Design of Lightweight Electric Vehicles

A thesis submitted in partial fulfilment
of the requirements for the degree of
Masters of Engineering
in Mechanical Engineering

by

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Abstract

The design and manufacture of lightweight electric vehicles is becoming increasingly important with the rising cost of petrol, and the effects emissions from petrol powered vehicles are having on our environment. The University of Waikato and *Hybrid*Auto's Ultracommuter electric vehicle was designed, manufactured, and tested. The vehicle has been driven over 1800km with only a small reliability issue, indicating that the Ultracommuter was well designed and could potentially be manufactured as a solution to ongoing transportation issues.

The use of titanium aluminide components in the automotive industry was researched. While it only has half the density of alloy steel, titanium aluminides have the same strength and stiffness as steel, along with good corrosion resistance, making them suitable as a lightweight replacement for steel components. Automotive applications identified that could benefit from the use of TiAl include brake callipers, brake rotors and electric motor components.

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Main Symbols, Glossary and Abbreviations

Symbols

P	-	Power
V	-	Voltage
I	-	Current, measured in Ampere (A)
Wh	-	Watt hour; the amount of energy required to complete a certain task for one hour, standard unit of electricity.
Ah	-	Ampere hour
η	-	Efficiency
g/km	-	Grams of CO_2 emitted per km driven; expression of vehicles GHG expression of vehicles greenhouse gas emissions.
Wh/kg	-	Watt hours per kg; energy stored per unit mass.
µH	-	micro Henries; units of inductance

From vehicle mechanics

$\rho = \text{density of air}$

$v = \text{velocity of car}$

$C_D = \text{drag co - efficent}$

$A = \text{frontal area of vehicle}$

$RR = \text{rolling resistacne}$

$a = \text{acceleration of the vehicle}$

$m = \text{mass of vehicle}$

$g = \text{gravity}$

$\theta = \text{incline angle}$

Glossary

Body in White (BIW) – Refers to a cars body before the engine, drive train, interior etc is added to the vehicle, it does include the body work and doors, handles, hinges etc ("Body in White", 2008).

Quadracycle – A light four wheeled vehicle designed for one person.

Abbreviations

EV	-	Electric vehicle
BEV	-	Battery electric vehicle
HEV	-	Hybrid electric vehicle
ICEV	-	Internal combustion engine vehicle
PHEV	-	Plug in hybrid electric vehicle
SUV	-	Sports utility vehicle
ULSBA	-	Ultra lightweight steel bodied automobile
CAD	-	Computer aided drafting
CAM	-	Computer aided manufacturing
CAE	-	Computer aided engineering
NC	-	Numerical control
CNC	-	Computer numerical control
CO_2	-	Carbon dioxide
GHG	-	Green house gases
NiMH	-	Nickel metal hydride; a type of battery chemistry
Li-ion	-	Lithium ion; a type of battery chemistry
Li-S	-	Lithium sulphur; a type of battery
DOD	-	Depth of discharge
DC	-	Direct current
AC	-	Alternating current
LED	-	Light emitting diode
IGBT	-	Insulated-gate bipolar transistor
MOSFET	-	Metal-oxide-semiconductor field-effect transistor
LVVTA	-	Low volume vehicle transport authority
GM	-	General motors
WSC	-	World solar challenge
HVAC	-	Heating, venting, and air conditioning
US/USA	-	Unites states of America
UK	-	United Kingdom
UV	-	Ultraviolet
γ-TiAl.	-	Gamma titanium aluminide
PM	-	Powder Metallurgy

Common Conversions

100 Km	=	62 miles	
1 kW	=	1000 W	
100 km/h	=	27.8 ms^{-1}	(1km/h = 3.6ms^{-1})
1000 kg	=	2.2 pounds	

Chapter 1 Introduction

1.1 Transportation overview

Oil experts agree that there is between 990 billion to 1.1 trillion barrels of accessible crude oil left in the world. At the current rate of usage, 30 billion barrels a year, it is predicted the world will run out of oil by the year 2043 ("Fossil Fuels", 2006).

Figure 1.1 Crude Oil Consumption vs Production (BP, 2007)

Since 1981, the world has consumed more crude oil than it has produced. The world has 39 years of oil reserves, and production is within 2.5% of meeting demand (*BP Statistical Review of World Energy June 2007*, 2007) . Although these figures support the theories of those who believe the world's oil supply is limitless, some facts about oil are unable to be seen from statistics:

- Regular oil, the cheap and easiest to extract, has already peaked somewhere in 2005 (Howden, 2007).
- Many plastics are made or derived from fossil fuels (Howden, 2007).

- The production of aluminium heavily relies on the use of crude oil (Howden, 2007).
- Former Vice-president of BP, Dr Campbell, has admitted to falsifying crude oil estimates. Reports of Iran and Iraq's oil reserves are said to be half of the government estimates (Howden, 2007).

The oil industry is very unstable. An example that highlights this is when, in the 1970s, a 5% drop in oil production caused a 400% price rise (Howden, 2007). Today, 31% of the world's crude oil is produced in the Middle East, and with the political problems and ongoing wars in these countries, is clear that the use of crude oil is finite and the end of petrol for transportation may come sooner than expected (*BP Statistical Review of World Energy June 2007*, 2007).

The reduction of fuel consumption trends are already beginning to show. In Europe, 35.2% of the 15 million new vehicles were small cars, an over 3% rise in one year. This trend is likely to continue as tougher carbon dioxide (CO_2) legislation and fuel prices continues to rise ("Small cars take bigger share of the market", 2007).

Sweden plans to be independent of oil by the year 2020 through the implementation of incentives including cheaper bio-fuels, and the increased availability of electric and hybrid fuels (Honeywill, 2007b). As the current world leader in alternative fuels, they are looked to by the rest of the world to be an example of what is possible in environmental welfare.

1.1.1 New Zealand's personal transportation

New Zealand is a relatively small country of 4.25 million people ("Population of New Zealand", 2008) spread over a large land area. Because of this, people in New Zealand rely heavily on personal transportation. Without the population base to support public transport, many New Zealanders rely on cars as their personal transportation.

New Zealand's domestic transport system relies heavily on fossil fuels, using 84.6% of the nation's petroleum supplies (Dang & Cowie, 2006). In 2006 there were 3.23 million registered vehicles in New Zealand. Of those vehicles 2.23 million were cars, not including taxis or rental cars (LTSA, 2006). Of the New Zealand population, 78.5% of people are by law allowed to drive a motor vehicle, meaning that in 2006, there were 3.23 million potential drivers. This does not include people who are unable to drive, including the elderly, and disqualified drivers. These statistics show that there are approximately seven cars for every ten people in New Zealand, assuming only a small number of people own more than one car.

General – Table 37 Source: Land Transport New Zealand

Fuel types: total vehicles as at year end 2006, by vehicle type and fuel type

Vehicle type	Petrol	Diesel	CNG	LPG	Electric	Other	Total vehicles
Cars	2,492,840	232,182	42	1,063	18	258	2,726,403
Trucks	169,093	328,990	139	432	5	52	498,711
Motorcycles	87,684	6	1	-	-	32	87,723
Tractors	2,830	32,863	6	31	3	97	35,830
Buses/coaches	3,323	15,773	66	115	76	-	19,353
Mobile machines	2,342	11,185	14	755	239	139	14,674
Motor caravans	4,128	18,855	12	108	1	8	23,112
Mopeds	22,692	6	2	3	198	60	22,961
ATVs	4,155	56	-	-	5	2	4,218
Special purpose vehicles	405	2,052	-	1	-	2	2,460
Agricultural machines	242	1,304	-	2	-	8	1,556
Trailers	-	-	-	-	-	-	554,882
Total	**2,789,734**	**643,272**	**282**	**2,510**	**545**	**658**	**3,991,883**

Figure 1.2 Fuel types for registered vehicles in New Zealand 2006 (LTSA, 2006)

Figure 1.2 shows that there are less than 280 alternative fuelled cars in New Zealand, and just 18 electric vehicles. New Zealand's Minister of Transport has stated that by 2040 NZ plans to cut CO_2 emissions from domestic transport in half. A key strategy to meet this goal is the use of electric vehicles in domestic transport; by 2040 60% of New Zealand's domestic and public transport will use alternative fuels.

The question that now needs to be asked is why this alternative fuel should be electric. Electric cars emit zero CO_2 gases whilst being driven, and with New Zealand's high proportion of renewable electricity production, we have a prime opportunity to utilise electric technology and minimise the overall production of CO_2 in transportation. The New Zealand Government is working towards positioning New Zealand to become a world leader in the use of new vehicle technologies, including plug-in hybrids and electric vehicles (King, 2007).

1.2 Emissions and global warming

In 2006, 23% of global green house gas (GHG) emissions come from transportation. The effects of green house emissions on global warming and the ozone layer are well known, and governments around the world are making a concentrated effort to reduce the overall emissions of CO_2. Transportation and energy production were the only two sectors to increase their greenhouse emissions over the five year period from 2001. With the rapid globalization of India and China, some predict a further 85% rise in GHG emissions in transportation by 2030. Trends show that by 2050 the amount of light vehicles will have more than quadrupled from 600million to 2.7billion (Meyera, Leimbachb, & Jaeger, 2007).

Car	Powertrain	Horsepower	CO_2 Emissions
2006 Honda Civic iCDTi	Diesel	138	135
Ford Ka	Petrol	68	147
2006 Honda Civic	Petrol	144	160
2006 Honda Civic	Hybrid	110	109
2007 Volvo C70	Petrol	218	217
Toyota Prius	Hybrid	76	104
Porsche 911	Petrol	325	275
Nissan Patrol	Diesel	159	313
Audi A4 Saloon	Petrol	140	192

Table 1 Vehicle Emissions (see Appendix 1)

European Parliament has called to cut vehicle CO_2 emissions across Europe to 125g/km by 2015 ("MEPs vote for tougher CO_2 targets", 2007). Even with these reductions, any CO_2 emitted is bad for the environment and will continue to increase global warming.

In the UK, the government has implemented a new CO_2 tax where vehicles that emit large amounts of CO2 are taxed. By 2009, the government hopes to increase this penalty to £1000. As can be seen from Table 1, very few vehicles fall under the maximum CO_2 emissions for Bracket A of 100 g/km. Average sized saloons such as the Audi A4 fit under the second highest bracket, F, showing that governments are becoming more stringent on vehicle emissions.

Bracket CO_2g/km	A <100	B 101-120	C 121-150	D 151-165	E 166-185	F 186-225	G >225
Tax (pound)	0	35	115	140	165	205	300

Table 2 UK CO2 taxes source: ("UK 'green' Vehicles CO_2 Emissions Directory", 2007)

The idea is to encourage drivers to only use the vehicle they require to commute or travel ("UK 'green' Vehicles CO_2 Emissions Directory", 2007). With 90% of vehicle emissions occurring during the driving life of a vehicle, these taxes begin to deter people from driving vehicles which emit large amounts of CO_2 (Happian-Smith, 2001).

1.3 Thesis structure

Chapter one gave a state of affair of the transportation industry, and outlined some of the problems facing the automotive transportation industry. Chapter two outlines future vehicle options, and provides an overview of current research and literature of electric vehicles. It focuses mainly on the history of electric vehicles, and briefly discusses the design and development of these vehicles.

Chapter three looks at the design methodologies of battery electric vehicle design, including a breakdown of components and systems. It discusses advanced product development, and the use of virtual engineering in vehicle design. Finally the chapter discusses the Ultracommuter design specification.

Chapter four examines the design of the battery electric vehicles; each part of the vehicle is broken down and options for different components and design strategies are looked at, with a focus on how this was completed on the Ultracommuter electric vehicle.

Chapter five is a discussion about the manufacture of the Ultracommuter and a review of its driving performance.

Chapter six looks into titanium and its alloys, specifically looking into the potential use of gamma titanium aluminide components in battery electric vehicles.

Manufacturing and commercialisation of electric vehicles is the subject of chapter seven. It explores the requirements to produce an electric vehicle from a small scale manufacturing stand point.

Chapter 8 gives the conclusions and recommendations from the research.

For ease of reading, all units have been converted to standard international (SI) units, and costs are in New Zealand dollars unless otherwise stated. Common conversions can be found in the glossary.

Chapter 2 Literature review

As outlined in the introduction, there are two main issues facing the personal transportation industry. These are:

- The decreasing supply of fossil fuels.
- The negative effects that the burning of fossil fuels is having on our environment.

These two main issues are forcing governments and social initiatives towards alternative transportation. Along with new incentives, new technology advancements are aiding the development of alternative transportation. This chapter starts by looking into the alternative vehicles currently available and investigates in detail, the history, and future of electric car development.

2.1 Vehicle options

Currently there are four main options for alternative transportation: hybrid vehicles, hydrogen fuel cell vehicles, bio fuels, and electric vehicles.

2.1.1 Hybrid vehicles

Hybrid vehicles were invented in the late 1800s. By 1899, the Lohner-Porsche was the most advanced hybrid made. It featured front wheel hub motors, which negated the need for a transmission and improved efficiency. However, hybrids were not a viable transport option due to production cost, so Porsche focussed on the internal combustion engine (Anderson & Anderson, 2005). Hybrids were not produced again until the Toyota Prius in the late 1990's (Anderson & Anderson, 2005).

There are two main types of hybrid vehicles: series hybrids and parallel hybrids. A series hybrid has an internal combustion engine (of varying fuels), running a generator to charge or maintain a battery pack. The engine can run very efficiently at low output, and the vehicle itself is driven by an electric motor. A parallel system is currently the more common system. In this system, an electric motor and petrol engine both drive the car. As well as helping to drive the vehicle, the petrol engine can also act as a generator to charge the batteries (Allan, 2005).

Toyota Prius

The Toyota Prius shown in Figure 2.1 was launched on December 10th 1997, and was sold only in Japan until late 2000 when it went on sale in rest of the world (Schreffler, 2008). The popularity of the Prius in North America meant in 2007 the Toyota Prius hatchback outsold the Ford Explorer SUV, the most popular SUV in America for more than 10 years (Bernard, 2008).

The day after the Prius was launched in 1997, 170 countries signed the Kyoto protocol, committing to cutting CO_2 emissions. With emission statistics of 104g/km, the Prius was the first successful hybrid electric vehicle. Since 1997 over 900,000 having been produced (Schreffler, 2008).

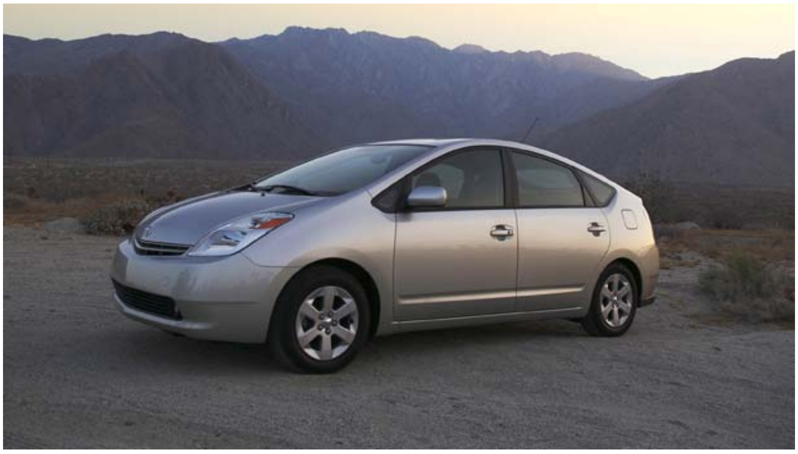


Figure 2.1 Toyota Prius (source:www.niot.net)

The key innovation in the Prius is the planetary gearbox that connects the petrol engine, generator, and electric motors together. It allows the vehicle to be powered by only the electric motor, only the petrol engine, or both. The unique factor about the Prius, is that it is both a series and parallel hybrid due to the motor being able to be run independently from the wheels, and charge the battery pack. Other features of the transmission include that it is a continuously variable transmission, meaning no manual or automatic gearbox is required; and because the generator can start the gasoline engine no starter motor is required (Allan, 2005). The battery pack consists of 168 NiMH cells producing a nominal voltage of 200 V. For safety purposes, it is housed in a crash-resistant case under the backseat of the vehicle (Allan, 2005).

Toyota has developed a plug-in hybrid electric vehicle (PHEV) version of the Prius. The plug in Prius gives drivers the option of driving on only the battery pack, and then charging it using a wall outlet once they return home ("Toyota Prius tests protoype plug-in Prius in US and Japan markets", 2007). By 2010 Toyota hopes to make the same amount of money from its hybrids as its other vehicles, and has the aim that by 2020 all of their gasoline powered vehicles will be hybrids (Aucock, 2007).

2.1.2 Hydrogen fuel cell vehicles

A hydrogen fuel cell consists of a chemical reaction of hydrogen and air, giving electrical energy and water as by products. A hydrogen fuel cell vehicle uses this electrical energy to power an electric motor.

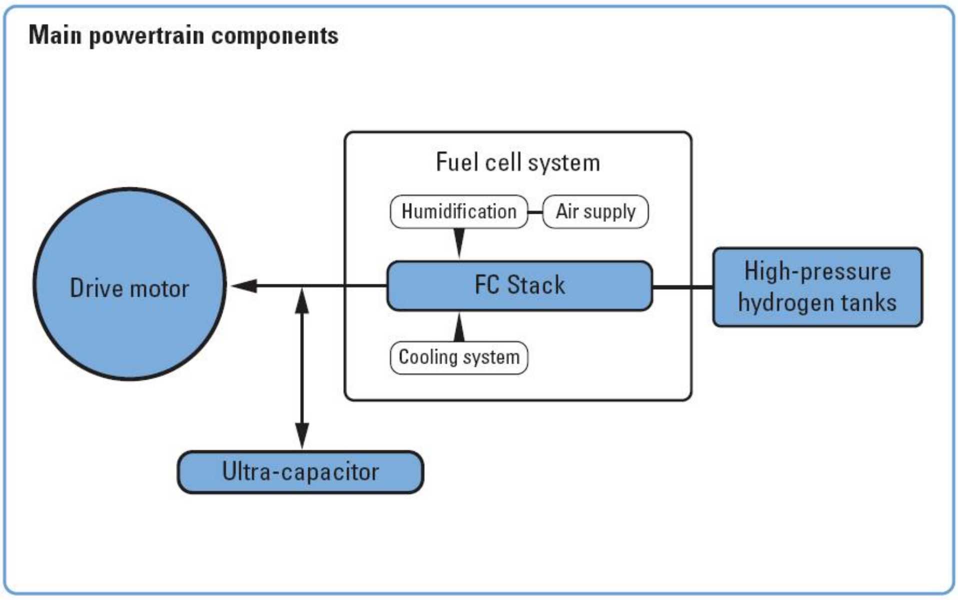


Figure 2.2 Hydrogen Fuel Cell components (*Honda fuel cell power: FCX,* 2004)

Figure 2.2 shows the drive system to the 2004 Honda FCX. In this drive system, Honda uses Ultracapacitors to store the electricity the fuel cell produces. Ultracapacitors deliver the large amounts of energy required during acceleration quickly and efficiently, and are then re-charged by the fuel cell.

Although hydrogen fuel cells show large promise as a future fuel, the introduction of hydrogen as a mainstream source of energy is an unresolved issue (Griffiths, 2007). Some OEMs (original equipment manufactures) believe that hydrogen cars will be on the roads by 2010-2012. However, most agree this will not be reality until 2020-2025, due to the high cost of production, and many technical issues (Bickerstaffe, 2007a). The technical issues that hydrogen vehicle manufacturers must overcome include the refilling infrastructure, and the storage of the hydrogen, both at the refilling station and in the vehicle itself (Griffiths, 2007).

Hydrogen can be stored in three ways, as a solid, liquid, or gas. The high energy costs of liquefying hydrogen negate any CO_2 emission gain over fossil fuels, and very little emission savings can be made with hydrogen gas. Although solid hydrogen would be the optimal storage option, this technology can only be performed in laboratories, and is at least ten years away from concept vehicles, let alone production (Griffiths, 2007). Also, the transfer of hydrogen from storage to ‘fuel tank’ can take hours depending on the material it is being bonded to. Many scientists describe this problem as being similar to charging a battery. The fuel tank for a hydrogen car currently weighs 170kg. This extra weight can affect the cars mileage, as well as affecting the handling due to the large size of the tanks limiting their placement in the vehicle to ensure adequate safety (Griffiths, 2007).

2.1.3 Bio-Fuels

Bio-fuels are not a new type of vehicle, they are simply a new fuel. A bio-fuel is defined as “a generic term for any liquid fuel produced from sources other than mineral reserves such as oil, coal and gas. In general, bio-fuels can be used as a substitute for, or additive to, petrol and diesel in most transport and non-transport applications. The most commonly used bio-fuels are biodiesel and bioethanol (*Biofuels*, 2005)

E85

To date, E85 is the most successful bio-fuel, consisting of 85% ethanol (from biomass, usually sugar) and 15% gasoline. Used in Sweden, it has been found that E85 can reduce the lifecycle of CO_2 emissions by 30-80% (Honeywill, 2007a). The success of E85 in Sweden is due to government subsidies, with E85 costing €0.4 less per litre than gasoline. While it is not as efficient as gasoline, it still results in a considerable saving. As an incentive, car companies have also received 20% tax breaks on vehicles that can be powered on E85, for example Saab receive this for their car, the Saab 9-5 (Honeywill, 2007b).

New bio-fuels are being developed constantly; in Germany a biomass to liquid facility will start production in early 2008. The facility will produce 310 barrels of bio-fuel a day; this new bio-fuel yields three times the amount of fuel per unit of land area, and the clean diesel it produces looks and behaves like normal diesel. The fuel can yield CO_2 emission savings of up to 90% and does not impinge on food crops (Honeywill, 2007a).

The main problem with bio-fuel is the practicalities of growing the plants to produce the bio mass. Table 3 (overleaf) shows the optimum fuel yield of different crop types, and the relative % of New Zealand and American landmass needed to grow crops on for each country to supply its own fuel. This does not take into account the processing of plants, and the effects these crops would have on our environment and economies.

Ethanol	Liters/hectare	% of NZ	% of USA
Sugar beet (France)	4,477	8	29
Sugarcane (Brazil)	4,151	9	31
Cassava (Nigeria)	2,571	14	50
Sweet Sorghum (India)	2,345	16	55
Corn (U.S.)	2,220	16	58
Wheat (France)	1,737	21	75
BioDiesel			
Oil palm	4,278	8	30
Coconut	1,937	19	67
Rapeseed	859	42	151
Peanut	758	48	171
Sunflower	691	53	188

Table 3 Bio Fuel yields (see Appendix 2)

The real environmental effects of a vehicle

Many car manufacturers give statistics about CO_2 emissions while driving and fuel consumption around town. But these figures are only one part of the energy consumption and pollution that a car uses and creates through its whole lifetime, from raw materials to scrap vehicle.

A Well to wheel analysis primarily looks at the fuel and drive system of a vehicle. Well to wheel analyses are a good way of looking at the emissions and consumption while driving as well as in the manufacturing of the fuel, and the use of that fuel for driving (Simpson, 2003).

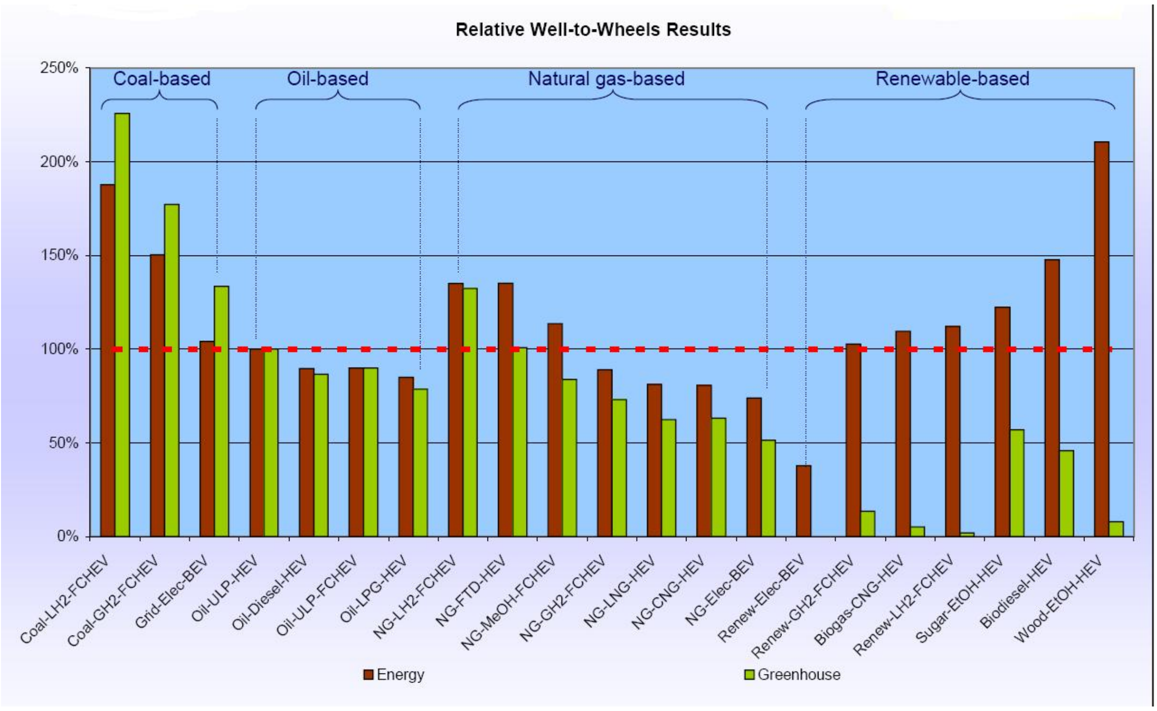


Figure 2.3 Well to Wheel analysis of Holden Commodore Australia (Simpson, 2003)

The above well to wheel analysis (Figure 2.3) shows a comparison of different drive systems for a Holden Commodore. The greenhouse emissions (in green) and energy consumption (in brown) of each drive system is compared to the 100% line of a standard unleaded petrol powered Commodore.

The clear winner of the analysis is a battery electric vehicle that is charged by a renewable electricity source, requiring less than 45% of energy compared with petrol, and emitting no greenhouse emissions.

This study was conducted in Australia where, in 2005, 90.2% ("Australia's Electricity Supply", 2007) of electricity was produced by the high polluting energy sources of black coal, brown coal, and natural gas. This showed that when a battery electric car was recharged using the national grid, the vehicle actually produced more greenhouse emissions and used more energy than a petrol powered vehicle.

Though they emit less greenhouse emissions, bio-fuels have a higher energy requirement. Bio diesel uses more than 145% the amount of energy than petrol in the manufacturing and running of a vehicle (Simpson, 2003).

Hydrogen fuel cell vehicles which us hydrogen produced from coal, emit 150% of the greenhouse emissions and consume over 175% the amount of energy of the conventional vehicle. Oil based and gas based hydrogen does not yield a significant decrease in the amount of energy required, implying that this will not help with the diminishing supply of fossil fuels (Simpson, 2003).

Hybrids all provide improvements in terms of energy consumption but similar to hydrogen, they do not solve the problem of oil being finite.

There is no perfect solution for using a single vehicle type for the future of personal transportation, but there are the possibilities of combining these technologies to create an alternatively fuelled transportation system. These include:

- Trucks and heavy transport could be powered by bio-fuels
- Personal transportation can consist of efficient battery electric vehicles
- Public transport could use hybrid buses
- Future electric vehicles could migrate to hydrogen fuel cells once the technology develops

Many people believe that the electric vehicle offers the best short term solution because electric vehicles can offer better energy efficiency, reduce our dependence on fossil fuels, and improve air quality for future generations (Ulrich, 2003; VanMierlo & Maggetto, 2006).

2.2 Battery electric vehicles

The 130 year history of the electric vehicle (EV) has six phases. The first phase began in 1880 with tricycles and carriages. The second phase was known as the "golden age" from 1900-1912 where EVs were used more than gasoline powered vehicles (Westbrook, 2005). The years from 1912 to the 1960s consisted of the domination of Internal Combustion Engine Vehicles (ICEVs), with low fuel prices and better performance. The 1960s was the beginning of the resurgence phase of the EV. This was due to the environmental concerns of the emissions of ICEVs, and the fuel price rise of the Arab oil embargo in the 1970s (Hussain, 2003). The fifth phase, in the 1990s, was due to the CO_2 emissions legislation in the United States. Now in its sixth phase, the future of EVs looks strong due to several factors including the environmental, economic, technological and social changes impacting the EV in the new millennium.

Tricycles, Carriages, and the early battle with the ICEV

In 1873, R. Davidson proved that a four wheel truck could be propelled by an electric motor powered by an iron/zinc primary battery. In 1881, G. Tourvé created the first electric vehicle powered by a Planté battery (plate battery). The EV was a tricycle driven by two modified siemens motors which developed 75W each, and powered the 160kg vehicle at 12 km/h (Westbrook, 2005).

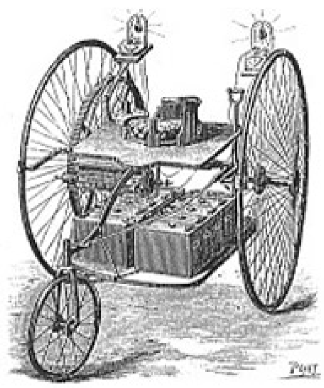


Figure 2.4 Aryton and Penny elektromobile (source:www.synergie.de)

In 1882, Professors William Ayrton and John Perry further developed the concept of an electric tricycle with 10 lead/acid cells in series to form a battery with

1.5kWh of storage, enough for a 16-40km range. The motor had 373W of power, and at the maximum voltage of 20V was able to propel the vehicle at 14km/h. This vehicle also had the first electric head lamps, with two filament lamps giving four candlepower, for night driving (Westbrook, 2005).

Similarly, in 1881, pioneers of the electric car Charles Jeantaud and Camille Faure, created the first electric carriage. Using a lightweight 'Tilbury' carriage, a Gramme motor, and a Fulmen battery pack, it was the first four wheel electric vehicle. Jeantaud later had further success with the development of a British electric motor in 1887. In 1893, Donato Thommasi designed one of the most critical components of the electric vehicle, a high energy density battery. This 27kWh//kg battery led to impressive ranges up to 80km (Mom, 2004).

