Issue: 578 | Section: Technical Features | 10 August, 2010

Technokill: Building a Blown Hybrid, Part 1

Applying forced aspiration to a hybrid petrol/electric car

by Julian Edgar

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At a glance...

- Part 1 of 3
- Forced aspirating a hybrid
- Turbos versus superchargers
- Potential hybrid-specific problems

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This article was first published in 2005.

Over the last 100 or so years, a number of alternatives to the reciprocating internal combustion engine have come and gone.

Electric cars were once more popular than petrol engine cars (and electric cars held the first speed records!); the rotary engine is now championed only by Mazda but once nearly every major car manufacturer in the world held licenses for its production (remember the rotary Corvette and Mercedes C111 prototypes?); and turbine cars were developed by both Rover in the UK and

Chrysler in the US.

But compared with the incredible number of piston engine cars that have been produced, none of these alternative powerplants can be viewed as having been successful.

The same may happen with hybrid cars like the Toyota Prius – those that combine a petrol engine with a battery electric system. Long-term, they may go the way of the turbine car. Or perhaps they'll be more like the rotary – still being produced, but for only a niche market.

However, our feeling is that hybrids may well be more than that. Either as a stepping stone to fuel-cell vehicles or as a long-term sea-change in their own right, we think hybrid cars are here to stay.

And modifying hybrids? Well, that's on the very leading edge of car tweaking.

The thing about doing what no-one else has done is that there's no obvious source of advice.

When I bought my Japanese-import '99 Toyota Prius, it was with the intention of making some fairly major modifications. That could involve increasing the capacity of the battery pack (perhaps the nearest analogy would be fitting a larger nitrous tank), altering the air/fuel ratio of the engine to provide more power-friendly mixtures, or even turbocharging or supercharging. And while someone has turbo'd a hybrid Honda Insight, no one had performed a modification of this complexity on a Prius.

The first engine modification step was to alter the air/fuel ratio at high loads, a process covered atAltering Closed Loop Mixtures. That resulted in a slight increase in power (long-term it proved less impressive than described in that article), and also showed that the mixtures could be changed at will once the car had been forced out of closed-loop.

About this time a half-cut Prius – complete with high voltage battery pack – was purchased. That then gave the option of adding battery capacity, but the battery pack is an unwieldy and complex thing, with lots of internal control systems and circuit breakers. Certainly, adding battery capacity is nothing like as simple as just connecting the two packs in parallel. Also, the battery pack outputs over 300 volts DC – potentially lethal if not handled very carefully.

Driving the Prius for thousands of kilometres also showed that the battery pack and electric motor worked very well in providing short-term power bursts. Especially when accelerating away from a standstill (electric motors have peak torque at zero rpm!), the electric assist was effortless and surprisingly strong. (Surprising, that is, for a car of this much weight – 1240kg – and this much power - 43kW petrol engine and 30kW electric motor.) In fact the performance downer was really only when the battery pack was short-term exhausted – then the little petrol engine simply didn't have enough power.

So if increasing the high voltage battery capacity was pretty difficult, what about increasing the engine's power output by forced aspiration?

Complexities

The Prius engine is a 1.5-litre four cylinder that's based on the Echo's 1NZ block. Up top, however, there's a different intake manifold, electronic throttle and other detail differences.

Most important of these differences is that the Prius engine uses what is called an Atkinson cycle. In this approach to valve timing, the inlet valve stays open for a long time – in fact, even as the piston is well into the compression stroke. This forces some of the intake mixture back out into the intake manifold and so reduces the amount of charge that is trapped in the chamber. The effective compression ratio is therefore much lower than the 13.5:1 mechanical compression ratio would indicate. However, the expansion cycle (ie when the mixture is being burned and the piston pushed down) remains at 13.5:1, which has benefits for efficiency.

Another odd aspect of the engine is its 4000 rpm redline, at which both peak power and peak torque are developed.

But the most complex part of the driveline is the way in which electric and petrol power are combined. The 'gearbox' (called the Power Split Device) contains two electric motor/generators connected to an epicyclic geartrain. The engine output is split between the wheels and one of the generators. The generator charges the high voltage battery or alternatively, feeds the other electric motor that in turn helps drive the wheels. This electric motor can also receive power from the high voltage battery to either assist the petrol engine or propel the car on its own. The PSD's gear ratio is a result of the balance between the speeds of the engine, the electric motor/generators and the wheels that depends on how much force is applied by each. This gives the effect of a continuously variable transmission (CVT).

One of the electric motors also acts as a quiet and powerful starter for the engine, allowing it to be stopped and started smoothly as needed. The other generator is used to recover energy from the car during braking, and store it in the battery for later use.

When the driver lifts their right foot when travelling slowly, the engine switches off.

Read it all quickly and the implications of forced aspiration aren't particularly clear. But take just these questions:

- How does an Atkinson Cycle engine respond to forced aspiration? (The Eunos 800M runs a supercharger with an Atkinson cycle engine – but what is the Eunos' effective compression ratio?)
- For forced aspiration, is the compression ratio of the Prius regarded as 13.5:1 - or much lower? If lower, how much lower?
- If it is regarded as much lower, is the ignition timing very well advanced to provide as much power as possible with the low combustion pressures? With forced aspiration, would this lead to early detonation?
- If the engine power is increased, will the power split device still be able to function?
- If not, will the control system shut the (electronic) engine throttle, so negating the effects of forced aspiration?
- In that case, could just the low rpm torque be boosted (ie fatten the torque curve while leaving peak power unchanged?)
- If a turbo is used, how will its bearing be cooled if the engine automatically switches off immediately after a full throttle event (as would occur when driving slowly down the other side of a steep hill that's just been climbed)?

Boost Choices

Of the choice between a supercharger and turbocharger, a turbo gives the highest efficiency. This is because it uses heat that's otherwise wasted out of the tailpipe, whereas a supercharger is drawing power directly from the crankshaft. So in terms of fuel economy, a turbo is a better choice.

In order that the turbo could survive all the hot engine shut-downs, a separate turbo oiling system could be used. This would use a small high pressure pump, and dedicated oil cooler and reservoir. In addition to the convenience of not requiring that the sump be removed to fit a turbo oil drain line, this would also allow the turbo to be mounted much lower than normal if required.

Alternatively, a system could be configured that prevented the engine turning off in some conditions. This could be done by accessing an ECU input from the air con. The air-conditioning system in the Prius has two modes. When in high power mode, the engine doesn't switch off. This input to the ECU could be accessed and a timer and relay used so that whenever the engine load had been high, the timer caused this 'engine on' request to occur for the next minute. That way, the engine wouldn't ever turn off directly after a boost event.

However, the major benefit of using a turbo over a supercharger is that the turbo boost can be easily mapped over the engine operating range. By using the Independent Electronic Boost Control kit (see the AutoSpeed shop), the turbo boost level could be set at each engine load point. This means that if the power split device control system has problems with extra engine power at high rpm, the boost curve could be tailored very accurately to take this into account.

The downsides of turbocharging? Firstly a very small turbo is needed – eg of a Japanese Kei class car or something like the Garret GT12 ball bearing turbo. And secondly, the exhaust manifold on the Prius faces the firewall and the top of the engine is also tilted in the same direction – making access very difficult, especially when working at home without a hoist.

A supercharger is much easier to fit. Because of the strange shape of the inlet manifold, there exists space for a small blower to one side of the throttle. In this position, the supercharger can be driven by a modified version of the standard belt drive. A supercharger also develops more bottom-end boost than a turbo, which may be important in the Prius if the peak power of the petrol engine cannot be increased without upsetting the power split control system. Compared with a turbo, a supercharger should also be able to be better matched to the engine by way of pulley diameter changes.

It also seemed to me that the supercharger boost could be mapped by using the Independent Electronic Boost Control to control the action of a large bypass valve, one that would direct outlet boost pressure back to the inlet. This same bypass valve could also act as a closed-circuit blow-off valve and to control when the supercharger stopped bypassing and started boosting. However, I have never heard of anyone else using this approach and it may prove very wasteful of power.

