*Original Article*

# Design and development of the Sunswift eVe solar vehicle: a record-breaking electric car

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**Abstract**
The Sunswift project of the University of New South Wales, Australia, exists to provide university students with a multidisciplinary engineering challenge, enhancing the true educational value of their degree with a unique hands-on real-world experience of creating solar–electric hybrid vehicles. The design and development of the low-drag 'solar supercar' Sunswift eVe car are described here, detailing the student-led process from initial concept sketches to the completed performance vehicle. eVe was designed to demonstrate the potential of effective solar integration into a practical passenger-carrying vehicle. It is a two-seater vehicle with an on-body solar array area of 4 $m^2$ and a battery capacity of 16 kW h, which is capable of sustained speeds over 130 km/h and a single-charge range of over 800 km. Carbon fiber was used extensively, and the components were almost all designed, built, and tested by students with industry and academic mentorship. The eVe project was initiated in mid-2012, and the car competed in the 2013 World Solar Challenge, taking class line honours. It subsequently set a Fédération Internationale de l'Automobile land speed record in 2014 for the fastest average speed of an electric vehicle over 500 km; it is now the team's intent to develop the car to road-legal status.

**Keywords**
Solar car, electric vehicle, land speed record, World Solar Challenge, engineering education

## Introduction

Increasing awareness and acceptance of climate change and environmental issues, and the considerable role transportation that plays in contributing to harmful emissions, have contributed to significant current public, private, and industry interest in alternative-energy vehicles. Despite existing as a high-niche area of motorsport, racing of solar–electric prototype vehicles has intermittently attracted public attention mainly because of an emphasis on unusual (and highly aerodynamic) zero-emission designs which participate in cross-continental races. While the majority of projects past and present were developed at universities as student-led projects, the teams often attract high-technology corporate involvement, both as partners and as sponsors.

A genuine commercial solar–electric hybrid vehicle is at present unfeasible because of the limited solar panel efficiency and the costs associated with arrays, but these vehicles are effective technological demonstrators for electric motor, battery, and solar cell technology. More importantly, they have also served as a vital training ground for thousands of student engineers. For 20 years the Sunswift project of the University of New South Wales (UNSW) Australia, has been an extra-curricular educational experience for hundreds of UNSW undergraduates in everything from composites, photovoltaics (PV), electric motors and control systems, aerodynamics, marketing and public relations, health and safety, and manufacturing techniques to project management, systems engineering, and industrial design on large and small scales.

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### *Solar–electric racing*

The modern era for solar cars began in 1987 with the inaugural World Solar Challenge (WSC), an Australian rally race from tropical Darwin in the Northern Territory, across the badlands of the outback deserts in the centre of the continent, to Adelaide in South Australia. The 3021 km (1877 mile) race continues to be run every 2 years. Similar events are held in North America, Japan and South Africa with newer events establishing themselves in Abu Dhabi, Chile, Europe and elsewhere. A recent stagnation in design innovation (the ubiquitous 'wing' shape covered in solar panels with a bubble canopy for a driver) and flagging public interest led WSC organizers to introduce a 'Cruiser Class' for 2013, in which cars had to feature four wheels, a standard upright seating position, and the ability to carry one or more passengers; for the first time, the competition included subjective judging on 'practicality' as well as the objective measure of outright race speed.

Solar car projects in the educational setting are relatively closely related to the more common and familiar Formula-SAE (F-SAE) design–build–race projects.[4] However, vehicles constructed for the WSC can be an order of magnitude more expensive to build owing to the cost of solar panels, electric motors, and controllers, and the nearly pre-requisite use of composites for much of the car. For overseas teams there is the expense of travelling to Australia with a car and team to race there. The race itself is held across 3000 km on public roads and is therefore considerably more risky than a controlled F-SAE or EcoMarathon event, and making the vehicles requires among the broadest ranges of skills, talents, backgrounds, and disciplines of any student engineering project.

### *The Sunswift Project at UNSW Australia*

Project-based learning in engineering has been widely shown to be an exceptionally effective method for empowering students to learn fundamental principles of science and to develop a practical understanding of how to apply them in engineering to solve real design problems.[1] Students value a realistic environment in which to see designs from a systems perspective and to appreciate technical challenges in the context of wider global economic, societal, and environmental requirements.[1] It is seen as an effective tool to develop life-long learning, to practice and refine technical expertise, and to reinforce engineering management principles;[2] as a result, the engineers graduating with Sunswift experience can be among the most job ready of their cohort. In the current absence of more formal educational material about teamwork and conflict early in the degree program, which has been shown to be highly effective when coupled with similar lower-stakes projects,[3] the multi-disciplinary goal-driven nature of the project offers students a unique experience in forming effective teams featuring different skill levels and different ethnic and cultural backgrounds.

Sunswift, otherwise known as the Solar Racing Team, UNSW Australia, has no written 'mission statement' per se, but it is accepted by students and academics that the goals of the project are threefold: to provide challenging hands-on real-world student training in the design and manufacture of a solar electric vehicle to compete in the WSC; to be a platform for broad promotion of UNSW's engineering programs and schools; to demonstrate renewable energy and sustainable transport technologies and possibilities to the public and, in particular, the upcoming generation of primary and high-school students (which is implicitly linked to the second goal). Sunswift is currently Australia's most high-profile solar car team, and is the UNSW Faculty of Engineering's flagship student project. 2015 marked its twentieth year.[5]

The team's most recent vehicle, the eVe two-seater solar supercar (Figure 1(a)), was an attempt to change the public perception of what a solar car can be. In the team's pursuit of having eVe certified as road-legal for unrestricted use, Sunswift arguably represents Australia's most ambitious and comprehensive undergraduate automotive project. The scope and scale present many challenges enhanced from previous years,


(a) (b)

