Racing on sunshine: designing, building and racing solar-powered electric vehicles

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I. INTRODUCTION

The author spent two summers working on the Durham University Solar car. The first summer was spent working on the cooling of the batteries on the solar car. The second summer was focused on adding a level of automation to a chassis dynamometer. The two summers included competing in the *Bridgestone World Solar Challenge* and an intent to compete in the *iLumen European Solar Challange*.

II. ELECTRICAL SYSTEM

The basic operating principle of the solar car is to take power from the sun to charge an onboard battery and drive the car forward. The onboard battery is used as a buffer when the solar power available is low and to charge when the solar power available is high. This is so that the car can be driven when the solar energy is insufficent to power it such as in the shadow of a building. An overview of the electrical system is shown in Figure 1.

A. Solar Cells

Starting with the energy collection medium, the car uses $4\,\mathrm{m}^2$ of silicone solar panels supplied by Gochermann Solar Technology. The panels provided an average power of around $900\,\mathrm{W}$ in Australia. This is the total power the car has to run on during the duration of the race. For context, a toaster or microwave is around $2000\,\mathrm{W}$. The solar panels are specially encapsulated to allow them to be flexible. This means they can be placed on a curved surface, allowing for greater freedom in the design of the aerodynamics. The panels also have a special prismatic coating, so that light that comes into the panel at a glancing angle is reflected into the panel rather than reflecting off as in a normal, untreated solar panel.

The solar panels are wired in series to two *DriveTek MPPTs* (Maximum Power Point Trackers). This device sets the load on the solar panel by balancing the current and voltage coming from the panel so that the panel generates the most power it can for a given solar state. The MPPT unit also boosts the voltage coming off the solar cell up to the voltage larger than that of the batteries, so that they can be charged from the solar panels.

B. Batteries

The solar car carries $20\,\mathrm{kg}$ of lithium-ion cells. There are 420 cells with a maximum voltage of $147\,\mathrm{V}$. The specific cells used are *LG Chem Lithium Ion INR18650 M36T* cells, each with $3440\,\mathrm{mA\,h}$ ($12.5\,\mathrm{W\,h}$) of charge, giving a total pack charge of $1444\,\mathrm{A\,h}$ ($5250\,\mathrm{W\,h}$). The batteries are arranged in a 35S12P configuration to give a maximum voltage of $147\,\mathrm{V}$ and a maximum discharge current of $60\,\mathrm{A}$. It would be more efficient to have a higher voltage, thus reducing the maximum discharge current, but the *Trium Wavescupltor 20* which controls our motor is limited to $150\,\mathrm{V}$.

The lithium-ion batteries carry a fire risk if not installed and managed correctly and safely. In order to mitigate this risk, we use an *Orion BMS* (Battery Management System). This constantly monitors the cells and cuts the high voltage from the battery pack to the rest of the car if the battery usage leaves safe operating conditions. These conditions are:

- Over temperature
- Under temperature
- Exceeding discharge current limit
- Exceeding charge current limit
- Cell overvoltage
- Cell undervoltage

The BMS monitors the 35 series strings of cells to determine if any one of them is outside safe operating limits (below $2.5\,\mathrm{V}$ or above $4.2\,\mathrm{V}$).

The high voltage of the battery pack has the potential to be deadly, and is therefore contained in an insulating, fireproof aramid (a generic version of the brand name product Kevlar) box to protect people from it. This box was the specific subject of the author's 2019 *Laidlaw Summer Research Project*. This is detailed in Section IV and an image is shown in Figure 9.

