Electric Hubcap™
Motor Building Manual

An earlier prototype with covers on a car wheel

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Note:
This motor needs speed reduction to the car wheel. Only a very oversize motor would have enough torque if directly connected. A versatile, efficient, mechanical torque converter is currently being designed. (Other options are planetary gears, chain drive, etc.)

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### Section 1. Motor Workings

**Electric Hubcap Overview**

The Electric Hubcap is a 'pancake' shaped three phase, axial flux, supermagnet motor designed for mounting on the wheel of a motor vehicle. A versatile, efficient mechanical torque converter couples it optimally to the wheel. Its unique features combine to make it an ultra-efficient drive system, delivering an estimated 1.5 times or greater thrust to the wheel than a typical electric vehicle drive (operating through the vehicle's transmission) for the same energy input. So little energy goes to waste that it doesn’t need a liquid cooling system. The motor's magnets act as fan blades to cool the coils.

This is a very simple motor to make at home from commonly available trailer and automotive mechanical parts - some of which may perhaps even be found at an auto wrecker for maximum economy. It can be made mostly with home tools. Some tools are needed, such as cheap drill press, an angle grinder for cutting metal, and various other common tools. (I just C-clamp the drill press to...
A simple motor configuration can be done with a trailer axle and hub, or perhaps even an automotive wheel hub from an auto wreckers -- no welding or machining. For the torque converter configuration, a trailer axle with flange holds two hubs made from a 1-1/2" pipe coupling, which are machined and welded to the rotor disks. (sorry - needs welder, machine lathe.)

It is also easier to simply add a motor to the wheel of a car than to rip out the gasoline engine and all the associated parts and fit a (bigger) motor to the inefficient and inappropriate drive train, and it leaves gasoline operation available "as usual", eliminating worries about running out of battery charge at a bad time or place.

OLD VERSION - PRE TORQUE CONVERTER, PRE SUSPENSION MOUNTING

The "Production Prototype" Electric Hubcap motor mounted on the car. (The original direct-coupled configuration without the torque converter is shown. The torque of this configuration is insufficient.) Also, the 'arms' across the stator have been replaced by 1/8" x 3/4" strap steel.

The magnet rotor (above, yellow and black) is a brake disk rotor faced with supermagnets. A trailer wheel axle, hub and bearings tie this to the motor stator (blue), which is another brake disk rotor, but with heavy electromagnet coils bolted onto it. The coils and magnets face each other with an air gap between. (surprisingly large gap: ~8mm) The steel straps (formerly thick arms as above, blue) and protruding brackets connect the stator to the axle (to the brake drum backing plate) to prevent it from turning.

Note: In the latest version with the experimental torque converter, the supermagnet rotor is a brake drum rotor with the magnets glued to the outer face, rather than a disk rotor. The inside of the rim contains a curved track which drives an inertia rotor within the drum. This inertia rotor is linked to the wheel by link pins and a flexible coupling.

Of course, the Electric Hubcap type of motor can be used anywhere a motor of its characteristics -- high efficiency, a few horsepower, high torque, lowish RPM range -- is needed. (It could for example make a great washing machine motor, perhaps eliminating much complex mechanism, a variable speed lathe motor (eliminating V-belts and pulleys), a marine or submarine propeller driving motor, and so on. Larger versions could power ships, locomotives, busses, and even aircraft if lightweight batteries become available.)

This type of motor is run in a six-state power sequence by a solid state electronic control system. At any given time, one phase is driven high (Battery +36 volts), another low (Battery -ground), and the third is idle, with the three drive wires switching continually based on the rotary position of the
supermagnets on the wheel. The basic control contains only a small number of commonly available electronic parts, and a dozen high power MOSFETs (= metallic oxide semiconductor field effect transistors) that drive the motor coils. With no microcontroller to program, this is a straightforward "hobby electronics" construction project.

A microcontroller version could offer more features.

A simple Optical Commutator in the motor, or three Hall effect magnetic switches, synchronizes the six-state motor coil timing sequence with the rotation of the supermagnets on the car wheel.

A potentiometer, for vehicle use connected to the accelerator pedal, determines the amount of thrust the motor provides via a pulse width modulation (PWM) circuit in the controller.

A safety circuit prevents overdriving the motor and controller, eliminating the potential for burnout under adverse conditions.

Detailed descriptions and schematics are given in the separate manual for making the controller, Manual for Making the Electric Hubcap Motor Controller. Another manual is to be created for making the mechanical torque converter, and installing Electric Hubcap drive systems is to be detailed in yet another manual.