The French led the early electric car performance and innovation, with Camille Jenatzy and Jeantauds rivalry in world speed records well documented (Anderson & Anderson, 2005). In 1899, 'Jamais Content', an electric vehicle built by Jenatzy in France, achieved the world speed record of 98km/h. Jamais Content featured an aluminium and tungsten body, as well as pneumatic tyres produced by M. Michelin (Westbrook, 2005). In April of 1899, the car broke the 100km/h speed barrier, with a recorded speed of 105.88km/h (Mom, 2004). Although there are various accounts of how this record was broken, from either a steam powered or gasoline powered vehicle, sources agree that this record stood for 3 years until broken in 1902 (Anderson & Anderson, 2005; Mom, 2004; Westbrook, 2005).

Not only did the French engineers lead in the development of speed, they were also leaders in innovation. In Paris in 1987, M. A. Darracq demonstrated an electric coupe that was the first to use regenerative braking. Regenerative braking allowed the vehicles motors to become generators, which used the cars resistance on the road to slow the vehicle, and effectively recharge the batteries. This regeneration of energy improved range by 10% (Anderson & Anderson, 2005).

The electric cab

Philadelphia engineers Henry Morris and Pedro Salom began producing electric cabs and carriages for a New York electric cab service in 1897 (Anderson & Anderson, 2005; Kirsch, 2000). After several company expansions, they merged with a motor carriage manufacturer and created the Electric Vehicle Company (EVC) in 1899. They established operations offering electric cab services in several major cities including Boston, Philadelphia, New York, and Washington DC. Although the goal to reach the public market was not achieved due to the vehicles lack of range, the cab services in New York, Philadelphia, and Washington ran successfully until approximately 1910. Furthermore, internal combustion cabs did not enter the market until 1906 (Anderson & Anderson, 2005; Kirsch, 2000).

1900-1912: The 'golden age'

Although gasoline powered vehicles were developing rapidly in the early 20th century, it is said that the first 12 years of the century were the 'golden age' for electric vehicles (Westbrook, 2005). Ferdinand Porsche developed the first hub motor in the 1900 Porsche No.1 Lohner-Wagen. In 1902 the Lohner-Porsche Rannwagen was produced. It carried an 1800kg battery pack and was powered by four 1.5kW wheel motors. In approximately 1902, Porsche also worked on the development of one of the first hybrid vehicles, named the mixtWagen. In the mixtWagen, an auxiliary gasoline engine drove a generator that charged the storage batteries, which in turn powered the front wheel motors (Westbrook, 2005).

The electromobile was one of the best known vehicles in the UK. It was produced using components from a variety of manufacturers and 20 of the vehicles were sold as cabs from 1905-1920 (Anderson & Anderson, 2005). In New York, Babock Carriage Company promoted safety and comfort in its vehicles, but were best known for setting a world record of a 161km on one charge, during a journey from New York to Philadelphia (Anderson & Anderson, 2005).

The most successful electric vehicle company was the Detroit Electric Car Company. From 1907 to 1939, the company produced 35,000 vehicles. The Detroit Electric Car Company offered six vehicles, all of which featured a front end which looked like the radiator of a petrol powered vehicle. In 1915, the company introduced rubber window seals, and in 1917, followed with a patented window lifting system, allowing the driver an open-aired vehicle for summer driving. The main reason for the company's success was their dedication to reducing the costs of production. The company reduced the vehicle manufacturing cost by US$600-750 to bring the price of the vehicle down to US$2000, which in turn encourage sales (Anderson & Anderson, 2005).

Figure 2.5 Detroit electric car company (source: www.autowallpaper.de)

The Waverly electric vehicle company was another leading manufacturer during the 'golden age'. In 1908, Waverly introduced a front resembling a radiator, as was popular with styling of the period. Waverly made several variations in layout with a four seat model in which the rear passengers faced backwards. Waverly were known for their luxury vehicles, offering options for the rich to personalise their vehicles, allowing them to request custom paint jobs or battery upgrades (Anderson & Anderson, 2005).

The electric vehicle drought

By 1912, the design of electric and gasoline vehicles had changed. Functional design was beginning to be implemented, with the design focussing more on the propulsion of the electric or gasoline system, as opposed to the typical horse carriage styled look (Westbrook, 2005).

The main reason for the internal combustion engine's success was in the energy density of the fuel. Even with 90% the efficiency of the electric engine, an energy density of around 27Wh/kg was obtained from the lead acid batteries to the drive shaft of the battery electric vehicles. Internal combustion vehicles use gasoline, an energy dense fuel with 9000Wh/kg. Although this number is reduced to 1800Wh/kg at the driveshaft of the gearbox, due to mechanical inefficiencies and the internal combustion process, it still produces more than a 60x energy advantage over a lead acid battery. When considering that today's vehicles use 45 litres (40kg) of gasoline (equating to 2.7 ton of batteries), this shows the large energy advantage that ICEV had over electric vehicles. These batteries in the 1900s were also very slow to re-charge, had a very high cost, and only lasted 2-5 years (Larminie & Lowry, 2003).

In 1912, the gasoline powered vehicle had taken over the market. With the implementation of the self starting motor (as opposed to hand crank), and the introduction of the silencer (to reduce the noise), the gasoline vehicle took over the market. The economic benefits were very clear, with a Model T Ford retailing for $550 as opposed to $1750 for a Century Electric Roadster (Westbrook, 2005).

The First World War signalled the end for the electric vehicle, with gasoline vehicles proving more reliable and practical in the front lines, even during the most testing conditions. When the last new electric vehicle was produced in the USA in 1921, it retailed at $1200, four times more than what a model T could be bought for, and with a range of just 50miles and top speed of 25mph. By this time, nearly all electric car manufacturers had either gone out of business or started producing gasoline powered vehicles. Only one company survived, Baker Electric Company of Cleveland, and they eventually gave up building electric cars in 1921 to focus on building commercial electric vans, and since have adapted again, now building electric forklifts as United Technologies (Westbrook, 2005).

It was not until 1937 with fuel shortages during the Second World War, that electric vehicles were once again produced. In 1949, 3,299 electric vehicles were being driven in Japan, equating to 3% of the total vehicle population. The use of these vehicles continued until 1954, when gasoline powered vehicles regained their supply of oil after the war shortage.

During the same time period in the United Kingdom, electric vans were being used to deliver milk. 20,000 electric milk trucks had been produced over the years, and many of these were still in use in 2001, as electric vehicles seemed perfect for this application of a quiet vehicle with a 30km range, with the ability to be charged overnight (Westbrook, 2005).

The Resurgence

The 1960s signalled the beginning of the electric vehicles resurgence in the transportation industry. This was mainly due to the environmental issues associated with the internal combustion engine. Large automotive manufacturers such as Ford and GM began research into electric vehicles, and consequently, GM poured $15 million dollars into the development of two vehicles, the Electrovair and the Electrovan.

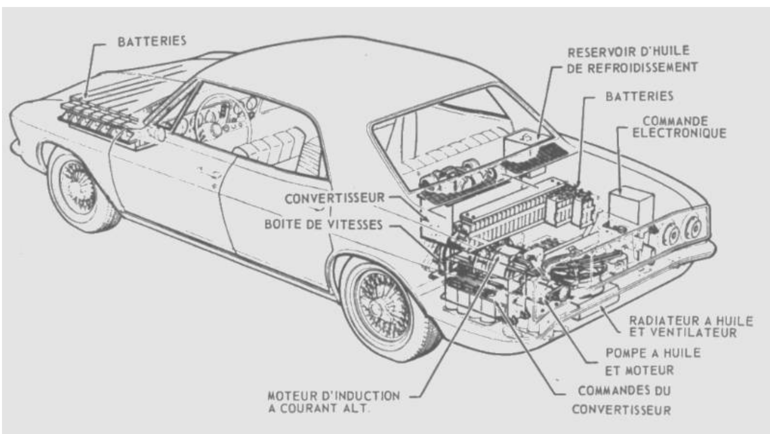


Figure 1966 GM Electrovair prototype electric vehicle (source: www.kartelec.com)

The GM Electrovair featured a 115hp AC induction motor, with a 308kg, 512V Silver-Zinc battery pack giving a top speed of 80 mph and a range of 40-80miles. The vehicle was a converted petrol powered car with a Chevy Corvair body.

Also in the 1960s, a "great electric car race" was introduced. This was a 3300mile race between participants from Caltech and MIT University. The race generated great publicity for the electric car, however the vehicles produced in the 1960s by GM were not production ready vehicles (Hussain, 2003).

The electric vehicle continued its resurgence in the 1970s with the 1973 Arab Oil embargo. Electric and hybrid vehicles became more desirable as countries wanted to become less dependent on foreign fuel. In 1975, 352 electric vans were distributed to the American postal service for testing, and in 1976, the US congress put through the Electric and Hybrid Vehicle Research Development and Demonstration Act of 1976. The Act authorized a federal program to demonstrate and promote electric and hybrid vehicle technology to the public. The American Department of Energy then issued a standardised EV performance criteria, as seen in Table 4 (Hussain, 2003). The success of the early trials with the postal service propelled them to purchase a further 750 vehicles.

EV Performance Standardization of 1976

Category	**Personal Performance**
Acceleration (0-50km/h)	<15s
Forward speed for 5 min	80km/h
Range	
Electric	50km
Hybrid	200km
Recharge time from 80% discharge	<10hr

Table 4 EV Performance Standardisation 1976 (Hussain, 2003)

By the 1980s, many governments had become increasingly keen on the environmental benefits of electric vehicles, with substantial government funding for electric vehicle programs. As a direct result from this funding, the Ford ETX-1 was developed, featuring a 70hp AC motor. The developments made by Ford through the projects in the 1980s-1990s led to the implementation of new high-power microprocessors, semiconductors, and transistors (Heitner, 2001).

In France in 1988, 500 electric vehicles were being tested in the industry, the majority being converted Peugeot 205's and Citroen C15 van conversions. Similarly, in Germany, GES had developed a VW golf conversion named the City Stormer. The City Stormer was designed to meet all of the European electric vehicle standards, and featured regenerative braking which improved the range by 5% to 90km. Simultaneously in Italy, Fiat developed the electric Fiat Panda. Meanwhile, in Japan, the DC drive systems used in Europe had been replaced by the beginnings of AC drive units, and nickel metal hydride batteries were being used along with the more conventional lead acid batteries (Westbrook, 2005).

The 1990s

Ford developed an electric utility van in the early 1990s. Although only 100 were produced and they were only used for research and development, they had an impressive range of 128-161km and could reach 120kph. Ford also introduced some of the first gasoline driving dynamics to an electric vehicle with a built in electronic creep to simulate how a gasoline vehicle creeps while in gear (Anderson & Anderson, 2005).

In the early 1990s, California created a mandate which stated that, by 1998 2% of a car company's production must come from zero emission vehicles (ZEV's) and by 2010 that amount must be increased to 10%. To comply, most car companies converted one of their petrol power vehicles, or created an electric van or cart for commercial use (Anderson & Anderson, 2005).

EV1

From the late 1980s, GM began the development of a purpose built electric vehicle called the EV1. It was designed by AeroVironment, a Californian company best known for their design of the 1987 World Solar Challenge wining solar car, Sunraycer. The company produced the GM Impact prototype shown at the LA show in 1990.

660 1st generation EV1's were produced for 1997 (Dowling, 1999). These vehicles were never sold to the public, and the 660 were only leased out to high profile celebrities, and other important people. In 1998, GM released 200 of the 2nd generation vehicle (nicknamed EV2) which featured a nickel metal hydride battery pack (Dowling, 1999). In 2000, after a total of almost 1200 vehicles being produced and leased, the EV1 plant was closed. In March 2000, all of the 1st generation EV1's were recalled due to a fault, and 200 were eventually re-released with a mileage limitation. The other leases were offered either a termination of their contract or a 2nd generation EV1 ahead of the huge waiting lists. In late 2003, the EV1 project was terminated by GM with large waiting lists for the 2nd generation remaining. Even with very positive feedback from the leases GM cancelled the project on the grounds of not being financially viable although this is debated in the electric vehicle industry ("General Motors EV1", 2007).

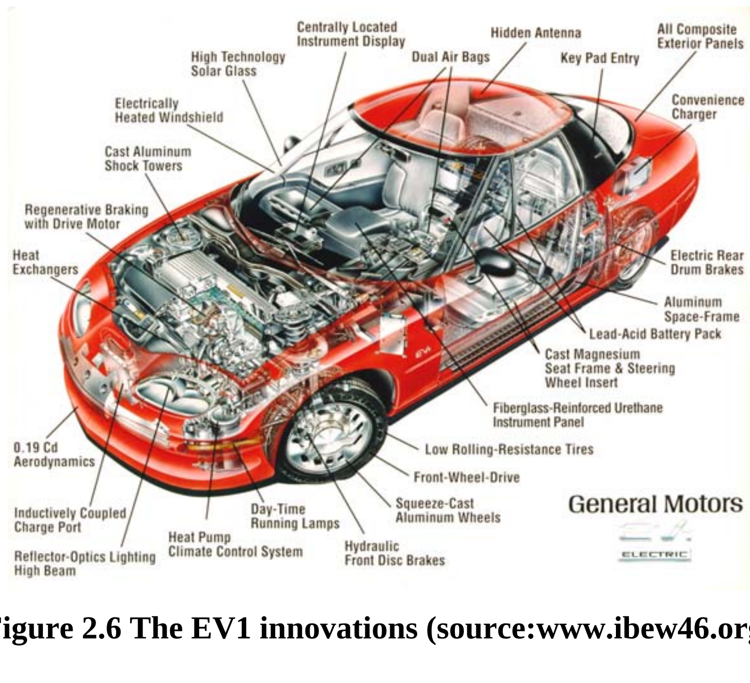


Figure 2.6 The EV1 innovations (source:www.ibew46.org)

The EV1 was a two seater vehicle designed for commuting and urban travel. It featured more automotive features than other petrol vehicles of the time including dual air bags, CD player, anti lock brakes, cruise control, as well as a special selection of chimes, as it was so quiet that pedestrians needed to be warned of its presence. However, it was underneath the vehicles outer shell that demonstrated the major engineering developments ("General Motors EV1", 2007).

The EV1 featured an aluminium chassis, made of aluminium extrusions bonded together with adhesives. The chassis was the stiffest chassis GM had ever constructed, being 20% stiffer than a Mercedes E-class which is well known as a rigid vehicle ("We drive the world's best electric car", 1994). The car also demonstrated improved aerodynamics, featuring a C_D of just 0.19 (Anderson & Anderson, 2005), reducing drag and improving the vehicles efficiency. The liquid cooled controller, the AC motor, and the vehicle, was a technological advancement to a level not seen in the electric car industry for 50 years ("We drive the world's best electric car", 1994).

The 21st century vehicles

Future Vehicles

Although the EV1 failed in the 1990s, several electric vehicles survived, and there are now more than 25 electric vehicle companies throughout the world producing electric vehicles and completing conversions on cars (Voelcker, 2006).

Vehicle	Manufacturing date	Description
Aptera Typ1	Projected late 2008	Lightweight electric vehicle 200km range
Reva/G-Wiz	2001 -	Small 2 person commuter vehicle 70kph top speed.
Zap Zebra	2006-	Small 2 person electric commuter
Zap-X	Projected 2010	2 person Electric sports car
GM Volt	Projected 2010	2 door sports EV
Nissan Mixim	Projected 2015	Lightweight EV
Fisker Karma	Projected 2010	Luxury plug in hybrid
Electric Smart car	2008-	Small 2 person Hybrid
Myers NMg ex Corbin Sparrow	1999-2003 2007-	3 wheeled Commuter vehicle
Tesla Motors	2008-	Sports/Performance EV
Miles XS500	Mid 2008	Highway rated sedan, 1st ever Li-ion vehicle
Miles X40	2007-	Around town commuter
Lightning cars	Projected late 2008	British luxury electric vehicle
NICE mega city	2007-	Commuter EV specifically designed for London
Visionary Vehicles EVx	Late 2010	Luxury plug in hybrid
Venturi Fetish	25 made	Luxury EV made for a select few
Hybrid technologies	Offer a range of electric conversions including; Toyota Corolla, Mini Cooper	

Table 5 Current electric vehicles (see Appendix 3)

Corbin Sparrow/Myers NmG

Corbin Motors, a Californian based electric car company, was founded in 1999. The company produced the Corbin Sparrow, a three wheeled one person electric vehicle (Anderson & Anderson, 2005). The Sparrow has a range of 64-100 km and can run at up to 160kph. Only 300 Sparrows were made, with many orders never filled. The planned successors of the Sparrow, the Merlin and the Roadster, never made it to production, and the company filed for bankruptcy in 2003 (Payne, 2007). The remains of Corbin Motors was brought by Dana Myers, and the new company, Myers Motors, improved the vehicle and renamed it the Nmg, an acronym standing for ‘no more gas’. The Nmg now features 50km range at a cost of two cents per mile (Schoenberger, 2007).

Reva/G-wiz

The Reva, more commonly known in the UK as the G-wiz, is currently the only mass produced electric vehicle. Although sold as a commuter car, the G-wiz is actually classed as a quadracycle due to its low weight, and therefore does not need to meet some government safety regulations ("Population of New Zealand", 2008).

The Tesla Roadster

The Tesla Roadster is a high performance electric vehicle. It is powered by a 240hp electric motor capable of sending the Tesla from 0-100kph in 4s. It has a top speed of 210kph and a range of over 300km. With sports car looks and performance, the Tesla is attempting to enter a different market. The Tesla Roadster is trying to convince the public to change their environmentally unfriendly car buying habits by producing an attractive, high performance electric car (Eisenstein, 2006). With high profile celebrities willing to pay the retail price of US$100,000 years before delivery, the Tesla organisation has made strong inroads in terms of business. This business acumen, alongside impressive performance demonstrations, for example the out-acceleration of electric Ferraris and Porsches, has the Tesla Roadster positioned for success (Voelcker, 2006).

The key innovation in the Tesla Roadster is the battery pack. 6,831 lithium ion cells make up the car’s battery pack; they have enough storage to drive the car up to 400km (Gawel, 2006; Wells, 2007). The lithium batteries also have a long lifetime, being able to survive 160,000km worth of charging. The battery pack is liquid cooled, and incorporates a sensor array to monitor temperature and battery performance, and a microcontroller to insure the pack remains at a high efficiency (Gawel, 2006).

Figure 2.7 The Tesla Roadster (source:www.sweetauto.net)

GM Volt

General Motors, not satisfied with their first effort of the EV1, is one of the large car manufacturers heavily researching electric vehicles with the GM Volt. The Volt is a series hybrid, where a one litre engine runs as a generator to charge the lithium ion battery pack. This gives the driver the flexibility to either drive only on electric and charge at a power outlet, or to use the generator engine to keep the car going up to 1030km on the 45L petrol tank (Eisenstein, 2007). The Volt is based on GM's E-flex chassis system where different power methods can be applied to the same vehicle. Whether it uses battery electric, hydrogen fuel cell, or bio-ethanol, the Volt will be able to cater to every market's needs. The Volt is currently under development with prototypes being produced and tested, and will begin production in 2010-2012. The current issue is the 16kWh Li-ion battery pack, with delays in production continuing to put off the vehicles release (Gawel, 2007).

Nissan Mixim

Nissan has shown a prototype electric vehicle at motor shows, and has begun a Hybrid and Electric Research Project (Eisenstein, 2007). The Nissan Mixim is a battery electric vehicle planned to weigh 950kg. The Mixim is planned to be in production between 2010 and 2015 ("Nissan expects to build electric vehicle by 2015", 2007).

Fisker Roadster

Fisker Automotive has set out to capture a different market, the luxury car market. Henrick Fisker, the founder of Fisker Automotive, is well known for designing Aston Martin’s DB9 and V8 Vantage, as well as BMW’s Z8 roadster. Fisker’s vehicle is designed to model a Manhattan apartment, and features a fully functional interior in leather, with buttons and controls flush on the dashboard (Durbin, 2008).

Although many electric vehicles have been rumoured or produced in small runs (see Table 5), no electric vehicle has yet truly broken into the mainstream automotive market.

2.3 Lightweight vehicle design

With public pressure building for car manufacturers to improve the efficiency of their vehicles, mass reduction has become a key concern. Every 100kg taken from a vehicle's weight improves CO_2 emissions by roughly 9g/km (Bickerstaffe, 2007b). Over the past 20 years, lightweight vehicle design has meant a reduction from 1588kg to 1134kg for a small vehicle. However, the small weight savings that can still be made while still using regular materials and conservative design concepts is becoming non-existent (Field & Clark, 1997).

In 1997, Ford demonstrated the p2000, a lightweight vehicle with the cabin size and safety of a Ford Taurus, yet weighing 40% less at just 200 pounds (Ashley, 1997). In 2002, Jaguar produced an aluminium alloy XJ coupe, saving 40% mass in the ‘body in white’ (Bickerstaffe, 2006). Most recently at the 2008 Detroit Motor Show, Honda, Toyota, GM, Ford and Jeep all showed lightweight vehicles under 1000kg.

New Materials

Vehicle design is becoming more complex, and the lighter the vehicle design, generally the more complex the structures and components are which make up the concept. Because of this, the use of modern materials is often required to overcome the new strains put on the vehicle components (Happian-Smith, 2001).

Plastic continues to be used more and more in automotive engineering. Thermoset composites have been used extensively since the early 21st century, contributing to a 35% reduction in weight of components inside the vehicle, while also reducing cost by 50% compared to using steel (Blanco, 2004).

Warwick University's manufacturing group in Coventry are known for their work with Lotus and McLaren, but are currently looking into the design of lightweight prototype vehicles that have a chance of mainstream manufacturing. Although lightweight prototypes have been constructed in the past, they have never undergone the research and development required to be produced for a mainstream market. Warwick are currently working on the Salvo project, an industry backed project to develop a structurally advanced lightweight vehicle. They are examining the potential of many advanced manufacturing techniques including new construction techniques, advanced materials, and supporting technologies, such as aluminium extrusion processing, hybrid structures, and thermoplastic and thermoset composites ("Concept gets a new spin", 1998).

New Designs

Not only are vehicles using more composite materials, they are now using composite structures. Significant weight savings can be achieved through the replacement of a steel chassis with an aluminium chassis as aluminium has one third the density of steel. Cast aluminium components as used in the Ford GT, are required to meet the minimum Ultimate Tensile Strength of 180MPa and 5% elongation (Ramsden, 2006). Manufacturers are investigating the use of aluminium for structural components and a small number have started production. Current vehicle manufacturers and cars with aluminium chassis include the Audi range (A2, A4, A8, TT and R8), the Jaguar XJ, the Ford GT, the Chevrolet Corvette, and the Lotus Elise. Due to aluminium's different mechanical properties, to replace a steel chassis with aluminium requires a complete redesign of the chassis. Different forming processes are able to be used with aluminium in comparison to steel. Extrusions, sheet, and castings are generally used, as well as some forged components. The Audi R8’s ASF uses 70% extrusions, 22% panels, and 8% vacuum die cast ("Audi R8: the design", 2007).

2.4 Light weight alloys and the automotive industry

Iron based metals have been most commonly used in automotive engineering because of their cheap and abundant supply, with aluminium and other light weight alloys only used in certain applications (Happian-Smith, 2001).

As previously mentioned, the all aluminium Jaguar XJ coupe demonstrated the potential for aluminium alloys in the automotive industry. They are also not the only prototype vehicle which has demonstrated this potential. In 1997, the Ford p2000 featured 700pounds of aluminium which equated to 35% of the vehicles total mass. It also had 85 pounds of magnesium parts as well as several titanium components (Ashley, 1997)

2.5 Fundamental vehicle mechanics

The design of any vehicle must follow the law of physics. To better understand the intricacies of vehicle design, one must first understand the physics behind it.

Following Newton’s second law, the forward motion of a vehicle can be expressed as;

$$F_T = F_D + F_{RR} + F_a + F_g$$

As shown in Figure 2.8.

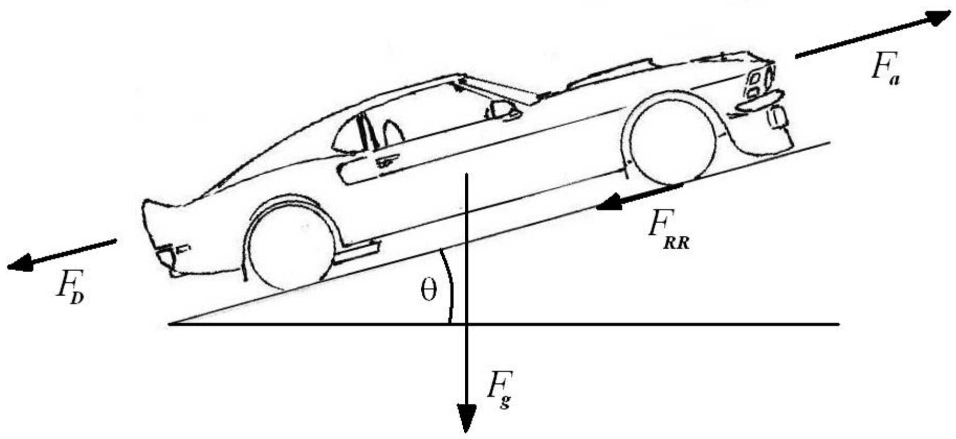


Figure 2.8 Equation of motion

Where:

F_D = The drag force due to air resistance (aerodynamic drag)

F_{RR} = The force due to th rolling resistance of the tyres on the road

F_a = The force due to acceleration

F_g = The force due to gravity

The aerodynamic drag can be further defined as (Hucho, 1998);

$$F_D = \frac{\rho v^2 C_D A}{2}$$

The rolling resistance of a vehicle can be defined as;

$$F_{RR} = mRR$$

The force due to acceleration by Newton's second law is;

$$F_a = ma$$

The force due to gravity can be given by;

$$F_g = mg \sin \theta$$

Giving our equation:

$$F_T = \frac{\rho v^2 C_D A}{2} + mRR + ma + mgsin\theta$$

Where:

$\rho =$ density of air

$v =$ velocity of car

$C_D =$ drag co - efficent

$A =$ frontal area of vehicle

$RR =$ rolling resistacne

$a =$ acceleration of the vehicle

$m =$ mass of vehicle

$g =$ gravity

$\theta =$ incline angle

By definition the power required to drive a vehicle at speed v is given by;

$$P = F_T \times v$$

$$P = \left(\frac{\rho v^2 C_D A}{2} + mRR + ma + mgsin\theta \right) \times v$$

Vehicle performance breakdown

To better understand the factors that effect vehicle performance, a review of current vehicle performance is required.

Factor	Honda Civic Highway driving		Honda Civic Uphill highway		Honda Civic Constant acceleration	
C_D	0.36		0.36		0.36	
A	1.82m^2		1.82m^2		1.82m^2	
m (curb+150kg)	1262kg		1262kg		1262kg	
RR	0.012		0.012		0.012	
a	0		0		10 kph/s constant acc	
Theta	0		10		0	
F_D	304 N	95.3%	304	12.3%	304 N	7.93% ***
F_a	0	0	0	0	3508	91.66%
F_g	0	0	2150	87.0%	0	0
F_{RR}	15 N	4.75%	15	0.61%	15 N	0.40%
F_T	319 N		2469 N		3827 N	

*** The drag force will not be constant whilst accelerating but for ease of demonstration at even 100kph the drag force is a fraction of the acceleration force.

Table 6 Car performance figures (see Appendix 4)

From Table 6 it is clear to see that whilst driving at constant speed on a flat slope the largest factor affecting the vehicles performance is aerodynamic drag, consuming 95.3% of the total energy required to power the vehicle.

When a vehicle is travelling up a hill, gravity effects the vehicle, thus the mass of the vehicle has a direct correlation with the amount of energy the vehicle will consume whilst travelling up a hill. Mass also is the largest contributing factor when a vehicle is accelerating. The force of acceleration is 91.66% of consumption even with a very high drag force. When accelerating from 0-50km/h, the drag force is much lower and the acceleration force is almost 100% of the force required to move the vehicle.

2.6 Proposition

As highlighted from the research, the key design elements of a lightweight electric vehicle include an integrated design solution, lightweight design, and the use of virtual engineering techniques.

Integrated lightweight design

The history of the electric vehicle shows a trend towards complete design solutions being more successful than vehicle conversions based on gasoline powered vehicles.

Complete Solutions	Converted Vehicles
EV1	1960's GM Electrovair*
Myers Sparrow	1988 Peugeot 205*
Tesla Roadster	1988 Citroen C15*
	1988 VW Golf*

* = never produced

Table 7 Design solution table

The conversion of petrol powered vehicles was never successful due to the large energy density gap between batteries and gasoline. ICEV's did not need to be efficient with the highly available energy source. Electric vehicles require the best design possible to minimise the amount of energy required to power the vehicle. One of the key benefits of an integrated design is a lighter overall vehicle, with efficiency as the primary focus. The lighter the vehicle, the less energy it will require to drive, and therefore the less greenhouse emissions the car will emit over its lifetime.

Prospects for Battery Electric Vehicles

History points towards performance as one of the determining factors towards the failure of the electric vehicle, but greater than performance are the economic reasons. With the cheap supply of a high energy dense fuel, and no consideration for its effects on the environment, there was no need for electric vehicles. However, as petrol prices continue to rise, advances in battery technology continue to reduce the cost of high performance batteries, and government subsidies and benefits are factored in, electric vehicles become a more viable and cost effective solution for both consumers and manufacturers.

Consumers have the additional benefit that, because manufacturing materials and techniques are at a new level, electric vehicles are being produced which are able to compete with gasoline powered vehicles in terms of performance and comfort.

The Ultracommuter

The University of Waikato and *Hybrid*Auto have designed and built a prototype electric vehicle. The car is based on a simple design concept incorporating five factors; producing a complete design solution, a lightweight vehicle design, using advanced manufacturing techniques, being energy efficient, and using modern materials.

