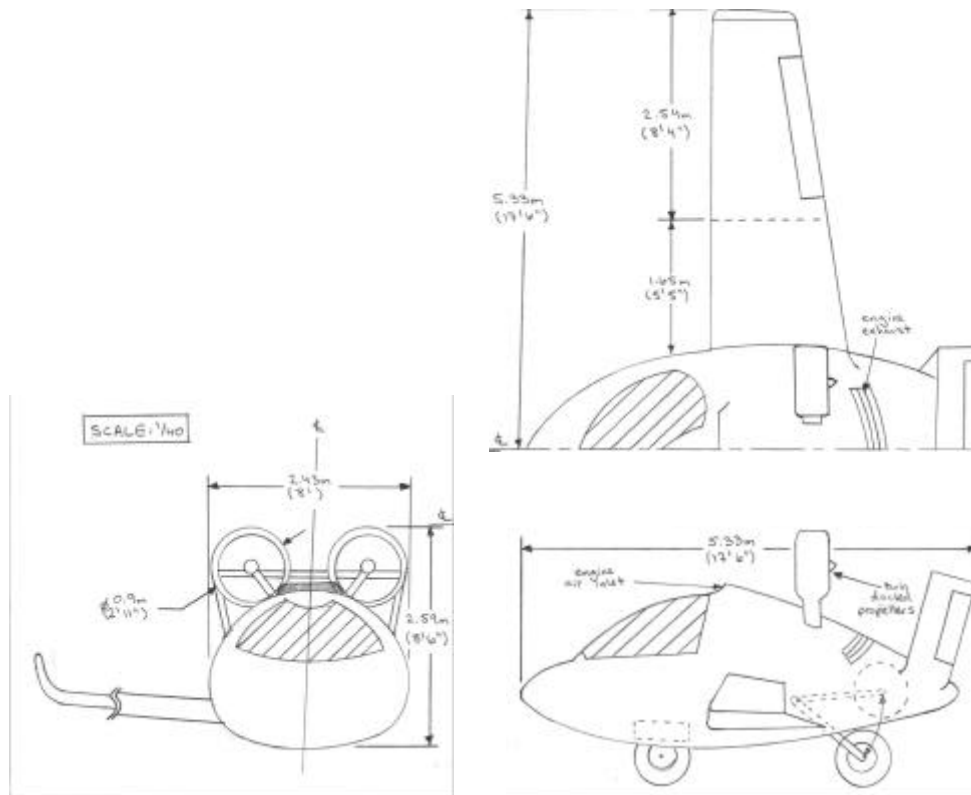


Figure 9: Intermediate Concept #5

Intermediate Concept #6*

Intermediate Concept 6, shown in Figure 10, is based on a conventional high-wing general aviation design. The concept contains a high rotating wing, a telescoping tail configuration, and an extending undercarriage. The wing is extended outward for flying and is rotated 90° counterclockwise and stowed on top of the vehicle, parallel to the fuselage for driving. The wing stowage creates many problems for road travel in that the span of the wing is extremely long, about 35ft. Thus when the wing is rotated it extends far out from the front and

back of the vehicle's body creating extremely unsafe driving conditions. The telescoping tail is extended for takeoff, landing, and flying, and is brought into the rear of the body for driving. The extendable undercarriage of the vehicle allows for takeoff rotation for flying and attainment of height restrictions for driving. The gear are extended for flight and semi-retracted for driving.

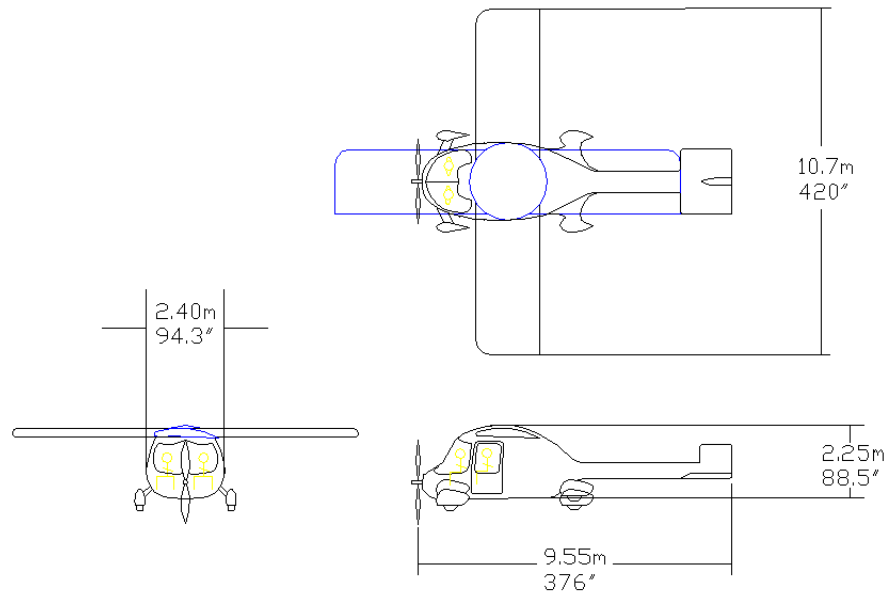
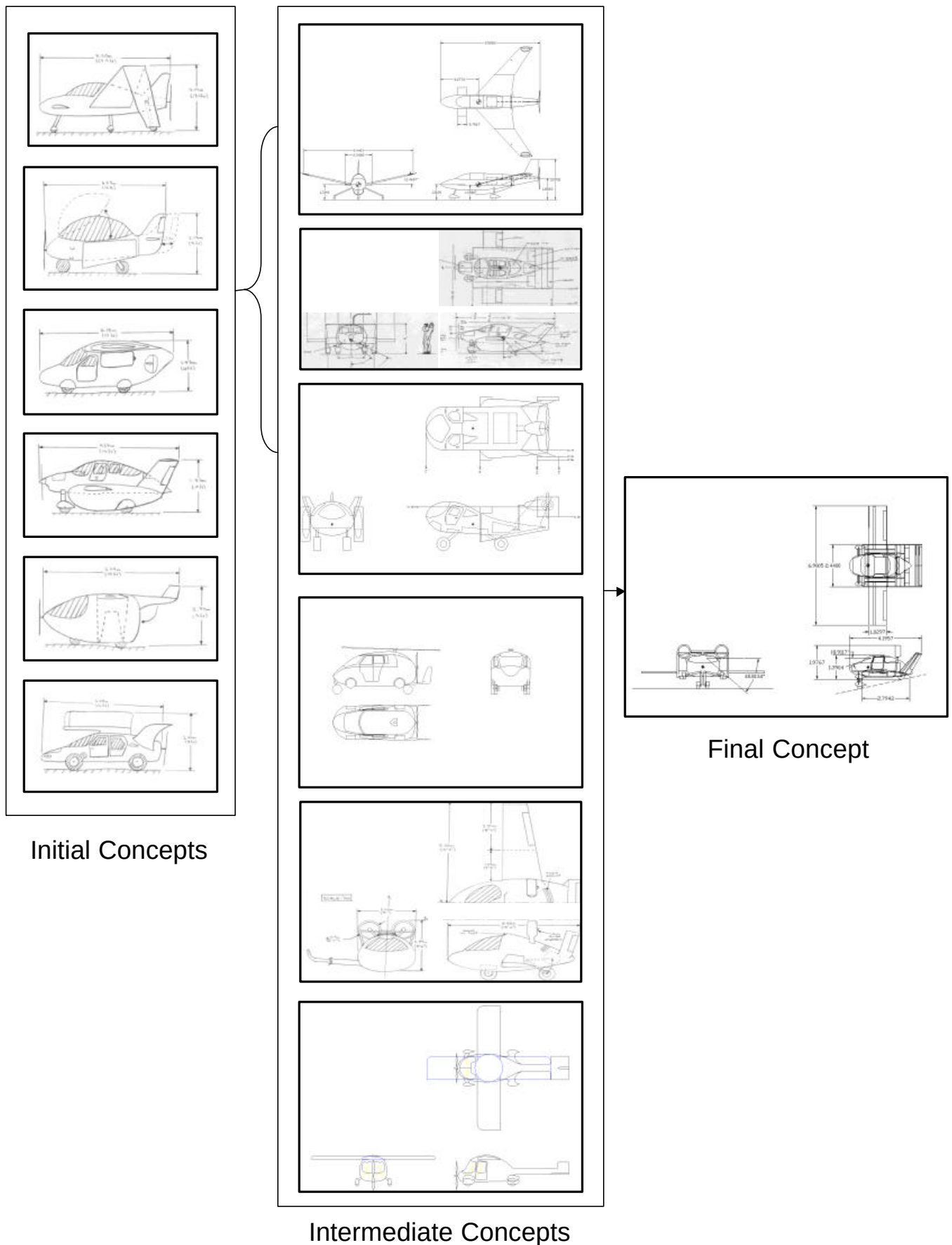


Figure 10: Intermediate Concept #6



Intermediate Concepts
Figure 11: Decision Tree for Final Concept

Propulsion

The primary problem confronting the propulsion of the roadable aircraft is whether two engines should be used or just a single engine. Aircraft engines normally run at a constant speed for a long time while automotive engines must withstand wide ranges in RPM. One option to overcome this problem is to use two engines for the roadable aircraft: one for the aircraft and one to use when driving the car. In this case a major advantage would be to use automotive fuel for both engines.