More completely, the power to the motor is regulated (a) by the choice of battery voltage, (b) the construction, wiring and connection configuration of the motor coils, and (c) by the pulse width modulation (PWM) of the supplied voltage.

The three phase "Y" motor wiring configuration is used, and the three coils of each phase are wired in parallel in order that the motor runs on a much safer 36-40 volts DC instead of the 108-120 volts that it would use if they were in series. The only disadvantage to low voltage operation is that the current is correspondingly higher, necessitating heavier power wiring. However the wire gauges are still reasonable, and the power wires are quite short. (At 12 volts the wires would have to be awfully fat.) And, the lower voltage rated mosfets have better specs.

Officially, the motor type is called a "permanent magnet synchronous motor" or PMSM, and you’ll see this acronym again, but driven with a PWM motor controller having magnet position feedback it is the drive signals which are synchronized with the motor rotation rather than the other way around. It is also called a "brushless motor" and "PM" (permanent magnet) motor.

Electromechanical Basis

Mounted on a car wheel or axle, the spinning rotor of the Electric Hubcap ("EH") motor provides torque pulses to the mechanical torque converter's inertia rotor. This rotor is attached to the vehicle wheel by link pins forming a flexible coupling.

The link pins are necessary because the inertia rotor moves in three dimensions. The flexible coupling allows for suspension of the weight of the motor system - it allows it to pivot up and down to a certain extent as the car wheel moves up and down with roadway bumps.

A typical procedure would be to gear down the motor by at least five to one in order to magnify the torque by the gear ratio and operate at a higher RPM in order that the car be able to start on an uphill grade and have acceptable acceleration at low speed. But this makes for very high motor RPMs at highway speeds, eg 6000 or more. This is overspeed for most motors large enough to propel a car, so gear shifting is required, complicating design and operation. It also seems amazingly inefficient: automotive transmissions typically waste 30-40% of the engine’s power internally.

For another example, a car starter motor can propel the car (along with turning the car's engine) in first gear because it is geared down 16:1 or more to the engine flywheel, and a further (eg) 4:1 in the transmission with the car in first gear. Thus its torque is magnified 64 times at the wheel. It would also be turning at a very high RPM before the car is going very fast, eg, on the order of 6400 RPM at 10 Km per hour.

With the mechanical torque converter, the "gear ratio" is continuously variable, and this is automatic and, with correct design parameters, optimum over the design speed ranges of motor and vehicle wheel. Thus the Electric Hubcap is able to supply very high torque at, eg, 750 RPM to get the car to start rolling, while on the highway with the wheel turning 1000 RPM, the motor is still only turning 1750 RPM to provide the same thrust.

The PMSM motor itself, with its supermagnets always at full strength, has much more torque at stopped and low speeds than any other electric motor family. (Their magnetic flux is in fact much higher than the flux in the stator electromagnet coils that drive them.)

The "standard" EH stator has nine cylindrical toroid coils spread around what was the inner disk
brake pad braking surface of a car disk brake rotor. These face six supermagnet magnetic poles similarly spread around the outside of the rotor. The coils are 1" tall x 2" round iron core diameter (the "magnetic size"), and a total of about 3" diameter with the copper wire "donut" around the core (the physical size). The magnet poles are formed of two supermagnets each, the twelve magnets each having dimensions 1/2" (thick) x 1" x 2". (These also act as 'fan blades' to cool the coils.)

Up to the point of magnetic saturation of the iron cores, the magnetic flux is proportional to the electric current through the coils, not to voltage or power. In fact, the voltage and power required to push the required heavy current through the resistance of the copper coils and overcome the residual magnetic retention (hysteresis) of the coil iron is waste energy. The lower the voltage needed to push the current through, the less energy is being wasted. We have:

36 volts * up to 127 amps = up to 4572 watts/6.12 HP (being wasted) at the moment we apply full power before the motor starts turning - and without a torque converter, before the car gets going.

If we had room temperature superconductors very little waste energy would be used to start the car rolling. Copper, though the second best known conductor of all materials at room temperature, has resistance, which wastes energy to overcome in supplying the current.

