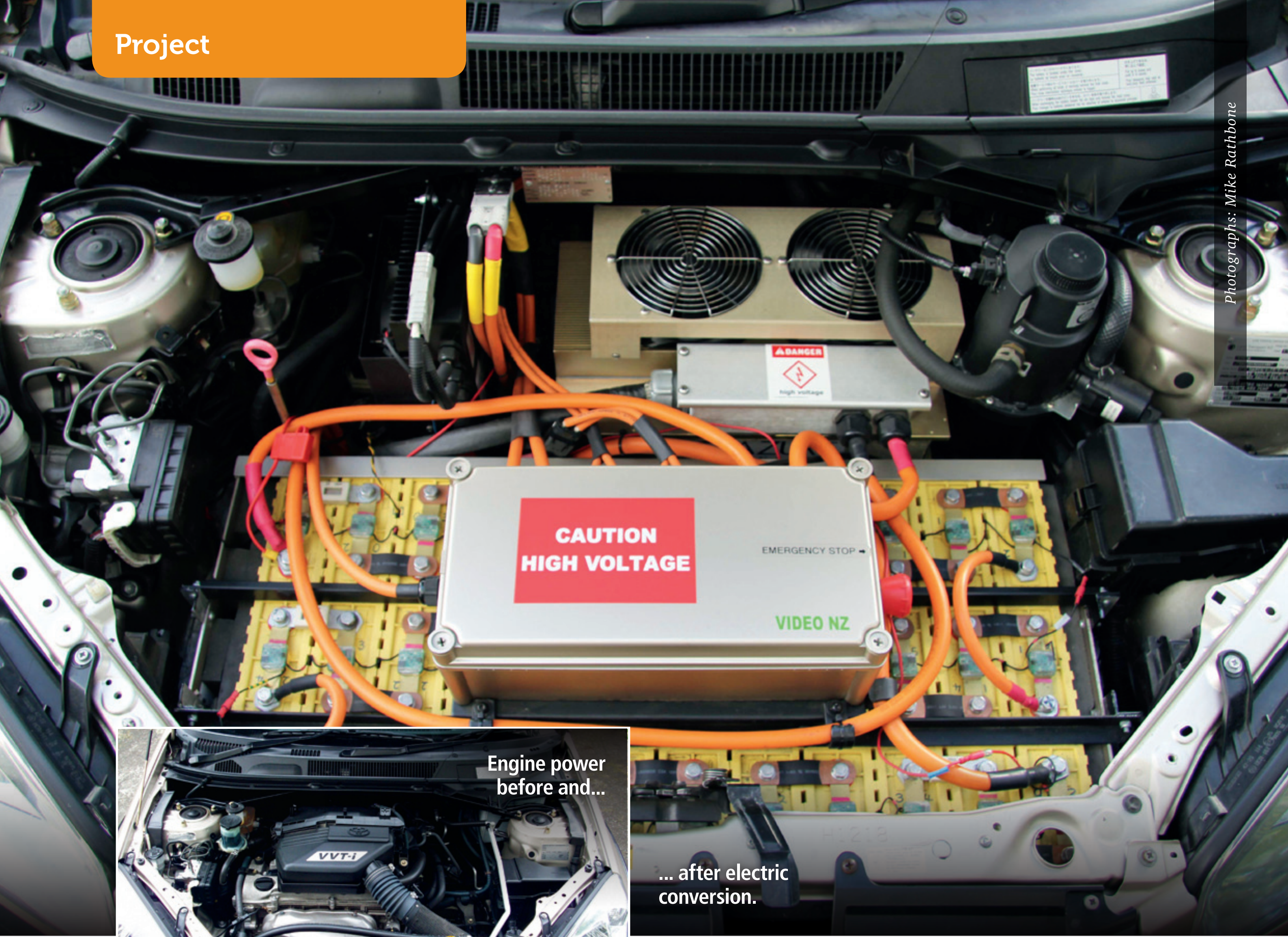


Photographs: Mike Rathbone

Engine power before and...

... after electric conversion.

How to Electrify your car

Ideas and challenges for an electric conversion

by Mike Rathbone

I had been wanting to own and drive an electric vehicle for many years and when the Chinese started producing lithium ion phosphate batteries, I felt the time was right. .

I had two main criteria:

1 I wanted to prove that an electric vehicle (EV) could be used as practical, everyday, work transport;
2 My wife and I wanted to use it as our main vehicle to avoid wasting fossil fuels.

I then spent my spare time over a year in preparation, by

- Researching to find the best EV parts from throughout the world;
- Finding the right people to work with;
- Buying the vehicle we wanted to drive for the next 10-12 years;
- Importing the parts.

The following year, I allocated two months to see if I could raise development funding for this project—a complete waste of time. Virtually every person said "Interesting idea. We don't have the money, but try such and such."

I thought, if you want something done, pay for it yourself. So, not counting my costs and the filming, it cost my wife and I about $70,000 (including the cost of the car).