C. Motor

The motor is a custom-designed, in house manufactured, axial flux permanent magnet motor specifically

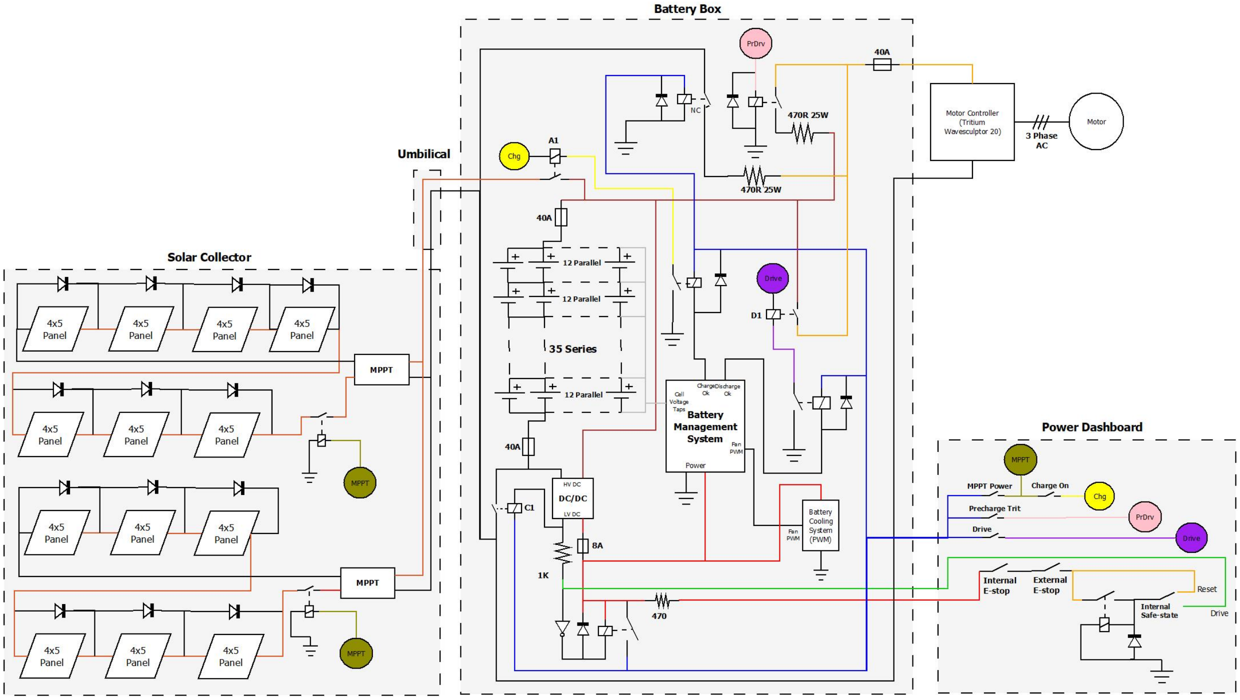

Fig. 1. A diagram showing the high voltage system on the solar car

for powering a solar car. As such, the motor is designed to be most efficient at the speeds we expect to drive: around $60\,\mathrm{km/h}$. The motor is an in-hub design and therefore avoids all the transmission losses found in a conventional electric car for example, losses in the gearbox and differentials.

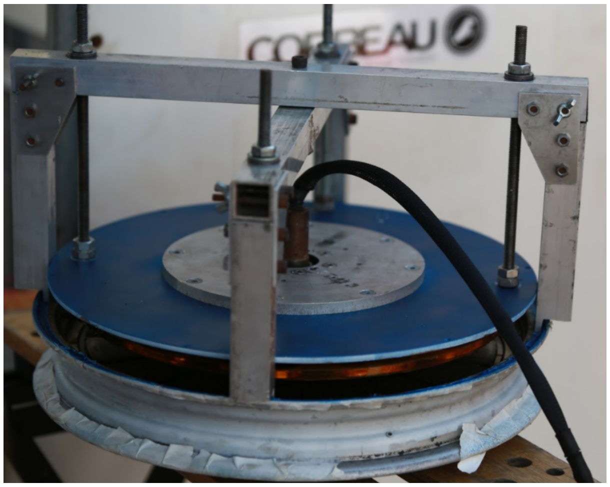

Fig. 2. The motor partially open showing the sculpted back irons and coils inside.

III. MECHANICAL SYSTEM

A. *Chassis*

The solar car's chassis is constructed entirely from carbon fibre reinforced polymer (CFRP) with foam core. The chassis is the part of the car that most of the components are mounted to such as the suspension and array and thus needs to be very strong. This creates a very stiff and light structure. The chassis was the first major part of the car to be layed up. The mould was made of plastic-coated chipboard and the chassis was layed up onto this using pre-impregnated carbon fibre (pre-preg). It was then cured in a custom made $5\,\mathrm{m}$ oven under vacuum. The oven is show in Figure 3

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Fig. 3. The mould in the 5m oven ready for post cure.