**Figure 1.** (a) Sunswift eVe at speed and (b) next to her predecessor, Guinness World Record breaker IVy.

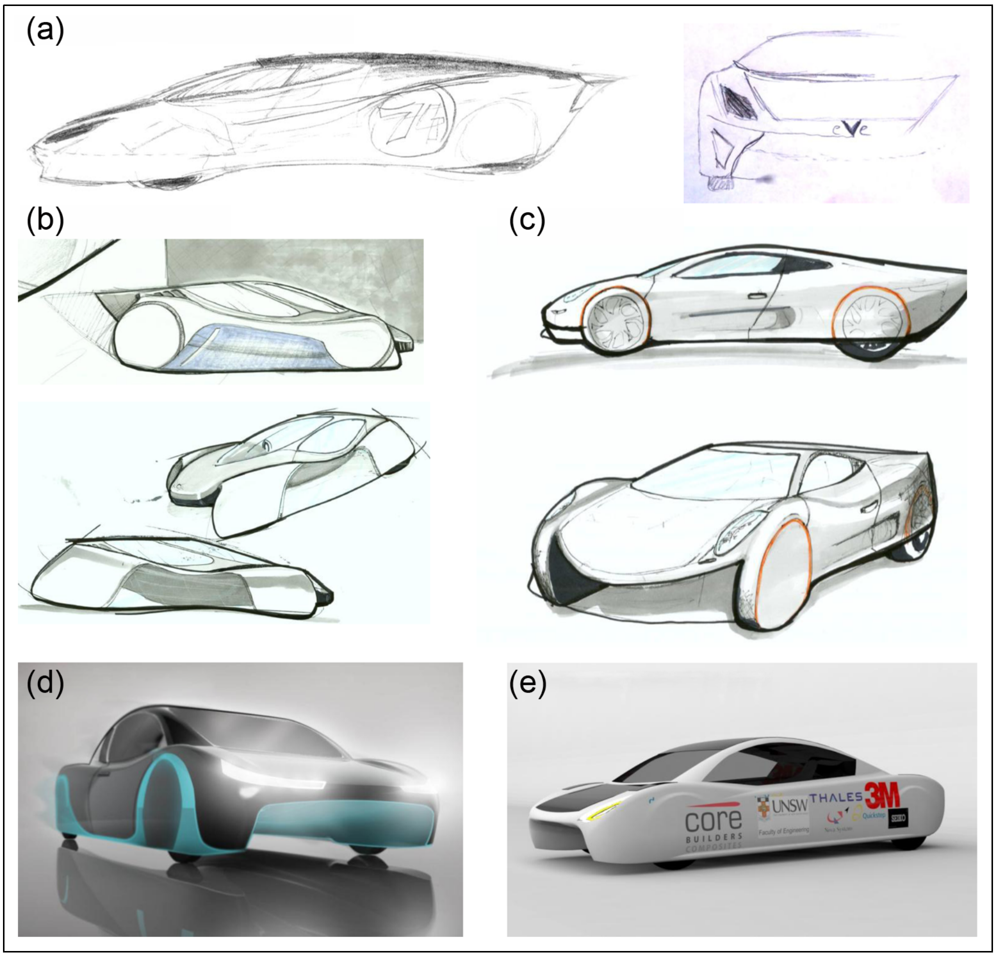


**Figure 2.** (a)–(c) Evolution of the Sunswift eVe concept from initial sketches ((a) July 2012, the initial concept; (b), (c) August 2012) through (d) the aerodynamic development phase (October 2012) to (e) the design freeze (January 2013, the finalized shape).

such as the increased opportunity cost for students working long hours for no academic credit, a requisite increase in budget, and how to manage the engineering and safety concerns at all levels. However, these challenges serve to enhance further the industry relevance of the training, with new considerations of legitimate safety structures, driver–vehicle interfaces, power-management strategies for city versus highway driving, and an overall systems engineering approach.[6]

## *Origins of eVe*

In the newly formed team of 2012 there gradually built consensus that the previous car, IVy, was well designed and successful and yet simply could not catch the better-funded or more graduate-student-dominated teams that have dominated competition for over a decade. The incoming team coalesced around the potential to build a solar–electric hybrid supercar even before the new Cruiser Class rules were announced. Therefore, in mid-2012, Sunswift embarked on a strategy to win the newly established category, despite operating in a very risk-averse university climate. The difference between the passenger-carrying eVe and her 'spaceship'-like predecessor IVy is highlighted in Figure 1(b). Despite the novel architectures of electric vehicles offering a 'blank page' on which to explore the potential for novel handling control aspects such as torque vectoring,[7] ideas more complex to develop and implement were discarded at the early stages to allow focus on completing the basics of a reliable vehicle.

Figure 2 outlines the initial design stages from concepts by the industrial design team to the finalized shape at the end of the aerodynamics development program. While many options were explored, the nature of the WSC race (the solar yield is at its best when from the north) virtually dictated the long sloping rear upper surface for the PV area and the power potential. This fitted best with the design inspiration taken from mid-engine supercars. Early input from industrial designers was essential in educating the engineers on the 'language' of car design. However, the student designers also needed education on the nature of solar cars: the requirements for array performance, the aesthetic compromises made for aerodynamic gains, etc. The relationship between the two groups was not sufficiently integrated to produce meaningful progress, and the aerodynamics became dominant.

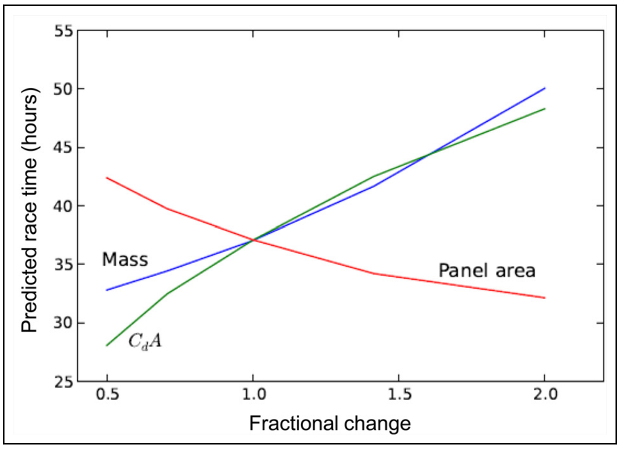


**Figure 3.** Estimated trade-offs when determining the design focus and the WSC race strategy.

Figure 3 gives insight into the approximate relationships between the most important predictable variables affecting the performance; this graph was generated following an analytical opinion of the published rules which indicated that carrying passengers and opting not to take available recharges from the grid at three points during the race are suboptimal. The fastest car to the line has the highest score for the non-subjective aspect of the race, and reducing the aerodynamic drag and the weight was prioritized in compromise with the array size possible (in this figure, a factor of 1.0 indicates the as-built values for the drag, the mass, and the panel area).

## Design and construction of eVe

eVe as built in 2013 is a mechanically simplistic car by any modern standards, but a significant design and construction challenge for students in a period of 12 months. Figure 4 presents a cut-away diagram showing the general construction and layout of the vehicle with the main design components described. The vehicle is approximately 4.5 m long and 1.8 m wide as dictated by the WSC rules,[8] with the majority of the external solar panel area of 4 $m^2$ of on the roof and the bonnet (hood); additional panels were squeezed on to the 'shoulders' above the wheel arches. The wheels themselves were inset from the vehicle extremities to allow them to remain fully enclosed at the maximum turning angle, for aerodynamic efficiency.

### *Aerodynamics*

The solar car performance is dominated by the aerodynamic efficiency, because of the extremely limited power available from the array and the long distances which must be raced with little battery power compared with that of a conventional road-going electric car.