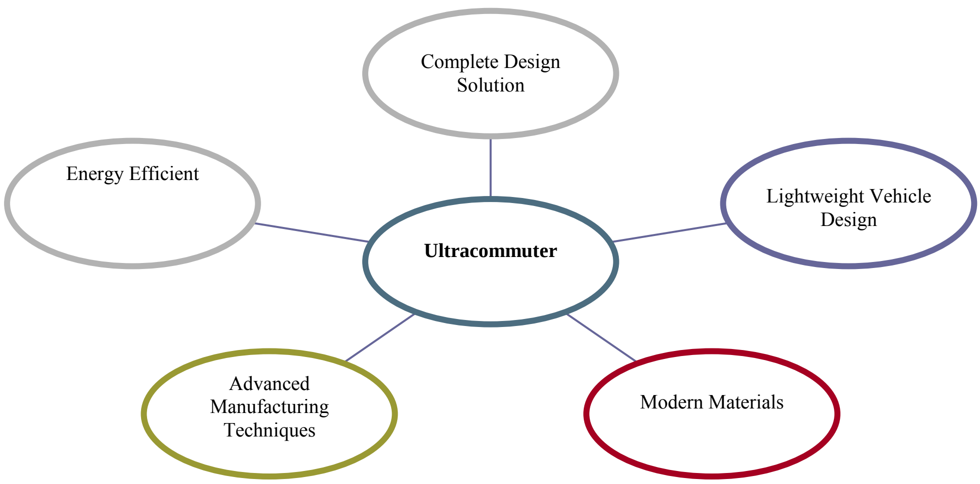


Figure 2.9 Ultracommuter design concept

Chapter 3 Electric vehicle design methodologies

The design of an electric vehicle needs to incorporate many factors. This chapter looks into the components and systems that make up a battery electric vehicle. It then investigates the use of modern engineering tools such as virtual engineering and looks at how these are incorporated in a battery electric vehicle design.

3.1 Battery electric vehicle components and Systems

The structure and design of an electric vehicle begins with four main design areas. As shown in Figure 3.1 the chassis, the mechanical components, the electronics, and the body shell make up a battery electric vehicle's design.

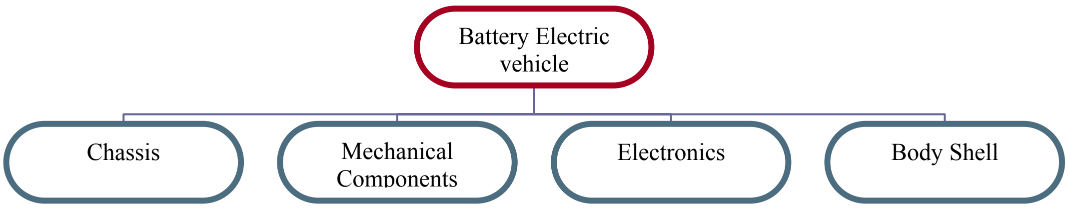
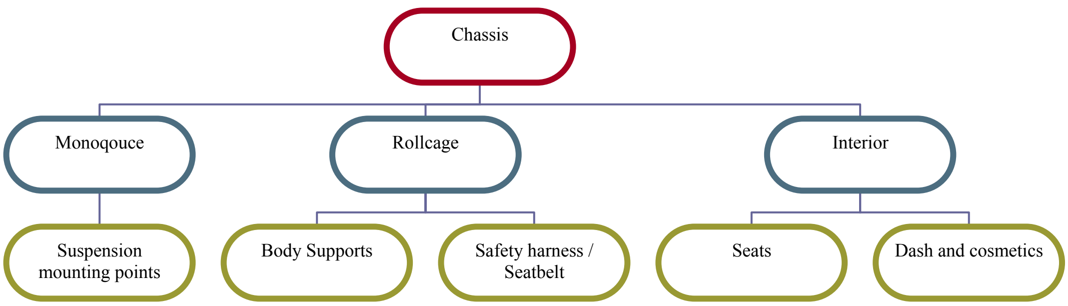


Figure 3.1 Main design areas of a battery electric vehicle.

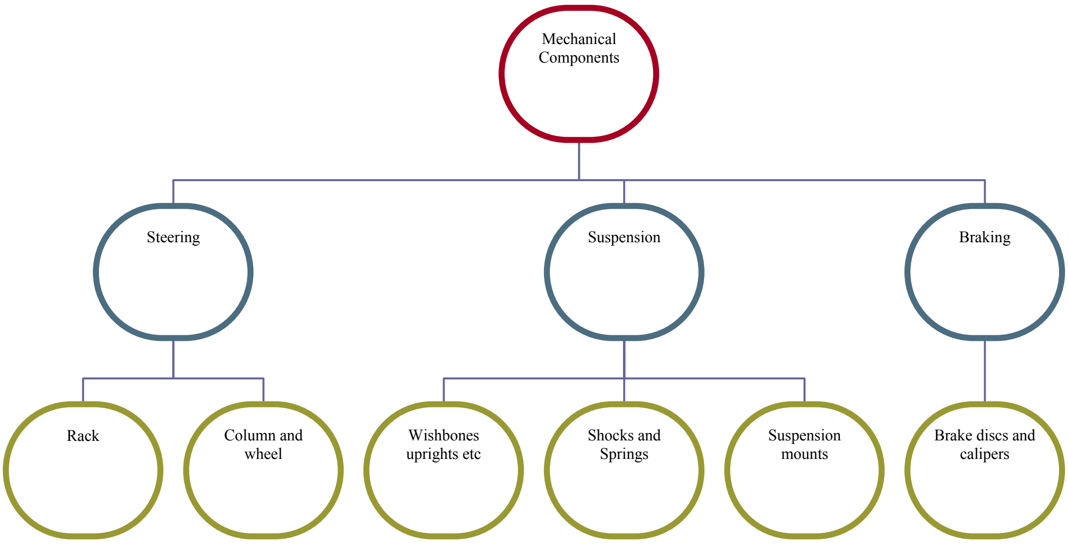
Under each subgroup are various components and systems that allow a battery electric vehicle to run. Each of these components and systems may belong to one of the major areas but all components and systems in a battery electric vehicle are designed to be integrated, and many components rely on the design of others.

Chassis



The chassis is the backbone of the vehicle. The chassis sub-system includes the monocoque or main structure, which incorporates suspension mounting points, exterior body mounts, and steering geometry. The rollcage is the second element of a chassis. A rollcage is designed into vehicles for roll over protection; a rollcage also incorporates body mounting points, and safety and seat mounting points. The interior is also classified as the chassis. The interior of a vehicle is important in both design and function with ergonomics and performance critical factors, as well as aesthetics and environmental factors.

Mechanical Components



The mechanical components in a battery electric vehicle mainly consist of the rolling stock. The suspension, steering and braking are the main subgroups of the mechanical components.

Electronics

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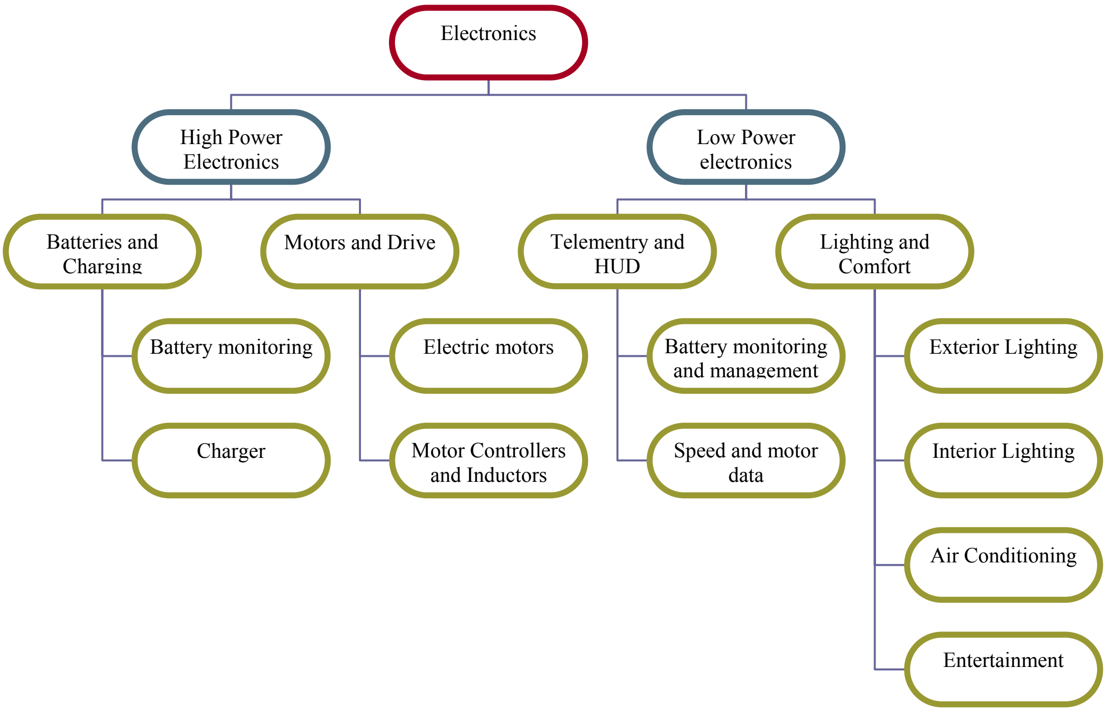
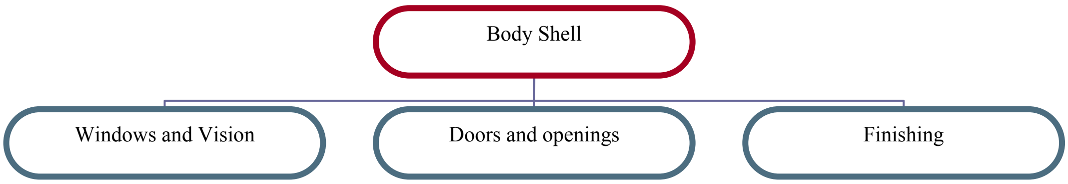


The electronic components in an electric vehicle are the newest technology in the vehicle. The high power electronics of batteries, motor controllers, and motors are all integrated with a low power system including telemetry, lighting, and entertainment.

Body Shell



Although the body shell is the largest part of an electric vehicle, it has the least number of components. The body shell consists of any part of the vehicle that is in contact with the outside elements, including the main body, doors, boot, bonnets, fuel caps, windows, and number plates.

Interaction

As previously mentioned, many of the components and systems on an electric vehicle interact and/or are dependent of each other. This creates design challenges as all components must be integrated into the design.

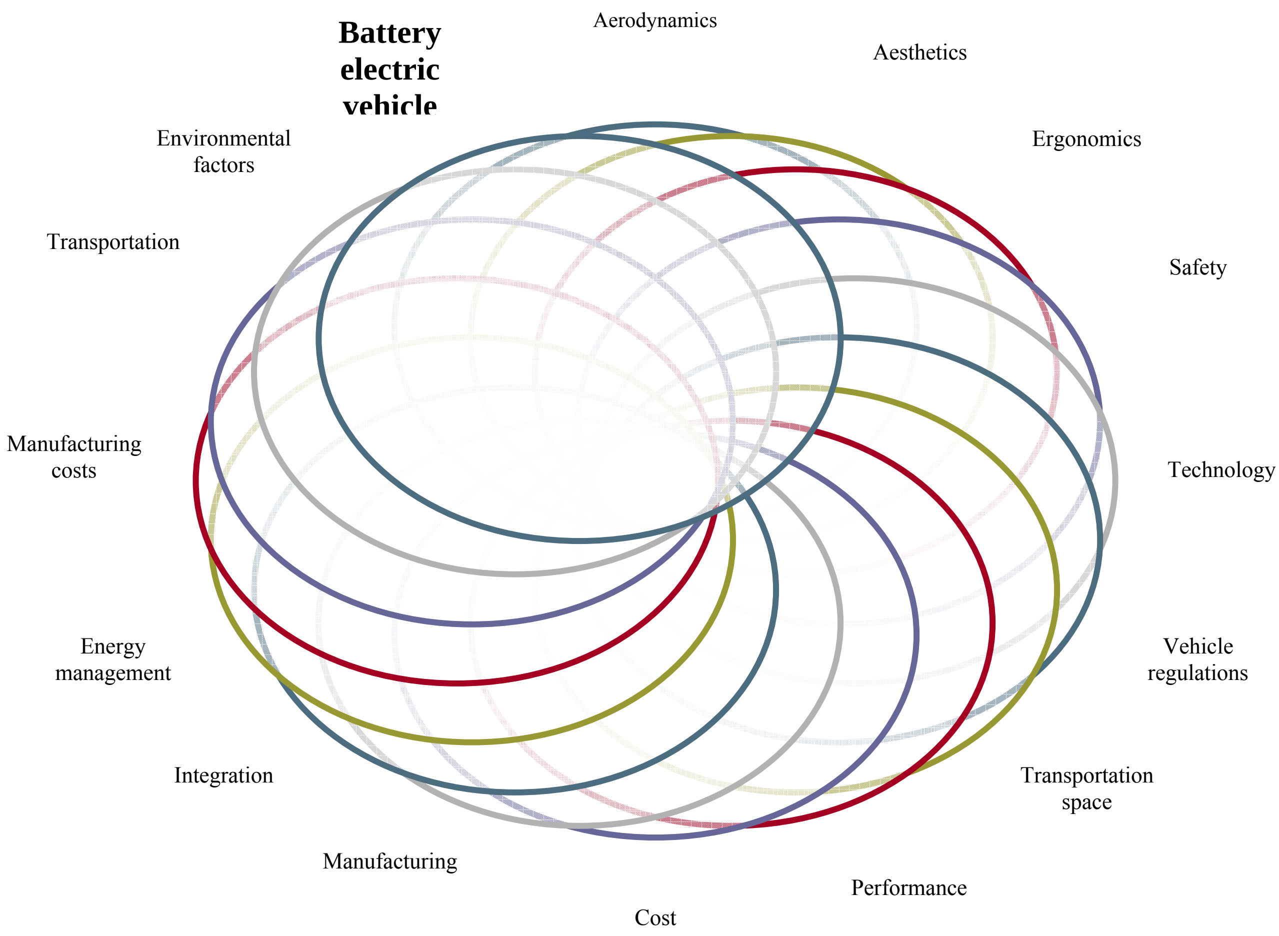


Figure 3.2 Diagram outling some of the factors involved with electric vehicle design

Figure 3.2 shows all of the factors that need to be considered when designing a lightweight battery electric vehicle.

3.2 Advanced product development

An ideal battery electric vehicle design requires development by a wide range of engineers including electrical, electronic, mechanical, materials, chemical, and automotive engineers.

3.2.1 Virtual engineering

“Computer Aided Engineering” (CAE) refers to the use of computers in the engineering process. CAE systems are used by engineers throughout the new product development process to design, depict, analyse, and manufacture, as well as inspect components, assemblies, tools and fixtures. CAE has become a fundamental part of engineering due to the development of technology. Today, computers are able to compute large amounts of data quickly. The software that engineers use has also become more intuitive and easy to use, as well as increasing accuracy and usefulness. Finally, new manufacturing techniques have been developed and can be integrated into the design process.

The automotive industry follows the same trends as most other engineering disciplines. The globalisation of markets, increasing complexity of vehicles, and the push towards shorter product development and lifecycles, means that there is a requirement for engineers and designers to implement the use of all available modern tools to be able to successfully compete in the market place (Crabb, 1998).

Ford began using solid modelling and finite element analysis in the 1980s (Crabb, 1998) Holden used math-based process SMBP computer technology to design their Holden Monaro in only 22 months for just $60 million (Newton, 2001).

Nissan used a software system called ICEM surf suite, which has the sole purpose of managing innovation and aiding in collaboration and knowledge sharing inside the company. The software helped Nissan to reduce its design and production time on the cars surface bodies and interior by 30% ("Team 05: Timely solutions", 2005).

The use of CAE, or virtual engineering, was evident throughout the design of the Ultracommuter. A complete model was designed in SolidWorks, and all components were integrated into the CAD model before production began. Figure 3.3 shows the complete SolidWorks model of the Ultracommuter.

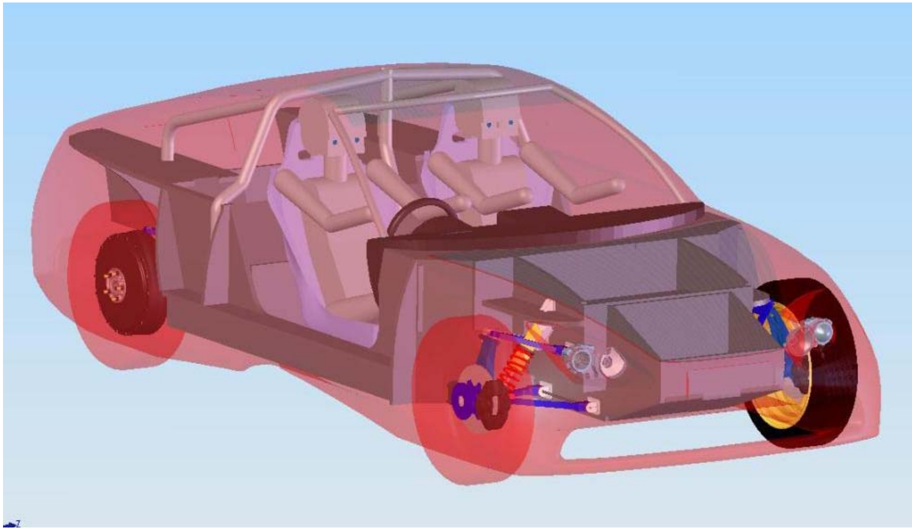


Figure 3.3 Complete Ultracommuter CAD model

Figure 3.4 shows the design evolution of a component with the use of CAE. The original suspension mount made from steel was designed using SolidWorks, and tested both virtually and with lab testing. After it was found to meet requirements, the design was then developed and made from aluminium. This meant that a 6kg weight saving was made on the vehicle mounts.

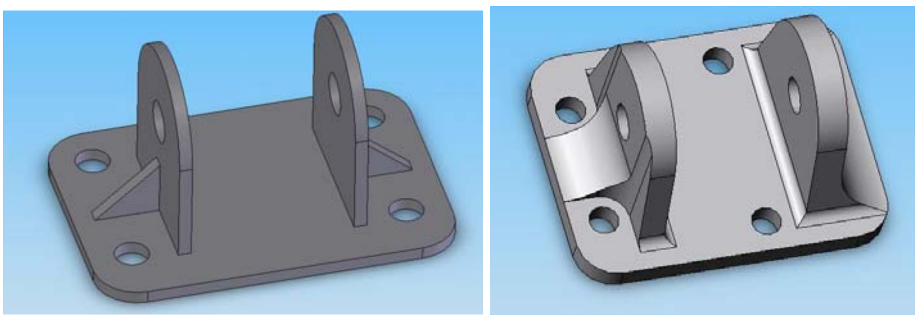


Figure 3.4 Design Evolution

3.3 Ultracommuter design specification

The Ultracommuter project had two main objectives

- To compete at the 2007 World Solar challenge
- To be a working prototype electric vehicle.

Because of these two factors, the Ultracommuter had a unique design specification. It was not designed purely for a commercial or prototype view point and some compromises were made to allow the vehicle to compete in the World Solar Challenge.

1. **Performance**

    1.1. The vehicle must be able to do 110 km/h.

    1.2. The Ultracommuter is to have 500km range per day.

    1.3. The car must reach performance and safety requirements of the low volume vehicle transport authority (LVVTA).

    1.4. The car must handle well and corner easily. It must perform all normal driving manoeuvres (U-turn, reversing etc).

    1.5. The car must use approximately ¼ the energy required by a combustion engine powered car.

2. **Environment**

    The Ultracommuter will be used outdoors in a wide range of weather conditions so the construction of the car must withstand outside temperatures ranging -10°C to 50°C, and must also be waterproof and wind resistant.

3. **Life in Service**

    The Ultracommuter must be designed as though it was to live a full vehicles life span (15-20 years).

4. **Maintenance**

Maintenance on the Ultracommuter should consist of no more than a gasoline powered car.

Maintaining the batteries and electrical system will be the major maintenance completed on the car.

Maintenance shall be easy to complete and must be designed so that a mechanic and auto electrician are able to complete it.

5. **Target Product Cost**

Manufacturing cost must be no greater than $45,000 NZD

6. **Quantity**

The project will consist of building one car.

Considerations when designing the car must be made for small scale manufacture.

7. **Size**

The car's size largely depends on design, but the car must fit the legal requirements of the LVVTA.

8. **Weight**

The goal weight of the vehicle is 600kg including driver, passenger and batteries.

9. **Aesthetic, Appearance and Finish**

The vehicle must look modern and be appealing to modern markets.

10. **Materials**

The Ultracommuter will be built from as many natural products as possible, with an emphasis on lightweight advanced materials that meet the performance requirements.

11. **Ergonomics**

The car must be designed so that everyone from the 5% Female to the 95% Male can operate the vehicle.

12. **Time Scale**

The timescale of the Ultracommuter project is from January 2007 to November 2007.

The car must be completed for shipping to the World Solar Challenge by the 21st of September 2007. (A total of eight and a half months from start date).

13. **Testing**

Components and the design of the car will be tested using several methods.

The cars design will undergo FEA and CFD testing.

Where possible, components, or materials of the components will undergo standard tests (tensile etc).

Road testing will be completed on the car prior to the completion.

14. **Safety**

Both the cars operators and observers must be under no danger while the car is stationary or driving.

The car must meet the LVVTA Safety requirements.

From the design concepts and this design specification, the Ultracommuter was designed and built with the ultimate goal of driving in the World Solar Challenge in 9 months.

Chapter 4 Electric vehicle integrated design

This chapter takes a detailed look into the design of a battery electric vehicle, and discusses the design and construction of the Ultracommuter electric vehicle.

4.1 Chassis

The chassis' roll in vehicle design is to act as the backbone of the vehicles structure. The chassis is the base for all of the other vehicle components to be integrated into the vehicle. There are three main types of chassis, ladder frame, space frame, and monocoque.

Ladder frame

Due to its simplicity, versatility, durability, and low development costs, the first chassis design was the ladder frame. The ladder frame was used in vehicles until the 1960s and is still used for Sport Utility Vehicle's (SUV's) and trucks. The ladder frame chassis is weak in torsion, and has a high centre of mass. The ladder chassis is not applicable for electric vehicle because it is heavy, and there is no integrated crumple zone for safety (Wan, 1998).

Space frame

A space frame chassis uses various tubes positioned in different directions to provide strength against forces from suspension and other components. The tubes are welded together and form a complex structure. High performance sports cars require a chassis of higher strength and stiffness, which a tubular space frame chassis can provide. As a consequence of the high strength structure, door sills are higher and occupants have more difficultly accessing the cabin. Space frame chassis' are very strong, and have a lower weight than ladder chassis', but are very time consuming to build (Wan, 1998).

Monocoque

Modern vehicle design uses monocoque chassis'; 99% of cars produced are made with a steel monocoque chassis. A monocoque chassis is a one-piece structure that helps to define the overall shape of the vehicle. While ladder frame, space frame, and backbone chassis' provide members for loading and require the body to be built around them, a monocoque chassis is already incorporated with the body in a single piece. A typical monocoque chassis is made by welding several pieces of steel together. The advantages of a monocoque chassis include good crash performance as well as efficient use of space. Aluminium monocoque chassis' were used by Audi with the A8 and A2 in an attempt to reduce the mass of the chassis. The ULSBA ultra lightweight steel body automobile chassis was a notable style of the monocoque chassis with Porsche initiating research into the use of composite structures to replace the heavy steel filled chassis of the past. Monoquoce chassis' manufactured from composite materials such as fibreglass and carbon fibre are becoming more popular; because of their low weight, they have been used in racing cars since the 1980's (Wan, 1998).

4.1.1 New chassis materials

New materials are being used for car bodies and chassis' to allow engineers to reduce the mass of vehicles. In America, the three largest car companies, Chrysler, Ford, and General Motors have invested in research into fibreglass and other composite chassis'. Well designed composite chassis are as strong as typical steel chassis', as demonstrated through successful crash testing in the mid 1990s (Ashley, 1996).

Aluminium honeycomb has been used in automotive design for many years; the Ford GT40 race car was built using aluminium honeycomb composites (Koganti, 2005). Honeycombs have excellent energy absorbing properties (McBeath, 2000). This is demonstrated by the use of 50mm thick Ayrlite® panels in the Australian V8 Supercars™ (Composites, 2007). Ayrlite® is used inside door panels to protect drivers from side impacts, offering a lightweight safety solution.

4.1.2 Electric vehicle chassis design

The design of a chassis must take into account the integration of all of the components of a vehicle. Not only does the chassis design need to incorporate these components so that they physically fit, but also distribute the loading in terms of weight throughout the vehicle. Because of this, a monocoque chassis is a good option for electric vehicles. With importance placed on weight reduction, weight can be saved from incorporating the floor and dash into the chassis. Monocoque chassis' also offer maximum storage for batteries and other electronic components. As mentioned earlier, ladder chassis are not applicable due to the heavy weight, and although space frame chassis offer good strength, the flexibility of a monocoque chassis makes it the best choice for electric vehicles.

4.1.3 The Ultracommuter chassis

The Ultracommuter chassis is an aluminium honeycomb monoquoce chassis. It was designed using the latest advanced engineering techniques, and incorporates the integration of all of the vehicles major components in a simple design.

Material selection

Aluminium honeycomb was selected due to its high strength and stiffness relative to its low weight. Whilst trying to keep the mass of the vehicle to a minimum it was critical to keep the strength of the structure similar to a typical steel framed chassis for safety. The aluminium honeycomb used Ayrlite 2022 which was supplied in a 2400 by 1200mm sheet, 20mm thick. The honeycomb weighs 11.3kg per sheet and can support 2.6MPa on its face (*AYRLITE 2022 Data Sheet*, 2007).

Design

The design of the chassis had two main objectives. The first was to integrate the following main components;

- Existing body shell design
- Existing suspension system
- 45 Thundersky Li-ion batteries

- Motor controllers
- Two seats

Secondly, the chassis needed to meet the criteria for the New Zealand low volume vehicle certification.

The strength in the chassis arises from the structure, not the material itself. Using an interlocking panel technique, the chassis is designed to be constructed like a 3D jigsaw. Finger and butt joints interlocked creating the strong, stiff structure shown in Figure 4.1.

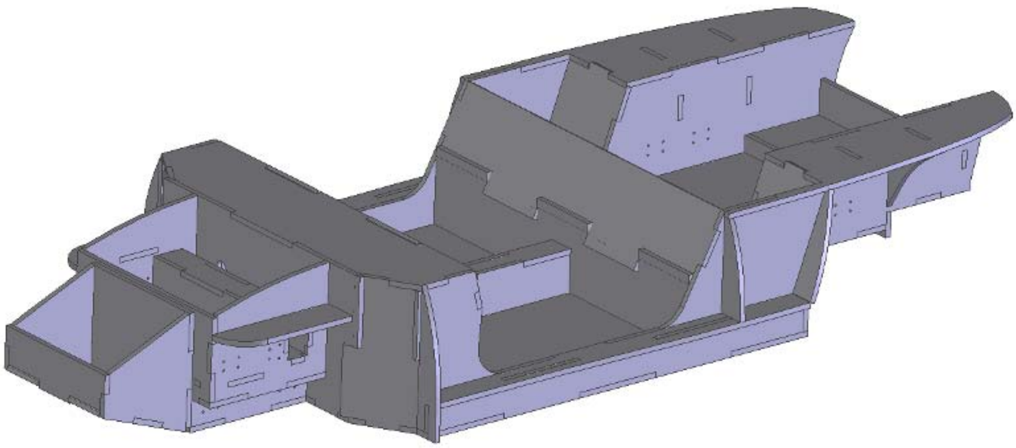


Figure 4.1 Ultracommuter Chassis design

The chassis is zoned in five parts; the front crumple zone, front box, passenger compartment, battery compartment, and rear box.

The front crumple zone is designed to absorb energy from a frontal impact. Section 5.5, of the LVVTA requirements states that all vehicles must include this feature from a safety standpoint (Johnson, 2007).

The front box has two 118mm x 80mm beams running longitudinally through the chassis to stiffen in the event of a front impact, and to support the suspension attachment points.

The passenger compartment has two 140mm x 80mm beams running down the outside of the compartment, as well as a centre console beam to give added strength in the longitudinal direction. The passenger compartment also features a dash, to protect the driver and to help minimize weight by allowing a superficial dash to be attached rather than a structural member. The passenger compartment also has back supports, ensuring that passengers are kept out of the battery compartment in the event of a crash.

The battery compartment stores 45 li-ion batteries, and is designed to allow the easy removal and replacement of strings of five batteries.

The rear compartment is designed to house the motor controllers and other electronic equipment, as well as serve as the mounting points for the rear suspension. Finally this rear section can be developed in the future as a luggage compartment.

Chassis construction

The aluminium honeycomb was waterjet cut using files straight from the CAD model; this minimised the time taken to produce the parts and maximised the use of the CAD design (Figure 4.2).

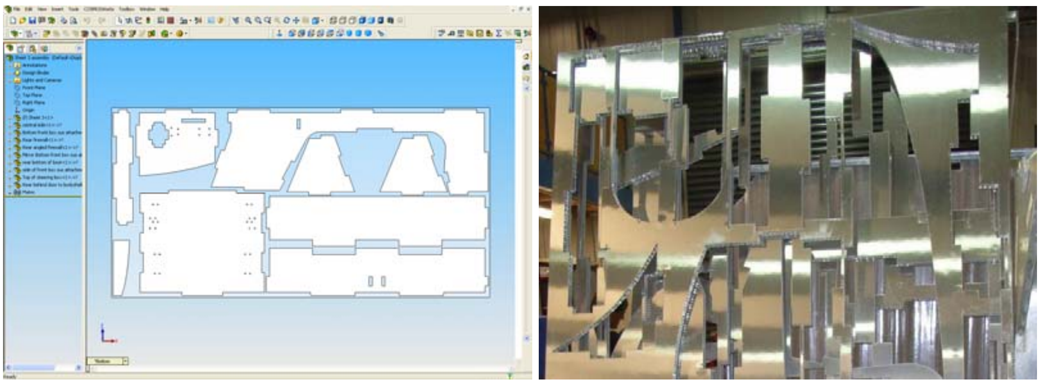


Figure 4.2 Chassis pieces laid out in SolidWorks model, and water jet cut aluminium honeycomb

The panels were then glued together using a rubber hardened epoxy adhesive. This was chosen because it has high strength but still offers the flexibility of being able to absorb small impacts due to vibration with its rubber hardening.