However, the choice was finally made on practical grounds – I found a small secondhand AMR300 supercharger available at the right price...

Next week – installing the blower and the first on-road testing

Issue: 579 | Section: Technical Features | 24 August, 2010

Technokill: Building a Blown Hybrid, Part 2

Applying forced aspiration to a hybrid petrol/electric car

by Julian Edgar

Click on pics to view larger images

At a glance...

- Part 2 of 3
- Fitting the supercharger
- Fitting the intercooler
- Testing

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This article was first published in 2005.

Last week in Technokill: Building a Blown Hybrid, Part 1, we backgrounded what needed to be considered before fitting a supercharger to a hybrid petrol/electric car – a first model Toyota Prius. This week we get on and do it!

Fitting the Blower

While on paper fitting the small ex-Subaru Vivio AMR300 supercharger looked easy, in practice it was a nightmare job.

This was primarily because of the very cramped engine bay in the Prius, which necessitated (for example) integrating the supercharger mount into a completely new fabricated engine mount. This bracket was made from mild steel, using 9mm plate, 12mm plate and 40 x 8mm bar, arc welded together. In addition to the heavily gusseted engine mount, the bracket also incorporated the fabricated belt tensioner. In all, something like 40 hours of work went into making the bracket.

When spending the many hours working on the car, it was always in the back of my mind that the supercharger may prove a complete failure – something which isn't conducive to lots of effort! In addition to the points made last week, there were further concerns:

- It wasn't known what boost level that the standard Prius crank drive pulley and standard Vivio supercharger pulley would give
- It wasn't know whether or not the engine would immediately detonate when given any boost
- There wasn't room to fit a larger supercharger pulley if boost proved to be too high
- It wasn't known whether the intercooler would be large enough
- It wasn't known whether there would be sufficient fuel available (injector duty cycle and pump flow) to maintain acceptable air/fuel ratios on any boost level

So rather than continue working until the system was completely finished – only possibly to find it could never work – I therefore resolved to do some testing with the system only half-installed. So with the supercharger running (but drawing air through a hastily put together and fairly restrictive intake, and with the intercooler projecting out the front of the car, held in place only with hoses and clamps!) I undertook a very careful test drive. The bumper wasn't fitted, the bonnet was held down with wire, and the numberplate was cable-tied into place. Mixtures were monitored with a MoTeC air/fuel ratio meter.

Because no supercharger bypass had yet been fitted, and because the supercharger was blowing into the throttle, at idle the intake air rapidly became hot. This lack of recirc valve also meant that the throttle had to be closed very slowly, otherwise the pressure build-up caused a hose to pop off.

However, the results of this preliminary test were a huge relief. The boost level was between 5-7 psi, the car didn't detonate, the air/fuel ratios were satisfactory (well within the range of being able to be tuned with the Digital Fuel Adjuster), the multi-rib belt drive (although having more whip than wanted) didn't come off and there was no apparent belt slippage, and the intake air temps after the intercooler were low.

So I could continue with the installation, which by this stage looked like it would take up a full month of work.

Installing the Intercooler and Airbox

The next steps were to properly install the intercooler and airbox, and make the plumbing.

The intercooler – from a diesel Mitsubishi Pajero – was to be mounted at the front of the car. It could be placed either behind or in front of the power converter radiator. (The underbonnet power converter runs its own dedicated water cooling system, complete with pump and front-mounted radiator.) Obviously, from a point of view of maximum cooling, the intercooler would be best at the very front of the car. However,autos.groups.yahoo.com sources suggested that during development of the Prius, Toyota engineers had difficulty keeping the temperature of the power converter down – and so the radiator for this dedicated system shouldn't be blocked.

But then again, keeping the boosted intake air as low in temp as possible would also be **very**important!

The decision was made – mount the intercooler in front of all the other heat exchangers. In this position it blocks about half the area of the power converter radiator.

In order that the intercooler could be mounted in this position, the power converter radiator needed to be moved backwards and the frontal intrusion bar modified to provide clearance. I cut out a section of the original bar and then had welded across the gap a section of the bar from the half-cut Prius that I had bought. Note that this bar is slightly curved in plan, so it couldn't just be replaced with straight rectangular tube.

The standard airbox sits on top of the engine and its outlet is in the wrong place to feed the supercharger. A new airbox was sourced from a Daihatsu Sirion and was mounted in the front guard. The original Prius airflow meter is built into the airbox. The airflow meter was carefully cut out so that it could be mounted conventionally in-line after the new airbox. The wiring loom to the airflow meter was extended to reach the new airflow meter location.

The supercharger inlet, outlet and intercooler plumbing was fabricated primarily from 50mm copper tube and fittings which were brazed together. Taking this approach gave high-flow bends which were still tight in radius, and also allowed much of the tubing to be fitted together (the bends incorporate sockets into which the tube pushes) before being taken to the welder. However, after the plumbing was in place, a major problem appeared. The tubes running to the intercooler passed over the top of the radiator, before sharply bending downwards to reach the intercooler.

And when these were in place, the bonnet wouldn’t shut....

While checking clearance to the bonnet seems an obvious step, in the case of the Prius the very steeply sloping bonnet (which also has an underside that actually wraps over and around the bonnet locking platform) meant that clearances in this area were far tighter than in other cars. To overcome the problem, the front tubes needed to be changed from copper to rubber, and part of the underside metalwork of the bonnet had to be (very carefully!) cut away.

There were also two other very tight spots – the inlet and outlet of the supercharger. The inlet, closest to the back of the car, is located very near an intake manifold head stud and the variable cam timing solenoid. The copper inlet pipe had to be hand-beaten to shape to clear both of these obstacles. The outlet was similar, although in this case it was the radiator filler neck and radiator fan shroud to which clearance was required. In fact, this area was so tight that the radiator was pulled forward a little at the top. As a result, both the inlet and outlet connections to the supercharger are smaller in cross-sectional area than would be expected with 50mm tube; however the reductions in cross-sectional area are made smoothly and so the flow will not be as restricted as it would if these changes were abrupt.

The placement of the intercooler plumbing and the moving forward of the top of the radiator meant that the original panel across the top of the radiator had to be replaced with a new panel. This was made from aluminium channel. Foam rubber was used to block the gap by which air could have otherwise bypassed the radiator. The removal of the panel above the radiator also meant that the bonnet lock needed to be supported by other means; an aluminium bar was bolted across the car in front of the air-con condenser and this carries the bonnet lock and the horns.

A supercharger bypass valve was incorporated in the system. This comprises a GFB recirculating blow-off valve, normally used on a turbo car. It has 32mm plumbing and is beautifully made. The connections to this valve were plumbed-in just after the airflow meter and just before the throttle body.

It was literally only at this stage – after nearly 3 weeks of work – that the system even started to look near complete.

Second Test

In order that – if necessary - changes could be made to the supercharger bracket, the inlet and outlet plumbing, the airbox and everything else new, the second test drive was undertaken without any of the supercharger system components painted.