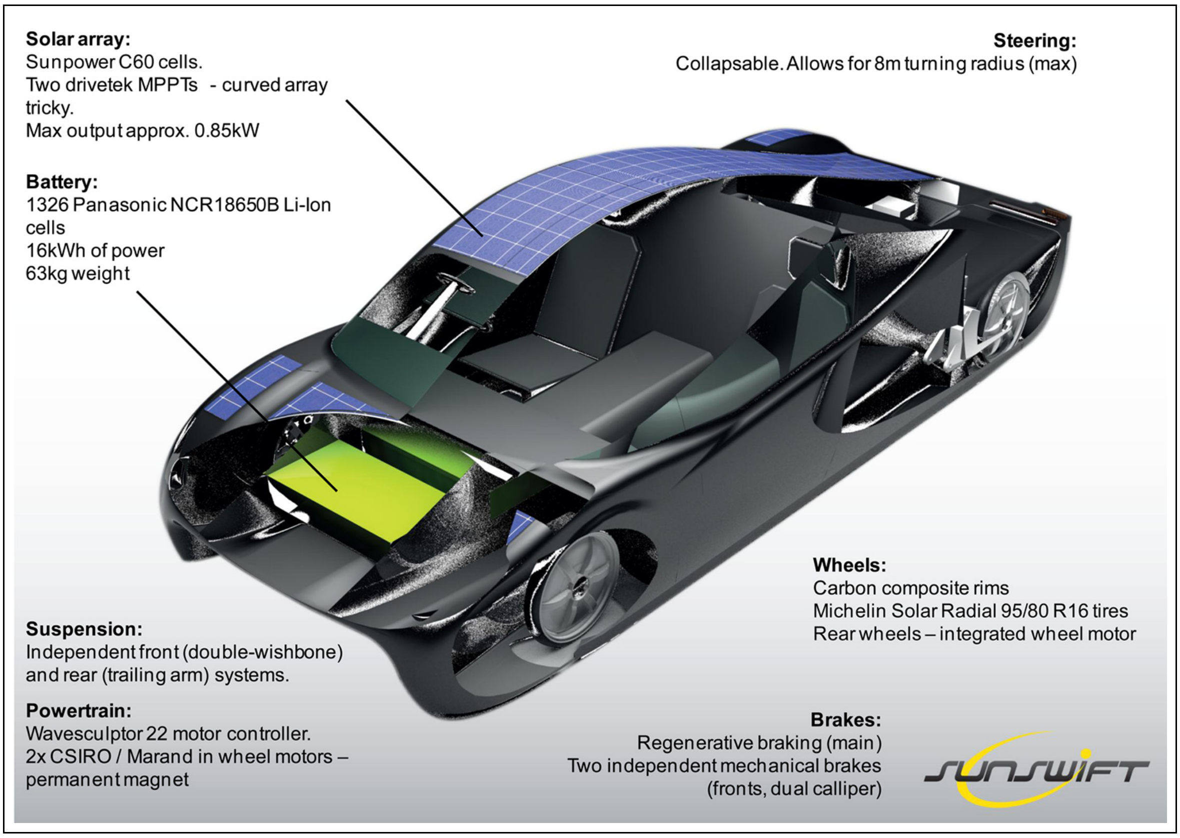


**Figure 4.** Cut-away diagram highlighting the significant features and construction of eVe.
MPPT: maximum-power-point tracker; max: maximum;.

Around 70% of the resistance to a solar car's motion is aerodynamic.[9] Sunswift eVe's shift to the WSC Cruiser Class automatically meant increased drag over the wing-profile shape of previous years. A determination to preserve sportscar aesthetics while minimizing the drag led to novel compromises.

As with Sunswift IVy,[9] the vehicle was designed exclusively using computational fluid dynamics (CFD), specifically steady-state simulations using the Reynolds-averaged Navier–Stokes equations as solved by the commercial software ANSYS Fluent. Although a wind tunnel could have been used, team inexperience with tunnel testing, an extremely tight schedule, no suitable rapid prototyping capability for models, and a lack of a moving ground to represent real-world conditions accurately meant that the only viable option to develop and optimize through a number of design iterations was CFD. A freestream turbulence level of 5% was assumed, considerably higher than that which is produced in a typical wind tunnel, but more representative of real-world conditions.

Hybrid unstructured meshes were constructed with a near-wall resolution (of approximately six cells) suitable for reasonable approximations of the skin friction, but without the grid density which is required to model the transition from laminar to turbulent kinetic energy. As a result, simulations were run as fully turbulent, using the $k$–$\omega$ shear stress transport model[10] after validation against simplistic aerofoils in the ground effect for which experimental data were readily available.[11] The effect of this modeling choice, which was made to ensure the rapid turnover of cases and the problem-free convergence of solutions, was later quantified (against a verification model with much higher resolution) as resulting in overestimates of the drag of about 10–15% depending on the vehicle speed. All simulations were run at approximate cruising speed (or anticipated average race speed) of 25 m/s (90 km/h) and an anticipated top speed of 35 m/s (126 km/h), although some additional simulations were run on later design variants at 50 m/s (to account for sudden headwind gusts, and to ensure a safety margin on undesirable excessive lift or downforce). The initial phases of design did not include the specific wheel geometry as this area was known to encourage potential unsteadiness in the solution.[9] Later models ran with a simplified wheel shape blended into a moving ground plane.

Computer-aided design models were generated in CATIA at an average rate of a model update every few days over the course of 3 months and over 50 body variants were run through CFD. Meshes generally consisted of (7–8) $\times$ $10^6$ cells for a half-car (symmetry) model and solved overnight on UNSW's Trentino and Leonardi high-performance computing clusters; scripts were written to automate post-processing for rapid evaluation of any separation, high-pressure gradients, etc., as evidenced in animations and standard repeatable contour plots. The lift and the drag were tracked throughout.

The overriding desire for an attractive, aggressively sporting design was merged with aerodynamic criteria which at the early stages involved simply establishing a largely separation-free shape that had an equivalent or better drag coefficient (by frontal area $C_DA$) than that known of a key competitor: 0.14. Flow separation regions can also result in local overheating of the solar cells,[12] providing an additional necessity to avoid extensive separation over the roofline and forward quarters. A second priority was a low downforce to minimize the rolling resistance, although no specific value was being chased. Initially, the array and packaging considerations were highly approximated, although the driver position and the required visibility were calculated in CATIA based on the WSC regulations.

Objectives changed from week to week to concentrate on specific areas of the car or to solve the new problems created as others were solved. It was not strictly an iterative or parametric optimization process as often several design ideas were incorporated from one variant to the next and, as the array and other teams formed in the background, certain geometric requirements were altered (for instance, the width of the shoulders above the rear wheels to accommodate specific solar cell widths).

Figure 5 indicates the design evolution with some images of key variants. Early bodies, up to body 7, followed more closely some ideas from the industrial designer which featured a more 'cute' family-oriented vehicle and a downward-sloping belt line from front to rear. It was decided that this was not sufficiently aggressive to suggest sporting pedigree and later generations featured an inversion to create a higher rear shoulder. An underbody 'tunnel' was planned from the early stages to reduce the frontal area (by up to 15%) and therefore the drag, as well as to alleviate the downforce, taking advantage of having no engine or other components occupying the forward quarters under the hood. It did result in a significant 'diffuser'effect which separated excessively until the more defined "dual-step" tunnel was introduced around body 15; the later bodies barely dip below horizontal in the central channel, and there is a lateral expansion of the tunnel area behind the front wheels to alleviate the excessive local flow velocity. It was desirable to keep the rear as low as possible to avoid over-expansion of the underside flow, leading to an exaggerated shoulder profile to retain an attractive side silhouette while dropping flow off the rear around 120 mm lower than the shoulder in the central upper array-covered region. A mild wake downwash resulted owing to the pressure differential above and below the tail.

Raising the nose and the rear (body) for the same minimum ground clearance greatly increased the downforce and was not pursued (body 19). Close to 20 modifications were based purely around optimization of the underbody, with only minor adjustments to the windscreen rake angle, the A-pillar angles, the nose height, etc. This was aimed at alleviating the continued