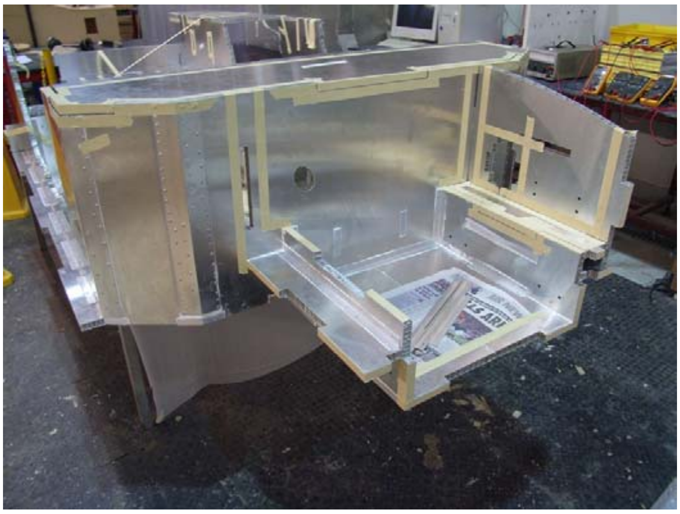


Figure 4.3 Aluminium honeycomb chassis under construction

Figure 4.3 shows the joining of the jigsaw panels, which was done using aluminium angle, and rivets. Box combing was the most common joint used, as it is the strongest due to the larger surface area for adhesive to bond to, and due to its interlocking nature and ability to transfer vertical forces a lot more effectively.

Rollcage

The use of a rollcage in the Ultracommuters design was to ensure that a high torsional stiffness was achieved. Although not required by the LVVTA, a roll hoop was felt necessary for the WSC. Using a rollcage also has other benefits; it allows easy attachment of the body shell to the vehicle, and also offers safe and secure mounting points for seatbelts.

The design of the rollcage shown in Figure 4.4 consists of a roll hoop, with trailing C-pillar bars with a cross. The back bars of the roll hoop come down over the top of the suspension uprights. This distributes the load from the rear suspension through the whole vehicle rather than loading up a piece of honeycomb.

The front section of the rollcage is laminated into the front bodyshell. This stiffened the whole of the front section of the bodyshell, and created a strong roof structure similar to a modern vehicle in terms of strength. It also gave the body shell fastening points to the chassis.

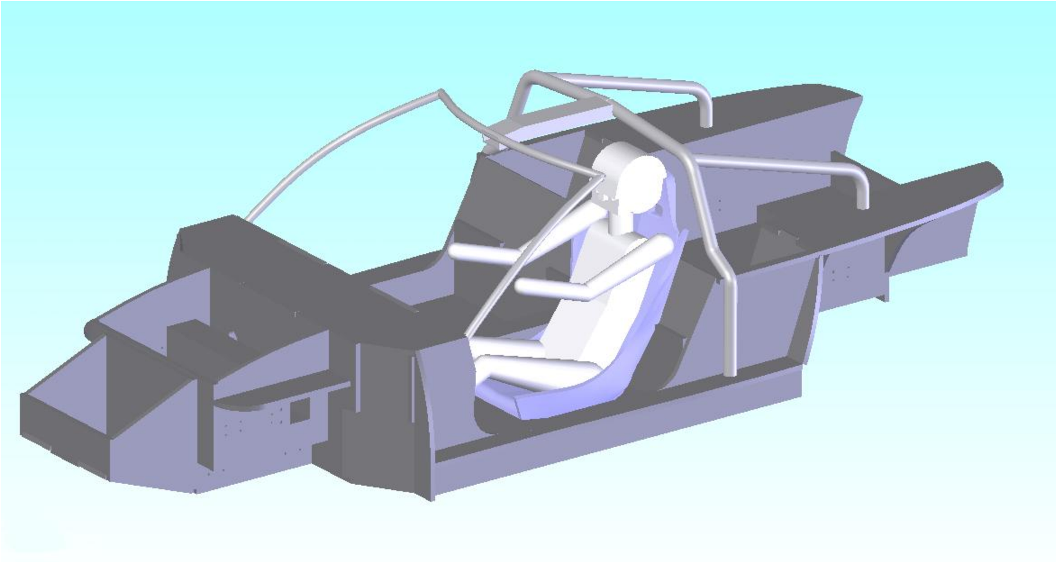


Figure 4.4 Roll cage design

There were three main options for the roll cage; steel, chromoly, and aluminium. Table 8 shows the weight benefits and relative costs for each option. However, the table does not show the ease of manufacture of steel. Steel is an easier material to fabricate a rollcage out of as it is easier to bend and easier to weld than both chromoly and aluminium.

	Steel	**Chromoly**	**Aluminium**
Specific strength	769	898	1148
Theoretical weight (kg)	20	17.1	13.4
Actual Weight (kg)	22	17.1	15
Cost	$1200	$2000	$5300
Saving over steel	N/A	4.9kg 23%	7kg 32%

Table 8 Rollcage weight saving

The use of two materials for the rollcage was a compromise between fabrication, cost, and weight saving. The roll hoop of the cage was made from Chromoly, saving approximately 3kg, and the front hoop section was made from steel for the easy manufacture of the complex curved structure.

Testing

Figure 4.5 shows the Ultracommuter chassis being tested. The chassis was put through a testing process, and some modifications were made to improve the strength of the chassis around the front suspension.

Figure 4.5 Chassis testing by Dr Mike Duke and Jing Zhao

4.2 Interior

The design of a vehicle interior is often overlooked, and considered inferior to other parts of the vehicles design. However, the interior of the vehicle includes several design functions including ergonomics, aesthetics, and usability. The passenger compartment must invite drivers and passengers to enjoy their travel, and act practically, allowing easy control of the vehicle for the driver. The interior of an electric vehicle could be quite radical, using joysticks and buttons to control the vehicle. However, an electric vehicle interior has the unique requirement of needing to integrate the public into a new vehicle type, so it makes sense to leave them with controls they are comfortable with, while making most of the benefits of not requiring gear leavers, and centre columns.

Well known vehicle designer Henrick Fisker set out to make the 'green-car' sexy with his Fisker Karma, in which the leather interior was modelled on a Manhattan apartment. Analysts agree that there is a market for luxury green vehicles, especially with electric vehicle technology not yet ready for the mass market (Durbin, 2008).

With the increasing importance being placed on interior design, engineers and designers now have an analytical system for evaluating their interior design. Kansei engineering is a method where many aspects of the interior are measured, for example, head room, number of steering wheel spokes, or seat colour. It gives an evaluation of the oppressiveness, and roominess of a vehicles interior in a mathematical sense (Chitoshi, Ishizaka, & Nagamachi, 1997).

4.2.1 Air-conditioning

For many years, people have relied on air-conditioning to keep themselves cool over long hot trips, or warm through winter travelling. However, the fact remains that air conditioning requires power, and decreases a vehicles efficiency. Air conditioners are both heavy and bulky as well as consuming a lot of energy in their operation.

Denso has developed a HVAC system for vehicles, best known for its use in the Toyota Prius. Thermal management may seem like a small issue, but with the increasing importance being placed on fuel economy and efficiency, this area of vehicle development will receive a lot of attention in the coming years (Yamaguchi, 2007).

A potential solution to air conditioning is the use of heated seats and steering wheel. The idea is that rather than heat up or cool down the whole car, only the objects in contact with the person are heated or cooled, minimising the amount of energy used. Direct contact is also the most efficient way for the body to absorb or have the energy removed from it.

4.2.2 New materials

The interior of a vehicle needs to be lightweight, and aesthetically pleasing. The use of new materials is the most common way of reducing the interiors mass, and with many new materials being made from natural fibers and sources, they also offer unique environmental benefits.

Mazda has developed a new biofabric which is made from 88% corn and 12% petroleum products, as opposed to 100% petroleum based fabrics. This new fabric is not only more environmentally friendly, but also performs better. It has three times more shock resistance and 25% better heat resistance, as well as retaining the durability and UV protection of conventional fabric (Hoffman, 2007).

Natural fibre composites are often present in vehicle interiors. FlexFrom technologies in the United States are one of the leading companies producing natural fibre composite panels made from hemp, flax, and other natural fibre thermoplastic polymers. In six years from 1999-2005, over 1.5million new vehicles in the US were installed with Flexforms panels (FlexForm, 2005).

Flocking is a lightweight coating used to cover custom interiors with a simple attractive finish. First, a polyester resin is sprayed to the surface, then the flocking powder is applied to this resin and it is left to set. Excess flocking is then removed from the surface, leaving a felt like texture to the object. Flocking is much lighter than fabric, and is easy and quick to apply to custom mouldings and fixtures.

4.2.3 Ultracommuter interior design

The goal for the Ultracommuter interior design was to produce a simple and lightweight interior that was also practical and well designed for driving. Because of the integrated chassis design, much of the vehicles interior was set by the chassis shape.

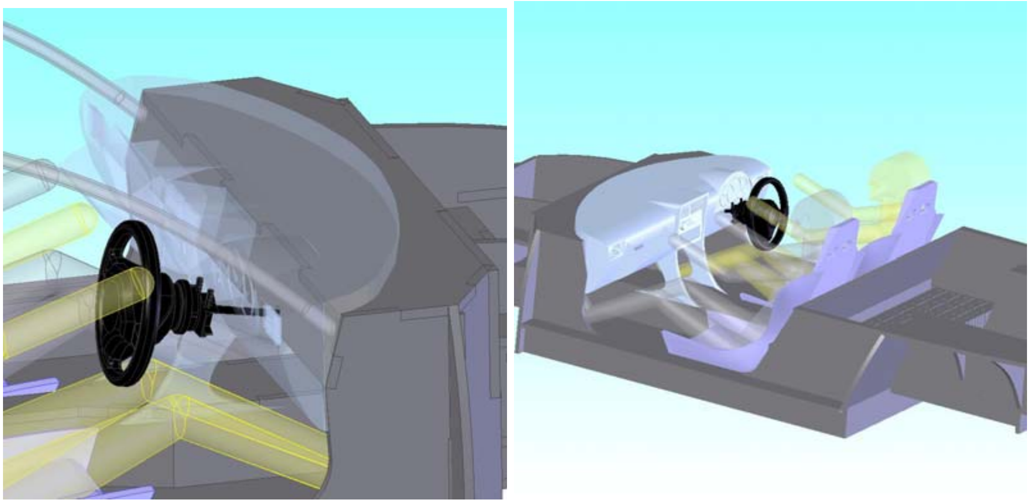


Figure 4.6 Interior models of the Ultracommuter

The Ultracommuter's goal of competing at the WSC meant that weight was a key issue; thus, the dash was made from lightweight foam, and was coated with one layer of fibreglass for strength before being 'flocked'. The dash weighed 1kg and incorporated a speedometer for the driver (see Figure 4.7).

Figure 4.7 Ultracommuter Interior

A laptop was mounted in the interior of the Ultracommuter. The laptop was used to give the driver feedback from the battery monitoring system and the motor controllers.

4.3 Aerodynamics

Aerodynamics describes the performance of a shapes movement through a fluid (Hucho, 1998). In the case of a vehicle, aerodynamics represents anything that affects the cars movement through the air, for example, the vehicles body, and appendages such as wings, spoilers, and mirrors. Internal flows are also a focus of aerodynamics, including air conditioning, and wound down windows. Aerodynamics is responsible for the greatest concessions to design and styling. For years, vehicle designers viewed aerodynamics as little more than an inconvenience (Hucho, 1998). However, with the increased emphasis now placed on efficiency, designers have to work with aerodynamicist, not against them. Aerodynamic design is also affected by safety and practicality. As the outer part of a vehicle, the body design must incorporate energy absorbing safety mechanisms to protect both occupants and pedestrians. When all of these factors are considered alongside practicality issues such as windows, doors, and storage entry, aerodynamics is a complex field.

Aerodynamics is a complicated field, incorporating many concepts and requiring complex mathematics. Section 3.5 shows that frontal area and co-efficient of drag are the two factors outside of mass that can be easily manipulated to improve performance. Both of these factors are dependent on aerodynamics.

The development and improvement of aerodynamics is also very difficult; computers are not able to simulate the fluid flows of vehicles exactly, so often aerodynamic testing is done using life size models in wind tunnels, a time consuming and expensive process.

Co-efficient of drag, and frontal area

The co-efficient of drag is affected by a bodies shape, and is a dimensionless unit representing the disturbance and therefore drag force of a shape through a fluid (Hucho, 1998). The frontal area of a vehicle represents the area of the surface perpendicular to the fluid flow. The C_D and frontal area are often played off each other, and careful attention to their relationship is important in aerodynamics. The best representation of a vehicles aerodynamic performance is by the term C_DA.

Vehicle Aerodynamics

The basis for aerodynamics on vehicles is to try and minimise the amount of boundary layer separation, which is when the air flow breaks away from the flow profile and creates turbulence. There are a number of factors that affect this; the five areas classically found to cause this on a vehicle are:

1. Front end
2. Windscreen and A-pillar
3. Roof
4. Rear end
5. Underbody

Front end

Electric vehicles have a significant advantage over petrol powered vehicles in that the front end of an electric car does not require an opening for air flow. Because a gasoline engine requires an air intake for the combustion process, and cool air for the radiator, most internal combustion engine vehicles are designed with a large intake on the front end. Electric vehicles using electric motors do not require this intake, so any air required for cooling and comfort can be obtained from a less critical area in the cars flow profile.

The front end of a vehicle can be described as a block. Because of a cars low profile to the ground, air tends to flow over and around a vehicle. This makes the front end important in directing the airflow to be streamlined in the best direction for the vehicles design (Hucho, 1998).

Windscreen and A-pillar

The windscreen and A-pillar have three areas where separation can occur, the join between the bonnet and windscreen, the join between windscreen and roof, and the roll off around the A-pillars.

Roof

Curving the roof can improve the aerodynamics of a vehicle, however the amount of curvature is limited. When the curvature is increased, so is the area, causing the overall effect of the C_DA to be positive or negative (Hucho, 1998).

Rear end

The rear or tail end of a vehicle plays a greater role in the aerodynamic performance of a vehicle than often considered. Once the air is streamlined on a vehicle, it then has to be rejoined to the normal airflow. The longer and more tapered the back section of a vehicle, the better the aerodynamic performance; however, having a section as long as the body of the vehicle out the rear is not practical for a road vehicle (Hucho, 1998).

Underbody

The underbody of a vehicle is the simplest area of aerodynamics and is currently disregarded by car designers. With up to a $0.045C_D$ saving available for simply smoothing the underbody of a vehicle, it is an area in aerodynamic design that is beginning to be noticed in modern vehicle designs (Hucho, 1998).

4.3.1 Ultracommuter aerodynamics

The aerodynamics of the Ultracommuter is one of the key efficiency improvements in the vehicle; by reducing the drag and surface area, the vehicle is able to reduce the total amount of energy required to run it.

Front end

The Ultracommuter features a rounded front end and front side profile. This forces the air flow meeting the car to be separated around the sides, top, and bottom of the vehicle, in a smooth manner. Although having to separate around the body, the air flow does not break from the body, meaning the cars entry into the flow is smooth (as shown in Figure 4.8).

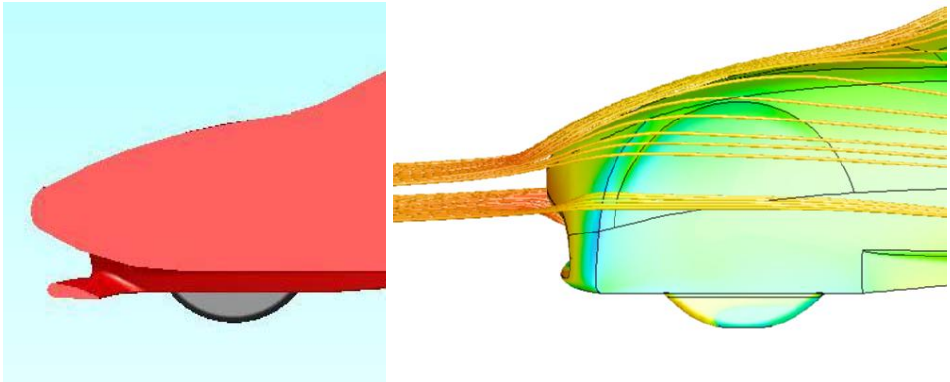


Figure 4.8 Ultracommuter front profile

As presented by (Hucho, 1998), the reduction in drag by having a curved side profile as opposed to a square profile is -0.05C_D. The front wing of the Ultracommuter is a concern when considering the front profile. The front wing was designed purely for aesthetics; it creates zero lift and zero down force on the aerodynamics. While the wing creates an unneeded drag, it shows the compromise between styling and aerodynamics.

Windscreen and A-pillar

The Ultracommuter features very large radiuses and smooth transitions between the critical areas on the A-pillar. The windscreen on the Ultracommuter is curved to minimise the potential of flow separation, and helps the air profile around the A-pillars. The windscreen is slanted, being 65° off vertical. The windscreen slant (shown in Figure 4.8) reduces the amount of 'windscreen bubble', the interference between the bonnet and the windscreen.

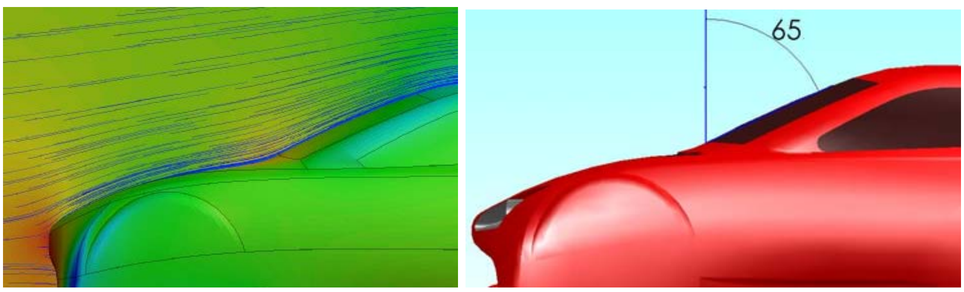


Figure 4.9 Windscreen bubble

The slanted windscreen minimises the amount of air forced around the A-pillars, (as shown in Figure 4.10).

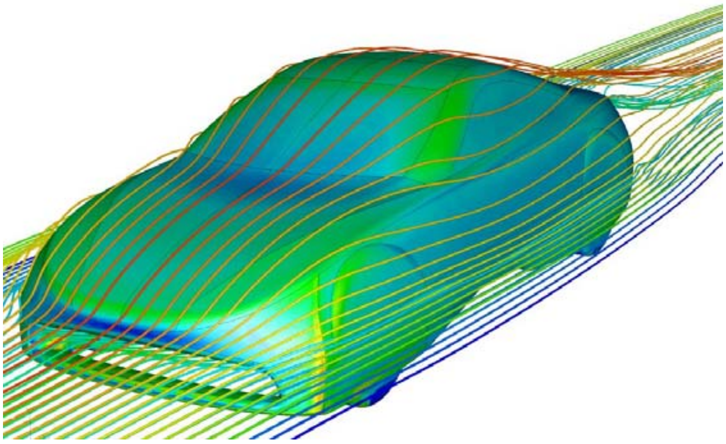


Figure 4.10 Large curved A-pillar and windscreen transitions

Roof line

The Ultracommuter has no roof line, instead there is an apex of the profile, which is situated were the drivers head is situated. This helps to improve the exit flow off the vehicle.

The rear end

The rear end of the Ultracommuter is a fastback rear end; the roof section and boot section are effectively molded into one piece to minimise possible disturbance and give a continuity of air flow. The C-pillar and rear chine of the car sweep back into the boot peak, a concept known as boat-tailing (Hucho, 1998). This design encourages the air to break from the cars surface stream at the peak of the boot. The rear is designed to create the minimal amount of turbulence and return the air to laminar flow as soon as possible after leaving the cars surface (Figure 4.10). The final feature of the Ultracommuter rear end is the underbody boat-tailing; a large uprise in the back underbody of the vehicle can be seen in Figure 4.11. This has been shown to improve aerodynamics by up to 28% (Hucho, 1998).

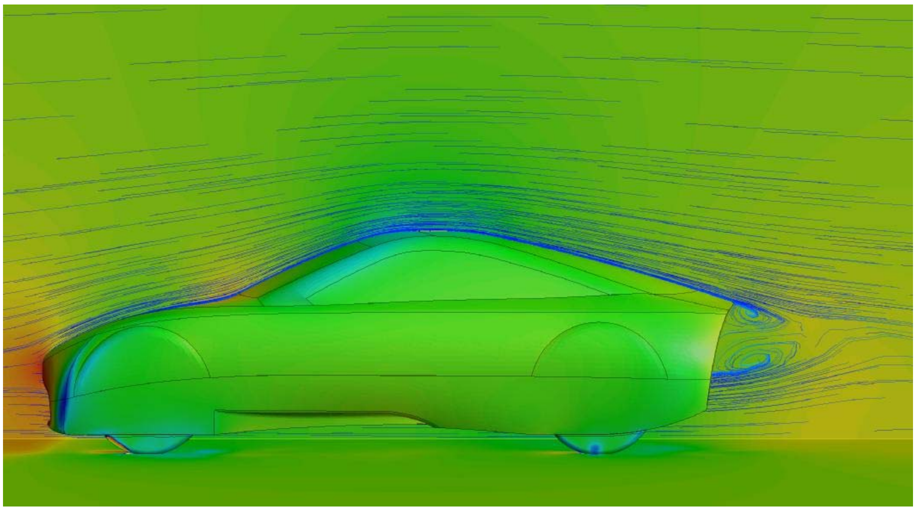


Figure 4.11 The rear end of the Ultracommuter, a classic fastback design

Underbody

The Ultracommuter features a full underbody to minimise disturbances in the air flow under the car and improve the drag co-efficient. This is achievable on the Ultracommuter due to some of the other design features of the vehicle; the integrated monoquocue chassis sits higher from the ground than a ladder or spaceframe chassis. The dual wishbone suspension mounts straight off the side of the vehicle, meaning that the underbody can cover the bottom wishbone. The biggest advantage comes with the drive system; because the Ultracommuter uses in-wheel electric motors and an electric drive system, there is no need for drivetrains and exhaust systems, allowing the underbody to be bolted directly to the chassis.

Wheel spats

The most obvious feature of the Ultracommuter's aerodynamic package is the wheel spats. The drag caused by the wheels on a streamlined vehicle can be as much as 50% of the overall drag. The problem with wheels is twofold; firstly, wheels are not very aerodynamic shapes, encompassing a brick like profile. To emphasise this point, the difference between 165mm and 195mm width wheels on the overall C_D of a vehicle is a C_D of 0.29 vs. 0.31 (Hucho, 1998).

Secondly, there is a lot of disturbance in and around a wheel. Mag wheels have holes in the sides, as well as brake disks, suspension arms, and many other components. Once the airflow gets inside the wheel, it is flung up and distributed into this area. The wheel arches and openings on a normal vehicle act as a giant parachute, and create a drag force.

The Ultracommuter features wheel spats on the under body of both the front and rear wheels of the vehicle, as well as completely sealed rear wheels, where only the bottom of the wheel is exposed to the road.

Ultracommuter aerodynamics

The combination of these features gives the Ultracommuter very low drag. Testing, as done by *Hybrid*Auto using Fluent demonstrates a C_D of 0.25. Similarly, Figure 4.12 testing done in FloWorks shows a C_D of 0.24.

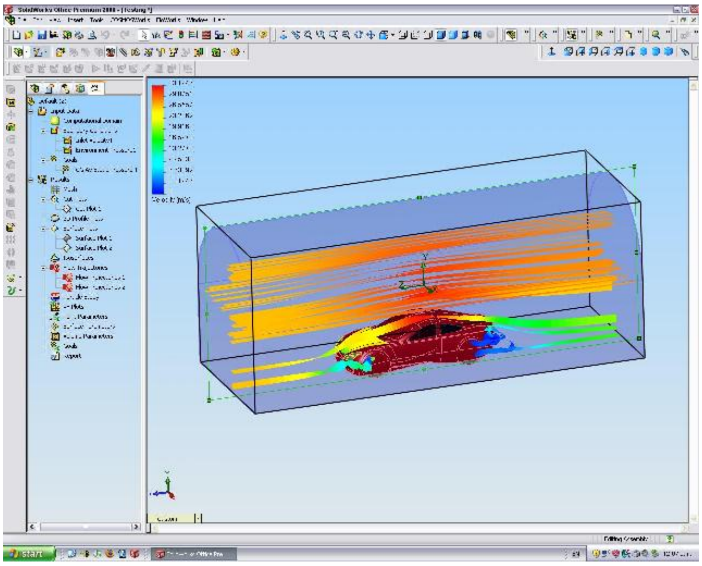


Figure 4.12 FloWorks analysis

Figure 4.13 shows the surface area of the Ultracommuter. The Ultracommuter has a small surface area of 1.42m^2 with no wing mirrors.

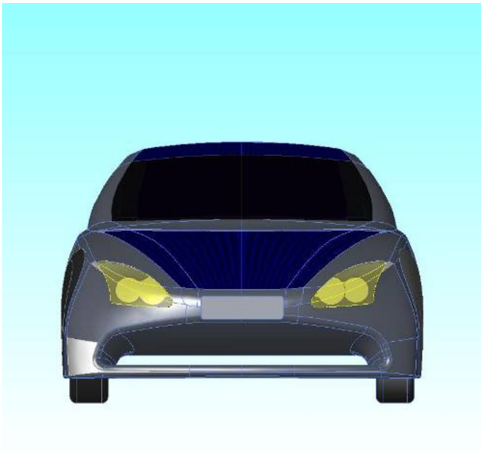


Figure 4.13 Ultracommuter surface area

Although no aerodynamic testing was done on the vehicle, some overall efficiency figures were gained and the overall energy usage was 7-8kW against a theoretical value of 7.3kW (see section 4.8.4). This included not having front wheel spats, and several split lines not being perfectly closed, implying that the aerodynamics must be very close to the estimated C_D values of 0.24-0.25

4.4 Body design

The body shell of a vehicle consists of all of the parts of the vehicle exposed to the air flow, this includes body work, windows and windscreen, as well as mirrors and lights.

4.4.1 Materials

Although many new light weight materials are used in the automotive industry, the use of steel for body panels remains an industry standard. This is due to two main reasons; its low cost and ability to be recycled. The cost to produce a die for a vehicle panel is very high, but once that die is produced, the cost of producing panels is very low. This is because very little labour is required; panels can be stamped out quickly and cheaply by automotive companies. Steel is also very recyclable; 90% of steel used in vehicles can be recycled, whereas other materials such as plastics and composites are not so easily recycled, and many people see them as less environmentally friendly than steel (Matthews, 1998).

The use of composites in vehicle bodies is becoming more common in order to reduce the weight of vehicles. The Ford GT uses a fibreglass bonnet and boot as well as reinforced injection moulded bumpers and rocker panels (Koganti, 2005). Body shells could also be manufactured out of more environmentally friendly materials such as hemp fibre. Figure 4.14 shows a prototype Ultracommuter body shell constructed from hemp fibre composite.

Figure 4.14 Prototype hemp composite body shell

4.4.2 The Ultracommuter body shell

The Ultracommuter body shell is designed to keep weight at a minimum, while completing all of the normal tasks expected of a cars body. To complete this, the body was made from fibreglass, and lexan polycarbonate windows were used for vision.

The Ultracommuter body shell was constructed in a six step process;

1. Plug production
2. Mold production
3. Body shell production
4. Split lines
5. Body shell attachment
6. Finishing

Plug production

The plug was produced using the advanced manufacturing technique of milling. The vehicles body was constructed from six large polystyrene blocks. The CAD model was taken to a 3D milling operation, where the company first split the model up into six parts, and then uploaded it into its Computer Aided Manufacturing (CAM) software Alpha Cam, as shown in Figure 4.15.

Figure 4.15 a) AlphaCam creating a cutting program b) An engineer simulates a virtual mill of the Ultracommuter body shell.

The milling program was then sent to the machine and the body shell was machined in six parts over 4 days, the milling is shown in Figure 4.16. The three hundred thousand dollar machine produced a polystyrene body shell to a tolerance of 0.2mm with a tool head spinning at up to 20,000rpm.

Figure 4.16 a) The 5-axis CNC creates a rough cut b) the finishing cut

Plug Preparation

Plug preparation includes the skinning of the polystyrene with fibreglass for strength, and the application of a bog and primer to make the plug smooth. The prepared plug is shown in Figure 4.17.

Figure 4.17 Plug after molds have been lifted with mocked shut lines on it

Mold Production

The female molds are produced by layering fibreglass onto the plug. First, the plug is comprehensively waxed to ensure the mold is easily released from the plug. The mold is then applied in several layers. Initially, a layer of gelcoat is applied to give the mold a smooth internal finish. Next, the gelcoat is skimmed with fibreglass to ensure it has no holes or imperfections (Figure 4.18). The mold then requires a large build up of fibreglass, which is done until the mold is approximately 10mm thick. This creates a very strong and stiff structure for the shells to be lifted out of. Finally, supports are laminated to the mold; these cross sections are used to ensure that the mold is as strong as possible and allows for easy manoeuvring of the mold around a workshop.

Figure 4.18 Ultracommuter mold, blue gelcoat coated by fibreglass layers

Shell Production

After the molds have been created, the shells can be produced. Because the shells are going onto the car and their weight must be kept to a minimum, the process is more closely monitored;

1. Molds are prepped with wax to ensure an easy extraction
2. Gel-coat is applied to allow an easy to paint finish
3. Fibreglass is applied to give strength. Fibreglass is only applied where required. In areas were extra strength or stiffness is required, core matt is used to increase the thickness of the shell. In areas where a lot of structural strength is required, aluminium bars are laminated in. The shells are shown in Figure 4.19

Figure 4.19 a) Ultracommuter body fresh from the mold b) Aluminium strengthening bars laminated in

Split Lines

The placement of split lines was one of the toughest decisions on the Ultracommuter design. Care needs to be taken for the split line design not to be placed across the streamline, and to be the minimum possible distance. Split lines in the flow direction have little or no effect on the overall drag of a vehicle (Hucho, 1998).