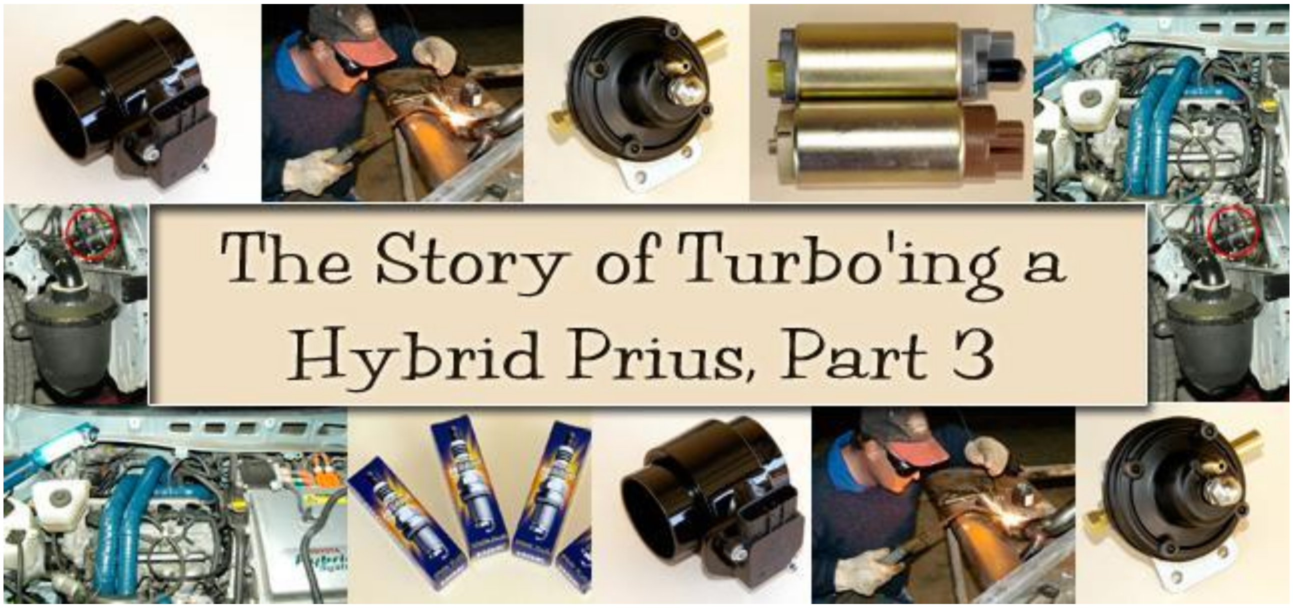
When the engine was started, the supercharger was very loud – because of insufficient intake manifold vacuum, the bypass valve wasn't opening. I disassembled the GFB valve and shortened the spring, which reduced the preload and allowed the valve to open at idle. However, the supercharger noise through the new airbox was still fearsome – **far** louder than desired. Blocking off some of the air inlet to the box decreased the noise substantially, indicating that the noise could possibly be reduced through further intake tuning.

However, the next problem was much more major: driving the car showed only 2 psi maximum boost. After checking clamps and blocking off the blow-off valve in case it was leaking, a simple mistake was found – the crankcase breather hose was off the intake manifold. With this huge boost leak plugged, boost again rose back to the previous level.

The belt drive had settled down (I gave it greater tension that stopped its whipping) and on the road the car was performing fine. The mixtures were a little leaner than preferable, but that could be easily changed with the Digital Fuel Adjuster.

So at this stage things were looking very good - but they weren't to continue that way....

Next week: on the road with the world's only supercharged, intercooler battery/electric hybrid



Issue: 596 | Section: DIY Tech Features | 3 May, 2011

The Story of Turbo'ing a Hybrid Prius, Part 3

The turbo might have worked, but the rest of the system was full of 'surprises'

by Julian Edgar

Click on pics to view larger images

At a glance...

- Trying to sort the mixtures
- New fuel system
- New intake and intercooler plumbing
- Making a new airflow meter
- Part 3 of 5

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This article was first published in 2005.

Last week we got the turbocharged hybrid Prius on the road. The turbo was on, exhaust finished and air intake system working. But the initial testing showed that the air/fuel ratios were much leaner than desired – and much leaner than expected. So the next job was to sort out the fuelling – something more involved than it first appeared: solving the problem the first time was easy; solving the problem the second time was a nightmare.

Air/Fuel Ratios

I must admit that I was almost blasé about testing the air/fuel ratios: I was running a turbo'd 6 psi and the previously fitted supercharger had been producing much the same boost level, so I didn't expect any change in air/fuel ratios. But after I inserted the MoTeC air/fuel ratio meter's probe, I was shocked to find that at high loads, the mixtures were much leaner than expected. (The car used the approach covered in Altering Closed Loop Mixtures to switch it out of closed loop and then adjust the resulting mixtures. Basically this involves using a relay to disconnect the two oxy sensors at a certain engine load and then setting the resulting mixtures with the Digital Fuel Adjuster kit working on the airflow meter output.)

Clearly, 6 psi of boost from the turbo was sufficiently different than 6 psi boost from the supercharger to affect the air/fuel ratios - or perhaps the new intake and exhaust were making a huge difference?

Unlike when the blower was fitted, this time the lean mixtures were unable to be richened by adjustment of the Digital Fuel Adjuster (DFA) working on the airflow meter output. There were three possible reasons for this:

- the airflow meter signal was as high as the ECU would accept
- the fuel pump couldn't cope
- the injectors were running flat out (ie 100 per cent duty cycle)

At that stage I thought the latter was most likely, so I used a multimeter to measure the full-load duty cycle. In fact, the duty cycle didn't much exceed 60 per cent – it appears that in this car, that's the ECU-fixed maximum injector flow.

But this wasn't initially clear and much fiddling later – including fitting a new fuel pump and modifying the in-tank regulator – I realised that I either needed bigger injectors, or higher fuel pressure to push more fuel through the factory injectors. I temporarily borrowed four injectors from a current Corolla (thanks Mr Avis for the hire car!) but found that despite their greater flow, the lower duty cycles of the Prius system resulted in mixtures that weren't richer – they were in fact leaner!

I then fitted a 'black top' Malpassi rising rate fuel pressure reg, with its diaphragm plumbed to the intake system before the throttle. To fit the regulator, a return line to the tank also needed to be installed and at the same time an external fuel filter was fitted. This upped off-load fuel pressure from the standard 44-50 psi to 60 psi and then caused an increase to 65 psi when on boost. Together with the oxy sensor switching, this resulted in stoichiometric mixtures (ie air/fuel of 14.7:1) being maintained until a full-throttle 2-3 psi was reached, with the mixtures then moving to 12.5:1 at higher loads.

However, I then found a full-load misfire. I changed the plugs to one heat range colder and at the same time went to iridium (from NGK BKR5EY to BKR6EIX) but the miss remained. In the end I realised that the still connected Digital Fuel Adjuster had somehow been set with a minus 127 correction at a high load site – I must have bumped the unlocked hand controller without realising it. With the fuel map returned to zero correction, the miss went away... in effect, I'd been running a high load fuel cut! Ooops.

Intercooler and Intake Plumbing

So far, all the test driving had been undertaken with intercooler (and inlet air) plumbing formed from copper 2-inch tube and fittings, insulated with thin foam rubber sheet and then covered in large diameter heatshrink. The use of copper pipe and fittings gives an easy push-together system that allows the pipework to be assembled and then taken elsewhere to be brazed, silver soldered or soft soldered. (The approach is covered in Copper Intercooler Plumbing) In the supercharger installation, the total length of copper piping was only about 50cm, but with the turbo positioned between the engine and the firewall, the pipe runs went up a lot in length.

And while I was happy with the appearance and functionality of short length of copper pipe and plumbing fittings, with several metres of plumbing now running around the engine bay, I wanted both a better appearance and also more gentle, flowing bends.

Making easier the decision to redo the plumbing was the fact that I'd bought a new friction cut-off saw (these days, extraordinarily cheap) and a secondhand arc welder. I didn't intend doing all the welding with the arc machine (it's very hard to weld thin gauge tube with an arc welder) but I thought that it would be straightforward to tack the tube together. Tube? Yes, I bought a heap of mandrel exhaust bends in both 2 inch and 1¾ inch sizes.

By using the cut-off saw and the arc welder, it was quite easy to come up with three completely new pipe runs – with the packaging flexibility of the bends (especially in the smaller 1¾ inch size), I decided to route the pipe in different directions to the previous approach. The tacked-together pipework was then taken to the local muffler shop for MIG'ing, before I spent a few hours at my belt sander grinding back the welds.

I then had a local welder silver-solder brass fittings on the plumbing for two crankcase breather hoses, a boost feed to the rising rate fuel pressure reg, a boost feed to the wastegate, a water injection nozzle fitting, and the two connections for the recirculating blow-off valve. The next steps were sandblasting and then powder coating the plumbing.