The advantages for using automotive fuel are numerous. Since only one fuel tank would be needed, a lot of weight would be saved. Requiring only one type of fuel makes it much more convenient for the user of the vehicle to buy gasoline. Despite these advantages, there is a primary disadvantage to this possibility. Because automotive fuel is more volatile than aircraft fuel, vapor lock is a greater possibility. This is especially true at high altitude and during takeoff when the engine is idling at a high speed. The Experimental Aircraft Association, or EAA, has performed 500-hour flight tests, though, and has determined that vapor lock is not a significant problem, even at the aforementioned extreme conditions.¹¹ Due to future EPA regulations, automotive fuel will have to have lower volatility, thus making this even less of a problem.

Recently, the FAA has approved this fuel for all aircraft engines that use 80 octane leaded fuel. Even though 100LL fuel is becoming the fuel most commonly found at airports, more than 65% of single-engine, privately owned aircraft still in use in the United States were originally designed to use 80 octane fuel. Using 100LL fuel with these engines significantly increases the operation cost of the engine, and the fuel itself is much more expensive. According to the EAA, 100LL fuel can be as much as \$1.00 per gallon more expensive than 80 octane automotive fuel. But, if automotive fuel were to become widely available at airports, the aviation taxes put on it would make the price comparable to that of 100LL fuel. Also, tests have been performed at Embry-Riddle University which show that the added maintenance cost from using 100LL fuel as opposed to automotive fuel in a Cessna 150 was as much as \$10.00 an hour. When using automotive gasoline with a motor that has 230 hp, the savings due to reduced maintenance and operating costs can amount to \$35.00 per hour. Another added benefit is that automotive fuel and aircraft fuel can be mixed without any problems.

A better option available for the roadable aircraft is the use of a single engine. A single engine would save a large amount of weight and reduce the difficulty of maintenance. Using one engine would sharply reduce the cost of the plane as well. Because of the fact that this vehicle is going to be used both on the ground and in the air, it was decided to examine single engines that have a history of being used in either application. It is believed that employing the use of a powerplant that has this type of versatility would prove to be much easier to use in this roadable aircraft.

The first engine that is being considered is the Dyna-Cam engine.¹² This engine has been developed by Dyna-Cam Engine Corp., which is located in Torrance, CA. The same basic engine has been designed for general aviation aircraft, boats, trucks, and motorhomes. This engine is about to enter the production stage; it is currently in testing and R&D. Thus, the primary concern with this engine is its lack of experience in real world applications. This engine has been thoroughly tested, however, and has been approved by the FAA.

This engine has good performance and specifications compared with other aircraft engines. Some of the specifications for this aircraft engine can be seen in Table 2. Compared with traditional aircraft engines, this engine has higher torque and less weight. Also, due to the

excellent performance of this engine, it can drive a propeller that provides better performance than other aircraft engines. Overall, this engine seems to be very promising to use for the roadable aircraft.

Table 2: Data for the DynaCam Engine

Total Weight	Power Output	Cost
136 kg	149 kW	\$30,000
300 lb	200 hp	

The second powerplant being examined for this application is a version of a Subaru engine¹³ converted for use in an aircraft. The engine block and cylinder layout is identical to that found in traditional aircraft engines. That makes this engine a better solution for conversion than traditional automotive engines manufactured by other companies. The cylinders are set up so that the pistons oppose each other; the firing order allows a reduction in airframe vibration. This engine has been installed in some small general aviation aircraft successfully, so it has the advantage of real world application.

The Subaru is a 2.5 liter, four-cylinder engine. According to Eggenfeller Advanced Aircraft, Inc.¹⁴, this engine installed on a GlaStar, a general aviation aircraft, provides much less noise than traditional aircraft engines and there are no cooling problems. Thus, this engine provides many advantages over other types of aircraft engines.

Specifications for the 2.5 liter, four-cylinder Subaru engine include:

Table 3: Data for the Subaru Engine

RPM	Power Output	Cost
5600	123 kW/165 hp	\$15,900

Data pertaining to the two main powerplants being considered for this roadable aircraft can be found below. In addition, five traditional aircraft engines have been added for comparison. As can be seen in Table 4, while the Dynacam has no problems in the power-to-weight-ratio area the Subaru engine is at the low end of spectrum. It is believed that the ease of conversion will make up for the Subaru's deficiency in this area.

Table 4: Main engine options being considered¹⁵

Engine	Power		Weight		Power/Weight		Automotive Fuel Certified
	kW	Hp	kg	lb	kW/kg	hp/lb	
Continental O-470	194	260	212	467	0.9151	0.5567	Yes
Continental O-520	231	310	198	436	1.1667	0.7110	No
Lycoming IO-360	119	160	134	295	0.8881	0.5424	No
Lycoming IO-540	216	290	198	437	1.0909	0.6636	Yes
Rolls-Royce GIO-470	231	310	209	461	1.1053	0.6725	No
Subaru EJ-22	119	160	134	295	0.8881	0.5424	No
Dyna-Cam	149	200	136	300	1.0956	0.6667	No

To be able to use a single aircraft engine, it should be coupled with a continuously variable transmission (CVT)¹⁶. It would then be possible for the craft, in automobile mode, to be accelerated by altering the amount of power transferred to the drive wheels instead of by

changing the amount of power produced by the engine. The use of the CVT would then allow the aircraft-based powerplant to be operated at constant speed, as it was designed to.

Unlike most transmissions found in today's automobiles, the CVT is belt driven; this allows for smooth power transfer through an infinite number of drive ratios. The CVT system works by transferring power by means of a specialized steel belt across two variable sized pulleys. The main control module then adjusts the final drive ratio according to information on changes in throttle position, ground speed, and engine RPM provided to it by various sensors.

Physically, the CVT is comparable in both weight and size to any automatic transmission found in a modern, medium-sized automobile. Various testing by independent researchers has shown that the CVT is also slightly more efficient than an automatic transmission, thus reducing superfluous fuel consumption due to losses.

The CVT appears to be a very viable solution to the powerplant problem; however, there are some issues that must be considered along with it. First of all, constant changes in gear ratios may cause the power-transfer belt to need replacement more often than expected. Possible redesign and strengthening of the belt may need to be looked into further. Secondly, noise pollution may prove to be a factor. Unwanted noise may be produced by the use of an aircraft engine, especially when being operated at an engine speed above that at idle. Lastly, because coupling a CVT with an aircraft engine is not a common occurrence, there may be problems with compatibility. Mounting hardware would have to be designed and produced to accomplish the linking; the expense of this may prove to be an issue.

As a means of propulsion, different sources of alternative fuels are being looked into. These fuels consist of different types of gases and liquids as well as batteries and fuel cells. The liquids and gases would provide a clean burning engine which could better integrate into the future of transportation. However, the drawbacks of weight, storage, and availability exist and make these fuels a difficult option to pursue. The weight and storage are closely related. Fuel weights themselves are acceptable, but the storage containers must include many safety features which add onto the weight. Also, many of the liquids and gases have to be either stored at large pressures or at low temperatures. The components that will do this onboard the vehicles add a tremendous amount of weight.

Batteries also provide an alternative for propelling the vehicle. They can provide clean, cheap, and reliable power that is also reusable. The main drawback of this idea is that the existing batteries must be installed in large stacks in order to provide the power necessary to propel the vehicle sufficiently. This again requires too much weight which is of the utmost concern in aircraft designs. Electricity is still a viable option, but a different way of storing the electricity must be found if it is to be used.

Fuel cells are an option which will provide the necessary power at a smaller weight, and this fuel selection combines the pros and cons of both ideas from above. It has the plus of using electrical power which is simple, cheap and effective, but it gets this electrical power from the combining of hydrogen and oxygen. This means that the hydrogen must be carried on board, which presents the same problems as the other liquid and gas alternative fuels.

After looking at the alternative fuels, it was determined that the technology does not exist yet that will allow a roadable aircraft to run on anything other than gasoline or similar fuels. Too many problems are present in the fields of storage and safety to use an alternative fuel, so existing mainstream engines must be used.

Human Factors

Human Factors engineering helps balance the line between machine and operator. The operator needs to be able to manage the vehicle in both car and plane mode. The user interface design may contribute to the vehicle safety and marketability due to ease of usability. There are several factors that must be looked at when designing the concept.

The driving qualitative factors are visibility and appropriate anthropometric dimensions. The visibility range is more of a challenge in the vehicle mode than as a plane. The critical angles are approximately 80-90 degrees peripheral vision without moving the head in the horizontal direction. In the vertical direction, the design will conform to approximately 15 degrees visibility from horizontal upward. See Figure 12 for the actual model layout and its explanation.