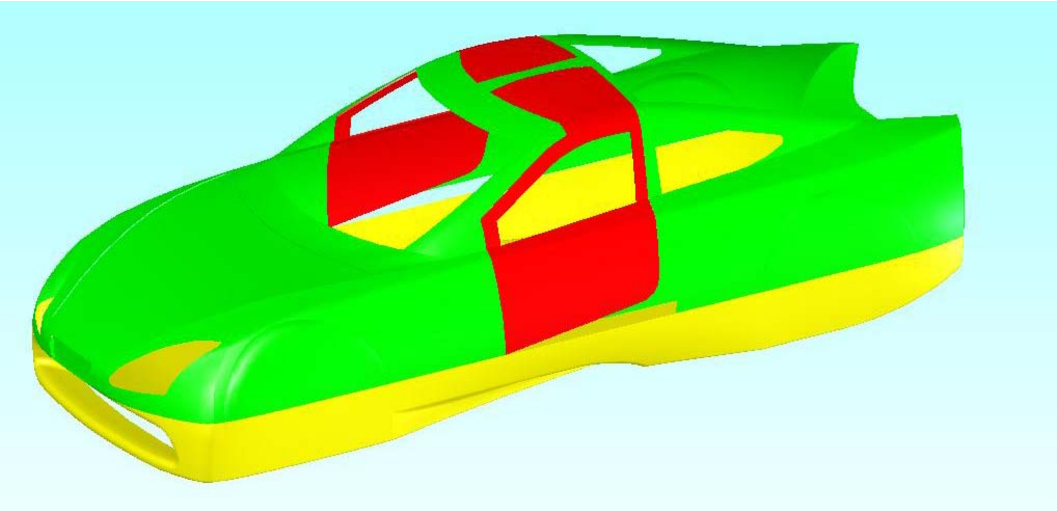


Figure 4.20 Ultracommuter Split lines

With the chassis having relatively high sides for the side beams in the passenger compartment, it meant that the doors had to open wide for the driver and passenger to be able to enter and exit the vehicle. Gull wing doors were selected because of their looks and styling, and to allow drivers to easily enter and exit the vehicle.

Other options for split lines included the use of a folding front half. Although offering more challenging design decisions, the use of an opening front section could be used in the future.

Body Shell Attachment

The body shells integration to the vehicle is far more complex on a vehicle with a shell like the Ultracommuter's. Because the body shell is not actually part of the vehicles structure as in a conventional monocoque, it is attached to the outside of the chassis.

The bottom part of the body shell is bolted directly to the underneath of the chassis, and is held firm by attachment on the side of the chassis. Connecting aluminium brackets are laminated into the shell so that no external bolt heads are required. The front roll cage's lamination into the shell makes the front part of the attachment relatively straight forward, with bolts holding it to the rollcage and the front of the chassis crumple zone. The aft section of the body shell is bolted to the rollcage and rear section of the chassis, as well as the bottom tray of the bodyshell. Finally, the boot is mounted to the rear body shell section, and the gull wing doors are mounted to the rollcage.

Figure 4.21 Ultracommuter bodyshell fitted to vehicle

Windows and Vision

Windows and vision is an important part of any vehicle. To comply with the glazing and vision requiremets of the LVVTA section 15.1 – 15.8 (Johnson, 2007), the windows were designed to ensure sufficient vision for the driver in the forwards direction. The windows were made from lexan MR10 polycarbonate. Lexan was only recently approved as an appropriate material for glazing of the windows. The MR10 variety of lexan is automotive approved, is scratch resistant, and has a chemical and UV protection layer. A 4.5mm scratch resistant lexan was used for the windscreen of the Ultracommuter and a 3mm thick lexan was used for the side windows.

	Glass	Lexan
Weight per m^2 (windscreen/windows)	6.67/4.67	0.54/0.45
Windscreen ($1.1m^2$)	7.34	0.6
Windows ($0.4m^2$)	1.87	0.18
Saving	**n/a**	**8.43 91%**

Table 9 Lexan weight saving (see Appendix 5)

The use of lexan in the vehicle saved a significant 8.4 kg. Polycarbonate windows and windshields are becoming more common, with automotive regulations beginning to accept lexan as a viable material source for glazing.

Finishing

The finishing of an electric vehicle body is very similar to any other car. The only difference is that extra care is taken in terms of keeping aerodynamic drag to a minimum. The Ultracommuter was painted red, and was brought to a polished finish; decals and stickers were applied as well as rear tail lights. Being a prototype, several exterior car features were not finished such as the windscreen wipers, wing mirrors, and head lights. A reversing camera replaced the wing mirrors, and windscreen wipers were replaced with rainx. The shells interior is finished with flocking to give the driver a more pleasant interior.

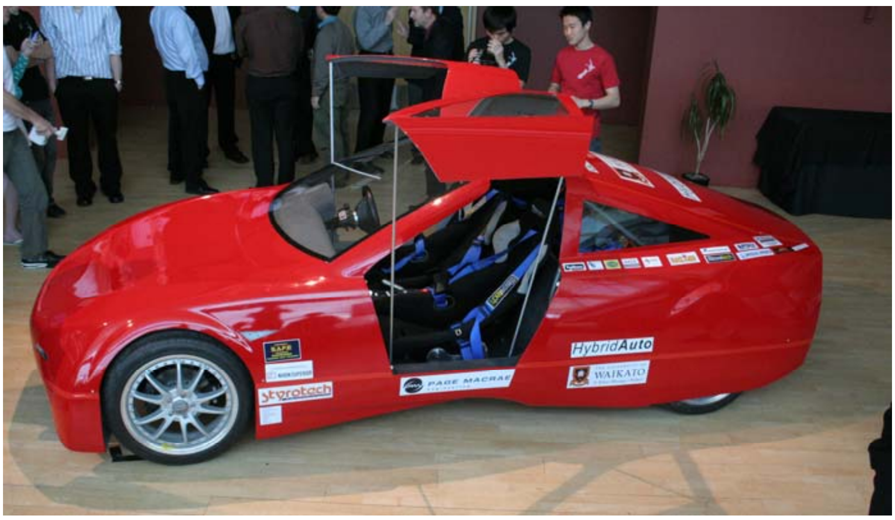


Figure 4.22 The Ultracommuter body shell completed in red

4.5 Suspension, steering and braking

The suspension, steering and braking system of an electric vehicle is one of the key mechanical components. Although these systems have been under development for many years it would be incorrect to think that this area could be simply copied from an existing petrol powered vehicle.

4.5.1 Un-sprung mass

Un-sprung mass consists of everything not under suspension of the shock and spring. The un-sprung mass ratio is the ratio of un-sprung mass to sprung mass; the higher the ratio the larger the amount of un-sprung mass in comparison to the vehicles total weight.

Un-sprung mass has a direct effect on occupant comfort. The higher the ratio, the more susceptible a vehicle is to accelerations up and down while travelling over bumps in the road. These accelerations are what cause the uncomfortable feelings inside a vehicle.

Because of the lightweight design of an electric vehicle, using a conventional cars suspension system would yield a high un-sprung mass ratio.

4.5.2 Suspension system

As most electric vehicles are conversions of petrol powered cars, most suspension systems in the past followed the same convention as the automotive industry at the time. However, with a new breed of lightweight vehicles being produced, the suspensions systems have to meet a new standard in driver comfort.

4.5.3 Steering System

The steering on an electric vehicle follows the same convention as an internal combustion vehicle. Rack and pinion steering is the most commonly used steering system. Power steering, or assisted steering, became popular as car weights became heavier; one advantage of lightweight vehicle design is that power steering is not required, and thus weight is saved.

4.5.4 Braking

The braking on an electric vehicle can be viewed as an opportunity to charge the batteries. First proved by M. A. Darracq in 1897, the principal behind re-generative braking is the reversal of the electric motors polarity, turning it into a generator, and thus generating a current which flows back to the batteries and charges them (Anderson & Anderson, 2005).

The EV1 was one of the first vehicles to incorporate a mechanical braking feel with regenerative braking. Controlled by the motor controllers software, the brake pedal eased on and the further the pedal was applied, the greater the braking force was ("We drive the world's best electric car", 1994). The EV1 also featured a complete hydraulic braking system in case of an electronic failure ("We drive the world's best electric car", 1994).

Regenerative braking is an area that has the potential to undergo extensive research and development over the next few years, especially in regards to its potential to completely replace mechanical braking. If this becomes a reality, the use of regenerative braking on all four wheels of a vehicle would be beneficial for three reasons;

1. Using the motors for braking would reduce the amount of un-sprung mass added to the vehicle by the use of the motors. Disc and drum brakes are relatively heavy, and because of their performance requirements, they must be made of heavier materials such as steel. If these can be removed, it would reduce the un-sprung mass significantly, giving a lighter overall vehicle weight and better ride comfort.

2. Because regenerative barking is electronic and uses the motors rather than friction, there is very little brake fade. A case could be made for the motor heating and becoming less efficient but the difference would be negligible.
3. Because regenerative braking is controlled electronically, it would mean that very fast control of all four wheels could be implemented by software, which is much faster than mechanical systems. ABS braking, traction control, and variable 4wd could all be implemented using algorithms taken straight from data sent to the motor controller. The implications of this offer cheap, fast, and safe systems that could be installed in every vehicle, not just high performance or luxury vehicles.

Outside of regenerative braking, many electric and hybrid vehicles still use a full hydraulic braking system. Many transportation authorities do not yet allow regenerative braking as a viable proven method of slowing and stopping a vehicle. For this reason, designers and engineers are combining the two systems to meet these regulations, while testing continues to be undertaken to prove the safety of the regenerative braking system. The efficiency of a vehicle is reduced by the use of hydraulic brakes. Not only does the extra mass of the brakes increase the amount of energy taken to drive the vehicle, the brakes also often rub, using energy. Braking systems on efficient vehicles need to have returning brake pads that do not rub or wear on the brake disc.

4.5.5 Ultracommuter Suspension Steering and Brakes

Suspension

The suspension system on the Ultracommuter was made up of double wishbone suspension front and rear. The design goal of the system was to integrate low volume manufacture with the use of water jet cutting and sheet aluminium. This would allow for the minimum amount of material and machining, lowering the cost of the suspension substantially in comparison to more complex systems.

Front Suspension

The front suspension was originally designed to fit a lotus chassis, and thus incorporated the lotus mounting points. The suspension arms were made from sheet 6061 aluminium and were waterjet cut and then anodised. The mounting tubes were made from thicker 40mm aluminium and were also profile cut using a waterjet cutter; the complete front corner can be seen in Figure 4.23.

The front upright was a complex casting, it was designed using Solidworks and then the upright was rapid prototyped. After being rapid prototyped, it was made with cast aluminium. The upright is both strong and functional with brake calliper and steering mounting points integrated into the design.

Figure 4.23 Ultracommuter front suspension.

The rear suspension also has aluminium wishbones, but consists of a more complicated design due to the loading increases on the rear of the vehicle.

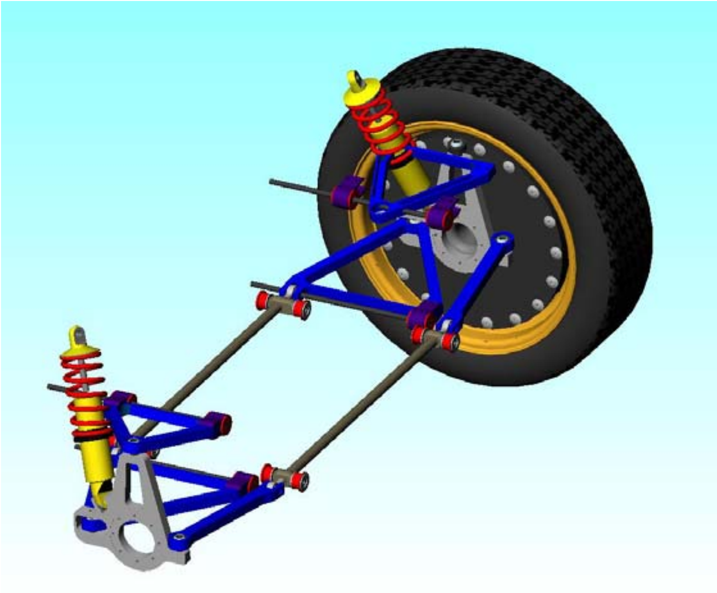


Figure 4.24 Rear suspension design.

Due to the use of wheel motors, the torque distribution in the Ultracommuter is different from the standard gasoline powered vehicle. With most vehicles, the torque is applied through a driveshaft in the centre of the wheel, however when using a wheel motor, the torque is applied at the ground Figure 4.25.

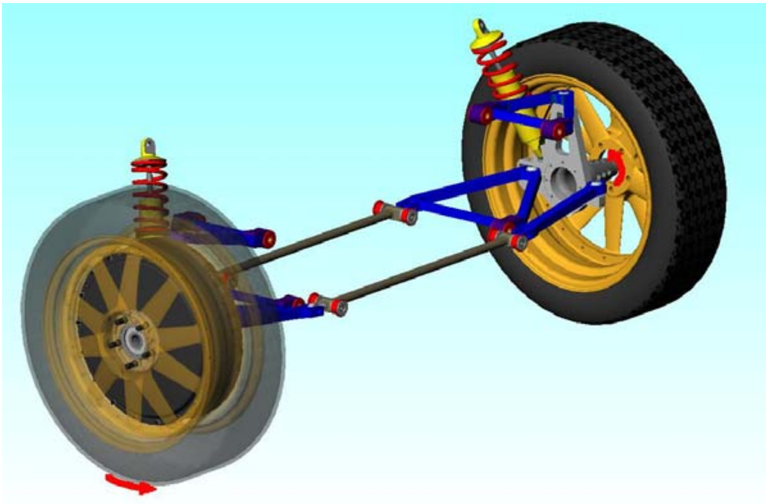


Figure 4.25 Torque application of wheel motor vs conventional driveshaft

What this means is that when the vehicle accelerates and decelerates, the wheels will have a tendency to pull out or in. To stop this, rear steering arms are installed across each end of the bottom wishbones. These hold the suspension square and evenly apply the torque to the road. More testing is required to discover the extent of the problem, and whether the steering arms need to be installed or could later be removed if not an issue. Removal would be ideal as these steering arms limit the space of storage etc in the rear of the chassis.

Braking

To meet the requirements of the LVVTA, two braking mechanisms are used. Hydraulic brakes were used on the front wheels of the vehicle, with regenerative braking on the rear. The front brakes on the Ultracommuter consist of an AP Racing CP5211-22S0 aluminium calliper, and Toyota Hilux rotors.

Regenerative braking

To meet the LVVTA requirements, a vehicle must be able to safely de-accelerate from 100-0 in 4.4 seconds.

To show the theoretical capability of re-generative braking, if you take a vehicle travelling at 100kph and under **constant** de-acceleration to zero over 4.4 seconds

$$a = \frac{\Delta v}{\Delta t} = \frac{27.8 - 0}{0 - 54.4} = 6.32 ms^{-2} \text{ decceleration}$$

$$F = ma = 6.32 \times 650 kg = 4108 N$$

$$P = F \times v = 4108 \times 27.8 = 114{,}202 W$$

$$P = 114 kW$$

$$P = V \times I \times \eta = 144V \times 200I \times 0.95 = 27.36 kW$$

$$\times 4 \text{ motors}$$

$$P = 27.36 \times 4$$

$$P = 109 kW + \text{Resistance from drag and rolling resistance}$$

$$P = 109 kW + 7.3$$

$$P = 116.3 kW$$

The power required to stop the vehicle under constant declaration at 100km/h is 114kW the maximum power produced by a vehicle with four wheel motors, plus the resistance from the aerodynamic drag and rolling resistance puts this figure at

116kW this shows that the regenerative braking is able to achieve this deceleration.

Note: that the actual power requirement to stop a vehicle would be far less than this; After the car has slowed to 50km/h only 57kW of power would be required to continue the deceleration at that constant rate. In reality the vehicle would begin the deceleration at a slower rate, and hold the power on to speed up the deceleration towards the end.

Steering

The steering on the Ultracommuter was set up to follow Ackerman geometry (Figure 4.26). The path of the inside wheel turns tighter than that of the outside wheel. The steering was also set up with the column at the same height as the top wishbone (to see where the steering was attached see Figure 4.27), so that no bump steer would be present while the suspension was moving up and down.

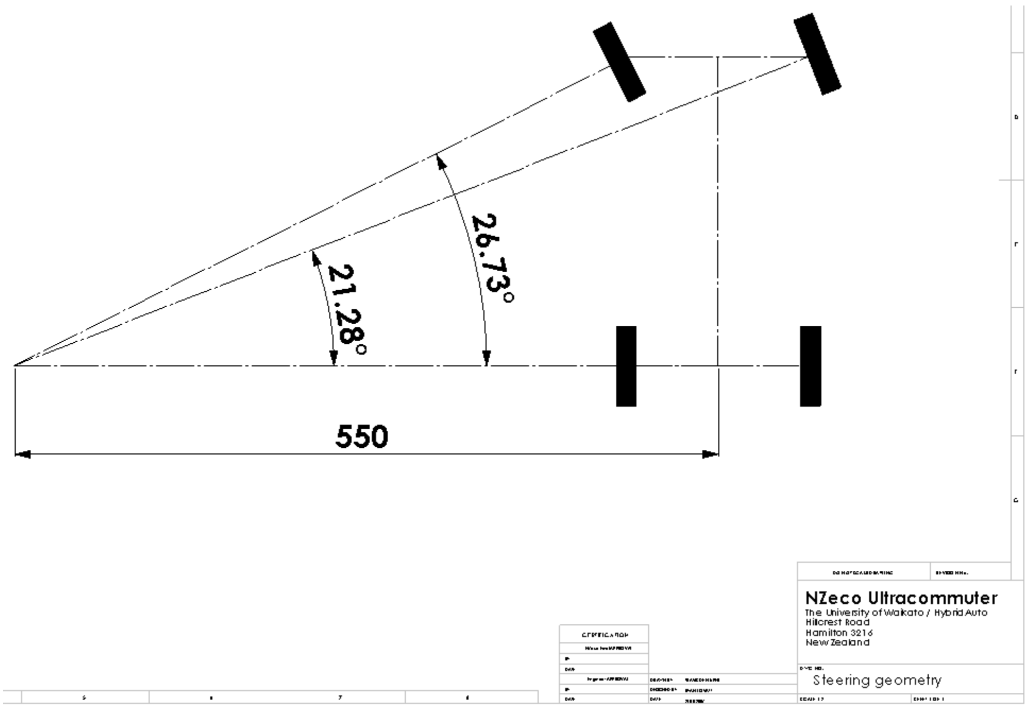


Figure 4.26 Ackerman steering geometry of the Ultracommuter

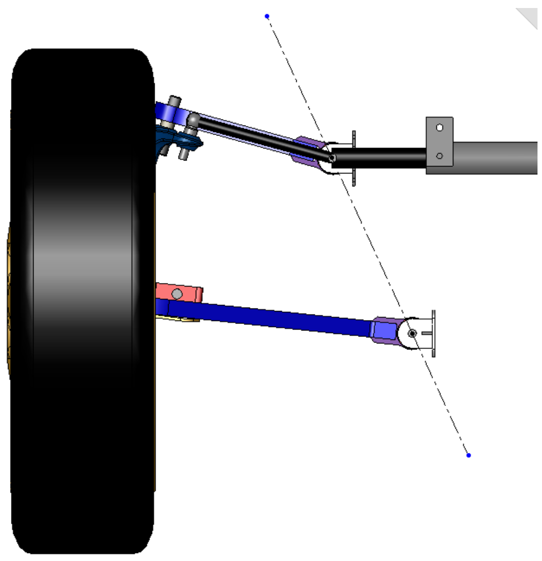


Figure 4.27 Pivot points of Ultracommuter steering

The steering column was placed so that the steering wheel would be in easy reach for the driver, and central to their driving position. As per LVVTA regulation 7.13 (Johnson, 2007), the universal joints connecting the column to the short shaft and then to the steering rack were no more than a 30° angle to either end of the joint. The short shaft or dog leg is designed into vehicles so that if the driver is forced upon the steering wheel in an accident, the column will move sideways or in to prevent harming the driver.

4.6 Wheels, tyres and rolling resistance

The wheels and tyres of an electric vehicle play more of a role than on a standard vehicle. The use of low rolling resistance tyres and lightweight alloy wheels on electric vehicles pushes the boundaries of these technologies more than gasoline vehicles.

4.6.1 Wheels

The selection of a wheel for a battery electric vehicle is much like that of a gasoline powered vehicle, it must be strong enough, and the right size for the tyres selected. The large selection of lightweight alloy wheels currently available helps with the move towards reducing un-sprung mass.

4.6.2 Tyres

When choosing a tyre for a high performance efficient vehicle, three main factors need to be taken into account, traction, durability, and rolling resistance.

The traction or grip of a tyre is important in how a vehicle will handle and behave on the road. The problem with choosing a tyre with very high grip is that it will have very bad rolling resistance; the better a car sticks to the road, the more energy will be wasted through that friction.

The durability of an electric vehicle is less important than traction and rolling resistance, however if this durability can be improved, the vehicle will cost less over its lifetime and be more appealing to the consumer.

The rolling resistance of a vehicle is the only factor outside of aerodynamics that affects the vehicles efficiency while travelling at a constant speed. The higher the rolling resistance, the more energy is wasted on the road. Although a smaller fraction of a vehicles energy usage is wasted in comparison to aerodynamics or mass, the reduction in rolling resistance can still play a significant roll in a vehicles efficiency.

4.6.3 Ultracommuter Wheels and tyres

The Ultracommuter uses Simmons custom made 3 piece alloy wheels as shown in Figure 4.28. The use of these custom wheels was for the added requirements of in-wheel motors. Due to the wheel motors, the wheels needed to be stiff so that no deformation or flexing of the wheel rim could come in contact with the motor.

Figure 4.28 Ultracommuter wheel and tyre

*Hybrid*Auto researched tyres, and the decision was made to use Bridgestone Potenza tyres (Figure 4.28). These offered the best compromise between rolling resistance and traction.

4.7 Drive system and motors

The drive system and electric motors is one of the most important parts of any electric vehicle. It is typical to select the motor the vehicle will run and then select the appropriate controller to match. However, every system is different and many new systems are being developed as technology advances. This section looks into the history of electric motors and drive controllers, and discusses in detail the modern vehicle drive system in comparison with the Ultracommuter's system.

4.7.1 Electric Motors

The principal of the electric motor was first developed by Michael Faraday in 1821, when Faraday built two devices that made a continuous circular motion around a wire. In 1831, Faraday discovered electromagnetic induction and then magneto-electric induction. These early experiments laid the foundations for the modern electric motor as well as generators and transformers. The modern DC motor as we know it today was invented by accident in 1873. Zenobe Gramme connected one dynamo he invented to another, driving it as an electric motor. The 'gramme machine' was the first successful electric motor (Drury, 2001).

DC motors

A DC motor works by providing an electric current through a rotor or armature between the poles of a magnet, causing a rotation of the rotor providing the torque of the shaft. There are three types of windings for the rotor of a standard DC motor;

- Series wound
- Shunt wound
- Compound wound

DC motors were the industry standard in electric vehicles until the late 1980s when AC motors were developed by the Ford motor company (Dr Heitner, 2001). AC motors consist of induction and synchronous types, and are more common in vehicles today because of their higher power and torque outputs over DC motors.

Wheel Motors

The problem with most DC and AC motors is that they still require some form of drive train; despite it being a gearbox or direct drive, efficiency will be lost. Wheel motors are connected directly to the wheel, eliminating the need for a drive train. However, this means that the motor is subjected to a lot of vibration and cannot be easily cooled or maintained.

4.7.2 Ultracommuter drive system

The Ultracommuter drive system consists of two ironless wheel motors and Tritium Wavesculptor controllers. The complete schematic is shown in figure Figure 4.29.

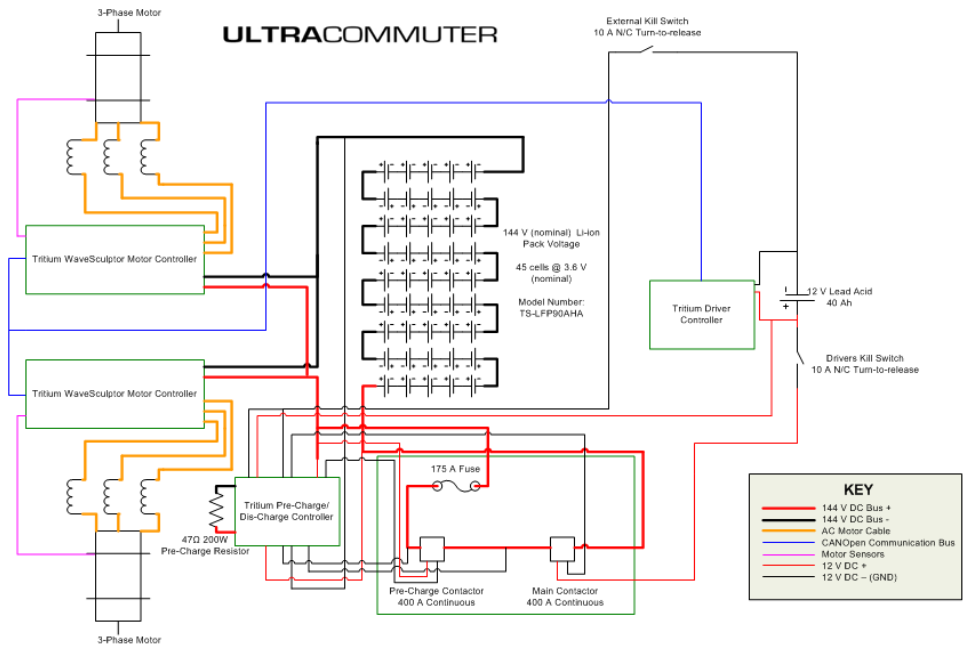
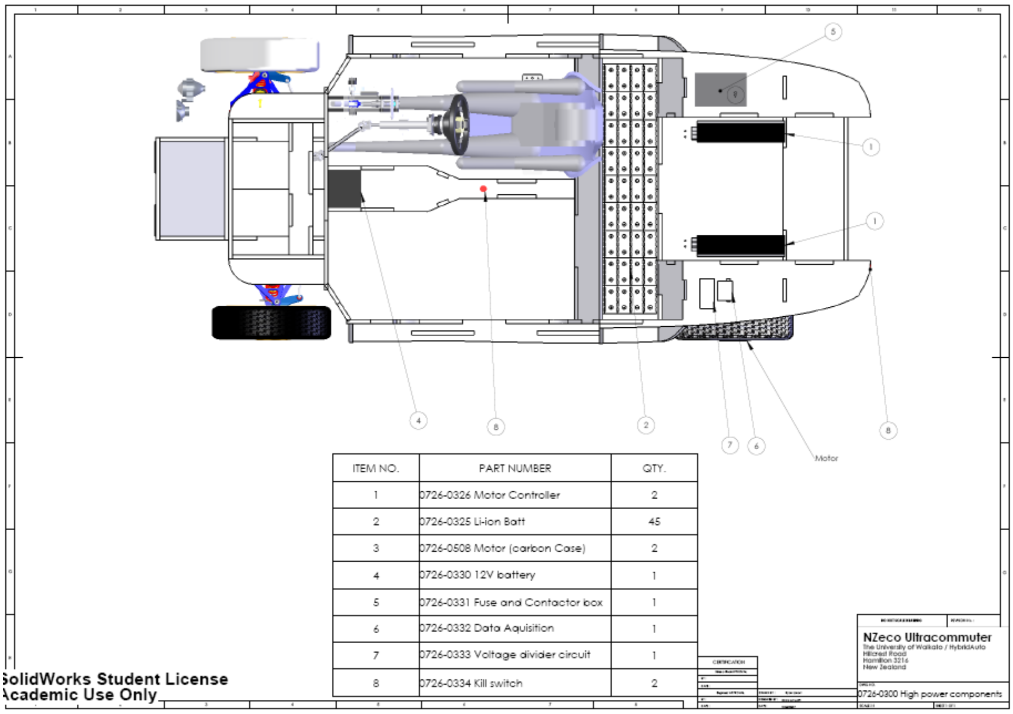


Figure 4.29 High power system schematic

To explain, starting from the motor end of the system; the motor is a 3 phase axial flux motor which receives power from the motor controller from 3 phases. Between each of these phases and the controller is a wound inductor. The motor is also connected to the controller using a Hall effects board; this board inside the motor senses magnetic field, and gives feedback to the controller. The controller can then determine the speed (in rpm) of the motor, and measures where the motor phases are in rotation, relative to were the controller 'thinks' they should be. This means that the controller can very accurately determine if the motor is running correctly or whether there is an error. There also is a thermister sensor inside the motor that the controller can read and communicate to the driver what the motor temperature is.

The controller makes decisions as to how much power to send the motor by looking at the data retrieved from the halls sensors, and also input from the driver controller. The driver controller is a microprocessor that takes inputs such as switches and the accelerator pedal, and feeds information to the controllers about what the driver wants to do. For example, if the driver puts their foot down on the pedal, the controller will send more power to the motors; alternatively, if the regenerative braking slider is pushed, the controller will switch the polarity and the motor will generate power.

The third component of the system is the precharge circuit. The pre-charge circuit is a circuit which helps to avoid accidents while switching the system on. At the first instance when the circuit is switched on, the capacitors in the controllers receive a large amount of current from the batteries (open current) and to avoid damage they are slowly charged up by this circuit.



ITEM NO.	PART NUMBER	QTY.
1	0726-0326 Motor Controller	2
2	0726-0325 Li-ion Batt	45
3	0726-0508 Motor (carbon Case)	2
4	0726-0330 12V battery	1
5	0726-0331 Fuse and Contactor box	1
6	0726-0332 Data Aquisition	1
7	0726-0333 Voltage divider circuit	1
8	0726-0334 Kill switch	2

Figure 4.30 Electronics layout

Figure 4.30 shows the layout of the electronic components in the vehicle. Careful design to minimise cable length was done to reduce the weight of the cables, and to keep the vehicle as safe as possible. All high power connectors and cabling are labelled for safety.

Ultracommuter motors

The Ultracommuter motor was designed and manufactured by *Hybrid*Auto. Years of development have gone into the wheel motor, an AC axial flux motor. The motor features an ironless Litz wire stator, and a Hachbar magnet arrangement. It can produce a peak torque of 500Nm, but more importantly, it is 97.3% efficient. A full specification is found in Table 10.

Number of phases	3
Number of poles	24 poles x 2 stators
Motor case outer diameter	391 mm
Peak Torque Continuous Torque	500 Nm 250 Nm
Total mass	24 kg
Throughput cycle efficiency - Highway Fuel economy test (HWFET)	97.3 %

Table 10 Motor specification (Greaves, Walker, & Walsh, 2002)

The Ultracommuter motor uses a carbon fibre case (Figure 4.31) to keep the weight down. With the heavier components inside the motor, including the magnets and windings, it was important to use carbon fibre to minimise the overall weight to 24kg (Greaves, Walker, & Walsh, 2002).