Incidentally, if considering a similar plumbing approach, don't disregard the significant costs - $120 for the mandrel bends, AUD$90 for the MIG welding, AUD$100 for the silver soldering, AUD$27 for the sandblasting, and AUD$50 for the powder coating. (So these bits of bent pipe ended up costing far more than the secondhand turbo!)

New Airflow Meter

Up until now I'd been using the factory airflow meter, cut from the airbox into which it is normally integrated and mounted in-line after the new Falcon V8 airbox. However, its small size and the slightly bodgie way in which the chopped-up airflow meter fitted into the intake plumbing caused me to reconsider the approach. I decided to kill two birds with one stone and build a new, larger airflow meter that had proper in-line plumbing connections.

The new airflow meter housing was made from a variety of PVC plastic plumbing adaptors, all available from the local hardware store. These were cut, filed, sanded and heated into shape, with the resulting airflow meter having a minimum internal cross-sectional area 31 per cent larger than standard. The airflow meter was located behind the right-hand headlight. The Digital Fuel Adjuster was then used to boost the airflow meter output signal so that the car ran as normal.

More Testing… and More Problems!

With the new intake and intercooler plumbing installed and the larger airflow meter in place, it was time to do some more testing. And to find still more problems...

The first issue was that the air/fuel ratios at high loads were again back to stoichiometric under full boost. That's despite the increased fuel pressure, the switching out of the oxy sensors and minor tweaking with the Digital Fuel Adjuster. So why not do some major mixture tweaking with the DFA?

Well, even with the oxygen sensors disconnected, the Prius appears to have the ability to revert over time to standard mixtures. I think perhaps it can determine how much power the engine is developing via the hybrid control system and has a look-up table that correlates expected injector pulse widths with measured power. This results in gradual shift back to standard mixtures, even with the DFA making major changes to the airflow meter output signal. This phenomenon was hard to isolate because it could be seen occurring only after a whole bunch of full-throttle events. Drive the car normally in closed loop and then nail it, and the mixtures would go satisfactorily rich. But repeatedly hammer the car up and down an (isolated!) test road and the full-throttle mixtures would gradually move from mid-twelves back to mid-fourteens.

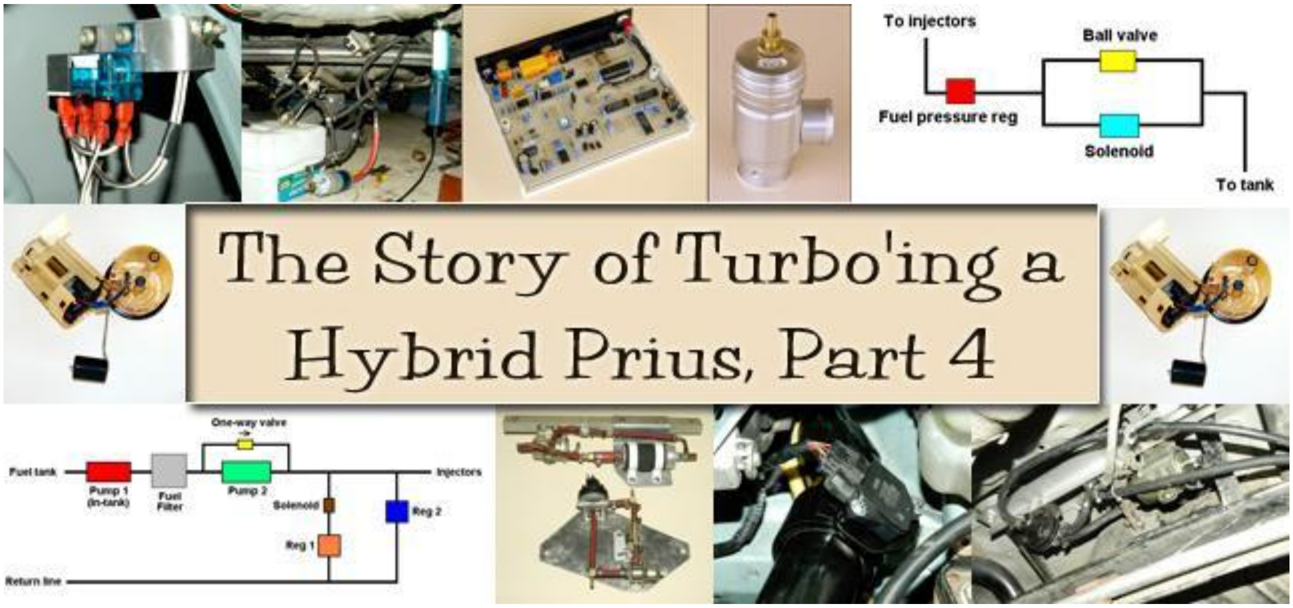
And there’s another complexity. The mixtures that occurred with the oxy sensors switched out depended to some extent on the correction that they’d been giving just prior to the switch-out. In other words, the long and short-term fuel trim values would affect what air/fuel ratios resulted with the oxy sensors switched out of the system. Perhaps it was this characteristic **and** the expected pulse widths for the given power that would then determine what air/fuel ratios the car ended up with?

The result was that full throttle air/fuel values could vary anywhere between 11:1 and 14.5:1. Do two full-throttle runs and the mixtures would be perfect – say 12.5:1. Then drive gently around the block and then hammer it... and the mixtures at full throttle would have changed to 14:1....

But what was the problem - hadn’t the mixtures been sorted earlier? That’s indeed the case – the problem reappeared only after the change in intake plumbing and the new airflow meter was fitted. It appears that these changes had further increased mass airflow – the engine was breathing better and better and the full-load mixture problem was getting worse.

Then yet another problem appeared. On the occasions when the mixtures were correct for full power, it was possible on the test road to hold full throttle for many seconds. And in this situation, a bizarre event kept occurring. After ten or so seconds, the electronic control systems of the car would momentarily close the electronic throttle! This could be seen on the vacuum/boost gauge which would dip from full boost to near full vacuum, before the throttle was again automatically opened. Perhaps some part of the hybrid system was being momentarily overloaded, which caused the system to reduce engine power?

Aaaaghhhh....



Issue: 597 | Section: DIY Tech Features | 17 May, 2011

The Story of Turbo'ing a Hybrid Prius, Part 4

Finally - finally! - solving the high load fuel problem

by Julian Edgar

Click on pics to view larger images

At a glance...

- Overcoming the auto throttle closing
- Developing a two-pressure fuel system
- Fixing the high load mixtures
- Part 4 of a 5-part series

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This article was first published in 2005.

Last week in The Story of Turbo'ing a Hybrid Prius, Part 3 we ended with two major problems affecting the turbocharged Prius: high load mixtures were completely inconsistent, and at full power, the electronic control system would momentarily shut the throttle. Solving both problems took over two weeks of frustrating work.

Throttle Shut-Down

So what was making the electronic throttle momentarily close itself at full power? If in fact it was because the hybrid system couldn't cope with the extra power, the effect would be most pronounced when power was at its maximum... say, on a cold night. And that's just what proved to be the case. When the weather provided me with an 11-degree C evening, I was able to get the throttle-shutdown to repeatedly occur. (But what about those inconsistent full-load mixtures? Well, if the air/fuel ratio meter was watched like a hawk, it was possible to get in peak power runs with the mixtures satisfactorily rich. You just couldn't do it consistently.)

So the obvious answer to the automatically closing throttle was to lower boost at the very top end, so reducing power. Since the greatest driving improvement over standard occurred due to the mid-range boost, dropping boost a bit at peak power would make very little difference. But how to decrease boost? With the ex-Subaru IHI turbo's wastegate connected, 7 psi was the minimum boost available – and that's what I was running. (The boost level had risen from 6 to 7 psi with the redesigned intake plumbing.) Modifying the turbo wastegate actuator to achieve a lower boost was possible, but it would mean taking off the turbo to access the wastegate actuator. Which in turn would mean removing a front driveshaft, taking off the exhaust, draining the 'gearbox' of oil, and so on. A **lot** of work.