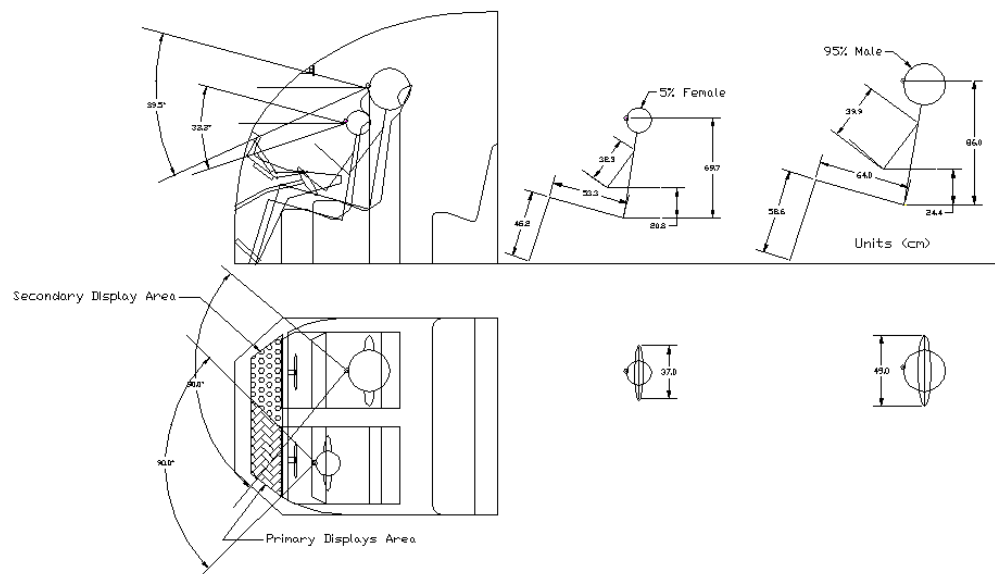


Figure 12: Anthropometric Cabin Layout

The most important anthropometric dimensions are the following listed in order of importance: eye height, functional normal reach, functional maximum reach, poplital length (height from foot to buttocks in sitting position), elbow rest height, knee height, leg length, upper arm length, shoulder breadth, functional overhead reach and thigh clearance height. The design limiting dimensions are determined from the statistical analysis of the larger end, of the 95% male clearance to the smaller end 5% female reach. These actual dimensions are found in Table 5.

Some features to be incorporated into the cabin are:

- Adjustable seats: Seats adjust in forward/ backward location, height, inclination, and head rest position.
- Adjustable console: The monitor board can be adjusted according the needs of the operator. The operator will encounter different visibility needs according to the mode in which he/ she is maneuvering. This display board can have various gauges and computer monitors to navigate in car or plane mode.

- Mirrors: The rear view mirror will be detached during flight and then attached when operated in car mode. Side mirrors can be mounted to the fuselage for road requirements.

Table 5: Anthropometric Data for Ideal Cabin¹⁷

Subjects are Seated	MALE		FEMALE		MALE & FEMALE		Optimal Design Range			
Dimension (units = in.)	50th percentile (average)	95th Dimension Limit	50th percentile (average)	5th Dimension Limit	5th percentile	95th percentile	low (in)	high (in)	high (cm)	low (cm)
Thigh Clearance Height	5.8	6.8	4.9	4.1	4.3	6.5	4.1	6.8	10.4	17.2
Elbow Rest Height	9.5	11.6	9.1	7.1	7.3	11.4	7.1	11.6	18.1	29.6
Eye Height	31.0	33.3	29.0	27.0	27.4	32.8	27.0	33.3	68.6	84.6
Functional Overhead Reach	50.6	56.0	47.2	42.9	43.6	54.8	42.9	56.0	109.0	142.4
Knee Height	21.3	23.1	20.1	18.5	18.7	22.7	18.5	23.1	46.9	58.7
Leg Length	41.4	44.5	39.6	36.8	37.3	43.9	36.8	44.5	93.5	113.1
Upper Leg Length	23.4	25.2	22.6	21.0	21.1	24.9	21.0	25.2	53.2	64.0
Upper Arm Length	14.5	15.7	13.4	12.7	12.9	15.5	12.7	15.7	32.4	39.8
Shoulder Breadth	17.9	19.2	15.4	14.1	14.3	18.8	14.1	19.2	35.8	48.8

Other qualitative measures will serve as design criteria. Safety requirements in the car mode must meet safety requirements of the European and American Departments of Transportation. Ease of ingress and egress are essential and therefore key components to develop in the design. The aesthetic value of the vehicle in both car and plane mode cannot be quantified, but drives the design because the market must like the vehicle's appearance. The design also considers how the vehicle will be converted from plane to car mode and general comfort of the operator and passengers.

Cost and Manufacturing

The costing of the design is one of the most constraining factors. The AGATE market survey¹⁸ included a section for respondents to indicate average annual income. The results of the survey are as follows:

- 14% Less than 50K
- 45% 50 –100K
- 26% 100-150K
- 12% 150-300K
- 3% Over 300K

With a majority of the respondents falling between \$50,000 and \$100,000, this should be the target income range. Many people would probably be willing to spend about one year's salary on a plane or roadable aircraft.

The cost is driven by several factors in the design. The propulsion system to be used will affect the cost. Higher technology engines, while being more efficient, are more expensive and could increase service and maintenance costs of the vehicle. A large cost could be incurred with addition of CRTs, fly and drive-by wire systems, and advanced avionics. The team intends to integrate pre-existing systems as often as possible. To minimize manufacturing costs, outsourcing of parts, entire systems, and sub-assemblies needs to be utilized where possible. The more conventional a part, the more likely it will be able to be outsourced. In essence, the higher the production the lower the cost to the consumer. Most of these decisions about the cost drivers

are in the form of trade-offs, such as fixed cost / variable cost, high / low tolerances, high / low volume production, and state of the art / conventional material selection. These tradeoffs must be considered while having a bottom line goal to best reduce the cost.

Since the cost is affected by the production of the vehicle, manufacturing is the next major factor to consider. The design team should keep in mind concurrent engineering, which is essentially the practice of having in mind all the phases of the design at each individual step. This means that the team considers manufacturability when making design decisions. The manufacturing facility will therefore be designed to accommodate maximum capacity. Given market trends and NASA's expectations, it is projected to take at least 10 years for the demand to utilize full capacity. Another important aspect in a manufacturing operation is to develop a quality control method to reduce cost and increase quality. The increased quality will assist in lowering maintenance costs. Development of low-cost inspection techniques and sampling plans will facilitate the quality control.

Advanced Technologies

There are many unique features and advanced technologies that can be incorporated into the design of the roadable aircraft. The first is a global positioning system, or GPS. This technology would be useful in flight as well as driving. It allows the location of the vehicle to be determined to within approximately 100 meters. Differential GPS¹⁹ is a more accurate version that can reduce the error to within 10 meters. Differential GPS calculates the error at a known location and applies this information to better account for the location of the vehicle. Besides GPS, other helpful automated flight services being investigated are fly-by-wire and computer flight stabilization systems.

A useful type of avionics system that can be placed on the aircraft is fly-by-wire. This allows electrical systems to relay flight commands to deflect the control surfaces of the aircraft. This normally is done by a stick controller in the cockpit that can transmit signals to the actuators on the flight control surfaces, such as the rudder or the ailerons. Using electrical systems eliminates the need to use cumbersome mechanical means like cables and pushrods to manipulate the control surfaces. Thus, aircraft engineers have more flexibility in their design, including the placement of the control surfaces, with the use of a fly-by-wire system.²⁰

Mercedes²¹ has improved sidestick steering in its SL roadster research vehicle. The newest version by Mercedes does not require a steering wheel or foot pedals. The sidestick controls steering, throttle and brakes. Applying pressure forward or backwards applies to throttle and brakes. The stick does not actually move, but is pressure sensitive. For steering, the stick still moves from side to side up to 20 degrees in each direction. The steering uses "force feedback" found on modern computer joysticks, that transmits feel back to the joystick in the same way a steering wheel would. The steering is also speed sensitive, the faster the car is moving the more the joystick needs to be moved. Many benefits of sidestick driving include a comfortable position, because of the lack of wheel and pedals, which also improves passive safety. Active safety is improved by the system in the drive-by-wire technology.

Selection Criteria

Critical Issues

In merging a general aviation aircraft with a roadworthy automobile, one must keep in mind many technical and economic dilemmas. However, safety issues are held paramount. The

same vehicle that is safe in the air is not safe on the ground. The current catch phrase in automotive design is a ‘crumple zone’, which is a portion of the vehicle that expends energy in a crash in order to divert damage from the passengers. Aircraft designers speak of ‘stability’ with regard to safety, though these notions are not absent in the rigors of automotive engineering. The roadable aircraft must be stable in the air, which requires a suitable weight distribution. It also must be stable on the ground, implying that the wheel distribution meets the mass distribution without permitting the vehicle to tip over in maneuvers.