To further digress into the subject of wires, there's a reason copper is almost universal for motor use:
Silver is the best conductor. But it is only a few percent better than copper and very expensive. It might increase efficiency from, eg, 90% to 92%, and there may be situations where silver is a better choice, but car motors probably isn't one of them. Silver wire for the Electric Hubcap would cost perhaps a couple thousand dollars instead of forty or fifty dollars for copper. (2009 prices)
Aluminum is the third best conductor. It is often used for electrical wiring, and a larger gauge of this cheaper metal can compensate for its somewhat lower conductivity. However, in motor coils there isn't much room to put copper wire that's as heavy as is desirable, let alone wires occupying more space. This contributes to motors overheating easily. Aluminum would make for less powerful coils that waste more energy.
Also, aluminum is more prone to becoming brittle and failing with vibration and in sometimes damp environments, the contacts corrode more easily and work loose by expansion and contraction with temperature changes. Bad connections not only make the car run badly, they may blow up motor controllers. So, though tempting for heavy cables, it may be a poor choice of wire for any vehicle use.
Also, work hardened copper (hammered, bent back and forth, squashed,...) is up to 5% less conductive than annealed (soft) copper.
No alloy listed has as good conductivity as these pure elements.

There is one more factor governing torque: the large diameter of the Electric Hubcap locates the magnetic forces farther from the axle, providing more leverage from the same magnetic force. In effect, having the magnets and coils at 4-1/2 inches effective radius from the center provides a torque advantage of over two to one versus a similarly magnetized radial flux PMSM with a two inch effective radius.
Further increasing the diameter without adding more coils and magnets (or increasing their size) will decrease the flux density over parts of the rotation. I don't pretend I've worked out the optimum except by an "eyeball" sense of proportions. Increasing the diameter while adding more magnets and coils (or using bigger ones) to maintain the flux density will of course provide more torque.

Once the vehicle is moving, the low RPM motor still needs a high torque, but power comes into play. E = 1/2 MV^2, so power of a given motor is closely related to the square of motor speed, the RPM. Also the power, Watts, = Volts * Amps.
But as speed increases, a motor starts to act as a generator. If, say, one is supplying 36 volts and the motor is generating 18 volts, the maximum current to the motor drops by half. At the speed where the motor is generating almost 36 volts, it won't go any faster and has no power to spare. This dictates the maximum RPM (which hopefully is below where the motor will fly apart).

Another facet of coil operation is that in an inductor, current lags voltage. On measuring the inductance per phase as 0.60mH, it turned out to be only a 3º lag at 1000 RPM, or 100 Km/hour with smaller 13 inch wheels, which is within reasonable limits for efficient operation. Over 2000 RPM or so it might become significant, but that's about the EH's maximum RPM.
Electronics are an important part of any modern car motor design. In the case of the Electric Hubcap, they energize the coils in synchrony with the rotation of the magnets. Without that, a synchronous motor can't be used as a car drive.

The control electronics, however, are simple, with a simple optical or Hall switch 'commutator' signals telling the motor controller which coils and polarities to activate based on where the magnets are in their rotation. This feedback system is an integral part the motor.

The optical part is in the motor itself, with a rotating component and a stationary component. Or, three hall effect solid state sensor switches are mounted on the stator - the simpler new system.

For the optical system, a plastic "tuna tin" (ABS pipe end cap) with slotted sides rotates with the magnet rotor. Wherever there's a north magnet, the sides are solid, and for a south pole, there's a slot. The stationary section is a circuit board with 3 light emitting diodes (LED's) and 3 phototransistors, one pair for each phase. These are rotated 40º from each other around the axle, the same as the angle between adjacent coils. The light from each LED to its phototransistor is interrupted by the solid sides of the rotating "tin" and passed through where there's a slot, much like a computer mouse. (In fact I got the LEDs and phototransistors for the prototypes from old computer mice.) The pairs are arranged around the sides of the can separated by the angle between phase coils on the stator.

With everything lined up, the proper timing for the coil drives is output directly from the phototransistors with no need for interpretation. The three phototransistor outputs can directly feed the motor controller chip to actuate the coil drives, to generate the six-state drive sequence.

For the Hall effect sensors - the new system - the three sensors are simply mounted on the stator between the coils and near to the passing rotor magnets. There are minor timing inaccuracies with this system (because they don't switch until slightly after the midpoint between two opposite magnets), but it's close enough, easier to make and install, and it's not sensitive to the stray light or dust buildup that might hamper the optical system.

To run the motor in reverse, the signals are simply digitally inverted (inside the motor controller chip.) If there is no microcontroller, this is done simply with 3 gates of a quad XOR gate chip. Of course, 'forward' and 'reverse' depend on the sensors and on whether the motor is on the left or right side of the car.