Instead, was it possible to bleed off some of the boost? Already in the system was a GFB blow-off valve running a shortened internal spring – a modification performed on the valve when it was fitted to the supercharged car as a recirc valve. In this design of valve, boost pushes on the base of the piston, trying to open it against both the internal spring pressure and the pressure in the boost-sensing hose. If the boost being fed in via the hose was reduced, it was likely that the internal piston would be pushed open, so allowing some boost to escape. By placing a bleed solenoid in the boost pressure feed hose, the pressure in this hose could be regulated. By using the Independent Electronic Boost Control (IEBC) kit, the action of this solenoid valve could be mapped. (See The Independent Electronic Boost Control, Part 1.)

The system was quickly set up and the solenoid valve opening set to 0 per cent at lower injector duty cycles. (The IEBC kit sets its output duty cycles on the basis of input injector duty cycles. That is, any relationship between injector duty cycle – ie engine load – and output duty cycles can be set via the hand controller.) At higher engine loads, the solenoid was gradually brought on line, until at very high engine loads, it was completely open, so acting as a bleed of the boost pressure in the feed hose to the blow-off valve.

The mapping of the control system was initially done very coarsely but the system soon showed it was possible to drop boost to 5 psi at the top end of the engine power band. This stopped the auto throttle shut-down procedure – the system was sufficiently sensitive that even a 2 psi boost decrease made enough difference.

Hmm, OK then – it was easy enough to stop the auto throttle shut-down with very little loss in performance. But what about these bloody mixtures?

Not Solving the Air/Fuel Ratio Problem

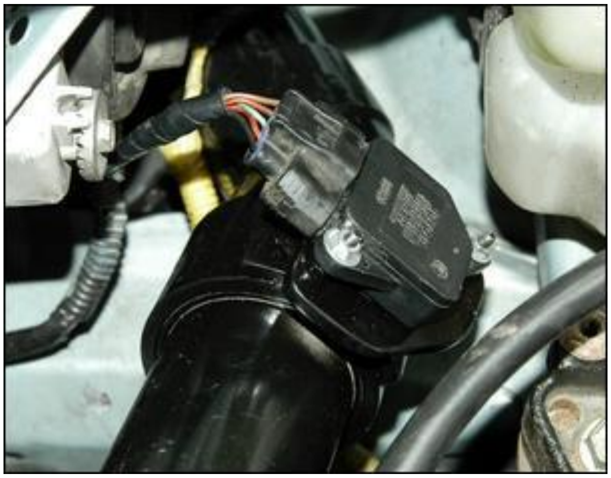
It's worth recapitulating what had so far been done to try to sort the high load mixtures.

A Simple Voltage Switch (SVS) kit had been fitted that allowed the two oxygen sensors to be disconnected on the basis of measured airflow meter output, so forcing the car into open loop. In the standard car this had resulted in the mixtures automatically going very rich – too rich in fact. The Digital Fuel Adjuster (DFA) kit had then been used to intercept the signal coming from the standard airflow meter, which allowed these 'oxy sensors disconnected' mixtures to be leaned out a little. However, once engine power had been increased by the use of the supercharger and then – subsequently - a turbo, these 'oxy sensors disconnected' mixtures had become leaner and leaner, and so for forced aspiration, the DFA had been used to richen the mixtures (ie increase the level of the airflow meter signal).

However, mixtures at full load were still too lean.

To ensure there was sufficient fuel flow and pressure, a new in-tank pump had been installed, together with a new adjustable external regulator (a Malpassi rising rate design) and a new external fuel filter. Installing the external pressure reg had required fitting a new return line to the tank. This system delivered plenty of fuel and allowed the adjustment of fuel pressure. The injectors from a Corolla had also been trial-fitted, but despite coming from a much more powerful engine, at the smaller duty cycles of the Prius system, had proved to flow less fuel than the standard injectors.

Adjustment of the fuel pressure was then carried out which resulted in adequately rich mixtures when the oxy sensors were switched out. In this approach, the DFA did little – mixtures were adjusted by altering fuel pressure. The Malpassi reg was plumbed so that it saw boost but not vacuum. In this way the off-boost fuel pressure remained constant (as it does in the standard system) but rose when on boost. This resulted in full-boost mixtures which were satisfactory – at least at first.



At this stage the airflow meter sensing element was installed in a custom-made body with a 31 per cent larger cross-sectional area. The DFA was then used to lift the output voltage value of the larger airflow meter to achieve correct closed-lop mixtures. New free-flow intake and intercooler plumbing was also installed at this time.

Next, the mixtures became erratic at full-load. At times they were correct (as set by fuel pressure and the DFA) and at other times, incorrect. Furthermore, in successive full-throttle events they could be seen to be heading back to stoichiometric, even with the oxy sensors disconnected.

An attempt was made to intercept the oxygen sensor outputs, using the DFA to modify their levels at high loads and leaving the system always in closed loop (ie oxy sensors connected). However, the car ignored this and maintained 14.7:1 air/fuel ratios.

The oxygen sensors were then disconnected at all loads, and an attempt made to tune the mixtures throughout the load range with the DFA. (This was done with great success on a Maxima V6 turbo, where the air/fuel ratio could be maintained very accurately at all loads despite the lack of an oxygen sensor feedback loop.) However, on the Prius it became clear that with the oxygen sensors disconnected, it isn't just the airflow meter input that is used to set mixtures. This could be clearly seen because even with the engine held at one load site (ie one airflow meter output voltage), the mixtures would gradually slide back from being rich to 14.7:1. (This is what so strongly suggests the presence of a look-up table that compares measured engine power with expected fuel injector pulse width.)

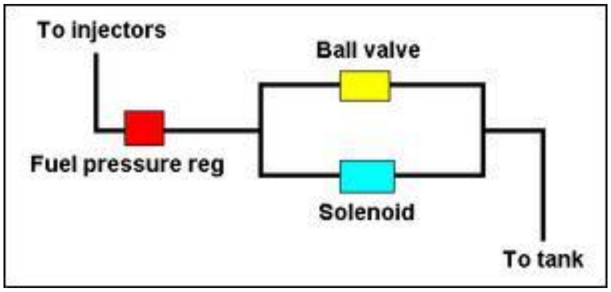
So despite trying each of the following, consistent full-load mixtures could not be obtained:

- Intercepting the airflow meter signal with the DFA
- Altering fuel pressure
- Switching the oxy sensors in and out on the basis of throttle position
- Switching the oxy sensors out as fuel pressure was progressively increased
- Switching the oxy sensors out and intercepting the airflow meter signal with the DFA
- Switching the oxy sensors out, increasing fuel pressure and intercepting the airflow meter signal with the DFA
- Intercepting the oxy sensor signals with the DFA
- Disconnecting the oxy sensors at all loads and then setting the mixtures via the DFA working on the airflow meter signal

It's no understatement to say that by this stage I was pulling my hair out!

I then decided to go back to an approach tried a long time previously – one covered at Electronic Fuel Pressure Increase. This involved switching a restriction into the return line from the regulator and so boosting fuel pressure in one hit. My thoughts were these: if the increase in fuel pressure occurred only when the oxy sensors had been switched out, the ECU couldn't be aware of the change. Therefore, even at the standard look-up table pulse widths with which it was triggering the injectors after the oxy sensors were disconnected, the mixtures would have to be richer.

(This approach contrasts with using a rising rate pressure reg that increases fuel pressure progressively when on boost. Taking the rising rate fuel pressure route, and switching the oxy sensors out only when boost over say 4 psi, means that often the system is in closed loop with slightly heightened fuel pressure. If the ECU can indirectly learn fuel pressure by looking at the injector pulse widths required to maintain an air/fuel of 14.7:1, then maybe the ECU can pull back all injector pulse widths to compensate for this increased fuel pressure. In other words, despite not having a fuel pressure sensor, the ECU can probably still calculate fuel pressure, and compensate for it. I don't want it to do that!)