As this was going to be my wife's car and we had two Labradors, we needed something practical, and a decent size

Mike Rathbone

* *Mike Rathbone is a lighting cameraman with Video NZ Ltd, Project Manager of Dunamis Project (www.dunamisproject.co.nz) putting solar panels into schools and Project Manager, Electric Vehicle Research Ltd.*

Bonnet window satisfies public curiosity.

to keep for ten years or more. As I was filming every stage of the conversion, even the colour of the vehicle was important. After much research we chose a 2005 five-door, Toyota RAV4 in excellent condition with 40,000 kms on the clock. It took two months to find the right one in Christchurch (we live in Wellington).

Engine removal

My automotive engineer brother Rob in Tauranga tackled the first stage, removing the engine, clutch, gearbox, exhaust system, petrol tank, heat shields, front driveshafts and much more. A local engineering firm designed the motor support bearing and worked out the motor layout. The next step was to design and build the motor brackets, the battery tray and the battery racks. I made all the major components out of cardboard to make working the layout easier and cut dummy batteries out of sponge foam to work out the layout and cable runs

I brought the RAV on a trailer to Wellington and auto electrician Cliff McKenna, who tutors at WelTec, took over. Harry Slowey, a mechanic and film camera assistant provided his expertise in fabrication work. (Harry is now living in Australia).

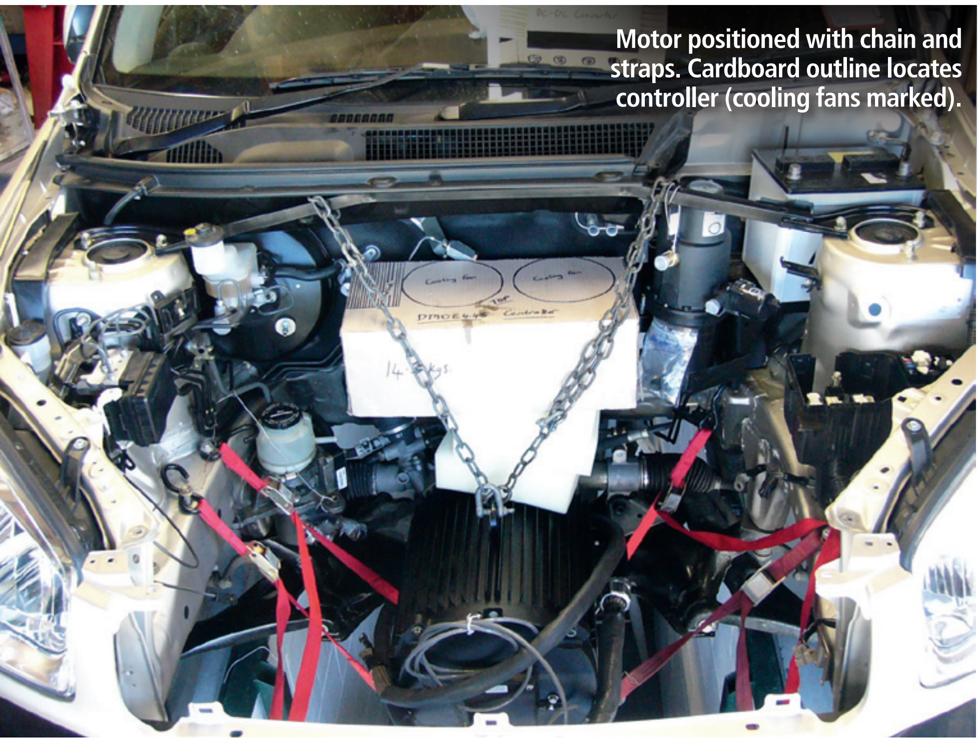
Decisions

Many times we would reach a point where we could go one way or another. We would talk about it, choose what we felt was the best option and continue. The photo with foam batteries shows how many physically fitted in the battery tray underneath. We decided on rear wheel drive, with the driveshaft running through the battery pack and clearance needed for cabling etc, so we ended up with 42 cells in there.

Even so, the battery tray has proved to be robust, well-designed and I can remove and service it in my garage by myself. To have the tray bolted to the chassis, with the weight low down between the wheels, makes the RAV a far better handling vehicle than before it was converted. One of my test "tracks" is the Rimutaka hill over to the Wairarapa. I am very pleased with the finished product.

Cost

Yes, the RAV was expensive but any product produced as a one-off is going to be expensive. Think of it like a hot rod—many hours spent to achieve the vehicle you want. There was no information available on converting RAVs. Toyota would not give us access to their workshop information so I bought



Motor positioned with chain and straps. Cardboard outline locates controller (cooling fans marked).