The car also features a composite roll hoop made from carbon fibre and aramid. This was made separately and later bonded into the car. In order to verify the integrity of the roll hoop, a test roll hoop was made and tested to destruction. The test rig is shown in Figure 4.

Fig. 4. The test roll-hoop undergoing a compression test to verify correlation between compuational analysis and physical strength.

B. Aerostructure

The car's Aerostructure was designed by masters student Alex Stemlar. It has an impressive wind tunnel CdA of 0.107, which is roughly equivalent to the wing mirrors on a normal car. The aerostructure was manufactured by first machining patterns out of model board using a CNC router. These patterns were sanded and polished and then used to create fibreglass moulds. These moulds were then joined together into one large mould. The aerostructure was then layed up all in one piece and cured in the 5 m oven under vacuum. After the areostructure was cured an "installation lay up" was performed where the chassis and roll hoop were bonded to the car. This again was done in the 5 m oven under vacuum.

C. Suspension

The front suspension is of a double wishbone design, with carbon fibre wishbones and a machined aluminium upright. The design of the front suspension is unusual compared to most cars, because all of the mounting points for the front suspension are above the centerline of the wheel, resulting in a very long and subsequently quite heavy upright. Both the front and back use mountain bike air shocks for shock absorbers.

Fig. 5. The completed chassis mould, ready for lay up.

Fig. 6. The very large vacuum bag used to cure the aerostructure.

The car's rear suspension uses a trailing arm design, and is made of carbon fibre.

IV. BATTERY BOX COOLING

The author's first summer of research was supposed to focus on the battery cooling design. However, due to slips in the solar car construction schedule, most time ended up being spent elsewhere to work to deliver a functional car. Nevertheless, time was still found to develop the battery box and the battery box cooling solution to a

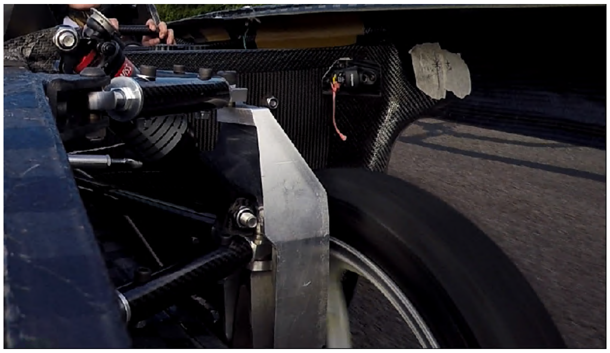

Fig. 7. The front suspension showing the carbon wishbones, aluminium upright and bicycle shock.

Fig. 8. The rear motor side suspension, showing the carbon fibre trailing arm and the bicycle air shocks.

standard that the batteries had no overheating problems during the 2019 World Solar Challenge, as they had had in the 2017 World Solar Challenge.

It was decided early on to construct the battery box from aramid-reinforced polymer due to its electrical insulation properties compared to carbon fibre which is a conductor. This is good because live conductors inside the battery box that could contact the inside skin will not be able to give someone an electric shock if they touch the outside of the battery box. Also, if the box was made from carbon and was damaged in a crash, carbon splinters – which are conductive – could create shorts on the inside of the box, starting a fire.

The final solution for battery box cooling was a fan drawing air from the base of the car, behind the front right wheel, and exhausting it through ducting to in front of the rear right hand wheel at the bottom of the wheel well. These two locations were chosen after analysis of computation fluid dynamics results to find the most optimum places for the inlet and outlet in such a way that air would be drawn through the box without use of the fan at lower thermal loads and the fan would turn on when the batteries were too hot.

Fig. 9. The battery box immediately after being released from the mould but before being trimmed and having holes for bolting components put in.