Figure 4.31 Ultracommuter motor

Wavesculptor Controllers

Due to the motors being developed with tritium, the decision to use tritium wavesculptors was made. There are two main parts for any modern motor controller, the microprocessor board, the 'brain' of the controller, and the high power board, where the energy is sent and distributed. The Wavescullptor acts as an inverter, converting DC electricity from the batteries into AC power for the motors. This is done with the high power board and the use of IGBT's. IGBTs allow higher voltages and currents to flow through the controller than the more typical MOSFETS. The 'brain' of the controller manages all of the information coming from the driver as well as info from the motor, and makes decisions about how much power to send, where to send it, and what feedback to give to the driver.

In the line of the motor phases between the motors and controllers were 50 µH inductors. Due to the use of Litz wire, the ironless motor has very low inductance; to raise this enough for each phase to regulate the current, wound inductors were put inline. The inductor is rated to 200A and 200V, limiting ripple to 20Hz (*Tritium 220A Inductors specification*, 2007). Wound with the Litz wire, the inductors are 99%+ efficient.

The Tritium Wavesculptor motor controller is very efficient. The efficiency plot in Figure 4.32 shows the expected efficiency of the controller at 100kph is 97.5-98% (T = 93Nm, w = 85.89).

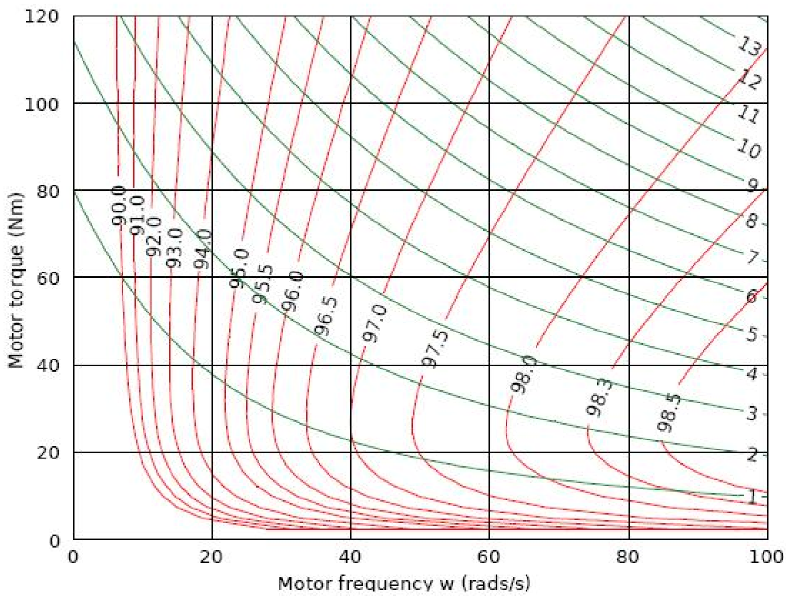


Figure 4.32 Tritium Wavesculptor efficiency plot (www.tritium.com.au)

4.8 Batteries and battery management

The battery pack is often thought to be the most important part of the electric vehicle, and is the area requiring the greatest innovation. The battery pack in the Tesla roadster consists of over 6300 cells, and is the vehicles heaviest and most expensive component, as well as its largest innovation (Wells, 2007). The GM Volt presently under development is currently waiting for its lithium ion battery pack to be completed so that testing can begin (Gawel, 2007).

There are two main types of batteries. Primary batteries are those that convert their chemical energy to electrical energy only once. Secondary batteries are designed as energy converters, to charge and discharge multiple times an 'electrochemical storage system' (Kiehne, 2003). An electric vehicle uses a secondary battery. The batteries of an electric vehicle are like the fuel tank of an ICEV, they store the energy used to drive the vehicle. While this concept seems simple, there are more factors involved with a battery than a fuel tank. These will be discussed below.

Cell/Pack voltage – The nominal voltage of a battery pack is the operating voltage of the battery; when a battery is full, the voltage will be higher, and when empty the battery voltage will be lower. The nominal voltage describes the voltage at which the battery operates, and the voltage at which the charge capacity is read.

Storage and Charge Capacity – The range of a vehicle is limited by the amount of energy a battery can store; this is measured in ampere hours (Ah). If a battery is stated as 100Ah, it can supply 1A for 100hrs or 100A for 1hr. Unfortunately, batteries often do not work like this. In general, the faster you drain the charge, the less charge you can draw from it. This is due to the side reactions inside the electrochemical cell, and is most prominent in lead acid batteries (Larminie & Lowry, 2003).

Maximum Discharge/Charge Rate – Because a battery is an electrochemical system, the rate at which the electrical energy can be discharged or charged from the battery is limited. Modern performance vehicles can require hundreds of kW of power to achieve fast accelerations or to hold top speeds; the battery must be able to supply the motors with this energy. Similarly, charging or 'refilling' the battery is also limited by this amount, meaning that battery electric cars need hours to charge up rather than seconds at a petrol station, which can exaggerate the issues with range.

Cycles – Unlike a petrol tank, a battery has a defined life, and with the strain of charging and discharging the electrochemical cell, a batteries performance will degrade, and eventually the battery will not be able to hold charge. In theory, it would be ideal for the battery pack to last the life time of an electric vehicle but with some types of battery, this is not achievable. Depth of Discharge (DOD) is a term used to describe how much energy is taken from a battery. As mentioned earlier, a battery is rated by Ah or charge storage; batteries cannot completely discharge this amount of current or they will not survive. The standard rating for cycles is said to be 'x' number of cycles at 'x' DOD, for a lead acid battery 50% DOD is common, whereas for Li-ion 80% DOD is more common.

Self-Discharge – The final problem with battery technology is self-discharge, or leaky tank syndrome. Unfortunately, many batteries discharge energy themselves, meaning that if a battery is left for too long without charging it will run out of energy. Li-ion batteries have a self discharge rate of 5% of the charge capacity per month. Lead acid batteries are well known for self discharge (Dhameja, 2001).

Battery history EV

Lead acid batteries were the first batteries used in EV's and were used until NiMH batteries were introduced in Japan in the 1970s (Westbrook, 2005). Today, a wide range of batteries are used. Table 11 shows a number of the new types of batteries, and their energy densities. An electric vehicle will always be limited in range in comparison with an internal combustion engine vehicle because of its energy density (Kiehne, 2003). A lead acid battery has an energy density of 40Wh/kg (Hussain, 2003) as opposed to 12000Wh/kg for gasoline (Kiehne, 2003).

However, batteries are now beginning to produce energy to an amount where electric vehicle drive efficiencies are making up for the difference to petrol.

Battery Type	**Specific Energy (Wh/kg)**
Lead Acid	30-55
Nickel Metal Hydrire (NiMH)	60
Li-ion	100-150
Li-Polymer	200
Zinc Air	200+
Lithium Sulphur	200-400+

Table 11 Table of Battery Specific energies (see Appendix 6)

Lead acid battery

The lead acid battery is the oldest and most well known secondary battery. Having been developed since the first electric vehicles, the energy density of a standard lead acid battery sits at 30Wh/kg. More advanced lead acid batteries such as gel filled rather than liquid filled batteries, have energy density of 35Wh/kg, but suffer from a short 700 cycle life. Laboratory developed lead acids have reached 55Wh/kg but have never been produced (Kiehne, 2003).

The American department of energy invested $19.5million in 1976 and 1977 in the development of the lead acid storage battery. With the development of the postal service electric vehicles, the lead industry stated that the lead acid battery “is the only viable power source for electric vehicles for the present and near-term future” (Anderson & Anderson, 2005). It has since been found that there are better alternatives to battery technology for the electric vehicle application in NiMH and Li-ion for higher energy densities, and longer life cycles (Kiehne, 2003).

Nickel Metal Hydride (NiMH)

NiMH batteries offered electric vehicles the first new chemistry battery. NiMH batteries were popular due to their higher energy density than lead acid of 54Wh/kg (Taniguchi, Fujioka, Ikoma, & Ohta, 2001). Development of the NiMH battery has lead to new energy densities as high as 100Wh/kg (Fetcenko et al., 2007). NiMH batteries also offer a longer life cycle than lead acid batteries, with up to 1000 cycles before needing replacement (Taniguchi, Fujioka, Ikoma, & Ohta, 2001). Despite promising energy densities and life cycles, the NiMH battery has one major downfall, self discharge. Large capacity NiMH batteries self discharge at a rate of 20% per month, meaning that in just 5 months your battery will be completely empty. This can cause significant issues with battery electric vehicles. Constant topping up of the battery would be required to ensure that, when required, the vehicle would be full and ready to go. This means that vehicles would need to be permanently plugged into the wall if left for more than a few days.

Lithium ion battery (Li-ion)

New lithium ion batteries take up 1/6th the space and are 1/6th the weight of a typical lead acid battery. They are less than half the size of nickel metal hydride batteries and a third of the weight (Bullis, 2007). Lithium ion batteries feature several advantages over other battery chemistries; they have three times the voltage of NiMH batteries at 3.6V and have no 'memory', meaning that they can be charged from any level whether 25%, 30%, 50%, or 80% full with no effect on battery life. Finally Li-ion batteries have a very flat discharge curve which means that the amount of energy in the battery can be easily calculated from the voltage (Donovan, 2005).

There are two main types of lithium ion batteries, liquid filled and solid batteries. Solid batteries have many advantages over earlier liquid batteries. Liquid batteries could never be considered for electric vehicles due to safety reasons. In comparison, solid batteries can discharge at high rates (2-3C), and due to their make up, cells of almost any charge capacity can be created (Dhameja, 2001).

Li-ion technology is undergoing large amounts of research. Toshiba, well known for their laptop Li-ion batteries, are aiming to produce a "super charge" battery for electric vehicles by 2010 (Franco, 2007). Ener1 is making the largest advances for electric vehicle Li-ion battery technology, being the only company to meet the requirements of Ford, General Motors, and Crysler. Ener1's battery technology could be seen in vehicles as early as the end of 2008. Think Electric, the largest European EV company, has already signed on to use Ener1 batteries (Franco, 2007).

Li-Sulfur

Li-S batteries offer energy densities far greater than any other rechargeable batteries currently available or being researched. They also offer battery properties very similar to the more popular Li-ion batteries (Frank, Tudron, James, Akridge, & Puglisi, 2004).

Li-S battery technology is capable of a specific energy of 400Wh/kg. Further research into the battery technology suggests that it has the potential to achieve 25% greater energy densities. Although not currently ready for production, development continues to increase the life cycle and improve the safety of the battery (Frank, Tudron, James, Akridge, & Puglisi, 2004)

Zinc-air

Zinc-air batteries are referred to as energy cassettes, offering very high energy densities of 200Wh/kg. Zinc-air batteries are made up of a zinc anode and have an air pocket that is released, allowing the chemical reaction of

$2\ Zn + O_2 = 2\ ZnO\ (E_o = 1.65\ V)$

The Zinc-air cassette is a primary battery; after one use, it can not be recharged. The problem with Zinc-air batteries is the requirement of the Zinc Oxide anode to be removed, refurbished, and replaced. Options for the use of Zinc-air batteries are shown below in Figure 4.33 with the suggestions that batteries could be delivered or exchanged at battery exchange stations (Goldstein, Brown, & Koretz, 1999).

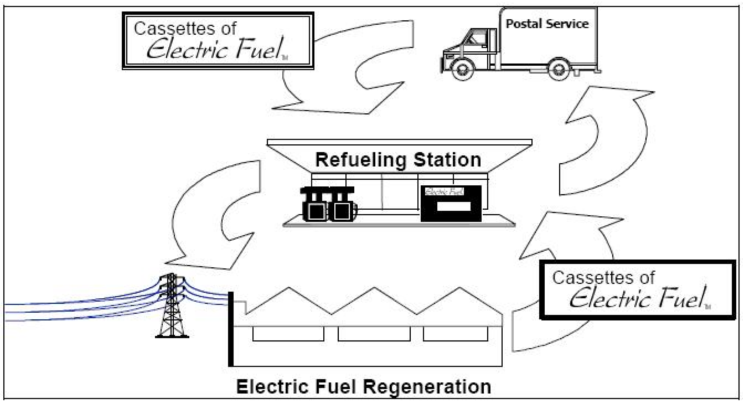


Figure 4.33 Zinc Air Issue source: www.electric-fuel.com

The real potential for zinc-air batteries are in emergency power supplies. A small zinc-air battery could be stored in the vehicle, similar to a spare tyre. The battery could be permanently plugged in and only the air released by an emergency tag; this could provide 20-50km of range to get someone home, or to safety.

Ultracapacitors

When Ultracapacitors became able to produce a high number of farads, they were touted to become part of a vehicle drive system. Ultracapacitors are able to absorb energy and expel energy very quickly with the ability to do this for thousands of cycles. The idea behind using ultracapacitors is to reduce the strain on a battery by expelling the large amount of energy required under initial acceleration of a vehicle and absorbing the energy under regenerative braking. The primary function of this is to extend the life of the battery, and may also improve a cars ability to accelerate and decelerate quickly (Tuite, 2007).

Overall, the development of battery technology is encouraging and is shifting batteries towards new levels of energy storage, safety, and reliability. The longer these developments continue, the more viable EV's will become. Ford believes that over the next three to five years many Li-ion battery electric vehicle's will be produced with large ranges and longer lives due to improved battery technology (Franco, 2007).

4.8.1 Battery Management

"The principal defect in a storage battery is its modesty. It does not spark, creak, groan, nor slow down under overload. It does not rotate, and instead stays where it is put, and will silently work up to the point of destruction without making any audible or visible signs of distress" (Mom, 2004). Although engineers have known about the battery's reluctance to express errors, batteries have often been viewed as a passive standalone component whose sole function is to provide energy (Karden, Ploumen, Fricke, Miller, & Snyder, 2006). Battery monitoring involves the continuous calculation of the batteries state; this is done by the measured values of the cells making up the battery pack. Generally, the voltage, current, and temperature are recorded. A battery management system takes this one step further and controls charge and discharge as well as thermal properties (Karden, Ploumen, Fricke, Miller, & Snyder, 2006).

4.8.2 Charging

Charging the battery pack is one of the critical selling points of any battery electric vehicle; the faster a vehicle can be charged the happier the owners. However charging a battery pack quickly is often not very efficient. Trickle charging of a very small amount of energy often extends the lifetime of batteries, and lead acid batteries must be fully drained before recharged. New battery technology is beginning to deliver solutions to these problems. NiMH and Li-ion do not have the 'memory' that lead acid batteries have, in other words they have the ability to be charged up at any point of the cycle. Li-ion batteries also now have the ability to accept a high charging current, speeding up the charging process. The problem now is not so much the rate at which the batteries can absorb the energy, but more the amount of energy that standard household sockets can put out. A standard wall socket in New Zealand produces 240V at 10A = 2.4kW. For a 13kW battery pack, that would mean a minimum 5+ hour charge. However, many houses now feature 15, 20, or 30Amp wall sockets meaning batteries could be charged up as quickly as 2 hours. It is the author's opinion that with Li-ion batteries, 2hrs is approximately all the time it would take to charge a well equalized battery pack to close to full charge.

4.8.3 Ultracommuter batteries and monitoring

The requirements of the Ultracommuter battery pack are as follows;

- 144V nominal Voltage (+- 10V)
- 200A discharge rate (Pref 400Amp)
- Minimum 10kWh capacity
- Maximum 12hr Charge time
- Small enough cells to be lifted in and out
- Reliable for more than >800 cycles
- Maximum weight 200kg
- Low cost

After research into all battery options, these requirements gave three main battery options as shown in Table 12. All three of these options were available and could be manufactured, shipped, and received under the timeline, by reputable companies. Much of the battery technology discussed is only available in small quantities and much of the latest technology has never been mass produced.

	Thundersky Li-ion	Kokam Li-Poly	Sunox Pb-acid SB 12-40
Nominal Voltage	3.2	3.7	12V
Capacity (Ah)	90	200	40
Capacity (Wh)	288	740	480
Weight (kg)	3	4.44	13.8
Energy Density (Wh/kg)	96	167	34.8
Cycles at 80% DOD	> 2000	> 800	<100
Volume	2.17	2.07	5.59
No. cells per Pack	45	40	12
Pack V	144	148	144
Pack capacity	12.96kWh	29.6kWh	5.76
Pack volume (L)	98	82	67
Pack weight	135	178	165.6
Est.range	200km	450km	<100
Price	$NZ17,357 3 packs	$NZ 108,178 1 pack	$NZ1200 1 pack

Table 12 Battery Options (see Appendix 7)

The decision to use the Thundersky batteries was made simply on price. With a small total budget, the $100,000+ Li-polymer batteries from Kokam would have used two-thirds of the projects total budget. The thunder-sky batteries also had added advantages, the Li-ion battery model LFP90AHA is a battery with a Lithium Iron and Phosphate core, different from the more conventional LCP and LMP batteries.

LCP		LFP		LMP	
Chemical Element	Index	Chemical Element	Index	Chemical Element	Index
Fe	0.005%	Fe	42%	Fe	0.1%
Mn	11%	P	16%	Ca	0.3%
Mg	0.7%	Mn	0.5%	PP	3.3%
Co	1%	Ca	0.3%	Ni	1.7%
C	5.1%	Graphite	5%	Mn	18.6%
Li	28%	Na	0.01%	C	5.1%
Cu	10%	C	3.1%	Li	25%
Al	6%	Li	3.4%	Cu	10%
PP	3.3%	PP	3.3%	Al	6%
Graphite	7.1%	Cu	10%	Graphite	6%
Ni	8.1%	Al	6%	PU	3.1%
Lix	9%	Lix	8%	Lix	9%
F	3.1%	F	3.3%	F	3.1%

Table 13 Thunder-sky battery content. (source: http://www.everspring.net)

Lithium batteries are known to be unstable and explosive, but the LFP style battery is known as the 'non-explosive' lithium, and also the most environmentally friendly lithium on the market. The LFP battery is only 3.4% Li compared with 28% and 25% Li for the LCP and LMP batteries, as seen in Table 13.

As shown in Table 14, the Thundersky battery meet the minimum recycle number, and the range and performance criteria required for the Ultracommuter.

Parameter	TS-LFP90AHA
Nominal Voltage	3.2 V
Operational Voltage	2.5 – 4.25 V
Nominal Capacity	90 Ah
Max. Discharge Current	3CA / 270 A (const.) 10CA / 900 A(impulse)
Cycle Life	≥ 2000 (80% DOD) ≥ 3000 (70% DOD)
Operating Temperature	-25 – 75 ºC
Weight	3 kg ± 100 g
Dimensions (L x W x H)	145 x 217 x 68 mm
Energy by Volume	135 Wh/L
Energy by Weight	96 Wh/kg

Table 14 Thundersky TS-LFP90AHA specification

The Thundersky batteries were first tested to acquire data about how the batteries behaved. Charge and discharge curve are commonly used in EV design to design systems that can be put in place for the safety of the driver and other road users.

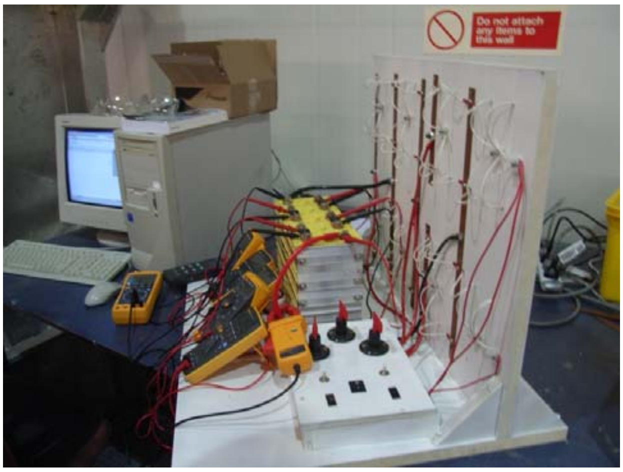


Figure 4.34 Battery testing rig

The testing of the batteries gave encouraging results, with very similar discharge profiles, implying that the cells were of similar nature in terms of performance (Figure 4.35).

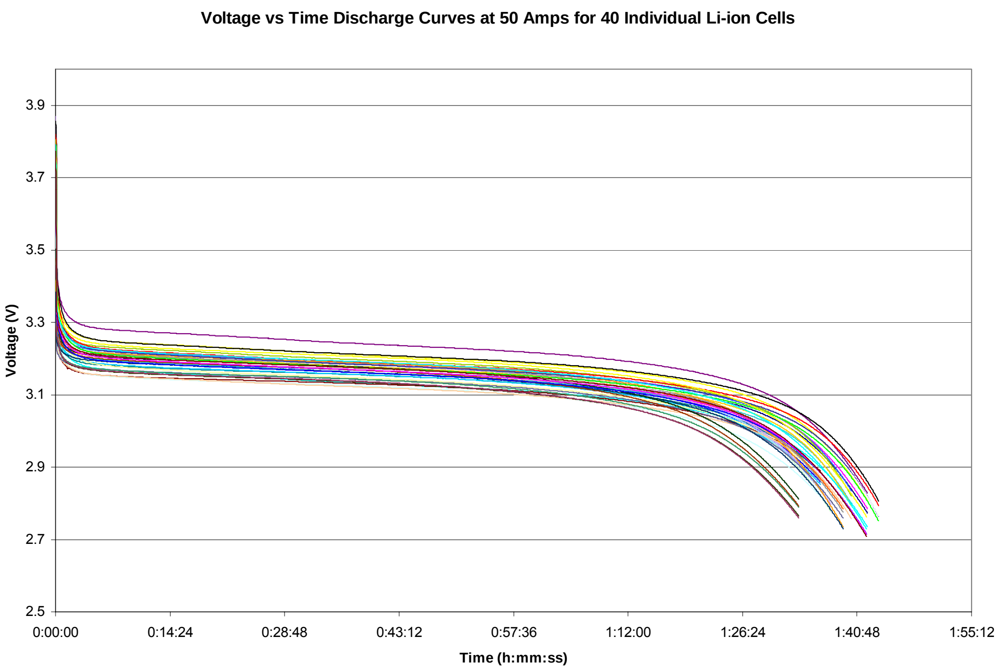


Figure 4.35 Cell discharge curves for Thundersky cells.

The Thundersky batteries have a unique charge voltage. Whilst charging, the maximum voltage is 4.25V and this is reached at very low currents ~1A, implying that the battery is full. But once the charge load is taken off, the battery voltage quickly drops Figure 4.35 shows the results from 40 cell tests at 50amp. As typical with lithium batteries, there is a drop of the voltage from a ‘full’ voltage of around 3.5V to around 3.3V when the load is applied, before reaching its nominal voltage of 3.2V. The voltage plateau of 3.2V is where the batteries will sit for around 70% of their capacity before reaching the point called the knee. The knee is when the drop off begins, and the batteries voltage will rapidly drop off to the minimum voltage of 2.5V.

Most promising from the testing results were the performance of the batteries; the batteries appeared to have a lot of energy storage. With battery specifications giving a maximum energy discharge of 72Ah (90Ah * 80% depth of discharge) the Thundersky battery outdid this mark yielding values of around 80Ah meaning more energy for the vehicle to use. The Thundersky lithium ion batteries also performed very well thermally, with only temperature rises of 5°C over the tests. Battery tests were also performed at 40°C and similar temperature rises were found.

To meet the requirements of the WSC, three battery packs at approximately 200km range each were needed. This meant that they needed to be easily removed and replaced when flat. The batteries were set up in strings of five cells; a single string of five batteries weighs 15kg and can easily be moved by one person. With nine strings making up one pack, a single battery pack consisted of 45 cells at 3.2V in series giving a 144V pack voltage.

Figure 4.36 Ultracommuter battery pack

Figure 4.36 shows a full battery pack inside the Ultracommuter including the battery monitoring system (green cables).

Ultracommuter Chargers

The charger for the Ultracommuter was set up to charge one battery pack. The decision to use an external charger was made for two reasons. The first was efficiency and safety; because of the short development, the battery chargers were operating well within their operational performance, meaning that several components were over specified for their tasks. This meant that the charge was larger and heavier than initially required, and would cause an overall heavier vehicle. With limited testing, the possibility of a malfunction inside the prototype vehicle was not wanted, so for safety the charging was done external of the vehicle. The second reason was for practicality. Having three packs and three chargers at the world solar challenge, the need to have the option to move away from the vehicle was required to make sure all three packs could be charged up in time.

Figure 4.37 Ultracommuter Charging on WSC

The charger was rated up to 20kW but with the differing supplies in the Australian Outback, no more than 2.5kW was ever extracted from the system. The charges proved simple to use and effective.

Ultracommuter battery monitoring

With the time pressures surrounding the WSC, the decision was made to use a basic battery monitoring system rather than an integrated management system. The system consisted of a Texas Instruments data acquisition (DAQ) card NI USB-6210 and was monitored using LabView as shown in Figure 4.38.

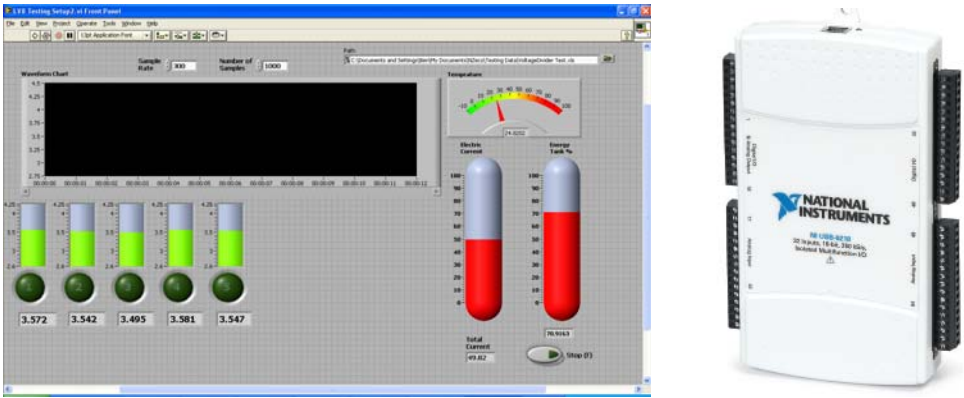


Figure 4.38 Ultracommuter battery monitoring – Labview and DAQ card

The DAQ card took 16 analogue inputs from a voltage circuit. The voltage circuit used a voltage divider due to the high voltage of the pack (up to 192V) to convert them to voltages falling inside the cards range (0-10V). Labview then took these inputs and multiplied them to get the voltages from the battery strings. Figure 4.38 shows the output the driver could see showing the battery voltages for five strings (nine for the complete system) and also giving the capacity in a bar graph form, as well as a temperature gage. This system was easily incorporated into the vehicle using the small laptop integrated into the vehicles interior.

4.8.4 Range estimates

The range of the Ultracommuter is estimated from the equation found in section 2.5:

$$P = \left(\frac{\rho v^2 C_D A}{2} + mRR + ma + mgsin\theta \right) \times v$$

Because no vehicle is 100% efficient, the drive efficiency of the system needs to be taken into account. This is done by dividing the whole equation by a vehicle efficiency factor (η) of 0.92, as the estimated efficiency of the system is 92%

$$P = \left(\left(\frac{\rho v^2 C_D A}{2} + mRR + ma + mgsin\theta \right) \times v \right) \div \eta$$

Where:

$\rho = 1.2$

$v = 100kph = 27.8ms^{-1}$

$C_D = 0.26$

$A = 1.44$

$RR = 0.01$

$a = 0$

$m = 700$

$g = 9.81ms^{-2}$

$\theta = 0°$

$\eta = 92\%$

Therefore **P =7.306 kW per hour at 100kph i.e. 7.3kWh to travel 100km**

Battery Capacity

$P = V \times I \times DOD$ for a battery

Where:

$V = 144V$

$I = 90Ah$

$DOD = 85\% = 0.85$

Therefore

$P = 144 \times 90 \times 0.85$

$P = 11016W = 11.0kW$

Range at 100km/h

$$Range = \frac{11kWh}{7.3Wh} = 1.5076$$

$1.5076 \times 100km = 150.8km$

The range of 150km for the Ultracommuter was less than the desired range of 200km, but the effect of speed as shown in Figure 4.39, shows that if the speed is reduced to around 81km/h the range is extended to 200km.

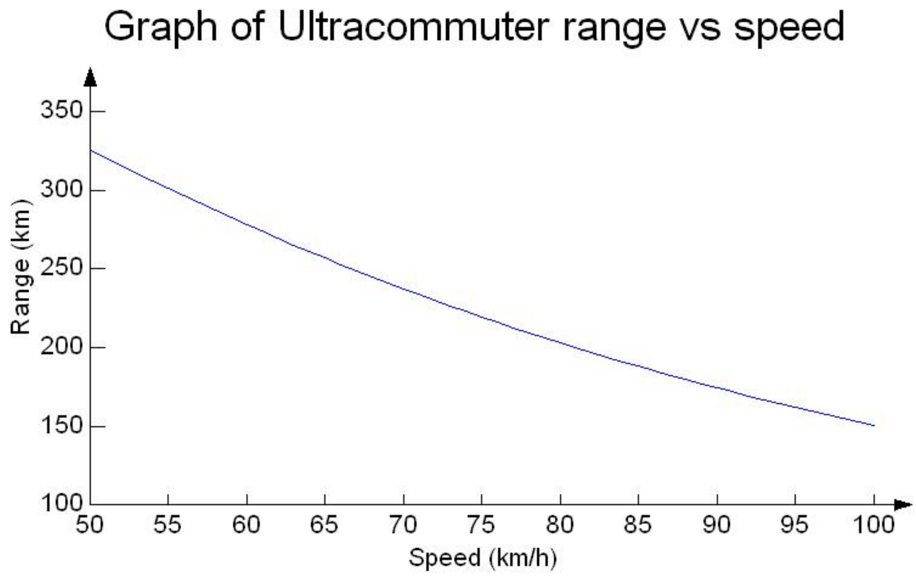


Figure 4.39 Ultracommuter range verse velocity graph

4.9 Low power electronics

The low power electronics system on an electric vehicle consists of everything that falls underneath 24V. The low power system consists of lighting, both interior and exterior, and the driver interface.

The convention for most modern electric vehicles is to have a separate low power electronics system; this is done for safety reasons. If drivers run down the battery pack they still have the security of lighting and perhaps communication, similar to a gasoline powered vehicle. Secondly, the use of air-conditioning, lighting etc can not run down the vehicles battery pack, ensuring maximum range for the vehicle.