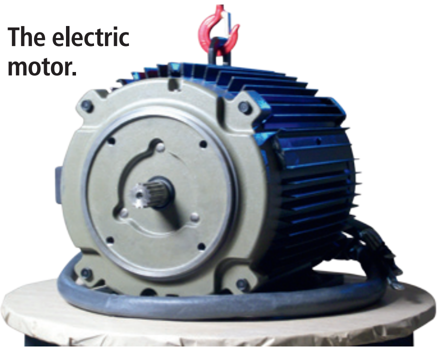
Facts and figures

The electric RAV has a range of 100-150 kms depending on the terrain and the average speed and has been used almost every day for more than four years since it was certified. The RAV has now covered more than 40,000 kms on battery power and we estimate we have saved around $10,000 worth of petrol so far. My wife uses the RAV for commuting most days and we would average about 30-50 kms a day, sometimes doing up to 100 kms between charges. The car is usually trickle-charged at 8 amps overnight, but its on-board charger allows up to 30 amps. The vehicle is the same weight ratio front and rear as it was before the conversion and weighs only 120 kgs more. It has 100 x lithium ion phosphate cells, each 3.2 volts, 90 amp hours so the pack total is 28.8 kW. A full charge for 100 kms driving costs $3.32. In order to help offset our electric "fuel bill" we have now installed a Solar PV system.—MR.

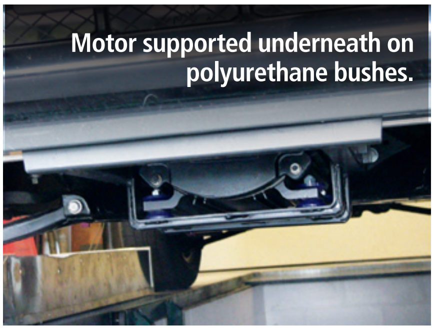
the service, workshop and electrical manuals from the USA. I have four of them each costing over $US100 each. We spent $20,000 on batteries but I see that as pre-paying my fuel bill for the next 8-10 years.

Once these batteries drop to 80 percent capacity, they will be used as backup batteries for solar PV.

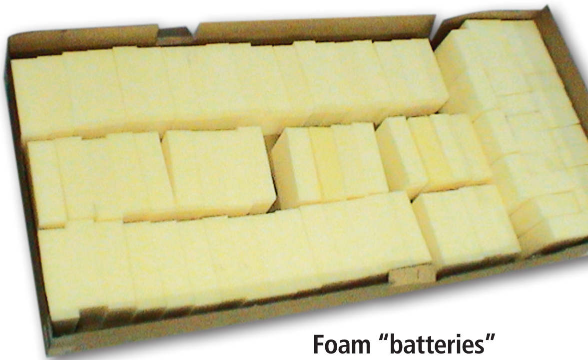
The RAV has also been setup as a test vehicle. It produces a continuous stream of data and on test runs I record that to a laptop. Some of that information is sent it to a university in Germany where they process it for research. The RAV could have been made with cheaper parts but it wouldn't be the reliable vehicle we now have. The cost included the vehicle which was $23,000.



The electric motor.



Motor supported underneath on polyurethane bushes.



Foam "batteries" test fit.

Difficulties, changes

We had to overcome some difficulties. An Australian company was over a month late in delivering the battery management system. This meant we had to charge the battery pack by constantly monitoring each cell—not recommended. In future, we would use a New Zealand company to manufacture these units.

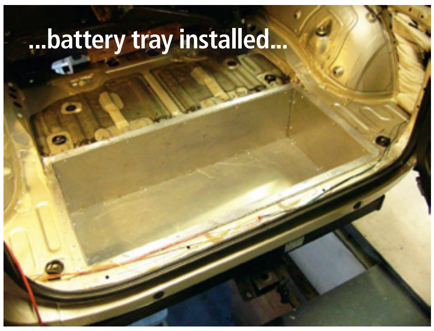
The differential ratio was initially wrong and required changing. At first, the top speed was phenomenally fast but the car really struggled to get off the mark; it was almost like trying to ride a mountain bike in its hardest gear. Once the diff was changed it was amazing how the performance was transformed, the electric motor giving smooth torque delivery all the way from 0 to 100 km/h. Because of the enormous amount of torque the electric motor produces in both forward and reverse, the clamp around the splined motor shaft was showing signs of wear after a year of driving. This has now been replaced with a sturdier type of unit. The manufacturers have now improved the motor shaft to have a keyway.

I wanted to retain the original gauges in the RAV. As we didn't have access

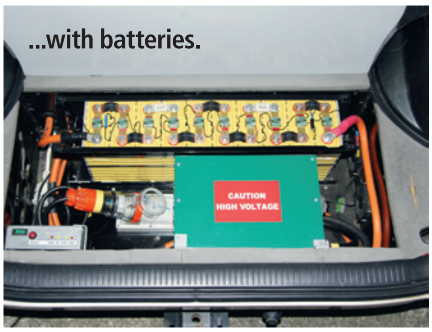
Team members (from left) Harry Slowey, Cliff McKenna and Mike Rathbone at WelTec.

The upper of two 3 mm-thick aluminium battery trays in the engine bay.

Rear boot floor removed and...



...battery tray installed...



...with batteries.

to Toyota's codes, each instrument had to have an interface made up to work accurately. Andrew Kopnoff did this work.

During the certification process we had to modify the front motor mounts to sliding bars to allow them to progressively collapse in an accident. The cells become part of that structure.