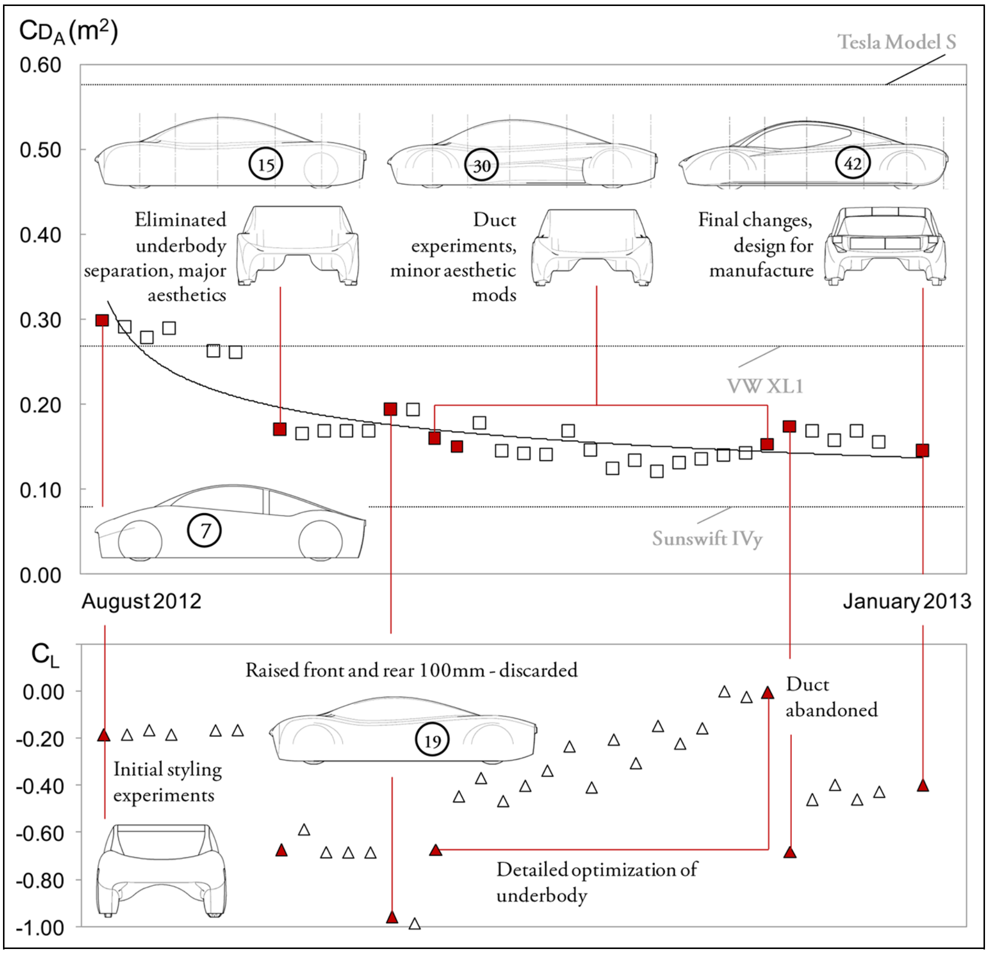


**Figure 5.** Aerodynamic development of eVe from August 2012 to January 2013, indicating the lift and the drag progression through various design iterations.

excessive downforce and the accompanying drag, by allowing flow to bleed to the underbody from the side of the car via a side duct. Perfecting this proved complex, and it was eventually decided to abandon the idea owing to the anticipated difficulty in manufacturing such details from carbon fiber using a minimal number of moulds in a short period of time. Modifications in January 2013 were almost exclusively for styling (lights and windows) rather than for performance. The final $C_DA$ for eVe predicted by CFD was an on-target 0.142, comfortably less than a conventional low-drag hybrid or electric car such as the $C_DA$ of approximately 0.26 for the production VW XL-1, and much greater than the real-world $C_DA$ of 0.09 for the Sunswift IVy. The drag could have been lower still with a side duct and the rear left unchopped, but a design freeze at a pleasing aesthetic point was agreed upon by the team's management.

Lack of proper testing time ahead of the 2013 WSC led to post-event evaluation of the actual drag coefficient of the car, augmented by more controlled but lower-speed (80 km/h) testing in Sydney at a track venue. All testing was wind affected but sufficient data were generated to construct reliable averages, indicating that the real-world $C_DA$ is slightly under 0.13 ± 5%, within an acceptable margin of the highest-resolution CFD prediction. eVe is exceptionally sensitive to the ground clearance, indicating that the vehicle is strongly influenced by the ground effect and that careful setup of the ride height and the rake angle is essential. The approximate "baseline" ride height of 75 mm was selected to provide clearance of rocks and cattle grids and meets the WSC regulations. If lowered by 25 mm, the drag increases by approximately 8% and the downforce by 77%. If it is 50 mm higher, the drag is approximately 3% higher, with the downforce reduced by 45%. If the rolling resistance was a major issue, the higher ride height would be preferable even at the drag expense; the drag values indicate that the as-built car exists in a relative 'sweet spot'.

CFD allowed a detailed breakdown of the force components produced by each area of the car, 20 in all (the windscreen, the underbody tunnel, the rear wheel, etc.) throughout the process. Minor changes to the windscreen rake angle reduced the drag and the downforce considerably, and individual component and global values were tracked. The car's drag makeup consists of a 55%– 45% split between the pressure and the viscous drag respectively, in stark contrast with the more streamlined Sunswift IVy and similar solar cars which

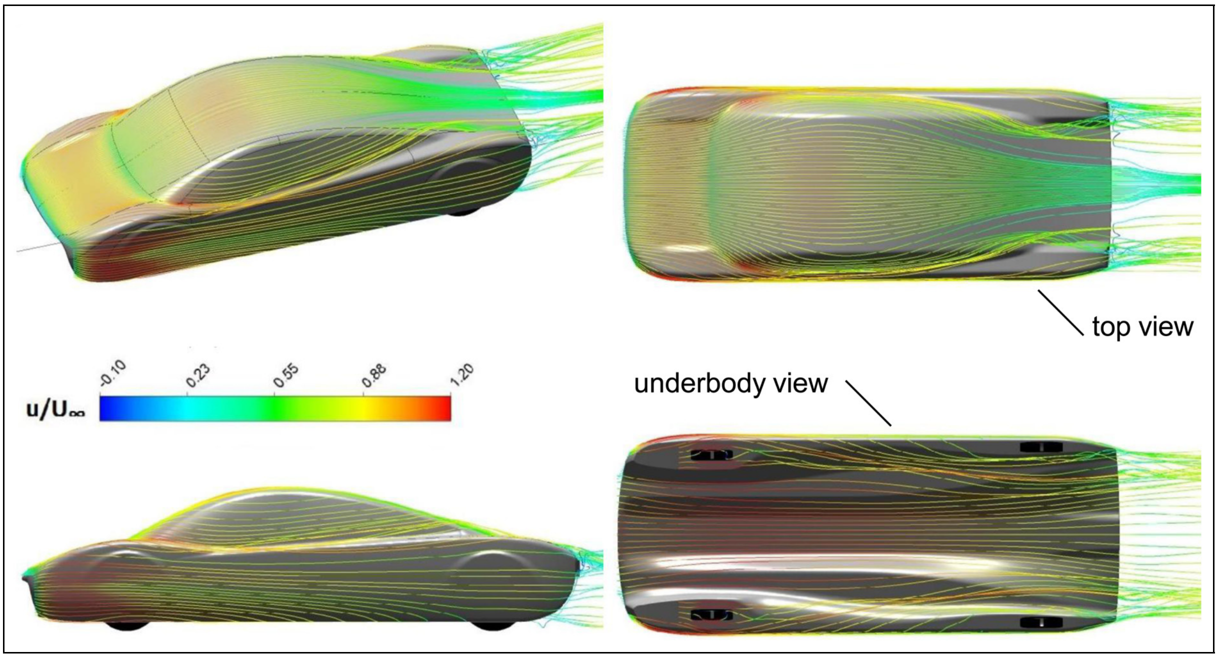


**Figure 6.** Visualization of the flow around the as-built design of eVe, highlighting the underbody aerodynamics and the vortices forming from the C-pillars and the trailing edges.

can derive as little as 20% of their drag from the pressure forces. As a result, it is also more susceptible to crosswind effects (such as an excessive low pressure around the A-pillar which caused the driver door to bulge outwards at one stage during the WSC), but the weight of the car and its normal lack of flow separation make it aerodynamically stable in all conditions. The vehicle is nearly pitch neutral. The total downforce at cruising speeds is equivalent to a weight of approximately 25 kgf, minimizing the rolling resistance on the tyres.

Figure 6 highlights the relatively strong vortices that form from the C-pillar as a result of the abrupt change from the roof slope to the shoulders above the rear wheels; the width of the roof was dictated by the array area rather than by the aerodynamics here, although more optimization may have solved this problem. The figure also indicates the tendency for flow on the sides of the car to become sucked underneath at the mid-body; this would have been alleviated by the duct options that were being explored at the time. Other than these aspects, the flow is remarkably smooth around the vehicle and there is negligible flow separation over the entire body.