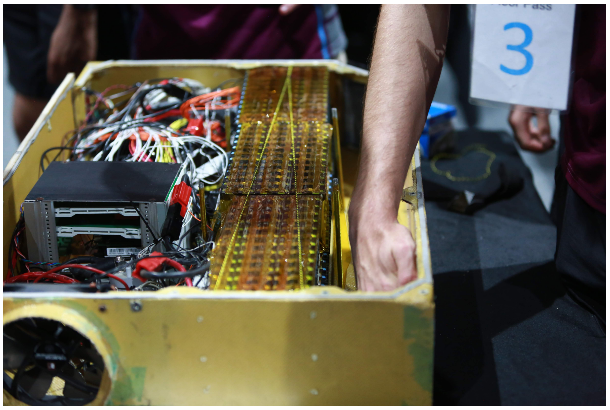

Fig. 10. The battery box during static scrutineering in Australia, showing the cooling fan on the lower left of the image.

V. TESTING

Once the mechanical parts of the car were complete we immediately began testing it, initially in the car park of the engineering department and then at *Bruntingthrope Airfield and Proving Ground*. For the first test we used the electrical system from the 2017 car. This test revealed some strength issues with the rear suspension and some sources of unreliability with the electrical system but these were all resolved after or during the test. Given the fact that this was the first time the car had turned a wheel it was considered a successful test.

The next test was done with the new electrical system as it would be raced in the 2019 race but without a solar array. This test was plagued with numerous reliability issues but saw the completion of the dynamic test that the car would have to pass in order to be race legal in Australia. These tests were a figure-of-eight stability test, a maximum turning radius test and a brakes test.

VI. THE WORLD SOLAR CHALLENGE

The World Solar Challenge, the event that the car was built to compete in, is a $3000\,\mathrm{km}$ race from Darwin in the north of Australia to Adelaide in the south. The team shipped the solar car to Darwin via container ship on the 13th of August and flew out later on the 24th of September to meet the car in Darwin.

Fig. 11. The staging area the night of the flight to Australia showing all the solar car components to be taken in our luggage on the flight. Items include: a 3D printer, two canopies for the solar car (in the cardboard box) and a spare motor.

A. Hidden Valley

The team arrived in Darwin and quickly worked to get the car and its container released from customs. Then the team immediately got to work on the car, as it was not completely ready to race. The car at this point had no working solar array or means of attachment, nor did it have working lights or a front visor (the team had taken the visor on the plane on the way out). We arrived a few weeks before the pit lane at the *Hidden Valley Racetrack* opened and got to work on the car at our campsite, turning the communal camping areas into a workshop. This set-up can be seen in Figure 12.

Once the pit lane garages opened, work was done on the car to get the car ready to race. This included installing the canopy in the car, wiring the array and ensuring our car would pass scrutineering. The car passed all of scrutineering first time except for number plate visibility which we were able to fix that evening; the car passed the next day.

Fig. 12. The communal cooking area of the campsite being used as a workshop before the pit-lane opened.

Fig. 13. The car in the pitlane with the team next to it

Fig. 14. The car being inspected at scrutineering with all the other cars in the competition

After static scrutineering, where the car was rigorously tested to ensure it comformed to all the regulations stipulated by the World Solar Challenge, the car moved on-to dynamic scrutineering. Dynamic scrutineering tests all aspects of the car that can only be tested while it is moving, such as stability and braking. Dynamic scrutineering is also where the qualifying order for the race is determined. This is done by each car doing one lap around the track, the fastest leaving the start line for the race first and the slowest last. The Durham team managed to qualify 18th with a time of 2:36.9. The fastest team, Top Dutch qualified with a time of 1:51.0.

B. The Race

Fig. 15. The route of the World Solar Challange showing all the control stops.

Day 1

The race began at 0830 on the 13th of October from State Square in Darwin Australia. From there, the solar car and it's support convoy navigated the tricky and busy streets of Darwin until the Tiger Brennan dual-carrigeway which then merged into the Stuart Highway which runs from Darwin to Port Augusta and would carry the car 2,714 kilometers of the 3,022 kilometers to Adelaide.