Driving

Passengers in an electric car have to get used to no engine noise when you stop at traffic lights. Driving around car parks also requires a higher level of concentration and common sense as people don't hear it coming. But lack of engine sound emphasises the road noise so I have sound-proofed the RAV throughout.

As it has no gearbox or clutch, the RAV is fairly slow up to 10 km/h and then the speed just keeps on building up to around 100 km/h, with the top speed around 120 km/h.

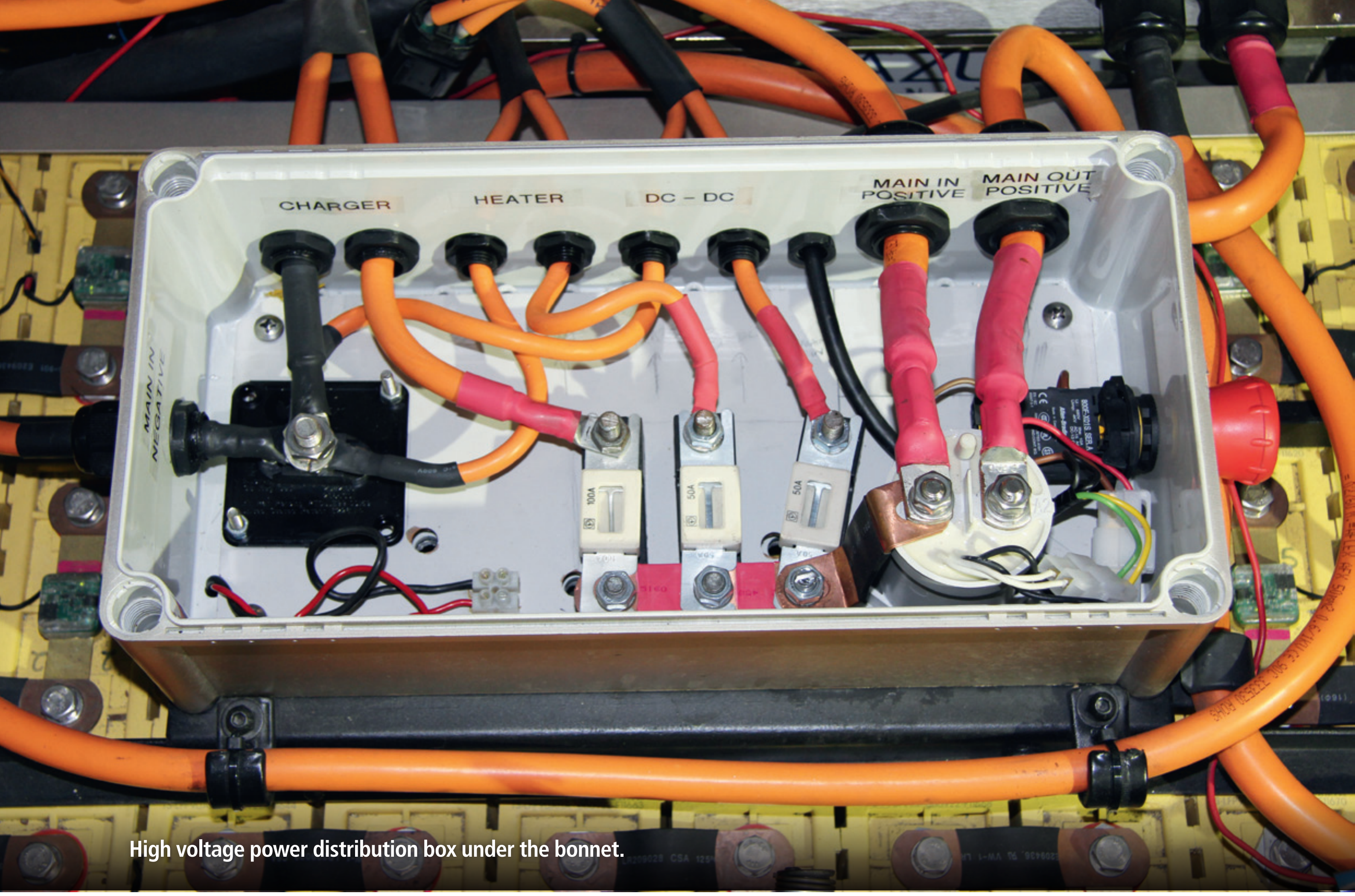
Regenerative braking slows the vehicle as the accelerator is lifted. The motor becomes a generator which charges the batteries (up to 120 amps). As foot-off-the-accelerator introduces the braking, on steep descents we rarely use brakes. You also never get tired of being able to drive past petrol stations. Due to public interest in this vehicle, Rob has since inserted a clear panel into the bonnet for people to have a look.

Testing

We have tested the car under every possible weather condition, including snow and flooded roads with no problem at all. We have now covered more than 40,000 kms on battery power alone. Our long-range tests show no degradation in battery power, even after four years of daily use on Wellington's steep hills. We have saved more than 4000 litres of fossils fuels (crushed dinosaurs) so far.