Small ducts (as developed by the National Advisory Committee for Aeronautics (NACA)) were cut into the windscreen to providing the only driver ventilation. With only partially sealed wheel wells and no dedicated air flow management, driver experience showed that air travels into the passenger compartment through the rear bulkhead holes cut to anchor the seats and the rollbar; otherwise, thermal comfort was rudimentary and the drivers suffered from high cabin temperatures caused by the sun on the black thin composite skin and the large low-rake windscreen. Temperatures in the cabin routinely approached 10 °C above ambient (typically 30–40 °C) and required the occupants to consume several litres of water per 2–4 h driving period during the WSC. The use of CFD as a viable trusted tool has only become accepted for accurately predicting the cabin air flow and the thermal behaviour in recent years[13] and, with Sunswift, since 2013 to devise a passive air flow management system which encourages air flow from the cabin to the rear of the vehicle as driven by the low-pressure regions at the base and the high pressure at the front of the car; a byproduct of this is better cooling of the motor controller and the exposed underside of the array in the rear quarters.

For the Fédération Internationale de l'Automobile (FIA) international land speed record attempt, which did not need the vehicle to conform strictly to WSC standards, an additional 'tail' was added to the vehicle which otherwise featured a 'chopped' rear to place lights and the licence plate (as well as for aesthetics); this had the effect of negating the excessive downwash in the wake, and reducing wake thickness. The result was close to a 10% reduction in the vehicle drag and a 5% reduction in the downforce, which equated to several kilometers per hour in the record attempt, and also indicated areas of potential improvement to the car performance for future versions.

## *Array and maximum power point tracking*

The salient features of the major electrical systems and their subcomponents are listed for reference in Table 1. eVe's power system converts solar energy to charge a

**Table 1.** Major electrical systems, subcomponents, and their specifications.

| System component | Subcomponent | Specification |
|---|---|---|
| Array | Layout | Two strings (105 and 143 cells) |
| | Cells | SunPower C60 |
| | Total area | 4 $m^2$ on car |
| | Efficiency | ≈ 22% post-encapsulation |
| | Array output | 850 W |
| | Power–temperature de-rating | –1.8 mV/°C; 0.32% power |
| Maximum powerpoint trackers | Type | Drivetek V4 |
| | Controllers | Bespoke ATMega64M1 based |
| | Efficiency | 99% theoretical peak |
| Battery | Weight | 63 kgf |
| | Cells | 1326 Panasonic NCR1865OB lithium-ion battery |
| | Configuration | 39 series × 34 parallel |
| | Total energy | 16 kW h |
| | Voltage range | 113.1–163.8 V |
| | Capacity | 113 A h |
| Wheel motors | Number | 2 |
| | Type | CSIRO–Marand permanent magnet synchronous with non-salient pole rotors |
| | Controllers | Tritium Wavesculptor 22 variable-frequency inverters |
| | Peak output | 20 kV A (98% efficiency) |

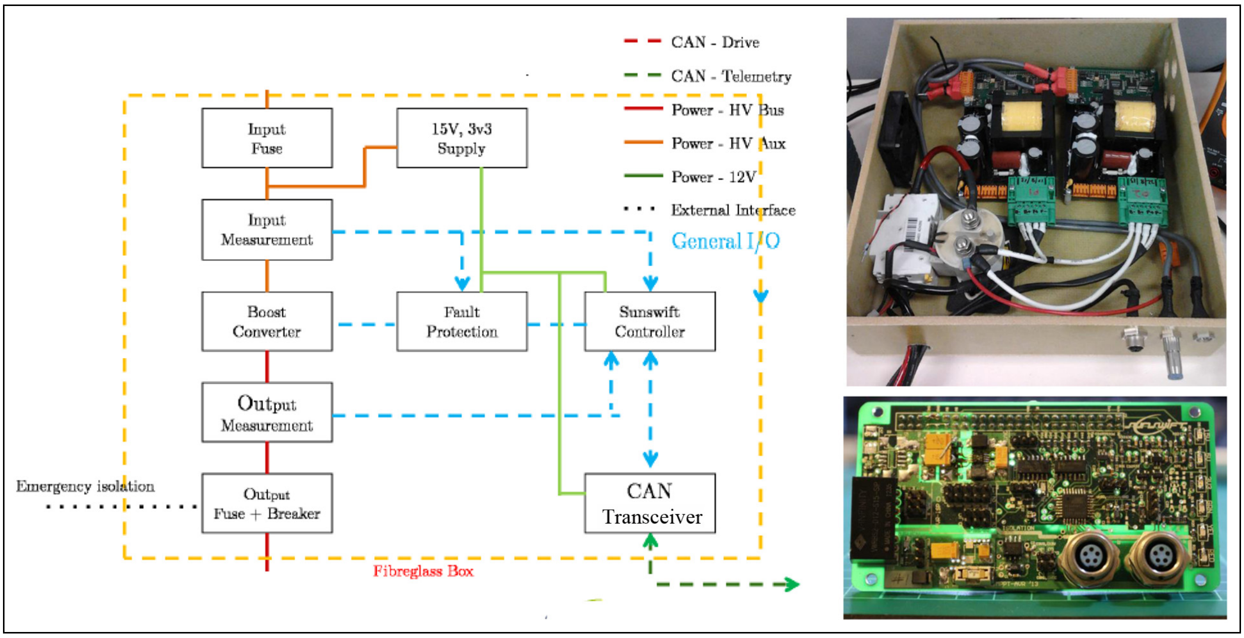


**Figure 7.** Block diagram of the MPPT system, together with the MPPT system as implemented in the car and also with the Mk I controller.
CAN: controller area network; HV: high-voltage; AUX: auxiliary; I/O: input–output.

battery and to deliver energy to a drive system. The sun provides energy which by the photovoltaic effect produces a voltage potential across the array. The array consists of two independent strings of cells which achieved an efficiency of close to 22% post-encapsulation. The cell area of 4 $m^2$ and the increased curvature of the body meant that the maximum array output was only 850 W compared with 1.2 kW for its predecessor, which had a much flatter 6 $m^2$ array. The average energy produced over the course of a typical WSC race day is 4.7 kW h. The primary requirements for eVe's power system were that it must be designed to be continuously completely reliable, and as efficient as possible in normal operation. The secondary requirement was that the entire electrical system must report back the operational status of the solar car for the purpose of strategy during the race; all telemetry data are collected by a Xbee wireless r.f. module. Strategy plays a vital role in monitoring the current condition and efficiency of the car when it is running.

Each of the two strings is connected to one of the two maximum-power-point trackers (MPPTs). Figure 7 shows a block diagram of the MPPT system, as well as the prototype controller and the overall package as implemented in the car. The MPPTs consist of a boost converter which steps up the voltage of the strings from their typical 50–70 V to that of the high-voltage bus at a nominal 140 V. In addition to this, the MPPT runs an algorithm to optimize the operation of the solar cells by keeping the strings operating at their maximum power points and drawing the correct amount of current from each of the strings for the present illumination conditions. The power from the MPPTs is outputted to the high-voltage bus where it can be used by the motor controllers to drive the car and any excess or shortfall is made up from the battery pack. There were mismatch losses caused by the curvature of the car, stemming from the fact that the current of the whole string is limited by that of the lowest current-producing cell in series, namely the current-producing cell which receives the least sunlight. This optimization problem also requires the design of fully customized MPPTs to handle the decreased input voltages.