The race is split up into control stops which must be reached before a certain time or the car will be disqualified from the race. It must travel in its trailer to the next open control stop where it can continue to run from but will have forfeited its position in the race. Between Darwin and the next control stop, Katherine, is 322 kilometers of open road. This section of the race sees the highest rate of attrition for solar cars and drivers for that matter. For many teams, the start of the race is the first time the car has been driven non-stop ever, including ours. Furthermore, the night before the race is the last opportunity to fix problems with the car before the race start at 0830. For this reason, many team members are operating on no or next-to-no sleep. It is also the most challenging environment for the drivers to operate in, as the humidity is around 100% and the air temperature around 45 °C making heat exhaustion a real risk. Furthermore, due to the sub-one minute spacing between cars leaving the start line, there is a big incentive to not stop the car to perform repairs or a driver change for risk of losing race position. This high density of solar cars on the road leads to a very hectic first few hours through a busy section of public road.

Fig. 16. The Durham car being overtaken by the Western Sydney team outside Darwin with heavy amounts of normal traffic on the road. Overtakes are generally done in a safe manner with the teams informing each other when it is safe to overtake over the radio. This image shows an overtake on a dual carrigeway with an overtaking lane, but most of the race was on single carriageway roads.

Once the team reached the Katherine control stop, the driver got out of the car and pressed a red button on the desk of an event official. This started a 30-minute timer before which the car could be legally touched again. During this time the support cars had to race to the nearest petrol station to be able to keep up with the solar car. Katherine also is home to the last supermarket for the next 1,200 kilometers and so was the venue for the stocking of all of our food and water for the next few days. By the time the team arrived at the Katherine control stop 6 of the 27 Challenger Class teams that started the race were out due to failing to reach Katherine by the 1530 cut-off, one of which was due to a battery fire. After a driver change, the car continued to Warloch Ponds at kilometer 443 where the team camped for the night.

At the stop point, the team worked to fix things that had broken on the car during the day, mostly 3D printed parts that had melted due to the high internal heat in the car.

Day 2

The rules of the race say that the solar car can only be on the road from 0800 to 1700 but there are no rules of charging during this time. For this reason the solar panel on the car can tilt to point directly at the sun rather than at an oblique angle like it is when the car is driving. This allows the batteries to get more power when the car is stationary than it can while it is moving. For this reason, the team tilted the array to point at the sun whenever the car stopped. This includes at the half-an-hour control stops and during the morning and evening when the car is off the road. This requires getting up an hour before sunrise to prep the car for charging in the morning so that every watt of sun available is harvested. This dominated every morning of the race.

Fig. 17. A typical morning with the array tilted at the sun.

Fig. 18. A typical overnight campsite in the Northern Territories.

The next control stop was at Daly Waters 145 kilometers away from where the stop point on the previous day. The team set off at 0800 and made the control stop by 1034 where the array was tilted at the sun and the driver swapped. That night, the car stopped at 1700 at around kilometer 938, only 39 kilometers from the next control stop Tennant Creek.

Fig. 19. The type of traffic the solar car had to share the road with.

Day 3

On day three, the team again rose before dawn to point the array at the sun. Unfortunately when the car went to drive at 0800 the motor would not spin. This turned out to be an electrical connection issue that took 45 minutes to fix, costing us valuable time. The car reached the Tennant Creek control stop at 0940 half and hour later. The next control stop was Barrow Creek, 220 kilometers further down the road. This was done in a single driver stint. This driving stint saw the car being overtaken by several oversized loads, an off-road section where the road was closed and an overtake of another solar car team *Solar Team Solaris*. This stretch also saw very large cross and tailwinds which enabled us to increase our speed due to reduced aerodynamic losses in these circumstances. However this caused stability issues for the 180 kg car, making it harder to handle the car in the strong winds. The driver at the time described the handling of the car as “Like steering a paddleboard”. Little did the team know that these woes paled in comparison to the effect that the winds were having on competitors further ahead in the race where many had rolled over and been knocked out of the race.

The car reached the Barrow Creek control stop at 1345 and continued on with a third driver. The car continued until 1700 where the team stopped to camp at around the 1383 kilometer mark.