Future

I have a Toyota Hiace van for work and I intend to convert this to full electric (finances allowing). My calculations indicate this will have a range of 200-250 kms and we will be developing a special clutch/gearbox/drive system to achieve this level of efficiency.



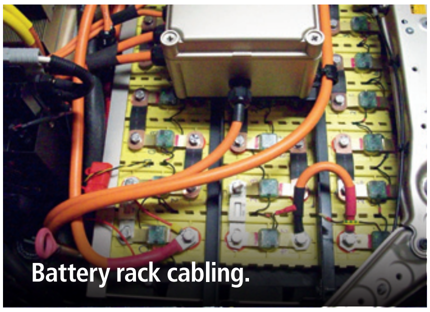
High voltage power distribution box under the bonnet.

The Build

by Rob Rathbone

From memory Mike and I first seriously talked about this conversion a year before we started. Once we put the vehicle over the pit and removed the exhaust, fuel tank etc we could get a good look to measure and plan where to fit the battery cells, controller, charger and so on. Mike's research was well under way, with cardboard mock-ups of parts and 100 foam rubber blocks the size of the battery cells to see how everything would fit. Stripping out the petrol engine, gearbox, fuel tank, exhaust system, cooling system, air con, front drive shafts and so on was all fairly straightforward.

We had originally planned to bolt the electric motor to the manual gearbox with an adapter plate. But once we had the motor out, it was clearly going to be fairly complex due to the dimensions of the electric motor. I suggested we direct-drive as I was sure the motor could handle this due to its maximum torque characteristics from zero to 2000 rpm.


Battery rack cabling.


Rob Rathbone removes combustion engine parts.

The next question was: where to mount the motor? We seriously considered putting it in the back, bolting it straight to the rear diff head, but this involved raising the floor under the rear seat and there was limited room available. We chose to fit it in the front engine bay and lengthened the driveshaft.

In hindsight, I think the first option may have been the way to go as I had to get another support bearing made for the longer driveshaft. We only had about 10 mm clearance for it to fit between the steering rack and the front suspension sway bar.

Battery trays

I fabricated the battery trays from 3 mm-thick aluminium sheet which I TIG-welded in places. Generally most joins

Driver's door sound-proofing against road noise.

were bonded (Fulaprene 303) and riveted.

The batteries were fitted with 42 cells in two rows either side of the driveshaft under the floor and 48 cells in two trays (one above the other) under the bonnet. The other 10 cells we added later in the rear tray.

This rear tray was originally planned for the charger and I made it as big as I could fit between the chassis rails in case we needed the extra space later. The tray under the floor was mounted to the chassis rails by 8 mm bolts with spacers fitted in the rails to prevent crush. The sides of the tray had to follow the contours of the floor.

Mount

I removed the original Toyota front sub-frame and fabricated another suitable for the electric motor to be to mounted to at the right height and angle to keep the driveshaft as straight as possible. This was MIG-welded from 40 x 40 x 2.5 mm box section with 45 degree angles in the longitudinal sections to allow for crash deformation.

Later, to satisfy the certification inspection, this had to be modified with round tube that could slide inside the sub-frame in the event of a crash. The electric motor was mounted to the sub-frame using polyurethane bushes as engine mounts.

The driveshaft was outsourced to an engineer who lengthened and balanced it. We also designed an extra support bearing and he made a splined front sleeve to match the spline on the motor.

Without the combustion engine there was no means to heat the air for the interior heater (vehicles use the heat from the engine cooling system to provide hot air). So I fitted an electric water heater (very similar to an electric jug) to the firewall. It has an inbuilt pump. Then I just plumbed it into the heater core—nice to have an easy job.

The electric-power steering pump from a Toyota MR2 I fitted to the chassis rail on the driver's side and plumbed it straight in to the steering rack—another straightforward job.

I made brackets to mount the controller and DC/DC converter above the front battery trays.

I spent around 176 hours to do my part, although I would say about 20 percent of the time went into planning and problem-solving. I wouldn't like to estimate how many hours of research that Mike has done on this project but I think he was very brave to put up considerable funds when there were so many unknowns and challenges to solve along the way.

Mike Rathbone filmed the whole process.

The Electrics

by Clifton McKenna

I work for the Wellington Institute of Technology (WelTec), have a background as a motor mechanic but later moved into the auto electrical field. My boss originally forwarded me Mike's email asking if we had any students who wanted to be involved in building an electric car as a project.

I went to have a chat with Mike over an orange juice at a local cafe thinking he would be some tree-hugging hippie who must have had some old wreck on his lawn he wanted to convert. Was I wrong. I was blown away by the research he had done, the very modern vehicle he chose for the conversion, his very forward-thinking project that was both loaded with technology and ground-breaking in the New Zealand EV market. He insisted that all modern vehicle features would be retained and had even calculated the possible driving range for his set-up.

The original idea was to fit an electric AC motor to the RAV gearbox, a fairly basic concept that also gave some scope for error. But the gearbox would give us suitable gear ratios for any given situation. All the battery cells were to be under the vehicle and there would be an east/west transverse drive with the rear drive shaft removed.