When viewed in terms of economics, automobiles are often more comfortable than GA aircraft. This is a question of the target market. Do the designers cater to typical drivers or typical pilots? GA aircraft interiors are often very utilitarian with two bucket seats in front with a bench seat in rear. Automobile interiors are often more plush, with bucket seats and adjustable front seats. Seat belts are common to both vehicles. Airbags are found exclusively in cars.

How does one size a roadable aircraft? One must first consider the primary mission. A vehicle that functions primarily as an aircraft but can be driven home in case of inclement weather might be considered. This vehicle would be aerodynamically efficient and would be nominally performant as a car. For instance, it might fit into the dimensions of a freight truck rather than a mini-van. The big struggle here is to fit an efficient lifting surface into the typical road width 2.44 m (8 ft). On the other hand, a vehicle that flies directly from driveway to driveway, or ‘portal to portal’, might be considered. This would have to fit roughly within the dimensions of a personal automobile. One might envision that this vehicle must fit within drive-through banking or food establishments.

Final Concept Selection

The selection process for defining the final concept began with six concepts, three from the Loughborough team and three from the Virginia Tech team. Students from both schools were grouped into sub-teams for different aspects for the final design, including teams for aerodynamics, weights, cost, performance, and others. The team split into the sub-teams to determine critical issues pertaining to the area of focus of the sub-team. Once a list of critical issues was established the sub-teams ranked each of the six intermediate concepts on a scale of -2 to +2. The critical issues from each sub-team were compiled in a matrix with a weighted sum of the technical areas. Different weighted averages were figured and finally an equally weighted sum was used. The top sum from each of the Loughborough and Virginia Tech designs were selected for final evaluation.

As an entire group each sub-team reviewed and explained the rankings the team gave to the final two concepts. Discussions about the mission, resulted in the selection of different aspects from each design for a final concept, almost a hybrid of the two designs.

Structures

Structural requirements for an aircraft and a car are vastly different. GA aircraft structures endure relatively constant loads throughout flight, whereas auto structures withstand a wide acceleration range. However, the severity of survivable aircraft crashes and survivable auto wrecks is approximately the same, as survivability indicates passenger acceleration tolerances, which are the same whether the occupants are in the air or on the ground.

The six concepts are evaluated in rank of structural feasibility and safety. Feasibility criteria are: lifting surface position, fixed surface aspect ratios, fixed surfaces sweep and taper, number of moving parts between aerial and road configurations, size of those moving parts,

lifting surface area specific loading, and weight distribution throughout the vehicle (or the relative moments about the CG). The sole safety criterion is crashworthiness in the road configuration.

Lifting surface criteria are ambiguous to use for overall evaluations. Obvious exclusions to these criteria are rotorcraft and lighter-than-air vehicles. These are ranked neutrally. The lifting surface position is crucial in its relation to the main structure. Low wings or high wings are better positions because main beams intersect the fuselage at lower priority positions – the beams don't intersect suitable engine, occupant, or payload positions. On the other hand, mid wing main spars do intersect useful fuselage volumes. Therefore, high or low-wing concepts fared better than mid-wing concepts.

Aspect ratio (ratio of span to average chord of a lifting surface) evaluated in terms of structural benefit or liability, is rather intuitively ranked. Long spindly members must be supported with denser, more expensive materials while short stubby members can be more sparingly supported.

While swept wings are beneficial in certain aerodynamic situations, they are structural liabilities in that they cause higher root moments than their unswept equivalents. Because lift distributions over wings are most often elliptic, the required stiffness diminishes toward the tips. Therefore the required amount of structural material diminishes toward the tips. Tapered wings match this load distribution so they are structurally desirable.

Parts that are transformed between aerial and road configurations are obvious structural problems. More specifically, the joints between moving parts are difficult to design for function and exceedingly difficult to design for matching performance with their stationary equivalents. Therefore, the concepts are quantitatively ranked in number of moving parts. Huge moving parts are difficult to move between aerial and road configurations, whether they are hydraulically, electrically, or manually maneuvered. Therefore, larger moving parts were more critically ranked.

Lifting surface area specific loading is an obvious structural criterion since lower specific loads require lower structural support, which reduces weight and expense. Local weight distributions are ranked in view of induced moment about the CG. For instance, heavier static loads perched out upon long branches require dense, expensive structures. Therefore, qualitative ranks are based on guessed local moments.

Road crashworthiness is best summed up by the word “crumple zone”. Crumple zones expend the energy of a crash in less crucial area, such as baggage stores. Concepts where the engine moves into the passenger cabin in an accident or where the occupants leave are in the outermost regions of the vehicle leave the passengers vulnerable to injury.

The structural evaluation of the intermediate concepts is perhaps a bit premature because no intermediate concepts specified materials or construction methods. Vague phrases such as, “composite materials will be used where suitable” abound in such conceptual stages. The concepts can only be evaluated in a conceptual capacity, where geometry and estimated weights are the only available information.

Aerodynamics/Stability and Control/Performance

The stability and control, aerodynamics, and performance subgroups combined to evaluate the critical issues of the six intermediate concepts based on the provided geometry. Both road and flight configurations were considered for each concept and were discussed amongst the groups to determine the effectiveness of the different concepts. For stability and

control in the air, the concepts were evaluated on control power and the location of the center of gravity for rotation in takeoff. For stability on the ground, the concepts were evaluated for cross-wind effects, center of gravity location, and the amount of lift generated during driving. Aerodynamic considerations included the ability of clean flow to reach all surfaces and propellers, front cross sectional area shape, aspect ratio, and wing placement. For aerodynamics on the ground, the concepts were evaluated based on the amount of profile drag generated after stowage. Several other stability and control, aerodynamic, and performance issues were discussed by the group but will require more detailed specifications that are unavailable at this stage in the design process. These points will be investigated for future validity of the concepts chosen.

Control power is the primary concern regarding stability and control of the concepts in flight. With this in mind, designs were judged based upon the distance of the controls from the center of gravity and the sizes of the surfaces. Large moment arms and large surfaces in the roll, pitch and yaw directions received the best marks. Center of gravity location for take-off is also an important issue. For designs requiring rotation during take-off, the aft gear should be 15° behind the center of gravity. Consequently designs with centers of gravity close to the aft scored the best.

Stability on the road involves center of gravity location and placement of the lifting surfaces. Designs received high marks for clean transverse cross sections that minimized cross wind effects. Centers of gravity that were located low and centered between the fore and aft wheels received the best marks. High marks were awarded to designs which minimized the aerodynamic lift in the car configuration.

Clean flow over all control surfaces and propellers is paramount to a successful design. Control surfaces and propellers, like any other airfoils, perform inefficiently in disrupted flow. Key things to observe for determining this clean flow include a streamlined body and ensuring that control surfaces do not lie in the wake of the propeller or airframe. The six intermediate concepts were rated on a scale from -2 to 2, as to how well they fulfilled these criteria.

As mentioned above, a streamlined body is aerodynamically favorable as it promotes clean flow. The cross sectional area of the design in flying mode can be examined to find whether the body is streamlined. Again, a rating from -2 to 2 was given to each concept depending on the cross sectional area.

A high aspect ratio, the ratio of the wing span over chord, results in a long range and efficient wing. Therefore, aerodynamically, a high aspect ratio is desirable in a design. The concepts were given a rating between -2 and 2, with a 2 being given for a very high aspect ratio and a -2 for a very low one.

Wing placement on the fuselage affects the aerodynamics of the design. A mid-wing, or a wing attached at the vertical center of the airframe, is most favorable aerodynamically. This is the case as the flows around the top and bottom of the wing are the same. For low wings, there is clean flow over the entire span of the bottom of the wing but discontinuous flow over the top at the fuselage. High wings have good flow over the top wing throughout, but poor flow over the bottom at the fuselage. As the pressure changes are higher at the top of the wing, keeping the flow continuous throughout there is more important than at the bottom. Also, there is less interference at the wing body junction of the mid-wing than at either the high or low-wing. These criteria were rated on a 0 to 2 scale, with a two being given to a mid-wing, a one to a high wing, and a zero for the low wing.

Low profile drag after stowage is an important factor in the aerodynamic effectiveness of the vehicle on the road. The concepts were evaluated on their general front cross sections after transformation from flight mode to driving mode. A concept with low profile drag after stowage received high marks.

Propulsion

The propulsion system of the vehicle consists of the engine(s), transmission and the drivetrain. It encompasses the systems that will allow the vehicle to move down the road. Six main critical issues were defined for the propulsion system.

The first and most important item is power. It will be the basis for all other propulsion decisions and will be directly related to other aerodynamic decisions as well. The size and weight of the engine and transmission are the next critical issues. They will help in determining many performance issues of the vehicle and will directly affect the power mentioned above.

It will be of great importance to watch the size and weight so that it will work well with the design and allow the vehicle to be sufficiently propelled. The propulsion system will be able to produce more power if it is allowed to have a larger size and weight.