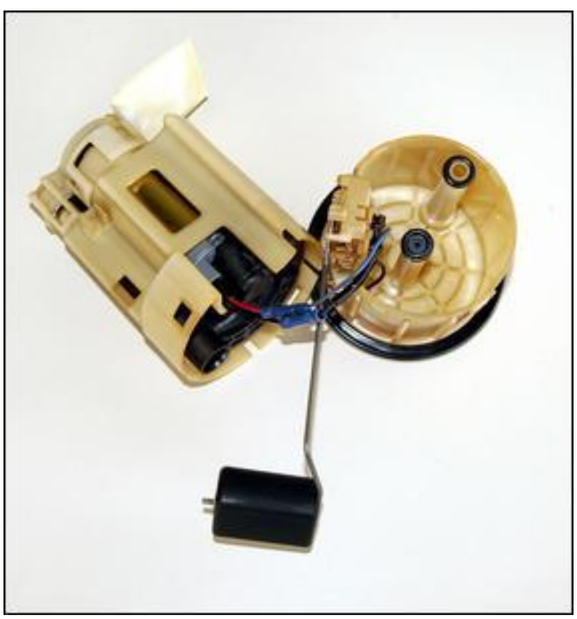


I then set up the system to allow the fuel return line from the pressure reg to be restricted, increasing fuel pressure. By closing a solenoid, fuel is forced to flow through a ball-valve, which comprises a restriction that can be varied in flow. Shut off the ball valve and when the solenoid closes, the fuel pressure will rise to the maximum the pump can flow (which is normally limited by an internal pressure relief valve). And in fact testing soon showed that to get adequate fuel pressure, the ball valve did have to be completely closed – ie, the pressure reg's return shut off. This resulted in an immediate increase in fuel pressure of 20 psi – from 50 to 70.

And what were the mixtures like when the oxy sensors were switched out and simultaneously the solenoid was closed? Finally – finally! – they were consistently close to what was desired – around 12.5:1 at full load. I rebuilt the underfloor bracketry to include the solenoid and performed a final on-road test.

But again the mixtures at full load were lean!

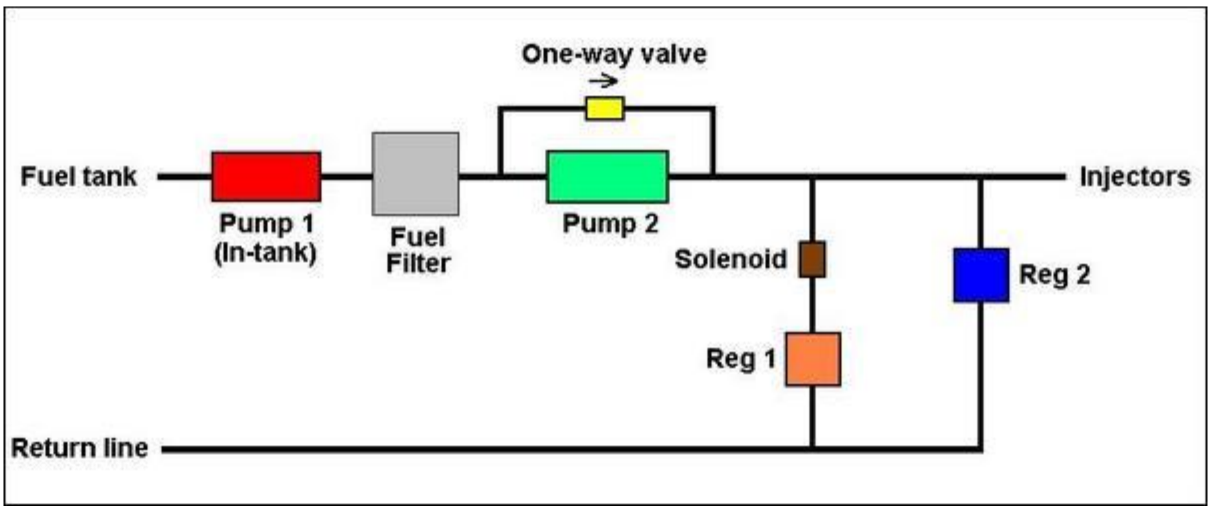
WTF was going on this time? Watching the fuel pressure gauge provided the clue: even with the return line shut off, the fuel pressure was now rising to only 60 psi – 10 psi of high load fuel pressure had been lost. Repeated testing showed that with the fuel pressure reg's outlet closed off, the fuel pressure could jump to anything from 60 to 80 psi...



Basically, it appeared that the pump couldn't cope with the increased fuel pressure requirements. I checked the voltage at the pump to make sure that it was getting full battery voltage - it was. This meant another pump was needed – but the in-tank pump had already been replaced and getting a physically larger pump in place would be near impossible. The only alternative was to add a second in-line fuel pump – one that could consistently produce fuel pressure of at least 70 psi. And to regulate this fuel pressure – which is much safer than using the pump's internal pressure relief valve – a second regulator would be needed.

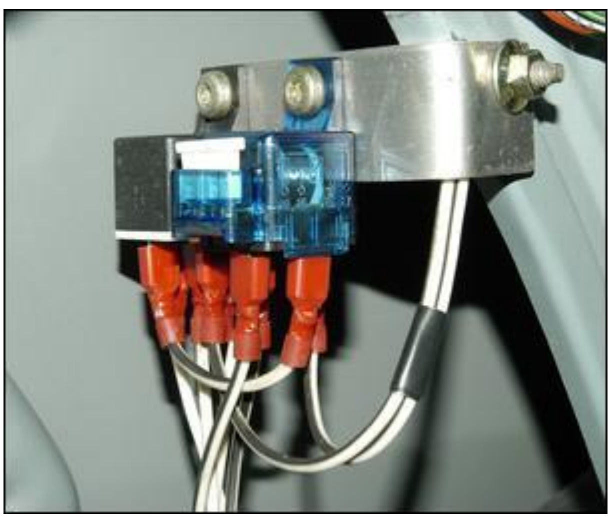
The New Fuel System

Many turbo and supercharger upgrades use a second fuel pump in series with the first, with the second pump activated only when the extra fuel is needed. In this approach, the first pump flows fuel through the second pump which is usually switched off. However, it is better to use a bypass one-way valve around the second pump so that the fuel can freely flow past it. When the second pump switches on, the extra pressure it generates closes the one-way valve.



The complete fuel system is shown in this diagram. The in-tank pump feeds the second pump with the one-way valve providing the bypass. The two pressure regs are plumbed in parallel, with a solenoid valve positioned in the feed line of the lower pressure reg. When the fuel pressure needs to be increased, the second pump is switched on and the solenoid closed. This forces the second reg into action and the fuel pressure is then regulated at the higher value. It's a complex and relatively expensive system but it's the only approach that gives two fixed (but adjustable) fuel pressures, with the second pressure much higher than conventional fuel systems normally use.

The system was installed under the car and testing carried out. Initially I just used a manual switch to turn on the new fuel pump and turn off the solenoid (the two steps that result in high fuel pressure). The oxy sensors were being disconnected by a Simple Voltage Switch working on the airflow meter output voltage (ie when airflow reached a certain value, the oxy sensors were disconnected) and when I heard that relay click, I manually toggled the fuel pressure increase switch. And watched the fuel pressure gauge. And watched the boost gauge. And watched the MoTeC air/fuel ratio meter....



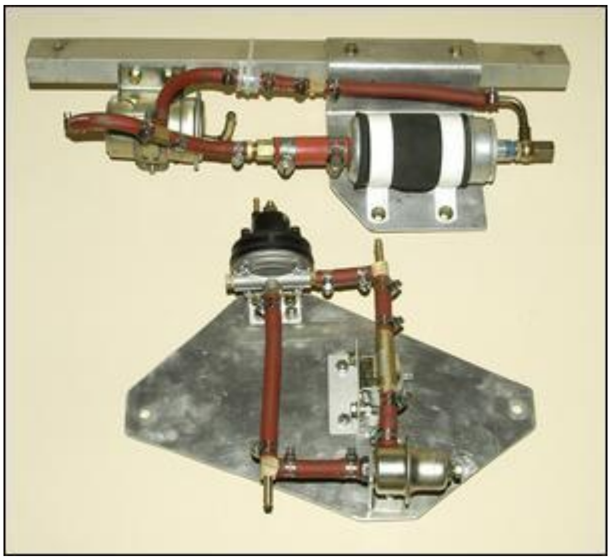
On-road testing showed that the system worked – consistent rich mixtures on high loads with no apparent learning around them occurring. I then added two relays – one the changeover from solenoid-off-to-fuel-pump-on, and the other a power feed relay for both the solenoid and the pump. A second relay was also added to the Simple Voltage Switch to trigger the fuel pressure changeover, so that the oxy sensor switching and fuel pressure switching occurred simultaneously.