As we met over the next few months, I was impressed with Mike's attention to detail and was gladly pushed into getting involved. But I realised it was too advanced for my students. The voltage was too high for students to work with safely and delays with equipment pushed the project timing to after their graduation, so I committed my annual leave to the project. The personal development this gave me had value beyond any training course.

Mike provided me with workshop manuals, instruction booklets and all manner of information as well as getting me hooked on a few EV owners' sites. I found myself interested in a field that was well beyond my usual project style—I'm used to restoring old Holdens and Fords. My bosses at WelTec were

Certifier John Brett (left) with mechanic Harry Slowey.

Fuel filler cap.

very keen to support the project by providing a workshop for the month of January.

Panic

When the RAV arrived in Wellington, Mike explained the too-large electric motor now meant the gearbox had been removed and the motor fitted in a traditional north/south direction directly to the rear driveshaft. I panicked. Without a gearbox, there was no way of changing the gear ratio to provide for different situations. I imagined the worst case: What if the controller became faulty while in the “GO” position? There would be no way of disconnecting the motor from the wheels—you would have to keep driving until the battery went flat. Which Mike was telling me would be 100-odd kilometres. Can you picture an out-of-control EV?

I tried to smile and say no problem although I’m sure Mike sensed I was a little uneasy. He placed a lot of faith in me despite never seeing my work. I decided to alleviate my

Design

Certification plate.

Car manufacturers spend billions of dollars designing a vehicle. Consider very carefully the weight and balance of parts taken out and new parts installed. There are a lot of compromises in converting an existing vehicle.

For EVs the most important area is the undercarriage. That is the best place to put the batteries. The undercarriage area on most combustion-engine vehicles is like a rubbish tip, with cables, hoses, heat resistant panels, brake lines, clamps, brackets etc. Streamlining is difficult due to the heat and fumes produced by the engine. Ideally, your EV should have a flush-mounted belly pan.

Tested in all weathers.

fears of a runaway EV by finding a way to "open-circuit" (turn off) the battery packs from the controller, but that was more easily said than done.

I asked the resident electricians at WelTec if a type of solenoid was available to stop the flow of approx 260 amps flowing at 300V. They reminded me that with DC, the large voltage and amperage would probably weld the contacts together. They put me on to the idea of a "contactor" used in industrial machines. Mike said no problem and promptly ordered one from overseas.

Mike, Harry (the engineer) and myself worked virtually every week day of January and at the end on weekends, but it was hardly work at all it was so enjoyable. Mike's wife Viv packed us morning tea, lunch and afternoon tea every day and all of our breaks were filled with stories of interesting situations that Mike and Harry experienced in the film industry. They were fun to work with and there was never a dull moment.

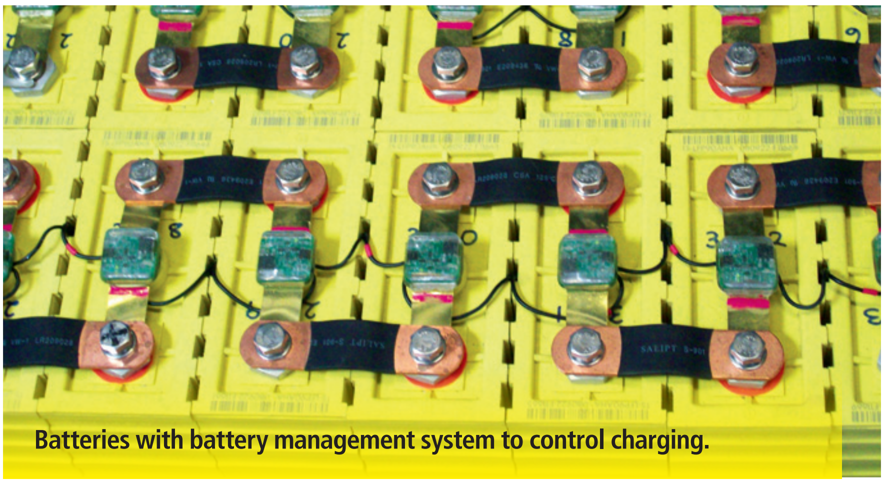
Technical bits

The battery packs were connected in series to the controller which would then convert the DC battery voltage into AC three-phase voltage to be delivered to the motor. My mission was to connect this altogether.

To prevent voltage drop, I decided to use 50 millimetre square welding cable for the long cable runs in the under-floor battery pack and between the under-floor and under-bonnet battery packs. Smaller cable was used for some shorter runs.

So Mike could disconnect the battery packs easily for maintenance, I put in an Anderson-style connector between the two battery packs. From a local electrical wholesaler I got a large plastic box as a safe, waterproof electrically rated power distribution box for under the bonnet. It was a safe option as a place to mount the contactor and run the battery pack cables to. It was also a point of connection for the DC–DC converter and for the main charge cable which runs along the vehicle to the "fuel" filler cap at the back.