Not only does size and weight dictate performance aspects of the propulsion system, but engine type does as well. Dramatic differences exist between different propulsion systems and their respective fuel types. Different situations will call for a different type of system, and this must be optimized for the specific vehicle configuration. The availability of the different types of fuels must also be considered under this issue. Some fuels are becoming less common for either the aircraft or automobile markets.

While looking at the fuel, efficiency of the propulsion system must also be looked at. This varies with the type of fuel and the engine(s) that are chosen. This important issue directly effects one of the most important goals set forth earlier, range. If the engine system is not working efficiently, then it can greatly reduce the overall range in the air and on the ground.

A marriage of all the other issues must be met in the cost of propelling the vehicle. If an engine design meets all of the criteria set before it, but it is of an impractical cost, then it is not a viable selection and an alternative solution would be found. Also, the cost of servicing the engine(s) needs to be taken into account.

This is directly related to the location of the engine(s), which is another critical issue. If the engine(s) lie in the middle of the vehicle, they would be much harder to access for service. Also, if an air cooled engine is used, ducting must be used if the engine is not directly on the outer spaces of the vehicle.

In terms of the overall design and layout of the vehicle, the engine is a very flexible system. This played a large factor in our rating of the critical issues. The designs were looked at and only given a rating other than neutral if there was a very noticeable advantage or disadvantage. The propulsion system could be designed around many different configurations and has many combinations that would result in an optimized system.

Roadability

Safety is the most important critical issue to be examined when the vehicle is on the road. After all, no consumer will purchase a vehicle that doesn't meet safety standards. The roadable aircraft must therefore meet the latest federal requirements for automobile crashworthiness. Requirements are things such as: one seat belt per passenger, driver and passenger side airbags, driver and passenger side view mirrors, front and rear crumple zones, and 5 mph bumpers.

Location of fuel storage is another safety concern when examining crashworthiness. Fuel must be kept internal to body, in a position with adequate protection from the frame. For this reason, wings that are to contain fuel must be retracted in to a safe location during any road use.

Additional safety issues, not dealing with crashworthiness, must also be examined. The location of the center of gravity while in automobile configuration is a major safety concern. A center of gravity too high on the craft could cause instability while rounding curves, therefore creating a danger of rolling. To be adequately stable at all speeds, the automobile configuration must therefore have a sufficiently low center of gravity. High wing designs or wings folded onto the top of the craft during ground operation are highly penalized. Driver visibility is another very important safety issue. The roadable aircraft designs must have adequate lines of sight while in automobile configuration. More specifically, after conversion from aircraft, no part of the configuration shall create blind spots for the driver.

To be street-legal, the roadable aircraft must meet all restrictions applicable to any other automobile. For instance, the exhaust system must meet all federal regulations by filtering both engine noise and emissions. Also, the craft must be able to operate at an average highway speed. Meaning, it must have a top speed of at least 65 miles per hour, the average highway speed limit in the United States.

To be viable as an automobile, the roadable aircraft must be road-friendly which is a term describing exterior dimensions and overall looks. More specifically, the craft must fit easily into an average size garage. Also, it must easily fit on all roads, width-wise in the lanes and height-wise under bridges and overpasses. Lastly, the craft must be visually appealing. No matter how practical, there are many consumers who may shy away from a roadable aircraft simply because of the an unappealing appearance

Human Factors/Manufacturing/Cost

The subgroup for human factors issues is ranked on a scale of -2 to +2 for the following categories of critical issues; safety, ingress/egress, visibility, ease of conversion, and aesthetics. A paramount issue is the general safety of the operator. Safety features such as bumpers, crash cells, and location of fuel storage are the main considerations. The next issue is ingress and egress of the vehicle in the plane mode as well as in the car mode. If the craft has a user-friendly way in and out in both modes, the craft ranks the highest score of +2. The subgroup also assessed the visibility. Since most concepts are designed with the plane functions in mind first, they all have fair to good visibility as a plane. The question actually is the visibility in car mode after the conversion. Folding wing location and other component placement become ranking factors. Of course it is considered that mirrors' placements are early for this stage and can assist in visibility needs later in the design.

The next human factor of importance is the actual conversion of the plane to car and vice versa. The feasibility of the conversion is a factor of the market. Businessmen would be less inclined to want to manually convert the vehicle. Increasing automation, in turn increases the price. The lower end design would still require the operator be able to perform the conversion and should be user friendly for the majority of potential operators. Therefore, the highest ranking is given to the most user friendly and yet simple conversion design. Last but perhaps equally as important is the aesthetics of the vehicle in car and plane mode. This criterion is simple. The highest ranking goes to the most aesthetically pleasing concept.

The critical issues for cost and manufacturing are market, development, simplicity, and service/maintenance. Marketing is mainly deciding what group of potential buyers to design for.

In this case, the small business and family markets are the focus. To reflect the market, the important design elements are a minimum of four passengers, primary function of flight, and a moderately good road capability. The closer the designs came to these criteria the higher the score. Development was considered on the basis that the less new technology required and the more standard, purchasable parts a design uses, the less expensive it will be to produce overall. Simplicity of design effects manufacturing, so the fewer moving parts and newly designed components, the easier a design will be to produce. Service and maintenance costs are given a better score for designs with fewer complex, detailed mechanical components. These raise the life cycle cost of a vehicle and therefore effect the marketability.

Discussion

A decision matrix, shown as Table 6, was used to refine the six intermediate concepts into a single final concept. The decision matrix consisted of a -2 to +2 ranking system, where -2 was poor and +2 was good. Each of the sub teams evaluated the six intermediate concepts by grading them based on the group's predetermined critical issues. The total scores from each sub team for the six intermediate concepts were then averaged under equal weighting. Intermediate Concept 1 received a total averaged score of -3.50, Concept 2 received a score of 2.83, Concept 3 received a score of 1.00, Concept 4 received a score of 3.50, Concept 5 received a score of 4.50, and Concept 6 received a score of 3.50.

Once the scores for the six intermediate concepts were averaged, the top American concept (Intermediate Concept 2 with an averaged score of 2.83) and the top British concept (Intermediate Concept 5 with an averaged score of 4.50) were chosen to be considered for final refinement. The final concept was then formed through a hybrid of these two concepts based on the positive qualities of each. The driving factor in the selection of the various portions from each concept was the market set forth at the beginning of the design process. The key issues in the design are safety and ease of transformation, since the vehicle is being marketed to small businesses and families.

Table 6: Final Concept Decision Matrix

		1. GA craft with transmission in wings	2. Lifting Body with telescoping wings	3. Lifting body with folding wings	4. Gyrocopter	5. Car with ducted fans and folding wings	6. Cessna with rotating wings
Structures							
1. Wing Position		-2	-1	-2	0	2	2
2. Aspect Ratio		1	2	1	2	1	1
3. Sweep/Taper		-2	2	1	0	1	2
4. Number of Moving Parts		0	1	0	1	0	1
5. Size of Moving Parts		-2	1	-2	1	-2	-1
6. Wing Loading		1	0	-1	-1	2	1
7. Weight Distribution (Moments)		0	1	-1	-1	1	1
8. Crashworthiness		-1	0	0	2	1	1
Subtotal	1/6	-5	6	-4	4	6	8
Stability and Control/Aerodynamics/Performance							
1. Control in All Aspects (Air)		0	1	1	1	1	1
2. Aft CG for Rotation (Air)		2	0	1	0	-1	1
3. Cross Wind Effects (Road)		-2	0	-1	1	-1	0
4. Low CG (Road)		1	0	1	1	2	-2
5. Central Longitudinal CG (Road)		2	1	1	-1	2	2
6. Reduced Lift (Road)		1	-1	0	2	1	2
7. Clean Flow Over Surfaces and Props (Air)		1	2	1	0	0	2
8. Streamlined Frontal Cross Section (Air)		1	1	0	-1	1	1
9. High Aspect Ratio (Air)		1	-2	1	0	2	-1
10. Wing Placement-Mid Wing (Air)		2	0	2	0	0	1
11. Low Profile Drag After Conversion (Road)		1	1	1	1	1	2
Subtotal	1/6	10	3	8	4	8	9
Propulsion							
1. Power		-1	0	0	-1	-1	-2
2. Size, Weight of Engine and Transmission		-1	-2	0	0	-1	1
3. Engine Type (Fuel)		0	0	0	0	0	-1
4. Fuel Efficiency and Range		-1	0	1	0	0	0
5. Cost		0	0	0	-1	0	1
6. Location of Engine and Transmission, Easy Access		0	0	0	0	0	-1
Subtotal	1/6	-3	-2	1	-2	-2	-2
Car							
1. Stability		-2	1	-2	2	1	0
2. Crashworthiness		-2	0	-2	1	1	-1
3. Driver Visibility		0	2	2	2	2	1
4. Road Friendly		-2	1	2	2	2	-1
5. Ease of Conversion		-2	1	-2	0	0	1
6. Aesthetics		-2	0	0	2	2	-2
7. Access		-1	1	2	2	1	2
Subtotal	1/6	-11	6	0	11	9	0
Cost/Manufacturing							
1. Market		0	1	0	1	0	0
2. Development (Outsourcing)		0	-1	-1	-1	0	2
3. Simplicity of Design		-1	1	-1	-2	-1	1
4. Service and Running Costs		-1	-1	1	-1	1	0
Subtotal	1/6	-2	0	-1	-3	0	3
Human Factors							
1. Safety		-2	0	1	1	0	-1
2. Ingress/Egress		-2	-1	2	2	2	2
3. Visibility		-2	2	0	2	1	1
4. Conversion Ease		-2	2	0	2	1	2
5. Asthetics/Noise		-2	1	-1	0	2	-1
Subtotal	1/6	-10	4	2	7	6	3
Total		-3.50	2.83	1.00	3.50	4.50	3.50