I then decided to see what would happen if I swapped the switch-over input signal from being triggered by the airflow meter to being triggered on the basis of accelerator pedal position. Initially, this seemed to work even better – at full throttle, you always got rich mixtures, irrespective of engine airflow – but then I found if the Prius was booted at full throttle from a standstill, the mixtures returned to stoichiometric. (How many times has this return-to-stoich now occurred?!) It appears the car needs to be running in closed loop for at least a little while before the switch-over occurs.

High, High Fuel Pressure

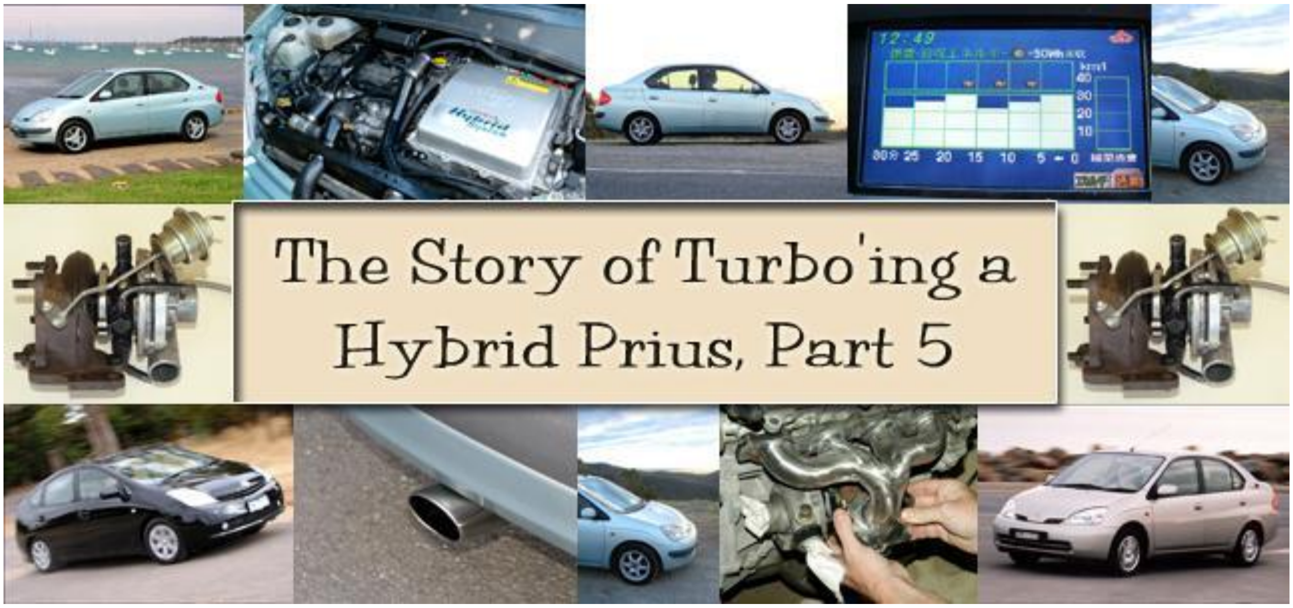
The fuel pressure required to consistently gain a full-load air/fuel ratio of around 12:1 – 12.5:1 is significant – about 85 psi. All the fuel hoses at the rear of the car have been replaced with hose good for 290 psi, and I intend to also replace the underbonnet injector fuel rail feed hose.

Fixed!



But with the high load air/fuel ratio problem solved, and the throttle shut-down problem consigned to the history books, I could finally see the light at the end of the tunnel: touch wood, that was it for the big problems. (Yes, it takes real skill to get three clichés into one sentence. Was this car really driving me mad or was I always like this?)

Now we could drive the turbo Prius, confident in its mixtures and performance. Hmmm, performance... so what's it like? And what's happened to the fuel economy? Next week, in the final in this series, we'll find out.



Issue: 598 | Section: DIY Tech Features | 31 May, 2011

The Story of Turbo'ing a Hybrid Prius, Part 5

The final result

by Julian Edgar

Click on pics to view larger images

At a glance...

- Massively improved hill-climbing performance
- Improved fuel economy
- Reduced noise
- A transformed car
- Part 5 of 5

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This article was first published in 2005.

So it’s been lots of work and there have been a helluva lot of problems to overcome along the way – but now, finally, what’s the turbo Prius like on the road?

In a word – fantastic.

The turbo NHW10 Prius now has **better than standard** fuel economy. And performance? Well, the key aim has been realised – country road hill-climbing performance has been completely transformed.

Fuel Economy

On an open road cruise at 100 km/h, the turbo Prius will turn in a best economy of about 4.6 litres/100km *[21.7 km/litre, 61.4 miles per imperial gallon, 51.1 miles per US gallon].* In the same conditions, the dead standard car used to get about 6.3 litres/100 km *[17 km/litre, 5.9 litres/100km, 48 miles per imperial gallon, 40 miles per US gallon]*, so the modified car has improved the fuel economy in these conditions by up to 28 per cent!

However, that’s a very best case scenario.

In a mixture of some urban, a fair amount of open road cruising at 110 km/h, and some steep country road hill-climbing (in other words, my most frequent driving mix), the economy now averages 5.5 litres/100 km *[18.2 litres/100km, 51.4 miles per imperial gallon, 42.8 US miles per gallon]* . In the same driving conditions it used to be 5.7 litres/100 km *[17.5 km/litre, 49.6 miles per imperial gallon, 41 miles per US gallon]*, showing that there's been an improvement of 3.6 per cent.

It's hard to make a comparison in heavy traffic urban driving, because economy varies so much with the conditions. However, a best economy of about 4 litres/100 km *[25 km/litre, 71 miles per imperial gallon, 59 miles per US gallon]* can now be gained in these conditions. I don't remember previously ever seeing economy that good.

And it needs to be kept in mind that's all achieved in a car with comfortable seating for four adults (it's a very roomy cabin for the size of the car), and having dual airbags, climate control, excellent NVH, etc. In other words, it's not a small, poorly riding economy box with a screaming engine.

Why the hell are the fuel economy figures being quoted is so many units?! There's a good reason: in Japanese domestic NHW10 Prius models, the display is in kilometres per litre. In Australian models, it's in litres/100km. In the US, in miles per US gallon. And well, after all of those, we thought we'd better include miles per Imperial gallon as well!

Performance

As mentioned earlier in this series, the Achilles Heel of this NHW10 domestic Japanese model is the lack of open-road performance when the high voltage battery is short-term exhausted – as happens after full-throttle has been used a lot. Without the additional electric motor power then being available, the performance is miserable. In fact, up a very steep open-road test hill, the full-throttle performance at the top could drop as low as 47 km/h, and was typically only about 50 km/h. But with the turbocharger, the Prius can consistently top the same hill at 86 km/h – an absolutely incredible 70 per cent improvement in real world open-road performance.

But what about the car's quarter mile and 0-100 km/h times? Well, while improved, the gain is nothing like as great as the lift in hill-climbing performance. What happens is that the hybrid control system acts in such a way that the peak combined power of the electric motor and the petrol engine is not substantially increased. In other words, total peak power is not much changed over the best it could previously ever be.

Part of the difficulty in describing the performance change is because the Prius Power Split Device varies engine revs according to speed and throttle position. So to reach peak engine power (as measured by the airflow meter signal), the car needs to be travelling at over 100 km/h at full throttle. At anything less than about 100 km/h, full throttle makes use of the typically much improved mid-range power. (It's improved because there's always plenty of electric power available.)