The voltages for each string are different, and the strings are electrically isolated from each other. Current flows from each string into one of the two MPPTs. The input stage of the MPPTs matches the impedance of each string so that it delivers the most power that the string can actually produce. The MPPT then delivers this power through a charging stage which boosts and regulates the output to a high-voltage bus, to charge the battery. Finally, the battery or MPPT outputs can then provide power to the two motor controllers so that they can drive the two rear electric wheel motors. To be able to stand the harsh Australian outback environment without incurring damage, the MPPT system had to be able to have an ambient operating temperature range from −10 °C to 80 °C, to have an ingress protection of at least IP42 (i.e. protection from dust, dirt and light sprays of water) to have protection from wind and abrasion, to continue to operate under sudden movements from the car, sudden braking, and normal road vibration, to operate in humidity ranges of 5% and 95%, to minimize the generation of electromagnetic interference, and to prevent electromagnetic interference from significantly affecting the signal integrity of the MPPT. The MPPT system was also required to be double insulated and protected by covers or protection grills that are reliably secured and marked and had to be accessible, testable, and repairable or replaced quickly in normal operating conditions using tools accessible by the Sunswift team. Bespoke MPPT controllers are used because they allow the escort vehicle to monitor and dynamically to configure operation of the MPPTs, features that the Drivetek controllers lack.

The battery system, the MPPT outputs, and the motor controllers share the same high-voltage bus. The primary function of the battery is to act as a reservoir of energy that is collected by the PV system. A new WSC requirement for the 2013 race was the introduction of a battery-monitoring system (BMS), which must indicate the battery status down to cell levels. In particular, the BMS was designed to detect any cell that is becoming overcharged, undercharged, or too hot. The BMS for Sunswift eVe also communicates over the telemetry system, allowing the escort vehicle to monitor the battery status.

An optimal number of cells have a minimum string voltage above the MPPT minimum to charge the battery, fit on the car with a minimum angle of mismatch between cells, maximize the efficiency by keeping the MPPT boost ratio low, and maximize the reliability by minimizing the wiring complexity. Having too few cells in the string means that the mismatch between the cells is very low; however, it usually means that the MPPTs cannot operate because the string voltage is below the minimum required. Increased complexity for many strings naturally means that more failures are likely, impacting the reliability of the power system. Having larger strings means that having partial shading over the string impacts the whole string current. Bypass diodes are used to bypass sections that are shaded and to maintain the maximum string current. Because of the orientation of the front string, it receives significantly less irradiance over the course of a day than does the rear string. This is so much so that the front-string MPPT cuts out of operation in the early morning and late afternoon of the day, because the input power is below the minimum at which the MPPT can operate.

## Battery and motors

The main medium for storing the electrical energy for Sunswift eVe is the battery. The battery pack was composed of lithium-ion cells which provided an energy storage capability of 16 kW h. The choice of cells was optimized for the maximum ratio of the energy to the mass: 253.89 W h/kg. There are two methods to charge the battery: through the solar array and through a power supply connected to an ordinary household socket. The battery has an integrated management system and also an isolation system; these are to monitor the battery voltage and temperature, and to contain the high-voltage wiring to the battery box respectively. The state of charge of the battery is determined by a Coulomb counting method where the current passing in and out of the battery pack is measured and integrated to determine how much charge has passed in or out of the pack. This is an important strategy to ensure that the car is performing as expected and that the battery pack is not depleted sooner than expected.

eVe is driven with two in-wheel motors. Each of the two motors are driven with Tritium Wavesculptor 22 variable-frequency inverters (the motor controllers achieve 98% peak efficiency). The motor controller generates the sinusoidal waveform required for the motor in sensorless mode and also a six-step switching waveform to start the motor from standstill. The Wavesculptor 22 also provides a regenerative braking function, allowing the kinetic energy of the vehicle's

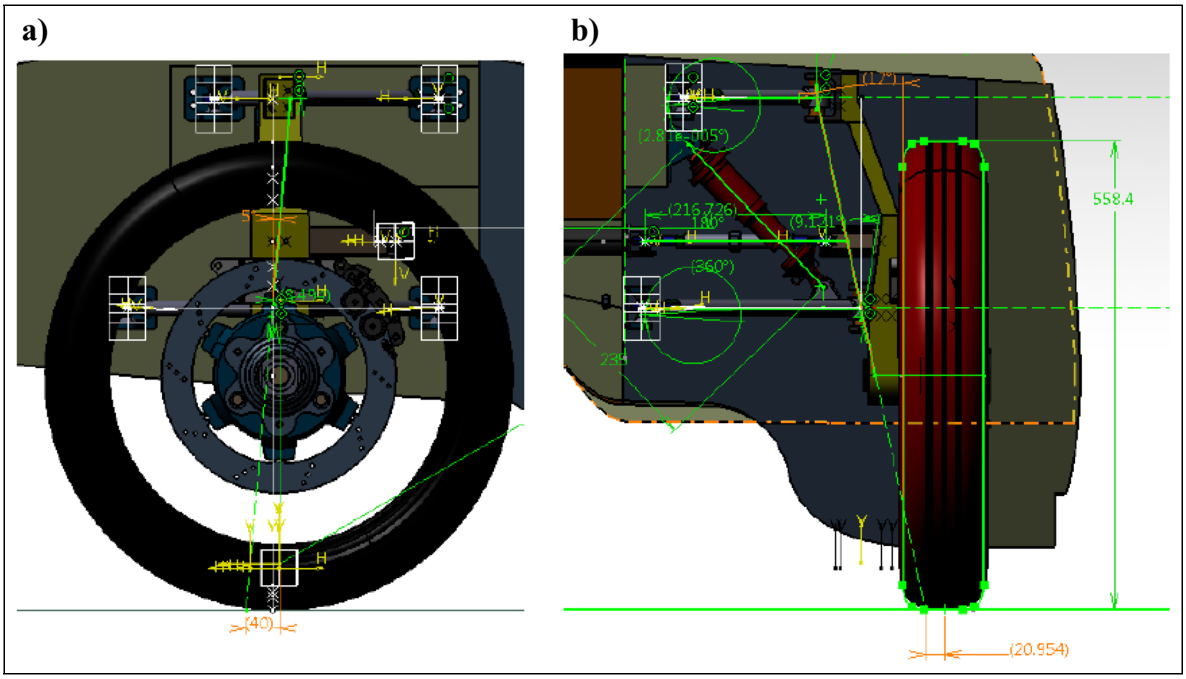


**Figure 8.** (a) Side view and (b) front view of the final front suspension design, with a mechanical trail of 40 mm, an inclination of 12°, a scrub radius of 21 mm, and a caster angle of 5°.

motion to be obtained and converted into electrical energy such that it can be stored in the battery pack. The Wavesculptor 22 also communicates over the telemetry network, but only to the bespoke Sunswift steering wheel. Statuses such as the motor speed, the motor phase voltages, the phase currents and the temperatures are sent via the steering wheel to the telemetry network, and to the escort vehicle where strategists can make informed calls.

## *Suspension*

Sunswift eVe utilizes independent designs for the front suspension and the rear suspension. Independent suspensions are more resilient to steering vibrations than are solid axles and provide more room for necessary components such as the vehicle's battery pack. They also allow the suspension components to fit within the tight confines of the car's aerodynamic shell.

A double-wishbone front suspension design was implemented as shown in Figure 8, because it is regarded as the suspension which allows the design parameters to be reached with the least amount of compromise.[14] The design features control arms composed of welded AISI 4130 (high-strength low-alloy) steel and a direct-acting coil over a shock unit custom built by Bilstein which dampens the road vibrations to ensure a more comfortable ride for the car's occupants. An aluminum alloy 7075 upright facilitates connection of the control arms to the front wheels. Because there were no strict requirements outlined by the WSC regarding the design of our solar electric vehicle's suspension system, self-imposed requirements had to be established and adhered to; some of these were based around meeting other explicit WSC requirements, and others around safety, driveability, and comfort.

Selection of the desired toe and camber angles was generally based on tyre wear characteristics rather than for handling reasons. As the minimum tyre wear occurs when the toe angle and the camber angle are both 0°, it follows that the desired toe angle and camber angle for Sunswift eVe should also be 0°. A caster angle of 5° was chosen in order to allow the car to lean into the turns, while a mechanical trail of 40 mm was deemed to provide a suitable compromise between straight-line stability and steerability.