Final Concept

The final concept of the roadable aircraft, illustrated in Figure 13, melds the best features from Intermediate Concepts 2 and 5. This design joins the fuselage of Concept 5 and the wings of Concept 2 with some adaptations. The fuselage of Concept 5 was selected due to its aesthetic appeal in the car configuration as well as the dual ducted fan propulsion system. The original Concept 5 cabin interior consisted of a central driving position with two offset rear passenger seats. The cabin was expanded to a four seat conventional cabin to match the selected market. A double width gull-wing door arrangement provides easy ingress and egress. These doors will rotate up to provide access to the front seat, rear bench and aft cargo space.

The ducted fans of this design provide greater road safety than a forward or aft mounted propeller. A drawback of this propulsive arrangement is the nose down pitching moment generated by the location of the thrust line with respect to the center of gravity. The engine that drives the ducted fans and the rear drive wheels was originally located at mid-fuselage. However, relocating the engine to the front of the vehicle proved to be more advantageous in terms of center of gravity location, accessibility, cooling and crashworthiness. The center of gravity location shifts forward and down to provide better road stability. With the engine mounted in the front, accessibility is improved and better airflow provides increased cooling. The crash survivability is also improved since the engine mass is located in front of the passenger cabin. Shafting is the primary drawback to the forward mounted engine. Moving the engine to the front necessitates long drive shafts for both car and airplane configurations, but this negative is outweighed by the numerous advantages of the forward engine location.

The lifting surfaces of Concept 2 were improved and blended with the fuselage of Concept 5. The lifting device consists of a main low aspect ratio wing with telescoping sections. The thickness of the high lift, low aspect ratio wing provides convenient stowage of the telescoping wings in automotive configuration. In roadable mode, the vehicle is 2.44 m (8 ft) wide, 2.44 m (8 ft) in height, and 5.18 m (17 ft) in length. The vehicle take-off gross weight is approximately 1591 kg (3500 lb). These dimensions should allow free travel on the road, including parking in garages and spaces. The low aspect ratio airfoil is end plated to reduce three-dimensional effects inherent in such high lift devices. It has a span of 2.44 m (8 ft) and a chord of 3.45 m (11.32 ft), resulting in an aspect ratio of 0.71. By stacking the wings in their stowed positions, the span of each telescoping wing extension was doubled. This increased the overall span of the wing from the 4.33 m (14.2 ft) of Concept 2 to 7.01 m (23 ft) in the final concept. The greater span results in more favorable aerodynamic performance such as lift and range, as well as increased roll stability.

Manual extension of the wings allows maximal span to be achieved, as no machinery is required. This simple telescoping design lends itself to easy conversion between modes. Theoretically, combining the high lift airfoil and telescoping wings will produce sufficient lift for takeoff without significant rotation. The configuration allows the gravitational center to be positioned midway between the front and rear wheels in the road configuration. The front wheels will be articulated to raise the nose of the vehicle from a negative angle of attack in road configuration to a slightly positive angle in the aircraft mode. A negative incidence will generate negative lift to better maintain contact with the road. In aircraft mode, the front wheels will raise the nose allowing the high aspect ratio wing to generate lift during take off should there be inadequate lift to provide take off without rotation.

Figure 13: Final Concept Configuration

In flying mode, the controls of the airplane are comparable to current general aviation craft. Large trim tabs compose the trailing edge of the low aspect ratio wing to compensate for the negative pitching moment produced by the thrust line. The craft has a large horizontal tail and elevator to provide pitch stability and control. This control surface will lie in the wake of the ducted fans, assuring flow over the surface and thus pitch control at all times. Twin vertical tails support the horizontal tail with rudders providing control in yaw. Flaperons are situated on the trailing edges of the telescoping wings, generating large moment arms for ample roll control. To keep the wing extensions from stalling, fixed leading edge slots will be incorporated into the airfoil design at their inboard sections.

Performance

The final concept initial sizing was performed using a sizing code that takes into account several initial specifications of the vehicle. The code is based on methods presented by Leland Nikolai and calculates the overall take off gross weight and the critical constraints on the aircraft in takeoff, landing, cruise, and climb. The code is broken into five sections: section one is the user input of various vehicle specifications, section two performs the preliminary calculations for the code, section three calculates the general take off gross weight calculations by calculating weight fractions for each mission segment, section four performs the iterations to calculate the actual take off gross weight, and section five calculates the power and wing loading constraints for each mission segment. The critical constraints were then used to determine initial wing loading and power loading for the final concept in an attempt to size the wings and control surfaces. The iterative method uses a curve fit to a generic comparator aircraft and an empty weight calculated by subtracting the fuel and payload from the gross weight. The first section of the code allows for the user input of initial specifications of the final concept. These initial specifications were based on general data taken from the comparator aircraft and from the initial geometry of the final concept. The range, cruise velocity, loiter time, and take off and landing distances. And the payload inputs were all based on the mission defined by the team. The span, wing area, and aspect ratio were all based on the initial geometry of the concept. The propeller efficiency, Oswald efficiency factor, $C_{L_{max}}$ and C_{D0} were all taken from comparator aircraft.

Table 7: Data input for the sizing codes*

Range	1389 km (750 nmi)
Cruise Velocity	277.8 km/hr (150 knots)
Loiter Time	30 minutes
Take off and Landing Distance	457.2 m (1500 ft)
Payload Weight	400 kg (880 lbs)
Span	7.01 m (23 ft)
Wing Area	13.7 m ² (147.16 ft ²)
Aspect Ratio	3.6
Propeller Efficiency	0.9
Oswald Efficiency Factor	0.9
$C_{L_{max}}$ for Take off and Landing	1.7
C_D	0.04
L/D_{max}	7.5

* The code required the English units in parenthesis as inputs.

The second section of the code performs initial calculations used in the third and fourth sections such as Mach number and lift over drag max. The third section of the code calculates the various weight fractions for each mission segment. The mission profile set forth for the concept consisted of a take off, climb and acceleration, cruise, loiter, and landing. The fourth section of the code actually solves the iteration setting the required empty weight, based on the weight fractions from section three, equal to the available empty weight. The code produced an initial take off gross weight of about 1588 kgs (3500lbs) for the final concept.

The fifth and final section of the code calculates the critical constraints for the final concept based on the same information described above for the take off gross weight calculation. The constraint diagram is shown in Figure 14. A low power and wing loading is desirable for this roadable aircraft concept to minimize structure and maximize performance. Based on the constraint diagram, the critical constraints for the concept are landing and cruise. The intersection of these two mission segments provides the lowest possible values of power and wing loading. A region of critical constraints was chosen for the final concept to provide flexibility in the design process for improvements to lower the required power and wing loading. This region is approximately a power loading between 0.018 and 0.021 kg/W (30 and 35 lbs/hp), and a wing loading between 102.5 and 146.5 kg/m² (21 and 30 lbs/ft²). Assuming an average value of wing loading from this range of about 122 kg/m² (25 lbs/ft²), the required wing area calculated by dividing the take off gross weight that was determined by the code by this average wing loading is about 13 m² (140ft²). This number is very close to the initial wing area of 147.16ft² based on the geometry of the final concept, indicating that the sizing of the wings of the final concept is acceptable at this point.