Day 4

The fourth day of running saw the car pass the Tropic of Capricorn before entering Alice Springs, the first town since we left Katherine four days ago. Day four was the most challenging day the team saw during the event. Once the car had entered the Alice Springs urban area, developed a motor problem that led to it not being able to pull away from a stop. In a busy town with lots of traffic lights this not ideal. This stop-starting to try and fix the motor led to around a one-hour delay in getting to the Alice Springs control stop which the team reached at 1053. This arrival time raised doubts about being able to reach the next control stop at Kulgera before it closed at 1600. The car left Alice Springs and carried on non-stop for four and a half hours, straining the support cars' fuel tanks, and arrived at the Kulgera control stop at 15:59:45, 15 seconds before it closed. After Kulgera, the team continued on for another half an hour, crossing the border into South Australia and stopping at kilometer 1800 for the night.

Fig. 20. Driver Ellie Desmond running to start the control stop timer.

Day 5

Day 5 began like the previous days with an early rise to tilt the array at the sun, although this time it was complicated by a nearby tree that needed to be removed to facilitate a clear view to the sun. The car set off at 0800 towards the next control stop: Coober Pedy. Coober Pedy was by far the most desolate landscape the team had travelled through, an active opal mining town filled with open, unmarked mineshafts and an unusual and eclectic mix of characters living mostly underground to escape the heat. The journey to Cooper Pedy was fairly uneventful expect for a frantic unscheduled toilet stop before setting off again. The car reached the Coober Pedy control stop at 1436 where the team replenished their food and water supplies before leaving half and hour later to cover more distance. The team then continued on until 1700 where the team stopped at kilometer 2307.

That evening, the team evaluated where in the race the car stood and if the car would make it the end of the race before the race cut-off after 1700 on the sixth day. It was then discovered that due to a miscalibration of the battery management system, the team had thought there was less charge in the battery and thus had been driving the car slower than was possible in order to not fully drain the battery. As a result, the car hadn't made as much progress as required and. To complete the race, the car would have to cover 717 kilometers on the last day, an average speed of 80 kilometers per hour. Through running computer simulations on a custom piece of software called *SolarSim* the team determined that this would not be achievable on the power available from the sun. It became clear that the team would not be able to finish the race.

Fig. 21. The car traversing the moonlike landscape of Coober Peady.

The miscalibration error was in part due to the difficulty of assessing the state of charge of lithium-ion batteries. This assessment is hard becasue the BMS uses the voltage of the cells to determine the state of charge, however the voltage of the pack is not always an accurate predictor of state charge. Furthermore, in the 20% to 70% charge region the voltage of the pack only changes by a small amount making it hard to determine where in that range the cells are. I was not all negative though because it meant the car was performing better than our simulations had predicted.

Day 6

Day 6 began early again, earlier than previously due to sunrise being earlier as the race moved south, and the team began charging the car. The strategy for this day was different than the previous days due to having a larger battery reserve than previously thought and thus were able to drive much faster. The next control stop was Glendambo at kilometer 2432, 125 kilometers away. The car made this in two hours, ariving at 1000, with an average speed of $63\,\mathrm{km/h}$, compared to our average speed of $55\,\mathrm{km/h}$ up to this point. The car left Glendambo towards the final control stop: Port Augusta. Port Augusta sat on the Great Australian Bight, the sea to the south of Australia, meaning that reaching that point meant the crossing of the whole continent, a major milestone. The car reached the final control stop at 1442 covering 289 kilometers in just over four hours at an average speed of $69\,\mathrm{km/h}$. Port Augusta also represented the first "proper town" that the team had past through over six days of camping in the desert and everyone felt for the first time how dirty and tired they had become over the week.

The next part of the trip after leaving Port Augusta was one of the hardest due to the high volume of normal traffic and the team processing the fact that we would not be able to reach the finish line in time. The car stopped at 1700 for the final time at kilometer 2834, with only 188 kilometers left to travel. The team loaded the car into the trailer and drove to our hotel in Adelaide, getting there at around 0100.

VII. CHASSIS DYNAMOMETER

The project for the second summer of research was finishing the work of a second-year design project by finishing a chassis dynamometer by developing electrical and mecahnical control systems for a chassis dynometer. These systems would allow it to be used to both simulate events in the lab and to determine drive train efficiency. The full scope was not achieved, but this section of the report will describe the progress made which is not insignificant.