The DC–DC converter is basically a transformer that steps the voltage down from the battery pack voltage to 14V to charge the normal car battery still needed to run the vehicle's body electrical system. In a way, the DC-



Batteries with battery management system to control charging.

Safety

High-voltage fuse protection.

Always wear overalls, gloves, safety boots and eye protection when working around the batteries. Isolate all working areas with towels. Cover all your tools in heatshrink and tape to prevent accidents. Remove jewellery. Whenever we work near the batteries we drop the voltage to around 30-40 volts by unplugging the main Anderson connectors.

Consider servicing. While you may have a fully equipped workshop for the conversion, you will probably have to do most of the on-going servicing yourself in your own garage.

Cover the visible cells with polycarbonate sheets. This means people cannot touch the exposed terminals. It also makes it easier to clean off the rubbish produced by combustion-engine vehicles.

DC converter replaces the job that the alternator did in the original set up. At the same time I suggested to Mike that he should change the normal 12V car battery to a deep-cycle battery, better suited to the work it had to do. The water heater was also connected to the main battery pack.

Fuses

All these high-voltage components needed to have fuses. Using some fuse holders from a forklift, I mounted these in the power distribution box. The fuses for these circuits were also the perfect length to fit between the cells, so I removed a cell link every 12 cells and put in a fuse. This gave me real peace of mind. If the vehicle was involved in an accident, there were plenty of circuit protection devices to prevent an unwanted fire or cell explosion. Safety was always very critical for me. If I was putting my name to the project, I didn't want to be known for the wrong reasons. So plenty of fuses and a contactor later, a very safe EV was emerging.

Charge monitor

The lithium ion cells used required close monitoring especially during charging and discharging, so a battery management system (BMS) was connected to every individual cell. The BMS system allows electricity to bypass a cell when charging if it determines the cell is charging up too fast. It allows the cells that require more charging to get the charge they require. Fancy little LEDS indicate each cell's state of charge. The BMS is a small electronic circuit fitted to the top of each cell. They are daisy-chained together and connected to a relay box that will turn the battery charger off if it determines any of the cells is being over-charged. It will also illuminate a light on the dashboard if any of the cells indicate a very low charge when being driven. This is a handy feature as the overall voltage reading doesn't help in this circumstance.

Controller

Integrating the high-voltage electric drive system to the vehicle body electrics was all too easy. The controller required a 12V battery, ignition and ground input, which were all available in the under-bonnet loom from the old engine. I removed and de-loomed as much wiring as possible to make a neat and professional looking under bonnet area. For this aspect of the project, the controller was easier to connect to the vehicle than a car stereo.

The driver's input to the controller to indicate how fast you wish to go is a potentiometer input connected to the accelerator pedal. It would have been awesome to use the standard Toyota item but unfortunately its resistance didn't match the Azure controller requirements. Harry fabricated a bracket to mount the Azure controller exactly where the original sat.

Regenerative braking

In electric hybrid vehicles, the accelerator pedal is a strictly "GO" pedal. The brake pedal has a potentiometer fitted and moderate pressure on it causes regenerative braking, both slowing the vehicle down and charging the battery. In an emergency, if the brake pedal is pressed hard the hydraulic braking system kicks in. In a hybrid, both brake pedal and accelerator pedal are regularly in use.

By contrast, in the system we have in the RAV, the first part of movement when the accelerator pedal is pressed is actually regenerative braking. You have to press the accelerator pedal to the half-way point before the vehicle starts to move (a little bit uncanny at first); to drive the car, you basically work the pedal from the half-way to the fully depressed position.

When you wish to slow down, you ease your foot off the accelerator, the pedal comes back half way, the engine speed drops and regenerative braking starts to kick in. The more you lift your foot off, the more regenerative braking kicks in and quicker you slow down.

If there's an emergency, you hit the standard brake pedal which has the normal hydraulic system in which a vacuum is produced by a small vacuum pump. We mounted this under the floor to the rear of the vehicle and it's powered by the old fuel pump wiring with a small modification to the fuel pump relay circuit. We fitted a vacuum reservoir (as in diesel vehicles) to provide more than one pedal press if the vehicle's body electrical system failed.

But in almost all situations, the RAV can be driven using only one pedal. It's great.

Thanks

Vivienne Rathbone, my wife and 24-hour support; Brian at Howat Engineering for driveshaft balancing and engineering work; Pom at Rowe Motors, Tauranga, for main bearing mount; Dave at Wellington Automotive Gearbox Services for differential work; Andrew Kopnoff, car whisperer for instrument interfaces; WelTec, Petone, for workshop facilities for the second stage; Hayden Fiddis. Firestone Direct for ECOPIA tyres; John at John Brett Technology. Low Volume Vehicle Certifier; Gavin Shoebridge. EV Converter. Inspiration!

Power steering pump.

Steering

The power steering uses a Toyota electric/hydraulic item from a MR2, an awesome little pump. However, it would be great to be able to slow the pump down when the vehicle speeds up as it's pumping flat out all the time and is just wasted energy at high road speed when power steering isn't necessary.