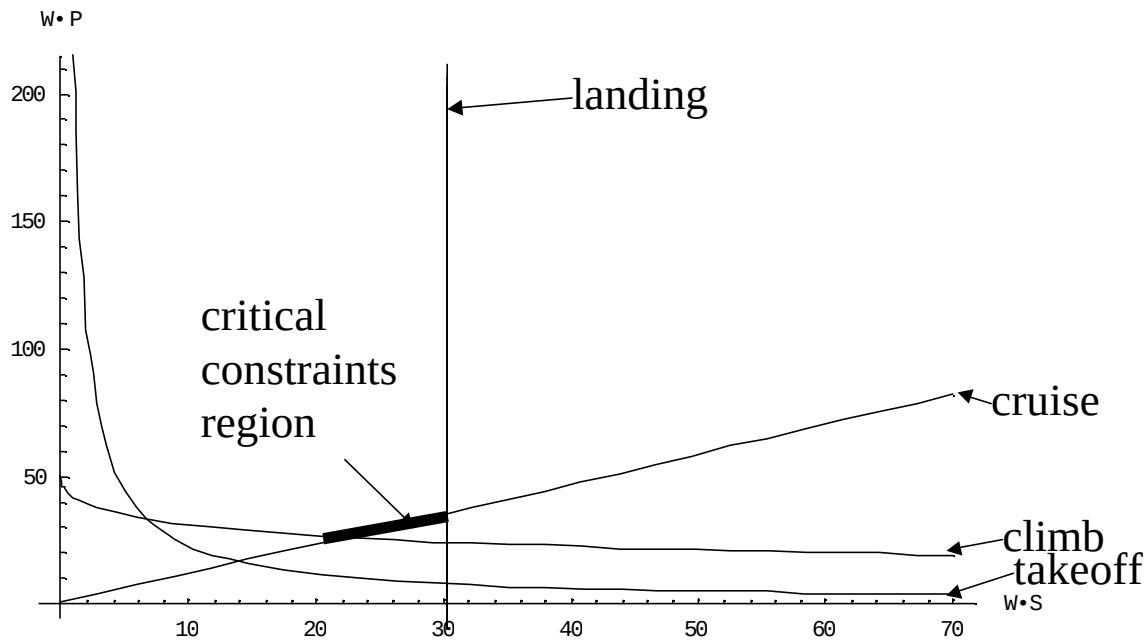


Figure 14: Constraint Diagram

Structures

Most important in the contribution of the structure to the overall performance of the vehicle is minimal weight. Less weight ensures a lower fuel consumption and possibly reduced operating costs through maintenance. Cost may further be reduced by less required labor for fabrication. Optimization theory plays a huge part in developing a structural design where weight is minimized while strength and stiffness are maximized.²² After overall dimensions for the major surfaces are given, location and dimensions of the principal structural members (ribs, spars) will be determined.

Several different materials are being considered for construction of the final concept. The most common material used in general aviation aircraft construction is aluminum, so this conventional metal is being considered. Other composite materials such as glass fiber and carbon fiber are also being looked at. Composite materials have many manufacturing advantages such as precision, durability, strength and resilience. Also, the new technology of resin infusion adds simplicity to the process but is more expensive. Besides being a structural factor, the cost of the material will also be looked into by the manufacturing group.

Since aluminum is a conventional aircraft material, it has already been certified multiple times by the FAA and is regarded as a good material to use for aircraft structures. Aluminum, however, is susceptible to corrosion, which can cause major problems in an aviation vehicle. Another problem with Aluminum occurs with fatigue at the rivets. The rivets and rivet holes are the sites of large stresses, which lead to fatigue of the material also causing problems with the structure. Overall, aluminum is a lightweight material with a low density and low yield strength. It is easily manufactured, but tricky to weld properly. Aluminum has a relatively high initial cost, but does not require much maintenance.

Fiberglass, or glass reinforced plastic composite, requires no maintenance and has a low fatigue strength. High strength is found only in a preferred direction. Absorption of water causes a loss of compressive strength and ultra-violet light exposure causes brittleness. Composite materials are gaining in popularity, but have not been completely accepted by the FAA. They have a high strength to weight ratio, but at a high cost. They can be custom-designed for specific needs.

In general, composites have some good advantages including a good strength to weight ratio and corrosion resistance. In composite structures, adding more fiber can tailor stiffness where it is needed. Composites can be molded around complex shapes and produce a smooth surface with easy repair. However, disadvantages include degradation due to high temperatures and humidity, labor-intensive manufacture, and weight control.²³

Another major structural issue to be contended with when working on the final concept is the design of the frame of the vehicle. The fact that our final concept uses 4 wheels in the road configuration (which gives better road stability and control authority) forces us to adhere to legal guidelines concerning the crashworthiness of a car, among other legal stipulations. Therefore, it is essential that we design to safety standards suggested by the American and European governments. The cheapest and easiest way to do this is to use the frame of a production automobile.

In the search for a suitable production automobile frame, it is essential to find the lightest such frame possible. A typical automobile frame normally has the infrastructure to support a reciprocating engine in the front of the craft, which is the desirable configuration of a GA aircraft. Additionally, the accommodation of a driveshaft from front to rear of a vehicle is important so that we can power the ducted fans in the rear.

In the automobile framing business, two types of frames have been tried on a large scale. The space-frame design is essentially a light truss with a thin skin. The unibody frame, short for unitized body frame, is a frame in which the vehicle's body panels are joined together to form a shell structure. Space-frames, while reminiscent of aerospace structures, have not achieved large-scale success, due to different manufacturing procedures. The Audi A8 has been constructed from an aluminum space-frame in collaboration with Alcoa automotive. However, the luxury perks aimed at attracting the high-end market have all but obviated the fuel economy gains found with a lighter frame.²⁴

The lightest automobile frames which are currently sold in the \$10,000-\$25,000 market are the so-called "aluminum unibodies". In production runs of 300,000, aluminum unibodies cost \$2000 compared to the \$1400 price of a steel unibody. While a steel unibody might weigh 600 lbs, aluminum unibodies would weigh around 325 lbs.¹⁸ The Audi TT is a design using an aluminum unibody. With 4 seats, it also meets our mission capacity requirements.

Next the load paths must be considered, in both aerial and road configurations. In both flight and on the road, the engine must be supported. Also, passengers and their baggage must be supported. The TT frame accomplishes these tasks. This auto frame must be supported in the air. The Burnelli wing boxes extend the span of the Burnelli wing, supporting the auto frame from the bottom of the chassis. Between them extend the Burnelli wing ribs, two on each side. The lift distribution must be transmitted as a lift force evenly throughout the body. The extendible wings must be very strong to support our unique lift distribution, shown conceptually in Figure 15. This figure combines the normal elliptical lifting shape of a wing and melds it to our concept. The discontinuity apparent in the graph is located at the junction of the Burnelli wing and the extendible wing.

They also must be retractable and have a control surface. Based on the above specifications, the extendible wings will be constructed from a large diameter composite spar, surrounded by foam. The foam will be laminated with fiberglass. Foam affords good rigidity based on the volume of the part. Foam also permits arbitrary placement of actuators for the control surface. The foam/fiberglass combination provides good cantilever strength. One foot of the extendible wing will not extend but will remain within the Burnelli wing. The pinions on which the two extendible wings retract will be on the top and bottom of the two main Burnelli spars.