The chassis dynamometer as it was when the project began consisted of a drum connected to an electric motor suspended on "balances", force-measuring devices that could measure the torque applied to the drum. The motor, depending on the electrical resistance connected to it, could change the resistance encountered in spinning the drum. There was also a handbrake that could be used to achieve the same effect. The problem was there was no way of setting the electrical resistance connected to the motor or actuating the brake.

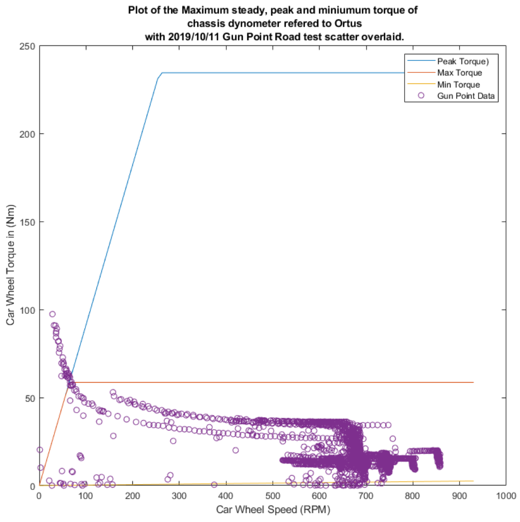

Fig. 22. A MATLAB plot showing the regions that the electrical brake can operate in and data from a typical test overlaid.

The scope of the project was to design, build and test a system to automatically set the torque demand of the dynamometer and the speed the test vehicle was driven at in order to simulate a variety of running conditions. The design phase was completed but the build phase was not.

The electrical side of the design consisted of a bank of resistors that could be turned on and off using MOSFETs along with three capacitors for smoothing.

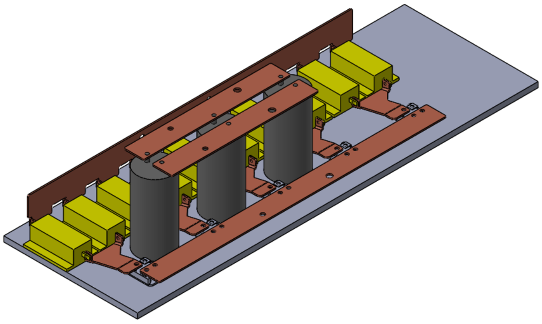

Fig. 23. A Solidworks screenshot of the electrical brake as designed, showing the resistors in yellow, the capacitors in black and the bus bars connecting them in orange.

The mechanical brake uses a master cylinder connected to a brake caliper which compresses on a brake disk attached to the drum, the same system as in a car. What is different is how the master cylinder is actuated. In the case of the chassis dynamometer, it will be actuated by a linear actuator pulling on a lever to press on the master cylinder.

The reason there are two separate brakes is because at low speeds the currents required to provide full braking torque are very high for the electrical brake. The mechanical brake is included to allow low-speed torque control. The electrical brake is easier to control and so is the preferred method.

VIII. OUSTON SOLAR CHALLENGE

The plan for the car, and what the chassis dynamometer project was supposed to inform was a campaign to race the car at the *iLumen European Solar Challenge*. Unfortunately, the team was unable to travel from the UK to Belgium where the race was to take place due to cornavirus restrictions. To make up for this, the team organised their own event and the former RAF base RAF Ouston (now Albemarle Barracks). The idea was the mirror the European Solar Challenge, which is a 24-hour track race.