That's why dropping the boost from 7 psi to 5 psi at high loads makes little difference to normal on-road performance – in fact, it's hard to even tell the change. But drop 3 or 4 psi of boost in the mid-range - and then climb a steep hill - and the engine can immediately be felt revving harder to generate enough power. And after only a short time of this (eg 30 seconds), Myrtle the Turtle will come on indicating that the high voltage battery is down in level... .and then performance is just woeful. With the turbo boosting the mid-range by 7 psi, Myrtle is completely banished.

But there's no getting away from it – even with the turbo, the petrol engine is still a low powered one. On the freeway at 110 km/h, the level of turbo boost varies from 0-2 psi – the engine is working much harder than you would expect in a conventional car. On **extremely** steep grades (eg marked at 18 per cent!) the Prius still struggles...although then, so do lots of other low-powered cars.

NVH

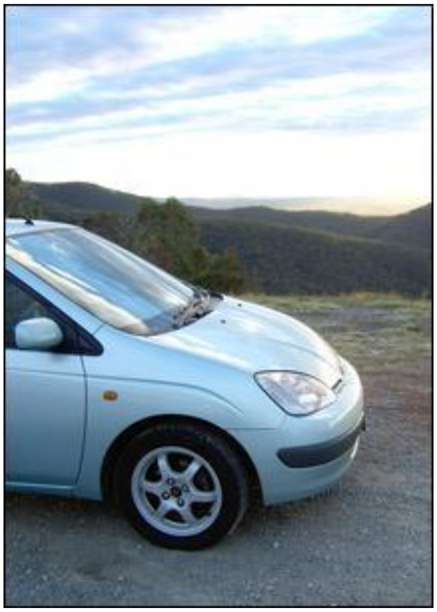
Amazingly, noise, vibration, harshness are now improved over standard. This is primarily because with the greater mid-range torque produced by the petrol engine, the 'gearbox' keeps engine revs lower for a given power output. So instead of engine revs flaring loudly at each small hill, the car now just torques its way up with engine revs and noise both much lower.

When the front undertray was off the car, some intake noise from the large airbox could be heard, but with the tray back in place, this is inaudible. There may – **may** – be a slightly deeper exhaust note on the overrun, where the injectors are switched off and the engine is freewheeling, but from inside the car, the new exhaust is otherwise dead quiet.

Outside, the exhaust has a deeper note and the turbo can be very faintly heard whistling-up – those noises overlay the (also faint) whistling/whine of the electric motor and power converter and the normal sounds of the combustion engine. From inside the car, about the only time you can hear any performance is at full throttle at higher speeds, where the engine makes a muted growl.

Conclusion

To achieve modification results on such a complex car that include superior fuel consumption and vastly improved open-road performance are very satisfying results.



The upshot is that the Prius drives exactly like a turbo factory NHW10-model Prius would. There's no added induction noise, no blow-off valve noise, no exhaust noise. There's no rush of boost as the turbo spools-up, no change in the sensitivity of the electronic throttle, no increase in vibration or harshness. Instead, the car is punchier in urban cut and thrust, and much more powerful when being driven hard along a sinuous and hilly country road. Drive it everywhere at full throttle and fuel consumption is far poorer than standard, but drive it normally and the fuel consumption is a little better than standard – the consumption depends entirely on the mood of the driver. Having said that, it's rare not to get 750 kilometres out of a single 45-litre tank...

In short, all the criteria for improved open road driving performance without a severe overall fuel economy penalty or poorer NVH have been met.

The *raison d'etre* of the Prius can be summarised in these words: fuel economy and emissions. The designers aimed at making it the most fuel-sipping, cleanest car in the world.

And despite the addition of the turbo, maintaining these characteristics was near the top of the priority list.

As discussed in the main text, the turbo Prius is often **more** economical than standard. Its emissions in nearly all driving conditions are the same as standard (using a new cat converter and staying at stoichiometric air/fuel ratios) but it must be admitted that at high loads, the richer than standard air/fuel ratio that is used results in higher hydrocarbon and CO outputs (although lower NOx).

Summary of Turbo Modifications:

- Turbo - ex-Subaru Liberty twin turbo IHI RHF4
- Fabricated exhaust manifold

- GFB recirculating blow-off valve
- Fabricated intake and intercooler plumbing – 2 inch and 1.75 inch mandrel bent
- Turbo oil and water cooling lines
- Intercooler - ex-diesel Pajero air/air
- 2-inch exhaust – 2 inch cat, 2-inch resonator, ex-Corolla rear muffler
- Airflow meter – original sensing element in larger body
- Airflow meter electronic interceptor – Digital Fuel Adjuster kit
- Intake airbox – Falcon XR8
- Fuel supply system – in-tank pump, external pump, two pressure regulators, solenoid, one-way valve, two control relays
- Decrease in high load boost using a solenoid-controlled bleed on BOV pressure line via Simple Voltage Switch working off airflow meter signal
- Engine 'on' signal provided for 30 seconds after boost event via a modified Simple Voltage Switch working on hybrid ECU 'full air con request' input
- One heat range colder Iridium spark plugs
- Electronic switching of oxygen sensors and fuel pressure via the Simple Voltage Switch kit working off airflow meter signal

So How Does it Compare?

So what are the different Prius models - and how does the turbo'd one compare?

The NHW10 model was released in Japan in late 1997.

The first model Prius sold outside of Japan was the NHW11 model, which looks much the same as the NHW10 but has some significant underskin changes.

The current model, the NHW20, has both a new body and even more significant driveline changes, although the fundamentals remain the same.

So is the turbo NHW10 now a match for the current model NHW20? The short and blunt answer is: it's not even close.

The NHW20 gets to 100 km/h in about 10 seconds, helped hugely by its near-doubled (at low speeds) electric motor power. The turbo NHW10 takes 14 seconds (see, told you it was still slow in standing start times!).

The NHW20 also shows superior fuel economy to the turbocharged NHW10, although this is a much closer contest. In fact, on a cross-country haul of the sort I did in an NHW20 (see Toyota Prius: Across a Continent) the economy sat for – at times – hundreds of kilometres at 5.3 litres/100km, a figure I am sure the turbocharged NHW10 could equal. (In fact, I would be hopeful of high Fours.)

But, as impartially as I can, the following table shows a comparison of the vitals.

Model	NHW10	NHW11	NHW20	NHW10 turbo
Engine Power (kW)	43	53	57	55?

Electric Power (kW)		30	33	50	30
0-100 km/h(seconds)		**16**	**13**	**10**	**14**
Japanese 10-15 test fuel economy*	km/l	28.0	29.0	35.5	-
	litres/100km	3.6	3.4	2.8	-
	mpg (Imp)	79	82	100	-
	Mpg (US)	65	68	83	-
Typical on-road fuel economy	km/l	17.5	19.2	21.2	18.2
	litres/100km	**5.7**	**5.2**	**4.7**	**5.5**
	mpg (Imp)	49.6	54.3	60	51.4
	Mpg (US)	41	45.2	50	42.8

(***** apparently there was an NHW11 mid-model update that resulted in the 10-15 economy test figure improving by 6.9 per cent. Note: the Japanese 10-15 mode fuel economy test is notoriously optimistic compared with real world fuel economy)

So hell, if in performance the turbo'd NHW10 is still slower than the standard NHW11 and NHW20 models, and in economy it's often no better, why didn't I just go buy a current model – or even an Australian-delivered NHW11 – and save myself the trouble?

Well, one really good reason is cost. The JDM Prius cost me only AUD$12,500. Add the turbo, fuel pumps, etc (which is hard to cost because fitting all this stuff also earns me money!) and you might add another $3000. I am still way ahead of a locally-delivered NHW11 (at about AUD$22,000) or a current model NHW20 (AUD$35,000 secondhand).

However, clearly I'd like to apply the turbo technology to a current model NHW20. Perhaps one day I will...