A 12° kingpin angle was specified by WSC regulations; the greater the kingpin inclination, the more the car is lifted when steering. For a passenger car, this angle is typically[15] between 10° and 15°. The 75 mm ground clearance was selected while performing the aerodynamic analysis of Sunswift eVe. Movement of the suspension had to be limited to a maximum of 40 mm to ensure that the bottom of the car does not scrape the ground while in a bump. It was also deemed desirable to ensure that there was roughly the same amount of travel in a droop as there is in a bump. As no data were available to the team to estimate the maximum possible cornering load that could be sustained by the tyres, an alternative load case based on the maximum speed at which the car can negotiate a tight bend was used. For this load case, the car was modelled as a pair of lumped masses, representing the masses at each axle. This resulted in predicted centripetal acceleration of 1.42$g$, which is more conservative than the 1$g$ load case recommended for solar cars by Carroll.[16] Because the car was deemed to be on the verge of rolling over at this speed, one of the lateral loading conditions that was assumed was that 100% of the load at the front wheel reacted with the outer wheel in the corner.

Another WSC regulation states: 'The front suspension shall be capable of sustaining braking loads in which the total mass of the car is concentrated on the front wheels'. For this load case, it was assumed that the car was on the verge of tipping over forwards, i.e. that the weight of the car was purely on the front wheels. It is at this point that the normal force at the front wheels is at its maximum. As a result, the maximum possible braking force that could be achieved was found to be 3375 N. This is equivalent to a 0.8*g* braking force, which is less conservative than the 1*g* braking load advocated by Carroll.[16] In order to test that the control arms are capable of sustaining these loads, a range of analyses are performed. First, assuming the suspension members to act as trusses, the tensile–compressive forces in each tubular member of the control arms is calculated. Second, the maximum bending loads imparted on the lower control arm due to the force of the shock absorber are calculated and superimposed on the tensile–compressive forces on the members to determine the true worst-case forces on the control arm members. Finally, a finite element analysis (FEA) was performed on the lower control arm, which is the most highly loaded control arm, in order to verify that the final design is indeed safe and also to optimize the shape of the bracket on to which the shock absorber is mounted.

A rising rate suspension was desired as it enables the vehicle's ride to be soft for small wheel deflections and gradually to become stiffer for increasing deflection.

Because a solar car is designed for conditions not dissimilar to those of a normal car, it was deemed suitable to aim for ride frequencies of around 2.2 Hz. This is similar to the ride stiffness of a high-performance sports car. Obtaining these ride frequencies required the selection of a suitable spring stiffness and a suitable spring length. The only real problem that was apparent with the front suspension during the race was that some of the nyloc nuts used to connect the control arm brackets and the shock brackets to the chassis loosened slightly after the day's ride. A possible reason for this is that the bolts connecting these brackets to the chassis did not have a sufficiently high torque. Suggested torques were to be calculated for these bolts; however, the torque wrench was not used because of concerns that too high a torque could damage the chassis rail, which would probably have halted any chances of finishing the race.

A trailing-arm rear suspension was chosen, because of its capacity to be used within the tight bounds of the car's rear-wheel fairings. It is composed of laser-cut welded mild steel and holds the wheels in double shear, similar to designs featured on the rear suspensions of motorcycles. It also uses Öhlins TTX25 Mk II F-SAE dampers. The coil-over-shock unit used in both the front suspension and the rear suspension ensure a ride frequency of approximately 2 Hz, resulting in a ride stiffness slightly greater than those found in passenger cars, and more in line with values found in a sedan race car.

## Wheels, steering, and braking

The Michelin Solar Radial 95/80 R16 tyres chosen are specifically designed for solar vehicles to ensure that the rolling resistance is minimized. The GHCraft CFW-S16-94C wheel rims used in the front of the car are designed specifically for solar cars. These carbon composite rims feature an aluminum honeycomb core, ensuring that the mass of each rim is kept to just 1800 g. The rear wheel rims, however, needed to be custom designed to house the wheel motors. As the solar car utilizes an in-hub axial flux, a permanent magnet, and synchronous d.c. motors mounted in the rear wheels, two unique aluminum housings needed to be designed to accommodate the different magnet mounting holes of each motor. The system used to attach the wheel to the rear suspension is a tongue-in-groove system. The stator flange is positioned axially using a shoulder on the shaft, with torque transfer by a key and fixed axially by bolts on a flange of the shaft.

Regenerative braking is preferred in almost all circumstances. In addition to regenerative braking, the WSC regulations stipulated that two independent mechanical braking systems had to be implemented in the solar electric vehicle, to ensure that the vehicle can still be stopped even if one of the systems failed. In Sunswift eVe, a dual-redundant hydraulic brake system was established. Two callipers are present on each brake disc, and redundancy is achieved by activating the front calliper on each brake disc using the handbrake and activating all four callipers using the footbrake.

Sunswift eVe is designed to handle like a typical road-going passenger vehicle and does so through implementation of the Strange Engineering S3447 Dragster Box, a 12:1 ratio rack-and-pinion unit. Ackermann steering conditions are closely approximated, which enables the car to turn while minimizing the scrub radius of the tyres. This steering system is also designed to allow the car to perform a sub-16 m kerb-to-kerb U-turn (as mandated by WSC regulations). Other features of the steering system include a steering column encompassing three universal joints, which allows the column to collapse in the event of a collision and also enables the steering wheel to be laterally offset from the pinion gear. A carbon fiber turret containing two acetyl bushings facilitates the lateral displacement of the steering wheel from the center-line of the car and also supports the steering shaft.

One further WSC requirement was that 'any steering shaft shall not be capable of spearing the driver in a crash'. The steering-column assembly consists of a steering rack at one end and a steering column at the other. Connecting these two sections of the steering system is an intermediate shaft, which is connected to the column and the rack via the use of two universal joints which are positioned 90° out of phase. The use of two universal joints is effective in preventing movement of the steering column in the event of a crash. The misalignment of 20° between the universal joints produced by the steering geometry was deemed to provide sufficient angular misalignment to ensure collapse of the steering in a collision.

### *Structural design and body construction*

While carbon fibre components specifically for large-scale body panels as well as structural members (as opposed to smaller internal panels and components, which is more common) are becoming a more viable option for low-volume to mid-volume high-end vehicles (such as supercars),[17] they are not currently a genuine option for mass manufacture of cars; however, for solar-powered vehicles it presents the only easily accessible route to competitive performance because of the exceptional weight savings over steel and aluminum, or other common composite materials, and the necessary strength for structural rigidity and safety in the absence of more conventional crash structures. Therefore, material alternatives were not considered other than for the rollbar. A rollbar is implemented in Sunswift eVe to protect both occupants in the event of a rollover. The roll cage meets all the requirements of the Australian National Code of Practice for Light Vehicle Construction and Modification,[18] section LK8 except for section LK8 5.1: tubular members (Table LK7), where the dimensions meet the CAMS manual of motor sport 2013, Confederation of Australian Motor Sport, General requirements for cars and drivers, Schedule J – safety cage structures, Schedule J8: material specifications (Table J-1).[19]

Carbon fibre composites were therefore used to construct the vast majority of the interior and exterior. From a partnership with Core Builders Composites in New Zealand, a subteam of 12 students were able to travel there and, over an intensive 2 week period, were assisted and mentored in all aspects of manufacture. Universally, the students reported overwhelmingly positive feelings about the experience, which exposed them to a level of design professionalism which they had not previously encountered, as well as a work ethic which could not have been achieved in their normal workshop and without strict deadlines. The chassis consists of a top shell and a bottom shell with three thicker Nomex honeycomb core sandwich bulkheads for lateral rigidity and torsional rigidity.