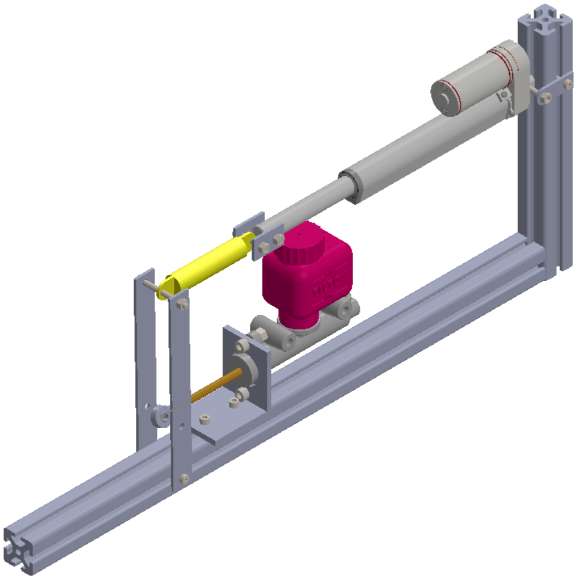

Fig. 24. A Solidworks screenshot of the mechanical brake as designed. Showing the master cylinder, linear actuator and lever arm. A spring is included to allow better control of the force applied to the master cylinder.

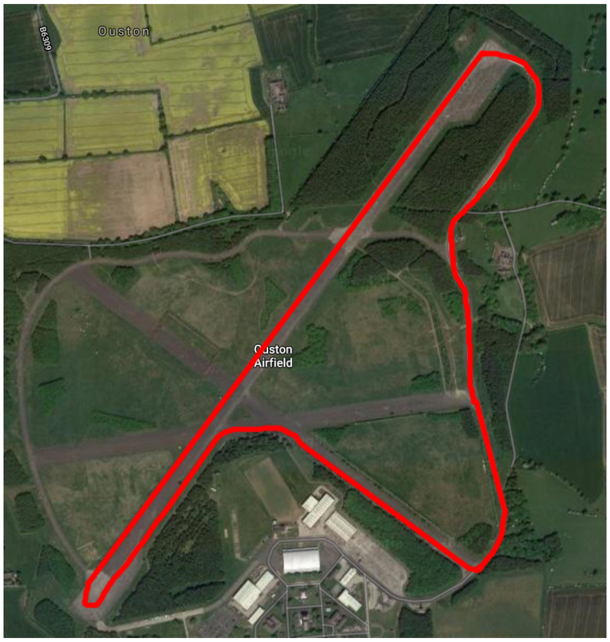

Fig. 25. An overlay of the route for the challenge on top of Ouston Airfield

The challenge began at 1200 on Saturday the 19th of September, a synchronised start with the European Solar Challenge, and would continue until 1200 the next day. The 24-hour race required careful scheduling of roles to ensure that everyone got enough sleep.

The general plan for the challenge was to have the car go around the circuit with a chase car following. The car would send telemetry data back to base via a large 10 m mast. At the base, there would be TV screens displaying the data where engineers could make strategy decisions about the challenge. The European Solar Challenge allows for two charges from the mains to get the car through the night. The main strategy decision would be where to stop and perform this charge. The nuance of this decision is that generally it is desirable to charge the car when it is at no or next to no charge and charge the car to full, but the car has to be driven in such a way that it uses just enough power to enable this and still finish the race with some charge remaining in the battery. The first charge ended up being at 0200. Unfortunately, the three-phase high power socket in the hanger we had kindly been provided with by the British Army didn't work. As such, a lower power charger had to be used, meaning the car took twice as long to charge as we had expected. This made our strategy unviable as the car would not be able to use all the power in the remaining time.

Another issue was the condition of the surface of the airfield. This led to seven tyre blow-outs during the challenge, causing a significant time spent stationary fixing these problems. The potholes also required the car to take a tortuous route to avoid them, meaning it had to accelerate and brake a lot in order to slow down and avoid potholes.

Fig. 26. An image showing the quality of the surface of the track.

At the end of the challenge, the car was able to complete a distance 414 kilometers, less distance than predicted by simulation but considering the unique challenges faced a good result.

IX. Conclusion

Two years of the Laidlaw Undergraduate Scholarship have provided enormous opportunities by allowing me to spend summers at university undertaking research in world-class facilities and working on cutting-edge technology. In addition, I have garnered experiences I could not have done any other way, the highlight obviously being able to attend the 2019 World Solar Challenge.

But the scholarship has also enabled me to develop an academic skillset both in project management and in technical skills by providing a structure to undertake two projects I otherwise would not have embarked on. These projects have allowed me to gain skills and knowledge that I would not have been able to gain until much later in my academic career.