4.9.1 Light Emitting Diodes (LED)

A LED is a semiconductor that emits both visible and infrared light. The light given off is caused by an energy release of electrons while falling back into ‘holes’ between the junction gap of the semiconductor. LEDs have been used in the automotive industry since the early 1980’s. Their use was mainly restricted to turning signal indicators and other dash lights. With the development of High-brightness (HB) LEDs, exterior lighting began to use LEDs. In 1988, Nissan used an LED centre mounted high rear stop lamp in their 280Z. This used an array of 72 aluminium gallium arsenide (AlGaAs) red LEDs, and was the first use of LED’s for exterior lighting. In 2004, 40% of high rear taillights used LEDs, but just 4% of other rear tail and signal lighting used LED’s; this is largely due to the high cost of LED technology. In 2004, the first use of LED’s in headlamps was in the Audi A8, a US$120,000 vehicle (Steele, 2005).

4.9.2 Ultracommuter LPE

The low power electronics system on the Ultracommuter consists of two areas, lighting, and battery monitoring (section 4.8.3).

Interior lighting on the Ultracommuter is planned to use high and low power LED’s to help reduce battery consumption. Lighting will also be done using coloured LED’s as the use of different coloured LED lights can aid passengers inside the vehicle. Courtesy lights could be blue to allow passengers to not be blinded by bright white light. Red LED’s could be used as reading lights for the occupants of the vehicle, meaning that the driver will not be distracted but the passengers may still be able to be entertained and read while travelling.

Figure 4.40 shows the lighting on the Ultracommuter. It consists of Hella LED rear taillights, custom made LED indicators. The total power use of the lighting system with all of the indicators going and stop lights running is 48W.

Figure 4.40 Ultracommuter LPE lighting

The low power system also consists of a horn to meet the safety requirements of the LVVTA.

Chapter 5 Discussion

The Ultracommuter project was deemed a success by the vehicles completion and participation in the World Solar Challenge 2007. The results for a project of this nature do not lend themselves to be easily judged; rather the vehicles success largely depends on its comparison to a conventional internal combustion engine vehicle.

5.1 Ultracommuter testing

Driving the Ultracommuter is much like driving an internal combustion vehicle. The driving position is low, with the driver sitting approximately 200mm off the ground. This leads to driver entry and exit from the car being a challenge. Once in the driver position the driver feels secure, and is able to lock him or herself into the Racetech seat and concentrate on driving. Even with the four point race harness fastened, the driver can still access all of the switches and controls inside the vehicle. The steering wheel is situated at the right height for most drivers, and has a speedometer mounted behind it. The leg room for the driver is not large, but adequate for the majority of people. The accelerator and brake pedal have good separation and feel sturdy underfoot. Front vision is excellent; the A-pillar does create a large blind spot but does not hinder driving.

Handling

The Ultracommuter handled in an un-tuned manner. The suspension was very hard, and the springs were slightly too stiff for the application. However, it was the dampers that were the main reason for the hard ride, as they were set up wrong. Because of the very stiff ride, and the high pressure run in the tyres for efficiency, the ride was uncomfortable. While driving, the Ultracommuter felt ‘loose’; a small correction would develop into a swerve across the road. The vehicle also felt uneasy when travelling over 85kph. Although the handling was uneasy while driving straight, cornering around the test track and through streets was different. The vehicle responded very well to turning and cornering. The most enjoyable driving experienced by drivers was through the turns. The steering was sharp and the vehicle responded well to purposeful cornering. This encouraged the drivers and engineers to believe that the suspension faults were due to the setup of the suspension rather than a fundamental design flaw. The vehicle is expected to drive like a regular car once the dampers are replaced.

Turning

Although the turning radius of the Ultracommuter may not be as large as a normal car, it was more than adequate for road driving. However a driver may find it difficult to manoeuvre in a tight car park.

Braking

Overall, the braking system on the Ultracommuter was very good. The biggest issue was that the hydraulic braking system was not powerful enough in isolation. Upon investigation, it was found that the wrong master cylinder was being used. The regenerative braking was excellent; drivers could confidently use the regenerative braking to stop the vehicle without the need to use the hydraulic braking system.

Acceleration

Under acceleration, the car felt good; the back end of the car sat down under acceleration due to the weight distribution and rear wheel drive. The car accelerated quickly once sine wave switching was reached on the controller (above 20kph). Acceleration between 30-70kph felt 'quick' for the drivers relative to a conventional gasoline powered vehicle.

Top speed

The top speed recorded by the Ultracommuter was 105kph down a slight hill. The top speed of the vehicle is limited by the back emf of the motor, once this reaches the voltage of the bus the vehicle can no longer accelerate. If the nominal voltage was raised by 5-10v (an extra 2-3 batteries) the vehicle would be able to travel at speeds of 120kph. Under full charge (170V) the vehicle should be able to reach speeds of 130-140kph.

Range/Battery performance

Before the WSC, it was estimated that the battery range would be 160-200km. During the WSC, the Ultracommuter completed ranges of up to 205km, despite the battery monitoring system failing. With appropriate battery monitoring and management, ranges of 200-210km should be able to be completed regularly.

Reliability

The reliability of the electronics system on the Ultracommuter was the only performance criteria that the vehicle failed. The 3000km WSC event consisted of six days of driving approximately 500km. Over the first four days, only 800km out of 2000km was driven by the electric vehicle, the rest was completed on a trailer. This was due to a fault in the left motor controller. Although not realised at the time, the vehicle was more than capable being driven on the last motor, so for the last two days the car was driven without problem on just one motor. Once reviewed, it was found that a small soldering issue in the controller was causing the problem. This was simple to fix, and the car now runs well with both motors. This issue illustrates that the quality control on these high performance electronic components needs to be of the highest level to ensure problems like this do not occur.

Figure 5.1 Ultracommuter driving on WSC 2007

Ultracommuter design and manufacture issues

Overall, the design and construction of the vehicle was inhibited by two main factors, cost and experience.

The cost problem

The design of the Ultracommuter was limited due to the budget available. This meant that several of the components could not be constructed out of the parts or materials that would solve the problem most successfully. Budget constraints also meant that several components designs were put off or altered as finances changed during the project.

Design intricacies

The design of the Ultracommuter relies on several individual components and the systems surrounding them. The integration of these components to produce the vehicle was quickly found to be the most critical factor. A good example of this was the manufacturing of the body shell. Although the process of producing the body shell was made relatively simple by the use of local industry, the integration of the shell to the body was very difficult. While stiff enough to perform its function, the body shell still sagged slightly under its own weight. This meant that when it was attached to the chassis it could be bent and twisted only mm to fit. Integrating further body parts became difficult because areas did not match up easily. Although the mechanism of attaching the shell (bolts and aluminium brackets) was easy to complete, making the panels line up correctly became more challenging, and resulted in the doors being misaligned.

Chapter 6 Titanium and its alloys

6.1 Titanium

Titanium has been used commercially since 1950 and is known for its high strength of 415 MPa for pure titanium through to over 1300 MPa for Titanium alloys. Titanium's other properties include good corrosion resistance and being lightweight, with a density of just 56% of alloy steel and a similar strength, giving it an excellent strength versus weight ratio. Titanium also has good mechanical working, up to 535°C, lending it to unique high temperature applications (Degarmo, Kosher, & Ronald, 2003).

6.2 Titanium Aluminides

Titanium aluminides are metals containing between 46 and 52% aluminium (Donachie, 2000). There are two main types of titanium aluminides, the more common alpha 2 phase α-2 Ti_3Al, and the gamma phase γ TiAl (Donachie, 2000) The focus of this research is around the gamma aluminide γ-TiAl.

Gamma titanium aluminide has a low density, 3900-4200kg/m^3 lower than pure titanium at 4500kg/m^3. This can be attributed to the high wt% of aluminium present of 45-48%. γ-TiAl also has a high melting point of 1460°C, high elastic modulus, and good corrosion and oxidation resistance. This is mainly due to γ-TiAl structure, it has a highly ordered nature, and strong directional bonding between atoms (Leyens & Peters, 2006).

The large amount of Al atoms in the materials structure gives γ-TiAl a higher corrosion resistance than typical titanium alloys. The gamma phased alloy has a tetragonal $l1_0$ structure shown in Figure 6.1 (Leyens & Peters, 2006).

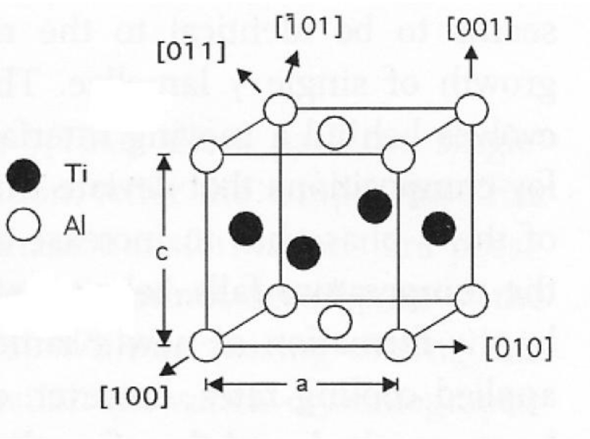


Figure 6.1 γ-TiAl structure (Leyens & Peters, 2006)

Gamma titanium components are termed as most attractive for mechanical applications due to their high temperature resistance, higher corrosion resistance, and higher modulus (Table 15) than other titanium alloys (Li, 1996).

Property	Ti-based alloys	Ti_3Al-based α_2 alloys	TiAl-based γ alloys	superalloys
Density (g/cm^3)	4.5	4.1–4.7	3.7–3.9	8.3
RT modulus (GPa)	96–115	120–145	160–176	206
RT Yield strength (MPa)	380–1115	700–990	400–630	250–1310*
RT Tensile strength (MPa)	480–1200	800–1140	450–700	620–1620*
Highest temperature with high creep strength (°C)	600	750	1000	1090
Temperature of oxidation (°C)	600	650	900–1000	1090
Ductility (%) at RT	10–20	2–7	1–3	3–5
Ductility (%) at high T	High	10–20	10–90	10–20
Structure	hcp/bcc	DO19	$L1_0$	Fcc/$L1_2$

Table 15 Titanium Alloy properties table (Kassner & Perez-Prado, 2004).

Other properties of gamma titanium aluminides include high strength, with a yield stress of 400-630MPa MPa (Kassner & Perez-Prado, 2004). Gamma TiAl suffers from low ductility at room temperature, but ductility rises to that higher than steel at temperatures over 500°C. γ-TiAl also has low fracture toughness which means that it has a low tolerance for damage (Leyens & Peters, 2006).

Titanium Aluminides are designed for applications where high temperature, low weight and high operating speeds are required (Leyens & Peters, 2006), and in relation to the automotive industry the most important properties of Titanium alloys are high strength to density ratio, and outstanding corrosion resistance (Froes, Friedrich, Kiese, & Bergoint, 2004).

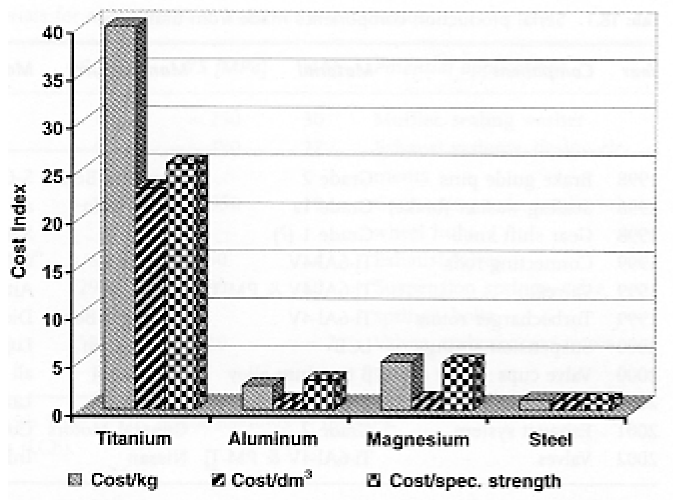


Figure 6.2 Comparions of lightweight materials (Leyens & Peters, 2006)

The problem with Titanium is its high cost. As shown in Figure 6.2 Titanium has a very high cost in comparison to Aluminium, Magnesium and Steel the major metals used in the automotive industry (Leyens & Peters, 2006).

6.2.1 Manufacturing/Production

Because of γ-TiAls low ductility at low (room) temperatures, the standard wrought processes surrounding metal working, like rolling and forging, are not able to be performed (Li, 1996). Investment castings is one of the most straight forward ways of producing γ-TiAl components, in the mid 1990s casting is more cost effective for producing parts than from wrought (Li, 1996).

Powder Metallurgy (PM) is also a popular method of manufacturing γ-TiAls due to more consistent results, with low variation between mechanical properties of samples (Thomas, Raviart, & Popoff, 2005) . Also it has been reported that PM components have better chemical and structural properties over cast components (Yolton, Habel, & Clemens, 1997).

6.3 Current Uses of Titanium in the Automotive Industry

By the mid 1950's Titanium was already being used in the automotive industry. The body of the Titanium firebird II produced by General Motors was completely manufactured from Titanium (Leyens & Peters, 2006).

Figure 6.3 The 1956 Titanium Firebird II with a body made completely from titanium source:http://www.diseno-art.com/images/firebird_II_rear.jpg

Since the 1950s, the titanium industry has been trying to break into the automotive industry maintaining to be the answer for the growing demand for weight reduction in vehicles, and the fuel efficiency and performance benefits of this. The developments in the reduction of cost of titanium continue to see a rise in the use of the metal in the industry. Although there is great potential for titanium and its alloys to be used in the industry, the high cost continues to restrict its use in favour of more cost effective light weight alloys such as aluminium (Leyens & Peters, 2006)

The use of titanium began in the automotive racing industry, but did not appear in the commercial automotive world until the Honda NSX in 1992. The titanium alloy connecting rod used in the Honda NSX supercar was 30% lighter than the standard medium carbon steel rod used previously; the use of this metal was necessary to reach the high 8000rpm of the VTEC engine. The development of the titanium component took 10 years (Furukawa, 1992)

Standard components manufactured from titanium.			
Year	**Component**	**Manufacturer**	**Model**
1992	Connecting rods	Ti-3Al-2V-rare earth	Honda Acura NSX
1994	Connecting rods	Ti-6Al-4V	Ferrari All 12-cyl.
1996	Wheel rim screws	Ti-6Al-4V	Porsche Sport wheel option
1998	Brake pad guide pins	Ti grade 2	Daimler S-Class
1998	Brake sealing washers	Ti grade 1s	Volkswagen All
1998	Gearshift knob	Ti grade 1	Honda S2000 Roadster
1999	Connecting rods	Ti-6Al-4V	Porsche GT3
1999	Valves	Ti-6Al-4V & PM-Ti	Toyota Altezza 6-cyl.
1999	Turbo charger wheel	Ti-6Al-4V	Daimler Truck diesel
2000	Suspension springs	TIMETAL LCB	Volkswagen Lupo FSI
2000	Wheel rim screws	Ti-6Al-4V	BMW M-Techn. Option
2000	Valve spring retainers	β-titanium alloys	Mitsubishi All 1.8 l – 4-cyl.
2000	Turbo charger wheel	γ-TiAl	Mitsubishi Lancer
2001	Exhaust system	Ti grade 2	General Motors Corvette Z06
2001	Wheel rim screws	Ti-6Al-4V	Volkswagen Sport package GTI
2002	Valves	Ti-6Al-4V & PM-Ti	Nissan Infiniti Q45
2003	Suspension springs	TIMETAL LCB	Ferrari 360 Stradale

Table 16 Current uses of titanium use in the automotive industry (Froes, Friedrich, Kiese, & Bergoint, 2004)

Due to its high price, titanium was initially only used in high performance race cars, exotic supercars such as Ferraris and Porsches, and high priced European vehicles as shown in Table 16. Now, in the 21st century, the use of titanium components is becoming more common in lower priced commercial vehicles such as the Toyota Altezza and Volkswagen golf (Leyens & Peters, 2006).

Titanium intake valves are used in the Toyota Altezza as the use of titanium valves reduces the mass due to the low modulus and density of titanium. The reduction in mass increases the engines efficiency by approximately 10%. Another benefit of the use of titanium is the reduction of valve chatter at high speeds (Froes, Friedrich, Kiese, & Bergoint, 2004).

6.4 Potential uses of TiAl in automotive components

Because of the cost limitations of the use of titanium, most research into the potential uses of titanium in the automobile industry have revolved around high value areas such as the engine and exhaust components.

6.4.1 Engine

The use of titanium in the automotive industry has largely in engine components. Mercedes, Volkswagen, Porsche, Nissan, Honda, Toyota, and General Motors all use titanium components in various engine components (see Table 16).

Similar to the titanium intake valves used in the Toyota Altezza, Gebauer (2005) believes that the development of titanium exhaust valves is on the brink of becoming mainstream. Due to the high temperature resistance of certain titanium compounds, these can be sprayed over a standard titanium valve, giving a light weight exhaust valve. The lighter the weight of the exhaust valve, the faster the spent gases from the combustion process are evacuated, which in turn will increase the engine performance (Gebauer, 2005).

Another component inside the engine that could benefit from the use of titanium are the connecting rods. The strength, fatigue resistance, and stiffness of titanium all meet the requirements of this application. The use of light weight titanium reduces the noise, vibration, and harshness of the engine, and can improve fuel economy and performance. Ferrari and Honda have also found that the use of titanium allows for the movement of the centre of gravity of the component, allowing an even larger improvement in the benefits (Froes, Friedrich, Kiese, & Bergoint, 2004).

Finally, piston assemblies could potentially be manufactured out of titanium. The potential increased operating temperatures of titanium over that of currently used aluminium, could, with the reduction in mass, lower the friction losers currently found in the engine, and thus improve fuel efficiency and engine response (Froes, Friedrich, Kiese, & Bergoint, 2004).

Smarsly, Baur, Glitz, Clemens, Khan, and Thomas (2001) explain the advantage of using titanium wheels in turbochargers. 'Turbocharger wheels made of γ-TiAl improve the rotational response, reducing so-called "turbolag" and thus increasing the acceleration speed since the mass momentum is decreased' (Smarsly et al., 2001). Other research into the use of γ-TiAl turbine wheels shows that a reduction in inertia of 42% can be achieved (McQuay, 2001).

Exhaust

Titanium alumina alloys have excellent corrosion resistance, and along with its light weight, it is a perfect material for this application. A typical stainless steel exhaust system lasts for only 7 years, in comparison to a titanium exhaust which lasts the lifetime of a corvette Z06, making it a cost effective solution. This, along with the weight saving (up to 50% in a VW lupo) demonstrates the perfect application for titanium alumina (Froes, Friedrich, Kiese, & Bergoint, 2004).

The Austrian sports motorcycle manufacturer KTM also uses a titanium exhaust system just 0.3mm thick for weight reduction. Remus, a world leading aftermarket motorcycle part manufacturer, manufactures titanium mufflers weighing at only 2.5kg compared with 5kg of a standard exhaust.

6.4.2 Suspension

Because of the low ductility of titanium, most situations where components are under dynamic loadings are ruled out, but the high corrosion resistance and low density offer some interesting opportunities in areas of un-sprung mass. As stated in section 4.5, the importance of reducing the weight of un-sprung mass means that it is a good place to start, relative to titanium's higher cost.

Looking at the components that make up un-sprung mass:

- Spring
- Damper
- Suspension links (wishbones)
- Upright
- Hub
- Brake calliper, lines, brake disc
- Wheels and tyres

The spring, damper, suspension shock, and spring set ups are a huge area of research, currently research into the use of any and all materials is under way; unfortunately, because of titanium's low ductility, it is not really suited to a damper application with the huge loads suspension struts are put under everyday.

Springs

Titanium's promise as a spring material is summed up in the statement by ("Worth the weight", 2004), "owing to its high-strength, low-shear modulus and low density, the space age alloy is particularly suitable as a spring material" 34. Ferrari went on to use titanium springs in their Challenge Stradale, which have an impressive weight saving of 39% on the front and 28% at the rear over typical steel springs. Titanium springs also allowed Ferrari to build springs much stiffer than they would usually produce, giving better feedback to the driver, and better vehicle performance. Finally, the corrosion resistance of titanium meant the springs would not need to be coated like typical steel springs. Saving weight.

It is not only high performance sports cars that use titanium springs, the VW Lupo, a relatively conventional family automobile, has used titanium springs in the rear of the car since 2000 (Froes, Friedrich, Kiese, & Bergoint, 2004)

Wishbones, linkages, and suspension rods

Wishbones, linkages, and suspension rods all have too higher loading for TiAl components. Suspension uprights, hubs, and wheels also undergo large impulse forces, making them unsuitable for titanium alloys.

Braking system

The brake system offers the most interesting prospect for the use of TiAl. With titanium already used as the pistons in the callipers of some disc brake systems, the ground work has already been done. Taking a more in depth look at the braking system;

Disc rotors

(Froes, Friedrich, Kiese, & Bergoint, 2004) suggested that brake discs are not a potential use for titanium alloys as "the low thermal conductivity and poor wear resistance of titanium negates use of titanium in brake rotors" (41-42). In terms of wear, TiAl has not yet had sufficient research and testing done, it is however the authors opinion that the wear should be able to withstand the requirements of braking, especially when the following factors are taken into account:

- Brake discs of the future are going to be put under less and less loading due to the reduction in mass of vehicle of the future. Brakes of the future will also be aided by the use of re-generative braking where electric motors will be absorbing as much of the energy as possible.
- Currently brake rotors are 'reskimmed' every 50,000 km's. TiAl coatings could simply be sprayed on instead.

The thermal conductivity of Titanium could be offset if the TiAl is used as a coating on an aluminium brake rotor, as against a solid titanium rotor. This would give the component the greatest potential weight saving with the use of aluminium, and the TiAl coating could act as a barrier to protect the aluminium from the heat.

6.4.3 Other Components

Fasteners

TiAl fasteners could potentially be used in a suspension system. With a surface coating to endure the pre-loading required (Froes, Friedrich, Kiese, & Bergoint, 2004), lightweight TiAl fasteners could play a critical role in reduction of un67 -

sprung mass, with applications as wheel nuts, or motor screws for in-wheel electric hub motors.

Batteries

While only a recent development in the battery industry, the use of titanium in battery packs is becoming more mainstream. Energizer, one of the world's largest battery companies has introduced a titanium branded AA battery. Although it is an alkaline based battery, the Titanium e2 uses titanium technology to increase battery life by a claimed 85%. With 25 patents on this technology, Energizer believes there is a potential benefit in the use of titanium in batteries (Energizer, 2007).

Although the main development in batteries for electric and hybrid vehicles is in Lithium based batteries, titanium is be a material that could potentially be used in the casing. With the features of being lightweight and having good strength, titanium could potentially be used in the casing of batteries in an electric vehicle.

Honeycomb

With an increasing amount of emphasis being given to light weight materials, the use of honeycomb in the production of monocoque chassis is a potential area where titanium could be used. This is a very viable option, as only relatively small amounts of titanium need to be used in the 1mm sheets on either side of the honey comb structure.

6.5 Potential TiAL uses for electric vehicles

Because of the high cost of titanium aluminide products, the most logical areas for which titanium could be used are in areas were mass reduction is most critical. Looking at the potential components for electric vehicles is similar to the conventional automobile industry, with the main difference between components being the motors.

6.5.1 Motor components

The electric motor in the Ultracommuter is an in wheel motor, which means that it is part of the vehicles un-sprung mass. The reduction of weight in the motor would increase the occupants ride comfort. There are two heavy components inside a wheel motor, the backing plate, which the magnets are attached too, and the shaft that the stators spin around. The shaft is not appropriate for TiAl because of the loading applied to it.

As the backing plate is currently made from a heavy tooling steel, and the magnets are secured using epoxy adhesive, the use of TiAl would be relatively simple for this component. A plate could be made using powder metallurgy, providing significant weight savings of 0.77kg per plate. With two plates per motor, this would equate to a 3kg weight saving overall. (**Appendix 1**)

6.5.2 Brake setup

As mentioned in section 6.3 and 6.4.2, research into the use of titanium in a braking system has been conducted. Due to the high un-sprung mass gains to be made in this area, in the authors opinion the use of TiAl components is viable.

Currently the braking system of a vehicle makes up a large part of the un-sprung mass in a light weight vehicle. This is especially evident with the use of aluminium wishbones, and light weight shock absorbers. Braking have had little work done on weight reduction.

Brake pad backing

The brake pads on a vehicle weigh between 200-300g and are backed by a steel plate. This small steel backing plate weighs 100grams. This weight could be reduced to around 50grams with the use of TiAl. With up to 12 pads (including separate park brake) on the vehicle, this could result in a 600g weight saving.

Brake calliper

The brake calliper used on the Ultracommuter was made of aluminium, a lightweight and affordable metal. Its weight was a low 1.3kg. Although this is typical of performance cars, family car brake callipers can weigh up to 4kg.

A basic FEA analysis is shown in Figure 6.4 below, purely for comparison purposes with a TiAl part.

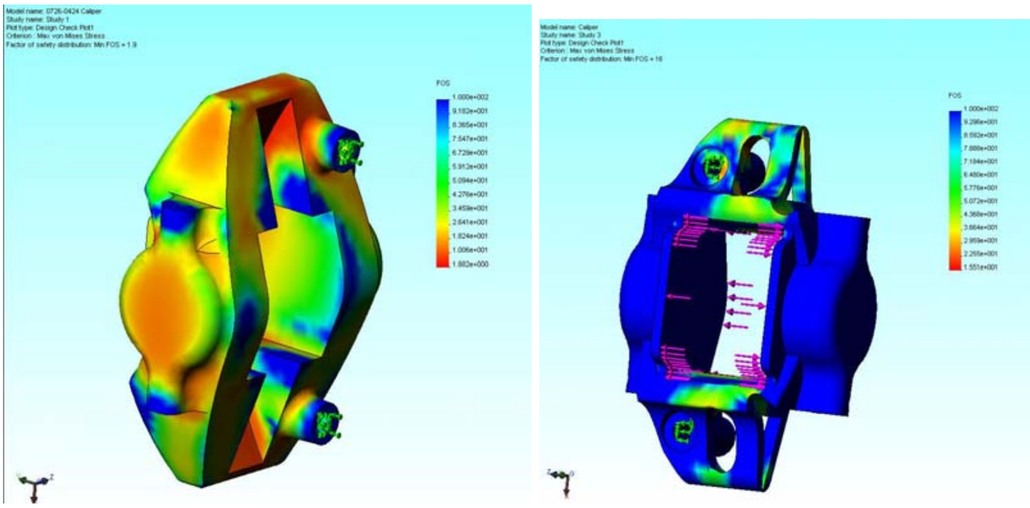


Figure 6.4 Ultracommuter Brake calliper FEA comparison

The design was altered for the use of TiAl because of its high strength. Considerably less material is required over the aluminium brake calliper. In comparison, the aluminium part weighed 1.3kg, and the titanium part 1.18kg. While these are similar masses, the TiAl component has a safety factor 10 times that of the aluminium part, implying that even less material could be used resulting in a higher weight saving.

In conclusion the use of gamma titanium aluminides in the automotive industry is increasing as technology continues to drive down the cost of manufacturing γ-TiAl components. The use of γ-TiAl in electric motors, and other niche industries shows the need from more research and development of the material.

Chapter 7 Manufacturing and commercialisation

The commercialisation of an electric vehicle requires a more complex project, not only in the development of the vehicle, but in all of the other requirements of commercialisation. The basis for commercialisation must begin with a desired market as a vehicle can be compromised if not designed for a certain market and situation. A detailed and honest budget must be done as the costs of designing, producing, and running a single prototype can run in the millions. A comprehensive market analysis must also be undertaken as investors are unlikely to invest in a project that is not forecasted to be a success.

Markets

It is the author's opinion that there are three main markets that could potentially be entered, the high performance car market, the family car market, and the light use commuter vehicle market.

High performance market

High performance electric vehicles can compete with gasoline powered vehicles, as the AC Populsion T-zero doing 0-100kmh in 3.5sec proves. With superior styling and no expense spared, the high performance market could produce electric vehicles with range capabilities of 200-400km, high top speeds, and fast accelerating. The advantage of the high performance market is that consumers expect to pay more for performance so the additional cost of electric vehicles is negated. In addition, many high profile celebrities and politicians would like to be seen to be environmentally friendly or "green", and an electric car is one of the most effective methods of portraying this message to the public.

Family car market

The possibility of manufacturing a family sized electric vehicle is high. With the increasing cost of fuel, and CO_2 carbon taxes, many families will look for a more affordable transportation option. If an electric vehicle can be produced at a low enough cost for the mainstream market, it has the potential to be very successful.

Light use commuter market

The commuter market is the currently the most successful market for electric vehicles. Small lightweight vehicles are ideal for business people who want to avoid the taxes incurred from driving gasoline powered vehicles into the city.