As the shell was manufactured out of carbon fibre and has a complex bespoke shape, there were no guides in design or strength abilities. In order to ensure that the shell maintains its integrity throughout its operation life, a model needs to be developed to determine the reactions when the car experiences braking, bumps, or cornering. An extensive static structural FEA using ANSYS was carried out on most of the major components of the car, including the chassis. Very little validation or destructive testing was possible, and digital structural analysis of composites is a challenging undertaking at the undergraduate level outside the classroom. Therefore, relatively conservative design margins were established, with typical factors of safety (FOSs) at least twice the anticipated failure levels but often considerably higher (a lowest FOS of 1.42 occurred around the seat but, excluding that particular attachment point, the FOS was as high as 18).

The thickness and the layers of carbon fiber were created by defining the core thickness, the material thickness, the direction of the weave and the number of layers to be defined. Modeling assumptions included homogeneous resin strength and fiber strands, constant temperatures and accelerations, and adhesives with the same strength as the carbon work. FEA meshes for the chassis (excluding the shells) consisted of approximately 500,000 elements; a maximum mesh face size (4 mm) was required to achieve suitable convergence and resolution. Virtual displaced masses were inserted into the body to account for the effect that they have on the inertia of the system. Considering the mass distribution in the car, it was found that 75% of the weight could be accounted for by including just the six heaviest objects: the masses of the driver, the passenger, the battery, the rollbar, and both motors. The masses were applied to the model remotely on to their contact surfaces in order to maintain the correct mass moment of inertia of the system.

There were four simplified cases that the car was designed to cope with as follows: a $3g$ vertical bump; $1g$ braking; $1.42g$ cornering; the combined effect of all the loads (worst-case scenario). The braking case involved an acceleration of $1g$ downwards (standard gravity) and $0.8g$ towards the front of the car.

Figure 9 highlights the stress normal to the surface of the car, where the ultimate stress that the material is capable of withstanding is 850 MPa. The only major stress concentrations start to appear on an iso-capped surface at 21 MPa and below. All the results had a common theme of the largest deformation and the areas of high stress concentration around the people seated in the car. This is realistic as the people in the car account for 37% of the car's total mass, and the weight of the people is distributed over six attachment points around the driver bulkhead. It was predicted that the maximum deformations are 1.4 mm in the area of the driver seat, with most of the chassis comfortably within 0.5 mm. In the $x$ and $y$ directions of the carbon fiber weave the material fails at 850 MPa, and so, depending on the maximum principle stress selected, the minimum FOSs were 9.4 and 18.

## Performance and achievements

Lack of testing before the 2013 WSC meant that electrical issues marred qualifying, and a costly brake rubbing

**Table 2.** WSC achievements and notes.

| | | |
|---|---|---|
| WSC 2013 position | First in class on race time | Third in class overall |
| WSC 2013 times | Race time, 38 h 35 min | Fourth fastest time in all classes |
| WSC 2013 speeds | Race top speed, 128 km/h | Sustained leg average, approximately 110 km/h ( $<$ 5 kW draw) |
| FIA World Record | Top speed, 132 km/h | Average, 107.2 km/h over 500 km |

WSC: World Solar Challenge; FIA: Fédération Internationale de l'Automobile.

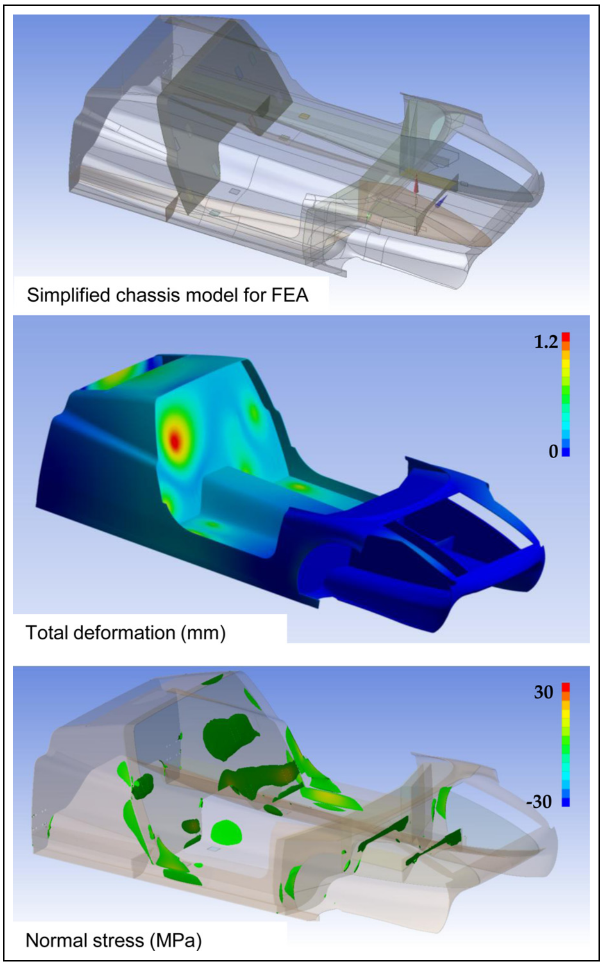


**Figure 9.** FEA results for the normal stress and the predicted local deformation for the worst-case structural loading on a simplified model.

issue on day 1 of the race. From day 2, however, the car ran well and took Cruiser Class line honours by a margin of almost 2 h. It was the only Cruiser Class vehicle to arrive successfully at its destination on every day of the WSC, i.e. the highest endorsement of practicality. There were no injuries or serious safety incidents. General achievements are summarized in Table 2.

The extrapolated highway range of eVe with the present battery pack is in excess of 800 km if driven at a near-constant energy consumption at around 80 km/h on average. Aggressive driving behaviour has a particularly strong influence on the overall range of an electrical vehicle,[20,21] and thus smooth driving strategies are required for managing eVe's energy budget. This extends to interactions with undulating terrain (long acknowledged as a significant factor in WSC solar car performance[22,23]) as well as overtaking; therefore, strategic driving even in non-race conditions is important for endurance.

In July 2014, the team, who used a slightly modified version of the car with improved brakes and the extension to the rear of the vehicle to correct the downwash and to reduce the pressure drag, attempted an FIA international land speed record (Category A, Group VIII, Class 1) for the fastest electric vehicle over a distance of 500 km. The ratified official average speed was 107.2 km/h, with professional racing drivers Karl Reindler and Garth Waldren completing all laps of the Australian Automotive Research Centre test track in Victoria.

## Conclusions

The Sunswift eVe solar–electric car represents a significant achievement for the students involved in its design, construction, and development. It claimed line honours in the 2013 WSC and has since set the FIA international land speed record for the fastest electric vehicle over a distance of 500 km (107.2 km/h). The car was made almost entirely out of carbon fiber composite material and was designed with a $C_DA$ of 0.14 m$^2$. The solar array produced a maximum of 850 W which, when combined with a 16 kW h battery pack, gives the vehicle a range of over 800 km at conventional highway speeds. The project has proved to be of enormous value to the core students who have been involved, their eventual employers, and UNSW's Faculty of Engineering. It has also been used to inspire younger students to pursue degrees and careers in science and engineering, and more recently this inspirational position has extended to the general public with a series of high-profile record attempts demonstrating the promise and potential of alternative-energy vehicles. Future challenges will involve planning effectively for the medium term in order to keep a sustainably funded team at the forefront of what is new, and most relevant to industry, in order to provide the most useful, educationally rewarding, and high-profile training experience for engineers at UNSW Australia, in the era of the electric car.

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## Notation

| | |
|---|---|
| $C_DA$ | coefficient of drag from the projected frontal area ($m^2$) |
| $C_L$ | coefficient of lift ($m^2$) |
| $k$ | turbulent kinetic energy (J/kg) |
| $P$ | power (W) |
| $\omega$ | specific dissipation rate ($s^{-1}$) |