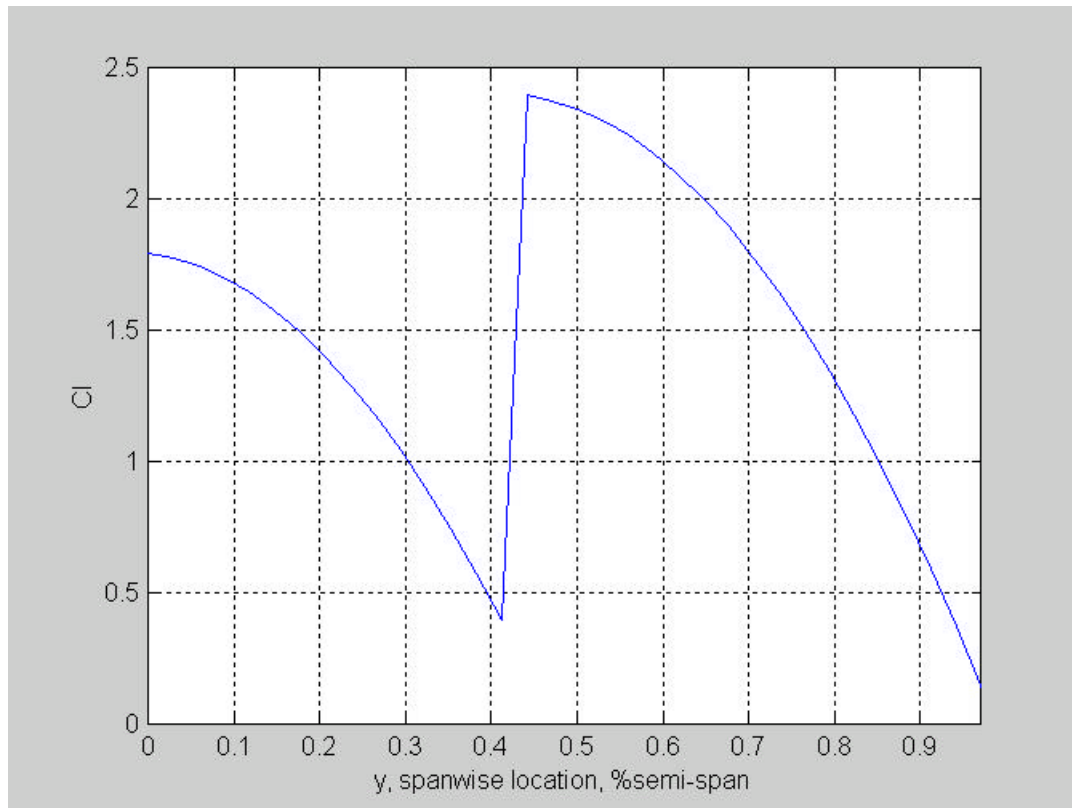


Figure 15: Predicted lift distribution of a segmented wing

Roadability

There are two main roadability alternatives considered in the design of the roadable aircraft. The major difference between the two approaches stems from the number of wheels. Thanks to Harley Davidson, any vehicle with three wheels is considered a motorcycle and needs only to obey laws pertaining to motorcycles. There is a very important advantage in using three wheels in the roadable aircraft design. The safety requirements for a motorcycle are much less stringent than for automobiles. More specifically, a motorcycle is only required to include headlights, taillights, turn signals, and a horn. In comparison, an automobile has a wide range of safety regulations that must be met. For example, safety requirements include impact protection devices, seatbelts, airbags, amongst others. The issue becomes whether it is more important to save money by avoiding all of the required safety features for an automobile, or to include these features and use them as a selling point. Safety is a huge selling point in our design since the target market is partially based around families. Consumers (especially families) are likely to be turned off from a vehicle they deem unsafe. Since many consumers are wary of new designs, especially a three-wheeled roadable aircraft, it is thought that having only three wheels on the design will detract from the positive aspects of the concept. The three wheeled option has been ruled out by the design team, but may need to be looked into further at a future point in time.

Future Plans

Upon leaving Loughborough University, the Virginia Tech and Loughborough students decided on a common mode of communication. Software versions include Microsoft Office 97 and AutoCad 14. File transfer will occur by utilizing portable document files (.pdf). All dimensions and calculations will be in SI units (with English units in parenthesis). Each sub-team has a point of contact to facilitate communication over email and at teleconferences. The first teleconference occurred on December 2, 1999. The purpose of the teleconference was to decide the course of action through the winter break and each university's finals. It was decided the plans for the rest of the semester and plans were made for the next teleconference to occur the week of January 17, 2000.

Communication is important between the two universities, but it is also critical to have effective communication between the sub-teams. Previously, each group established expectations required of the sub-teams and, in addition, determined what was required from other sub-teams to produce the results. A CAD drawing with dimensions of the final concept will be needed by every sub-team, as well as, an initial take-off gross weight. To find the take-off gross weight each university will use its own codes and then an average of the two initial take-off weights will be used. Each sub-team will use the information gathered to produce outputs of the final concept.

The Propulsion sub-team will use the weight with the speed, engine location and the driven wheels to determine the power output and the specific engine and engine deck. Stability and Control will use those measures to calculate the center of gravity and approximate size and location of the control surfaces. The Structures sub-team needs the initial drawing with location of the fuel storage in addition to the weights and wing loading to develop models and an interface for wing and fuselage research. The Structures group and the Roadability & Human Factors teams will be researching impact and crashworthiness requirements. The Structures team has looked into using a car body frame for the frame of the fuselage to help with crashworthiness and also facilitate manufacturing of the final product. Roadability and Human factors sub-teams will be researching the road requirements for passenger safety. The cost group will study exactly what the market wants in a roadable aircraft to make sure the final concept meets these requirements to reduce the giggle factor. Each team will look at the cabin layout. The Human Factors sub-team has split some of the research with students looking at the current interiors of different cars and general aviation planes. The Systems sub-team will look at the control system and needs to know the electrical requirements for the different parts of flying driving and the conversion between each. They will determine the weights and costs of such systems and will research the required Avionics. AGATE has an ideal cockpit layout that the sub-team will incorporate into the final design.

The sub-teams have begun work on the information needed and as discussed in the teleconference Loughborough will continue work while Virginia Tech has finals before winter break and then at the start of the new year Virginia Tech will pick up the work while Loughborough has final exams. The teleconference scheduled in January will provide an opportunity for the work to be passed on. By February 7, 2000 both universities will be on regular schedule and weekly teleconferences will occur. The main focus of design will occur in the months of February and March with completion of the design to occur before the end of the semester at the end of April. The students from Loughborough University will be coming to

Virginia Tech the week of April 17 to finish the design, do a final presentation and participate in some additional team bonding.

Conclusion

With the continuation of the detailed design in the next semester, the team will look more in depth at the critical issues and further establish a final concept according to the target market. Several factors, such as a specific engine deck, a lightweight structure that will provide crashworthiness, a specific control system design, and a detailed cost analysis, will be considered. Through continuous, effective communication between the two universities and technical sub-teams, a feasible, affordable, yet innovative roadable aircraft will be designed. A final design presentation will be given during the Loughborough visit to Virginia Tech with the final paper to be submitted to the AGATE competition on May 2, 2000.

APPENDIX 1: Final Concept Initial Sizing Code

Section 1: User Input

Inputs (in English Units)

R = 748*5280; (* Range input in miles and converted to feet *)
Vcruise = 172.62 *5280/3600; (*Speed input in mph and converted to fps *)
LoiterTime = 30 *60; (*Time input in minutes and converted to seconds *)
hp=.9; (* Propeller efficiency, typical values for GA craft *)
sfc=.45/3600*Vcruise/(550*hp) ; __(* Thrust sfc converted to Power specific *)
span=23;
area=147.16;
AR =span^2/area; (* Aspect Ratio *)
Cdo = .04; (* Zero Lift Drag Coefficient *)
Wpayload =880; (* Weight of 4 people and baggage *)
e = .9; (* Typical Oswald Efficiency Factor for GA small craft *)
KS = 1; (* Required Empty Weight Coefficients *)
A = .911;
B = .947;

Section 2: Preliminary Calculations

Clear[Wfuelreserve,Wfueltrapped]
 $M = V_{cruise} / (1.4 * 1717 * 148.3)^{1/2}$; (*Mach Number Calculation at 10,000ft*)
 $K = 1 / (p * AR * e)$;
 $LoverDmax = 1 / (2 * (Cdo * K)^{1/2})$;
7.9702

Section 3: Weight Fractions for each mission segment

$W2overW1 = .975$;
 $W3overW2 = 1.0065 - .0325 * M$;
 $W4overW3 = \text{Exp}[-R * sfc / (V_{cruise} * LoverDmax)]$;
 $W5overW4 = \text{Exp}[-LoiterTime * sfc / LoverDmax]$;

Weight if the reserve and trapped fuel (Using common values as a percent of TOGW)

$W_{fuelreserve}[TOGW_] = .05 * TOGW$;
 $W_{fueltrapped}[TOGW_] = .01 * TOGW$;

Total Weight of Fuel

$W_{fuel}[TOGW_] = (1 + W_{fuelreserve}[TOGW]/TOGW + W_{fueltrapped}[TOGW]/TOGW) * (1 - W2overW1 * W3overW2 * W4overW3 * W5overW4) * TOGW$

Section 4: Iteration to Solve for TOGW

Clear[ReqdWE,AvailableWE]

```

ReqdWE[TOGW_]:= KS * A * TOGW^B ; (* Added 200 pounds here to account for extra
equipment due to car portion of mission *)
AvailableWE[TOGW_]:= TOGW - Wfuel[TOGW] - Wpayload;
FindRoot[ReqdWE[TOGW]==AvailableWE[TOGW],{TOGW,3500}]
{TOGW@3500.29}

```

Section 5: Constraints for Takeoff Distance, Landing Distance, Cruise, and Climb Rate

These equations are from Roskam, Jan. Aircraft Design: Part I.

```

Sto = 1500 ft.
Slnd = 1500 ft.
Clmax for TO and Landing = 1.7

```

Equations are derived using 5000 ft as ground level and 10000 ft as cruise altitude.

```

span=23;
area=147.16;
Cdo=.04;
Clmax=1.7 ; (*About the middle of the range for GA A/C*)
Clmaxto=Clmax;
s=.8616;    (*For 5000 ft*)

```

```

Takeoff
Clear[Sto]
Sto[TOP23_]:=8.314*TOP23+.0149*TOP23^2;
TOP23 = WoverS*WoverP/(s*Clmaxto);
Solve[Sto[TOP23]Š1500,WoverP]

```

```

Landing
Clear[Vstall,Sl]
r=s*.002378;
Sl=1500;
Vstall=Sqrt[Sl/.256]*1.688;
WS=((Vstall^2)*r*Clmax/2)/.95
30.6062

```

```

Cruise Speed
Ip=1;
WoverPcruise[WoverS_]:=WoverS/(Ip^3*s)

```

```

Climb Rate
hp=.9;
CloverCdMAX=1.345*(AR*e)^(3/4)/Cdo^(1/4);

```

```
RCP=600/33000;  
Plot[{WoverPTO[WoverS],WoverPcruise[WoverS],WoverPClimb[WoverS]},{WoverS,0,70},A  
xesOrigin@{0,0},AxesLabel@{"W/S","W/P"},Axes@True];
```

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