7.1 Vehicle cost

The cost of producing the Ultracommuter can be seen in Table 17

Item	*1 off car*	*50 cars*	*200 cars*
	Body Shell		
Mold Maintenance	1000.00	200.00	150.00
Shells	7000.00	4000.00	2350.00
Windows/Windscreen	1000.00	500.00	400.00
Hinges door pieces	1000.00	500.00	300.00
Materials Total	***10000.00***	***5200.00***	***3200.00***
Labour 1	1200.00	800.00	600.00
Labour 2	800.00	600.00	550.00
Labour 3	100.00	50.00	50.00
Labour Total	***2100.00***	***1450.00***	***1200.00***
Bodyshell Total	***12100.00***	***6650.00***	***4400.00***
	Chassis		
Al Honeycomb	310.00	280.00	200.00
Glue	120.00	100.00	80.00
Al Angle	50.00	45.00	40.00
Jig Maintenance	50.00	40.00	20.00
Misc	150.00	100.00	80.00
Materials Total	***680.00***	***565.00***	***420.00***
Labour 1	960.00	800.00	650.00
Labour 2	600.00	500.00	300.00
Labour 3	250.00	200.00	200.00
Labour Total	***1810.00***	***1500.00***	***1150.00***
Chassis Total	***2490.00***	***2065.00***	***1570.00***
	Suspension		
Wishbones	2000.00	1500.00	800.00
Shock spring	4000.00	3000.00	2500.00
Mounts	2000.00	500.00	350.00
Uprights	500.00	200.00	190.00
Misc	300.00	200.00	200.00
Brakes	2000.00	1500.00	1000.00
Materials Total	***10800.00***	***6900.00***	***5040.00***
Labour 1	210.00	150.00	96.00
Labour 2	90.00	60.00	30.00
Labour 3	50.00	50.00	50.00
Labour Total	***350.00***	***260.00***	***176.00***
Suspension Total	***11150.00***	***7160.00***	***5216.00***

Electronics			
Batteries	21000.00	18000.00	12000.00
Battery Management	2000.00	1500.00	1200.00
Battery Boxes	1000.00	800.00	600.00
Home Charger	5000.00	2000.00	1000.00
Car Charger	1500.00	1000.00	800.00
Plugs	200.00	200.00	180.00
Box	20.00	20.00	10.00
Circuitry	500.00	150.00	100.00
Low Power	1000.00	500.00	400.00
LED's	150.00	100.00	80.00
Connectors/wiring	300.00	280.00	200.00
Materials Total	***32670.00***	***24550.00***	***16570.00***
Labour 1	350.00	300.00	260.00
Labour 2	400.00	500.00	300.00
Labour 3	500.00	450.00	250.00
Labour Total	***1250.00***	***1250.00***	***810.00***
Electronics total	***33920.00***	***25800.00***	***17380.00***

Interior			
Seats	2000.00	1500.00	500.00
Seat Belts	300.00	200.00	180.00
Carpet	300.00	250.00	200.00
General Finishing	1500.00	1200.00	700.00
Materials Total	***4100.00***	***3150.00***	***1580.00***
Labour 1	1000.00	800.00	500.00
Labour 2	200.00	150.00	30.00
Labour 3	150.00	100.00	50.00
Labour Total	***1350.00***	***1050.00***	***580.00***
Interior Total	***5450.00***	***4200.00***	***2160.00***

Driveline			
Motor Controllers	15000.00	7000.00	5500.00
Driver controls	1500.00	900.00	600.00
Motors	20000.00	10000.00	6500.00
Materials Total	***43450.00***	***23250.00***	***15390.00***
Labour 1	1500.00	1200.00	1000.00
Labour 2	800.00	750.00	500.00
Labour 3	500.00	450.00	250.00
Labour Total	***2800.00***	***2400.00***	***1750.00***
WSC Total			***12600.00***

Total Materials	**$101,700**	**$63,615**	**$42,200**
Total Labout	**9660.00**	**7910.00**	**5666.00**
Total	**111360.00**	**71525.00**	**47866.00**
US$	**83520.00**	**53643.75**	**35899.50**
UK	**44544.00**	**28610.00**	**19146.40**

Table 17 Ultracommuter Budget

Table 17 shows that the main costs of the Ultracommuter are in the electronic components of the vehicle. As manufacturing and development of these components continues to improve, the cost of producing vehicles rapidly decreases. The components that make up the electronics cost very little, however the design and development is expensive. Because this area is so new, the costs involved with designing and developing are much higher in comparison to other areas, for example, the suspension or brakes.

The cost analysis of a gasoline powered vehicle shows that the transmission system, ignition and exhaust system, and engine, equate to 31% of the vehicles total cost ("Technology And Manufacturing Process", 2003). The Ultracommuter cost analysis shows that with production of 200 vehicles per year the electronic components equate to 37% of the vehicles cost.

7.2 Financial benefits

As mentioned in section 1.2 and shown in Table 2, the UK government is using CO_2 tax incentives to encourage drivers to use vehicles that emit less greenhouse gases.

Incentive	**Saving (£/NZ @0.4)**
CO2 Tax	£205 / $513
Congestion charge	£2800 / $7000
Fuel Savings	£1000 / $2500
Free parking	£1000 / $2500
Total Savings	£5005 / $12,512

Table 18 Incentives for electric vehicle owners in the UK. (see Appendix 9)

This is not the only incentive for electric vehicle owners. In London, there is a congestion charge to discouraging drivers to enter the city in their vehicles. However, because electric vehicles are relatively silent and emit no greenhouse gases, they are exempt from this charge. This creates an £8 saving daily, equating to an annual saving of £2800 or $NZ7000 (based on 350 working days per year). Electric vehicles also require less fuel to run. Electricity costs £0.05 kWh overnight in the UK. To travel 15,000km, the Ultracommuter would consume approximately 1200kWh of electricity, meaning a years worth of energy may cost only £54 / $135 in comparison to £1100 / $2750 for petrol. Free parking is also being offered as an incentive to drive electric vehicles, resulting in a further saving of £1000 / $2500. The total savings, as shown in Table 18, total £5005 / $12,512 per year; this financial saving encourages the public to accept the introduction of these vehicles.

Drivers are not the only people receiving incentives; incentives are also being offered to electric vehicle companies. Tax benefits are being discussed in the European Union for electric vehicle companies, resulting in cheaper vehicles for the consumer.

The three major automotive producers, Nissan, Toyota, and Honda have recently experience large share value drops. This has put pressure on the automotive industry to start looking for new avenues to grow into. Over the last year, Nissan's shares have lost 33% of their value, Toyota's have lost 27%, and Honda has lost 30% (Chang-Ran, 2008). This loss encourages automotive manufacturers towards new technologies. Honda have committed to moving part of their eco-car manufacturing to Thailand to make the most of tax benefits. Thailand are offering US$150million in tax incentives, as well as reduced taxes on eco-cars sold in Thailand ("Honda gets Thailand's eco-car rolling", 2007).

7.3 Other factors

When designing an electric vehicle for commercialisation, the complete life cycle of the vehicle needs to be considered. This includes the amount of energy and emissions used in the production of materials and components, as well as the driving life of the vehicle and its disposal. Many of the new modern materials are being produced using methods that create pollution and require large amounts of energy, to the extent that it is sometimes more environmentally friendly for the vehicle to be less efficient and use simpler materials.

7.4 Manufacturing the Ultracommuter

Many aspects of the Ultracommuter's design were made with consideration for small scale manufacturing. For example, the suspension system was designed to be cut from a sheet of aluminium. The base for small scale manufacturing of the Ultracommuter already exists as the main area of development required to produce the vehicle is in detailed design.

With the use of rapid manufacturing tools, such as waterjet cutting, cnc machining, and large scale vacuum bag composite manufacturing, the main components of the Ultracommuter could be produced quickly and efficiently. Detailed design would help to minimise human resources, and the high cost associated with such resources. With a full detailed design, CAD files of the complete vehicle could have all major mounting holes, brackets, and assemblies drawn. These components could be manufactured with these holes, fittings, and brackets, so that a bolt or adhesive would be all that would be required to complete the assembly of the vehicle.

Electronics require a lot of testing and fine tuning, but once product satisfaction is achieved in expensive one off components, prices will decrease, and become cost effective with mass production. Motor controllers, charges, and battery management can be mass produced for approximately \$1000 worth of components. The reason for the high one off cost of these (\$10,000+) are the costs which lie in the development, requiring highly trained and experienced engineers to develop them.

Charging

Charging the Ultracommuter in real applications would involve the use of two chargers. The first would be a high speed high capacity charge capable of charging the batteries in 2-3 hrs. This would need to be installed into the owner's home. This would allow owners to quickly and efficiently charge up their vehicles after driving around that day. A secondary on board charge would also be integrated into the vehicle. This charger would allow the driver to plug in at any 240 or 110V wall socket and charge their vehicle. Although much slower to charge (closer to 4-6hr), this would give the driver a large amount of flexibility, and allow trips of 500km+ a day.

Lotus chassis

One option for production of the Ultracommuter would be to use the Lotus chassis and an electric drive system. Similar to Tesla motors, Lotus would construct a vehicle including the chassis, interior, front suspension, steering, and braking. The vehicle would then be shipped to a production plant were the vehicle would have the electronics installed, including the batteries, controllers, low power system and charges. The vehicle would also have a custom designed rear suspension system and motors installed; finally, the vehicle would have the body shell attached.

The vehicle would then be sold to the high-end consumer niche market in the UK. It could receive the safety and recognition of the Lotus chassis, while maintaining an innovative design with the back of the vehicle and the electronic system. Overall, this concept allows the least risk in entering a market where competition is large and the need for security is necessary to attract investors and business people.

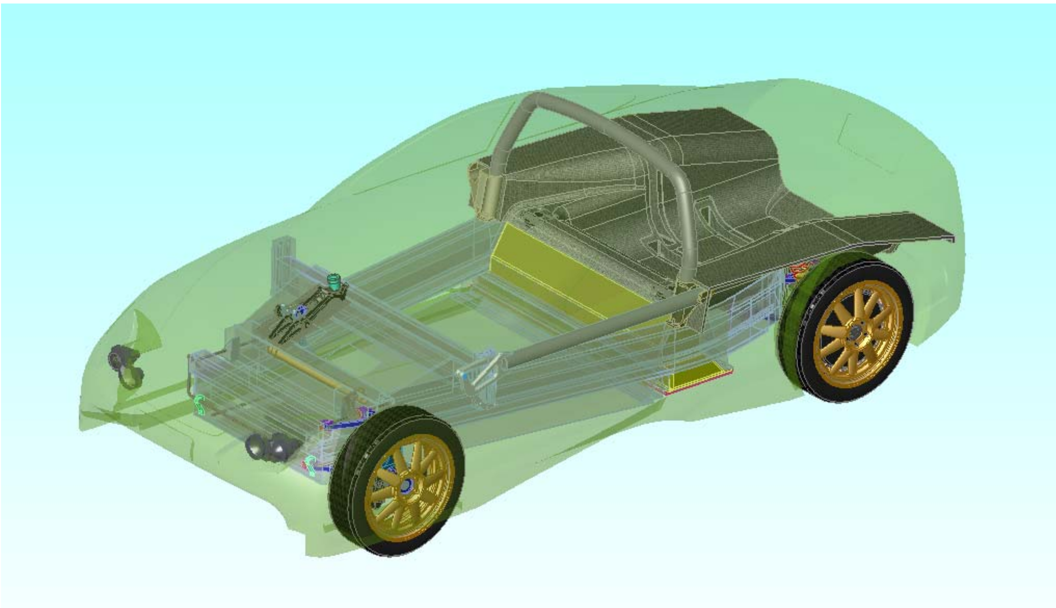


Figure 7.1 Ultracommuter on a lotus chassis (courtesy of *Hybrid*Auto)

Chapter 8 Conclusions and Recommendations

8.1 Conclusions

Developing a lightweight electric vehicle requires the use of the modern materials and engineering techniques. Most importantly, the design of a lightweight vehicle must integrate all of the components together in a way that allows for the minimisation of weight.

The development of the Ultracommuter prototype was deemed a success from its performance at the World Solar Challenge. The 3000km event from Darwin to Adelaide over Australia's harsh outback was completed by the Ultracommuter. 1800km was completed by the car driving, the other 1200km forced to trailer due to technical issues.

The future of lightweight electric vehicles looks bright, with government incentives for both owners and manufacturers to push our personal transportation needs to a more sustainable system. The latest developments in battery technology, allow electric vehicles to continue to improve their performance including sports car type acceleration and long ranges of 300km.

The potential for gamma titanium aluminides in use in the automotive industry is good. Several options for gamma TiAl components exist including use in braking systems, and electric motor components.

8.2 Recommendations

Future development of electric vehicles must include more research into the following areas;

Battery technology – As battery technology continues to improve the development of the electric car will rapidly improve. Batteries need to reach energy densities of 200-250Wh/kg to become competitive with the ICEV. However, as petrol prices continue to rise, other technologies such as electric become more economically viable.

Battery management – The battery management system is a key element of a vehicles electronic system. Although the Li-ion batteries used in the Ultracommuter appeared to perform well, at low and high voltages they became quite unequal, which meant a) the batteries never reached full capacity when charging, and b) they could never be discharged to a true 80-85% DOD because some cells would be too low and continuing to drive would damage them.

Integration – Future body shells could not only use composite materials, but also incorporate composite structures. The body shell could be further integrated into the chassis, to minimise the difficulty of attaching the body shell to the internal chassis structure.

Aerodynamics – Although the Ultracommuter was thought to have performed well aerodynamically, a lot of work can still be done in this area. The development of turning wheel spats offers the greatest efficiency improvement. Smaller areas such as split lines, wheel arches, and cabin airflow could all be developed to minimise the energy required to drive the vehicle. The refinement of aerodynamics on efficient electric vehicles will continue to be a key area in improving vehicle efficiencies.

Gamma titanium aluminide components – With the increased un-sprung to sprung mass ratio of a lightweight electric vehicle, the use of lightweight titanium aluminide components could help to reduce the un-sprung mass of a vehicle. Research is specifically needed in the areas of manufacturing and production of cast and PM titanium aluminide parts. As well as testing into the materials wear and thermal properties.

References

Allan, R. (2005). Setting the standard for hybrid cars. *Electronic design, 53*(25), 41.

Anderson, J., & Anderson, C. (2005). *Electric and Hybrid cars a history*. North Carolina: McFarland and company.

Ashley, S. (1996). Composite car stuctures pass the crash test. *Mechanical Engineering, 118*(12), 59.

Ashley, S. (1997). Lightweight car prototypes. *Mechanical Engineering, 119*(5), 8.

Aucock, R. (2007). Electric Potential. *Automotive Engineer, 32*(7), 20.

Audi R8: the design [Electronic (2007). Version]. Retrieved 22/1/07 from http://www.carbodydesign.com.

Australia's Electricity Supply. (2007).

AYRLITE 2022 Data Sheet. (2007).).

Bernard, S. (2008). *Toyota Prius sales pass Ford Explorer in US.* Retrieved 10/1/08, from www.ft.com.

Bickerstaffe, S. (2006). Mixed Messages. *Automotive Engineer*.

Bickerstaffe, S. (2007a). Racing Cells. *Automotive Engineer, 32*(10), 34-35.

Bickerstaffe, S. (2007b). Weight savings all round. *Automotive Engineer, 32*(10).

Biofuels. (2005). Retrieved. from www.eeca.govt.nz.

Blanco, A. (2004). Putting the :Pedalk to Composites". *Plastics Engineering, 60*(3), 10.

Body in White [Electronic (2008). Version]. Retrieved 6/3/08 from www.wikipedia.org.

BP. (2007). *BP Statistical Review of World Energy June 2007*.

BP Statistical Review of World Energy June 2007. (2007).).

Brown, L. (2006). *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble*: W. W. Norton & Company.

Bullis, K. (2007). Electric Cars 2.0. *Technology review, 110*(5), 100.

Chang-Ran, K. (2008). Nissan CFO won't say co's shares undervalued [Electronic Version]. *Reuters News*. Retrieved 4/2/08.

Chitoshi, T., Ishizaka, K., & Nagamachi, M. (1997). Kansei Engineering: A study on perception of vehicle interior image. *International Journal of Industrial Ergonomics, 19*, 115-128.

Composites, A. (2007). Welcome [Electronic Version]. Retrieved 6/2/08 from http://www.ayrescom.com/.

Concept gets a new spin. (1998). *The Engineer*, 25.

Crabb, H. (1998). The virtual engineer-21st century product development. *Society of manufacturing enigeers*.

Dang, H., & Cowie, P. (2006). *New Zealand: Energy in Brief*. Retrieved. from.

Degarmo, P., Kosher, J., & Ronald, A. (2003). *Materials and Proccesses in Manufacturing*: John Wiley and Sons.

Dhameja, S. (2001). *Electric Vehicle Battery Systems*. New Delhi: Newnes.

Donachie, M. (2000). *Titanium: A technical guide* (2 ed.). USA: ASM International.

Donovan, J. (2005). Battery Management comes of age. *Portable Design, 11*(10), 28.

Dowling, T. (1999). EV1 VIN [Electronic Version] from http://ev1-club.power.net.

Dr Heitner, K. (2001). *AC Powertrain Technology for Electric Drive Vehicles*. Retrieved. from.

Drury, B. (2001). *The control techniques drives and controls handbook*. Herts, UK: Institution of Electircal Engineers.

Durbin, D.-A. (2008, 17/7/08). Green, mean, plush plug-in machines. *The seattle times,* p. C1.

Eisenstein, P. (2006). Second Chance. *Professional Engineering, 19*(16), 29.

Eisenstein, P. (2007). Batteries Included. *Professional Engineering, 20*(1), 26.

Energizer. (2007). Energizer e2 Titanium battery [Electronic Version]. Retrieved 19th May 2007 from http://www.everything2.com.

Fetcenko, M., Ovshinsky, S., Reichman, B., Young, K., Fierro, C., Koch, J., et al. (2007). Recent advances in NiMH battery technology. *Journal of Power Sources*(165).

Field, F., & Clark, J. (1997). A practical road to lightweight cars. *Technology Review, 100*(1), 28.

FlexForm. (2005). Flexform: Natural Fiber Composites Used in More Than 1.5 Million Vehicles [Electronic Version], 1. Retrieved 12/2/08 from http://plasticker.de/news/shownews.php?nr=1376.

Fossil Fuels [Electronic (2006). Version]. Retrieved 17/10/06 from http://www.biotour.org/fossilfuels.html.

Franco, J. (2007). Fuel Cell and Battery Briefs. *Octane Week, 22*(50).

Frank, B., Tudron, James, R., Akridge, & Puglisi, V. (2004). Lithium-Sulfur Rechargeable Batteries: Characteristics, State of Development, and Applicability to Powering Portable Electronics [Electronic Version] from www.sionpower.com.

Froes, F., Friedrich, H., Kiese, J., & Bergoint, D. (2004). Titanium in the family automobile the cost challenge. *JOM, 56*(2), 40-44.

Furukawa, T. (1992). Titanium crucial for new NSX - Honda NSX sports car [Electronic Version], 1. Retrieved 4/12/2007 from http://findarticles.com/p/articles/mi_m3MKT/is_n121_v100/ai_12275952.

Gawel, R. (2006). Roadsters charges up the electric car. *Electronic design*.

Gawel, R. (2007). Volt: chargers up the crowd in detroit. *Electronic design*, 23.

Gebauer, K. (2005). Performance, tolerance and cost of TiAl passenger car valves.

General Motors EV1 [Electronic (2007). Version]. Retrieved 4/2/08 from http://en.wikipedia.org.

Goldstein, J., Brown, I., & Koretz, B. (1999, May 1999). *New Developments in the Electric Fuel Zinc-Air System.* Paper presented at the International Power Sources Symposium.

Greaves, M., Walker, G., & Walsh, B. (2002). Design optimisation of Ironless Motors based on Magnet selection. *Journal of Electrical and Electronics Engineering Australia, 22*(1), 43-48.

Griffiths, J. (2007). Hydrogen cases its state. *Automotive Engineer, 32*(10), 30-31.

Happian-Smith, J. (2001). *An Introduction to Modern Vehicle Design*: Elsevier.

Heitner, K. (2001). *AC Powertrain Technology for Electric Drive Vehicles*. Retrieved. from.

Hoffman, J. (2007). Mazda develops first biofabric for interiors. *Machine Design*, 122-123.

Honda fuel cell power: FCX. (2004).).

Honda gets Thailand's eco-car rolling [Electronic (2007). Version]. Retrieved 27/2/08 from www.hindustantimes.com.

Honeywill, T. (2007a). Biofuel grows up. *Automotive Engineer, 32*(10), 32.

Honeywill, T. (2007b). Go-faster Green. *Automotive Engineer, 32*(10), 28-29.

Howden, D. (2007, 14 June 2007). World Oil supplies are set to run out faster than expected. *The Independent*.

Hucho, W.-H. (1998). *Aerodynamics of Road Vehciles*: Aociety of Automotive Engineers.

Hussain, I. (2003). *Electric and Hybrid Vehicles design fundamentals*. Florida: CRC Press.

Johnson, T. (2007). Hobby car technical manual. *New Zealand hot rod association*.

Karden, E., Ploumen, E., Fricke, B., Miller, T., & Snyder, T. (2006). Energy storage devices for future hybrid electric vehicles. *Power Sources, 168*, 2-11.

Kassner, M., & Perez-Prado, M. (2004). *Fundametnals of Creep in Matals and Alloys*: Elsevier.

Kiehne, H. A. (2003). *Battery Technology Handbook* (2 ed.). New York: Marcel Dekker.

King, S. (2007). *Towards an Electrical Transformation of the New Zealand Light Vehicle Fleet*.

Kirsch, D. A. (2000). *The Electric Vehicle and the Burden of History* (1 ed. Vol. 1). London: Rutgers University Press.

Koganti, R. (2005). Re-Engineering a Legend. *Manufacturing Engineering, 135*(3), 101.

Larminie, J., & Lowry, J. (2003). *Electric Vehicle Technology Explained*
John Wiley and Sons.

Leyens, C., & Peters, M. (2006). *Titanium and Titanium Alloys: Fundamentals and Applications:* : Wiley-VCH.

Li, J. (1996). *Microstructure and properties of materials*: World Scientific.

LTSA. (2006). *New Zeland motor vehicle registration statistics 2006*. Palmerston North.

Matthews, C. (1998). *Case studies in engineering design*. London: Wiley and sons.

McBeath, S. (2000). *Competition Car Composites: a practical handbook.* Haynes Publishers.

McQuay, P. (2001). Cast gamma TiAl alloys

MEPs vote for tougher CO_2 targets. (2007). *Automotive Engineer, 32*(10), 5.

Meyera, I., Leimbachb, I., & Jaeger, C. (2007). International passenger transport and climate change: A sector analysis in car demand and associated CO2 emissions from 2000 to 2050. *Elsevier*.

Mom, G. (2004). *The Electric Vehicle*. Baltimore: The John Hopkins University Press.

Newton, B. (2001). Holden Delivers its cyber-age baby [Electronic Version]. Retrieved 6/2/08 from http://www1.autotrader.com.au/mellor/MELLOR.NSF/story2/2AA87A45919CBEFCCA256AE1008022DA.

Nissan expects to build electric vehicle by 2015. (2007). *Automotive Engineer, 32*(9), 8.

Payne, E. (2007). Corbin Motors [Electronic Version] from http://www.3wheelers.com/corbin.html.

Population of New Zealand [Electronic (2008). Version]. Retrieved 7/1/08 from http://www.stats.govt.nz/populationclock.htm.

Ramsden, D. (2006). Spaceframe propels Ford GT. *Modern Casting*.

Reed, P. (2007). Miles Automotive's Electric Car Breaks Battery Barrier [Electronic Version]. Retrieved 2-3-08 from http://www.edmunds.com/advice/alternativefuels/articles/122759/article.html.

Schoenberger, R. (2007). Myers Motors aims to produce a good electric commuter car [Electronic Version]. Retrieved 25/12/07 from http://blog.cleveland.com/business/2007/12/myers_motors_of_tallmadge_aims.html.

Schreffler, R. (2008). Toyota Prius Turns 10. *Wards Auto World, 44*(1).

Simpson, A. (2003). Comparing Future Alternative Fuels and Powetrain Technologies for Vehivles. *University of Queensland*.

Small cars take bigger share of the market. (2007). *Automotive Engineer, 32*(10), 4.

Smarsly, W., Baur, H., Glitz, G., Clemens, H., Khan, T., & Thomas, M. (2001). *Titanium aluminides for automotive and gas turbine applications.* Paper presented at the International Symposium on Structural Intermetallics, Jackson Hole, USA.

Steele, R. (2005). LED automotive hadlamps move closer to market. *Laser Focus World, 41*(11), 91.

Taniguchi, A., Fujioka, N., Ikoma, M., & Ohta, A. (2001). Development of nickel/metal-hydride batteries for EVs and HEVs. *Journal of Power Sources*, 117–124.

Team 05: Timely solutions. (2005). *The Engineer*, 48.

Technology And Manufacturing Process [Electronic (2003). Version] from http://www.indiainfoline.com/sect/atca/ch05.html.

Thomas, M., Raviart, J., & Popoff, F. (2005). Cast and PM processing development in gamma aluminides. *Intermetallics, 13*.

Toyota Prius tests protoype plug-in Prius in US and Japan markets. (2007). *Automotive Engineer, 32*(8), 10.

Tritium 220A Inductors specification. (2007).). Brisbane.

Tuite, D. (2007). No Ultracaps in Electric vehicles yet, but maybe there should be. *Electronic Design*, 24.

UK 'green' Vehicles CO_2 Emissions Directory. (2007). Hampshire

Ulrich, K. (2003). Estimating the technology frontier for personal electric vehicles. *Transportation Research*.

VanMierlo, J., & Maggetto, G. (2006). Fuel Cell or Battery: Electric Cars are the Future. *Fuel Cells*(2), 165-173.

Voelcker, J. (2006). Electric Cars For Enlightened Stars. *IEEE Spectrum, 43*(11).

Wan, M. (1998). Differnet types of chassis [Electronic Version]. Retrieved 27/1/08 from http://www.autozine.org/technical_school/chassis/tech_chassis.htm#Ladder.

We drive the world's best electric car. (1994). *Popular Science, 244*(1), 52-59.

Wells, H. (2007). Gone in 4s. *Current Science*.

Westbrook, M. (2005). *The Electric car*. London: IEE.

Worth the weight. (2004). *The Engineer*, 34-35.

Yamaguchi, J. (2007). Denso turns up the heat *Automotive Engineering International, 115*(8), 58-60.

Yolton, C., Habel, U., & Clemens, H. (1997). Advanced particulate materials and processes. *Metal Powder Report, 52*(7), 161.

Appendix

Appendix 1: Table 1 Vehicle Emissions

Column 2 vehicle horsepower's;

2006 Honda Civic iCDTi	http://autos.msn.com
Ford Ka	http://www.ford.co.uk
2006 Honda Civic	http://www.honda.co.nz
2006 Honda Civic (hybrid)	http://autos.msn.com
2007 Volvo C70	http://autos.msn.com
Toyota Prius	http://www.toyota.com
Porsche 911	http://www.porsche.co.nz
Nissan Patrol	http://www.nissan.co.nz
Audi A4 Saloon	http://www.audi.co.nz

All vehicle emissions; http://www.vcacarfueldata.org.uk/search/searchResults.asp

Appendix 2: Table 3 Bio fuel analysis

Land Figures				
New Zeland	268680	km^2 =	26868000	hec
USA	9,826,630	km^2 =	982663000	hec
Fuel Consumption				
New Zeland	7.2	million tons =	9767	million L
USA	938.8	million tons =	1273433	million L

Ethanol	Gallons/ acre	Litres/ acre	Litres/ acre*	Litres/ hectare	Hectare required NZ	% of NZ	Hectare required USA	% of USA
Sugar beet (France)	714	2,706	1,813	4,477	2,181,615	8	284,458,405	29
Sugarcane (Brazil)s	662	2,509	1,681	4,151	2,352,981	9	306,802,570	31
Cassava (Nigeria)	410	1,554	1,041	2,571	3,799,203	14	495,373,906	50
Sweet Sorghum (India)	374	1,417	950	2,345	4,164,902	16	543,056,956	55
Corn (U.S.)	354	1,342	899	2,220	4,400,207	16	573,738,140	58
Wheat (France)	277	1,050	703	1,737	5,623,370	21	733,224,915	75
BioDiesal								
Oil palm	508	1,925	1,733	4,278	2,282,680	8	297,636,072	30
Cocnut	230	872	785	1,937	5,041,745	19	657,387,497	67
Rapeseed	102	387	348	859	11,368,640	42	1,482,344,357	151
Peanut	90	341	307	758	12,884,459	48	1,679,990,271	171
Sunflower	82	311	280	691	14,141,479	53	1,843,891,761	188

*the second litres per hectare allows for the low energy yield of biofuels 67% for ethanol, and 90% for biodiesel (Brown, 2006)

References for data

Crop yields	(Brown, 2006)
NZ land stats	www.wikipedia.com
NZ fuel usage/energy requirement	(BP, 2007)
US land statistics	www.wikipedia.com
US fuel usage	(BP, 2007)

Appendix 3: Table 5 Current electric vehicles

Aptera Typ1	www.aptera.com
Reva/G-Wiz	www.revaindia.com
Zap Zebra	www.zapworld.com
Zap-X	www.zapworld.com
GM Volt	(Eisenstein, 2007)
Nissan Mixim	(Eisenstein, 2007)
Fisker Karma	www.fiskerautomotive.com/
Electric Smart car	www.smart.com

Myres Nmg	(Schoenberger, 2007)
Tesla Roadster	(Eisenstein, 2006)
Miles SX500	(Reed, 2007)
Miles ZX40	(Reed, 2007)
Lightning cars	www.lightningcarcompany.com
NICE mega city	www.nicecarcompany.co.uk
Visionary Vehicles EVx	www.vvcars.com
Venturi Fetish	http://www.venturifetish.fr/#
Hybrid technologies	http://www.hybridtechnologies.com/

Appendix 4: Table 6 Car performance figures

Note constants:

$g = 9.81\text{ms}^{-2}$

$\rho = 1.2\text{kgm}^{-3}$

$v = 100\text{kph} = 27.8\text{ms}^{-1}$

Civic info;

Weight	http://www.internetautoguide.com
Drag, Surface area	http://en.wikipedia.org/wiki/Automobile_drag_coefficients

Appendix 5: Table 9 Polycarbonate window analysis

Weight Windscreen;	Quoted from Tauranga windscreens
Weight of Lexan;	Quoted from Mulford plastics
Windscreen, window sizes;	from Solidworks

Appendix 6: Table 11 Battery energy densities

Lead Acid	(Kiehne, 2003)
Nickel Metal Hydrire (NiMH)	(Fetcenko et al., 2007)
Li-Ion	(Kiehne, 2003)
Li-Polymer	(Kiehne, 2003)
Zinc Air	(Goldstein, Brown, & Koretz, 1999)

Lithium Sulphur (Frank, Tudron, James, Akridge, & Puglisi, 2004)

Appendix 7: Table 12 Battery options

Thunder-sky information:	www.thunder-sky.com
Kokam information:	www.kokam.com
Sunox lead acid:	http://www.sunoxpower.com/

Appendix 8: TiAl motor component weight saving

For TiAl backing plate;

Volume from Solidworks = 212705mm^3 = 0.000212705m^3

Density of Steel 7800kg/m^3 x 0.000212705m^3 = 1.66kg

Density of TiAl 4200kg/m^3 x 0.000212705m3 = 0.8934kg

Weight saving = Steel – Titanium = 1.66 - 0.8934 = 0.767kg

Note: This does not include any component re-design even though TiAl is stronger that Steel, a re-designed component would reduce mass even further.

Appendix 9; Table 18 incentives for electric vehicle owners in the UKTable 18 Incentives for electric vehicle owners in the UK. (see Appendix 9)

Table is based on Ultracommuter EV, and Audi A4 sedan

CO_2 Tax	("UK 'green' Vehicles CO_2 Emissions Directory", 2007)
Congestion charge	http://www.tfl.gov.uk/roadusers/congestioncharging/
Fuel savings	15,000km/year, EV charging at Night off peak rate
	UK electricity cost: https://www.britishgas.co.uk/
Parking	http://www.pure-parking.com
Currency conversion	£0.4 = $1