Another option to be investigated would be a purely electric, power-steering system like those fitted to modern vehicles. But sticking to the electric/hydraulic pump meant the standard RAV rack could be used which made certification easy.

The standard features retained as Mike intended include ABS brakes and air bags, central locking, electric windows. Air conditioning was lost as the pump was driven by the combustion engine which was long gone. But this wasn't a priority, as the weather in Wellington doesn't really warrant air conditioning.

Reversing camera

Mike and Viv were concerned the RAV could be dangerous in car parks as it's silent and has that high rear window found with many SUV type vehicles. So as well as fitting the reverse beeper required for certification, they got me to put in a reversing camera, cleverly fitted over the rear view mirror.

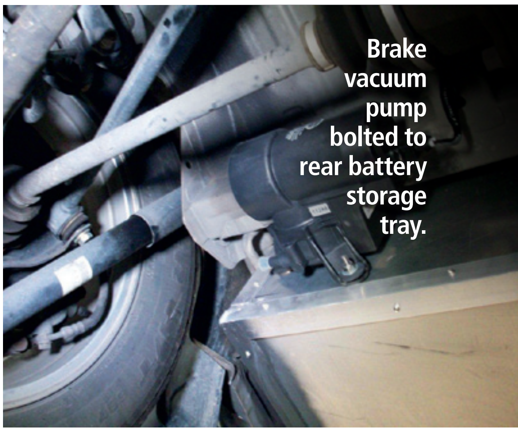
The mirror displays the driver's normal rear view until reverse is selected when it turns into a monitor screen and displays a bumper-height view out the back. Great to see those things which would normally be in the vehicle's rear blind spot: children.

Gauges

A special gauge fitted to the centre console monitors system voltage and amperage.

The Azure controller has a motor speed output signal. The direct drive via the rear diff to the wheels meant I could connect this signal to operate the road speed display in the speedometer and the motor rpm display in the tachometer.

Getting the temperature gauge to read the electric motor temperature was a challenge I eventually farmed this problem out to local electronics guru Andrew Kopnoff. The vehicle's temperature gauge required a pulse-



Brake vacuum pump bolted to rear battery storage tray.

width modulated signal from the engine computer rather than the usual thermistor-controlled gauge found on older vehicles.

Andrew developed an electronic circuit to convert a thermistor varying resistance reading into a pulse-width modulated signal to suit the gauge. It is a tricky little circuit that works very well, given the narrower temperature band the electric motor works in compared to the old combustion engine.

After a few problems, a new fuel-gauge driver circuit converts the state of charge of the battery pack into an output signal that lets the fuel gauge accurately indicate how "full" or "empty" the battery pack is. This gauge driver also has a function that uses the tachometer to display Amperage (1000 rpm =100 amps, 2000 rpm = 200 amps etc).

So now the speedo indicates road speed, the tacho indicates system amperage, the fuel gauge reads battery pack state of charge and the temp gauge reads the temp of the motor, a very nice little set-up and all the information an EV driver needs.

It was great to work with the team of Mike, Rob, Harry and guys for whom no challenge seem ed too great and I have learnt a huge amount. The project was remarkably quite simple and I'd support anyone who wanted to give it a go.

If you want to do it...

Choose people that are fun to work with, are confident, able to think outside the square, and are good at what they do. Very few people know much about electric vehicles. All the work needs to completed to a professional standard. Use your common sense and keep it safe.

Choose a vehicle that you want to drive and own for the next ten years. Don't choose a vehicle because its engine is worn out and the car is cheap.

Set a sensible budget based on your research and double it. If your project starts taking too much time, your team will lose interest. You can't drive a vehicle that is not completely finished.

Photograph and document everything before and during the conversion. Bag and label every piece which comes out of the vehicle.

You are required by law to have your converted vehicle certified. Always remember that your work will be certified by a person who has an engineering and/ or an electrical background. It is their job to be thorough. If your work is not professionally done, they will fail your entire project.

Get hold of the Low Volume Vehicle Standards document from the Low Volume Vehicle Technical Association. Read it and understand it before you start your conversion. (http://www.lvvta.co.nz/documents/standards/LVVTA_STD_Electric_and_Hybrid_Vehicles.pdf)

Find your local EV certifier and talk to him about what you want to do. They will be invaluable to your conversion project. Trust me on this one.

Keep a daily diary of all the work done to the vehicle, part numbers, contacts, where to buy materials etc.

I think car alarms are a waste of time and money. All they do is annoy people. Fit a tracker system when the vehicle is in pieces. That way you have a chance of getting your car back. All our vehicles have Mongoose trackers fitted.

Insurance is another consideration. Most people working for insurance companies cannot understand the concept of a battery-powered vehicle and are hesitant to fully cover it. They also don't understand the value of tracker systems.

Just make sure you get someone with good sound electrical knowledge as you're working with dangerous voltages and need to take safety precautions to prevent injuries.

Hopefully Mike wants to do another EV one day.


Under floor battery trays...


...installed.