Electromagnetic Workings

The three motor wires are driven in a six state sequence. Since there are 9 coils and 6 magnet poles, they line up the same every 120º and the sequence repeats itself 3 times per revolution. (This 3:2 ratio of coils to magnets is necessary for proper three-phase PMSM operation.) Each phase wire is driven for 2/3 of the time, and only two phases are driven at a time. All three are never on at once. Each coil is "on" for two states then "off" for one, and at the midpoint of its "on" state, the other two coils swap over as the magnets rotate. The three states, high, off and low, or 36 volts, undriven and ground, create magnetism north, off and south in the coils. Here is the sequence:

| øA | --------------- | --------------- |
| øB | S--------------- | --------------- |
| øC | --------------- | --------------- |

When one line is driven to +36 volts while another line is driven to 0 volts, the coils driven to +36 are north at their top ends and south at the bottoms, while the coils driven to 0 volts are the opposite magnetic polarity. Both sets of coils provide the same magnetic strength. (Don't ask me which, "N" and "S", is really which!) Two wires (and hence two phases) are driven at a time, one high and the other low. The third phase coils are idle. Each set of coils goes N, O, S, S, off, repeatedly. The intervening off state, not going directly from high to low, reduces the inductive spikes made by the coils, reducing the amount of filtering required.

The power is timed so that adjacent coils become north and south as a magnet passes between them, one coil repelling the magnet and the other attracting it to provide turning torque. As the magnets pass directly over a coil, it is turned off. Energized coils here would simply repel or attract
the rotor magnets to the stator coils without providing turning force. Note that right in the middle of one set of coils being "north", the other two sets swap being "south", and vise versa.

With spread out magnets along the rotor, it is the position of the center of force that is being considered.

At the risk of being repetitive, here is another representation of the six state drive sequence:

<table>
<thead>
<tr>
<th>State</th>
<th>Phase A coils (0°)</th>
<th>Phase B coils (40°)</th>
<th>Phase C coils (80°)</th>
<th>North Rotor Magnets</th>
<th>South Rotor Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>36v (N)</td>
<td>0v (S)</td>
<td>-</td>
<td>10° to 30°</td>
<td>70° to 90°</td>
</tr>
<tr>
<td>1</td>
<td>36v (N)</td>
<td>-</td>
<td>0v (S)</td>
<td>30° to 50°</td>
<td>90° to 110°</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>36v (N)</td>
<td>0v (S)</td>
<td>50° to 70°</td>
<td>110° to 10°</td>
</tr>
<tr>
<td>3</td>
<td>0v (S)</td>
<td>36v (N)</td>
<td>-</td>
<td>70° to 90°</td>
<td>10° to 30°</td>
</tr>
<tr>
<td>4</td>
<td>0v (S)</td>
<td>-</td>
<td>36v (N)</td>
<td>90° to 110°</td>
<td>30° to 50°</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>0v (S)</td>
<td>36v (N)</td>
<td>110° to 10°</td>
<td>50° to 70°</td>
</tr>
</tbody>
</table>

Note that at all times (disregarding the PWM that repeatedly turns all the drives on and off during their "on" times) one phase is driven high and another one phase is driven low, providing continuous north-south magnetic thrust forces at all points of rotation.

The maximum rotational force is generated when the rotor magnet pole is directly between two energized coils, one attracting it and the other repelling it.

Since the sequence repeats every 120°, each coil is north for 40° then off for 20° (half the sequence), then south for 40° and off again for 20° (the other 60° half). That 120° also sees the two magnet poles, north and south, 60° each, go by the three coils of phases A, B and C.

The astute student will notice that with only three photo-optic elements, the six states aren’t entirely decoded for the six inputs to the MOSFET driver. "A" would seemingly be high for 60° and then low for 60° of the 120° cycle with no "off" time, instead of only on for 40° and off for 20°. Where is the translation? For the answer we look to the digital logic and to the way the optics connect to it.

The truth table for an IR2130 MOSFET driver chip is:

<table>
<thead>
<tr>
<th>Input for HIGH drive (phases A, B &amp; C are alike)</th>
<th>Input for LOW drive (A, B &amp; C are alike)</th>
<th>MOSFET Outputs: High side &amp; Low side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (&quot;off&quot;)</td>
<td>1</td>
<td>Both Off</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Low On, High Off</td>
</tr>
<tr>
<td>0 (&quot;on&quot;)</td>
<td>1</td>
<td>High On, Low Off</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Both OFF (NOT both on!)</td>
</tr>
</tbody>
</table>

If both high and low of a phase were on at once, the high and low side MOSFETs would create a short circuit from the 36 volt batteries to ground, and blow the fuses (and maybe burn up first themselves). The chips don’t let that happen, and they also insert a very short delay in any transition directly between high and low drives being on to ensure the same. Other logic chips could provide the same functionality - the IR2130 does it on one chip.

We utilize these protection circuits to supply the 3 high and 3 low drives (6 inputs) from just the three phototransistor outputs by crossing phases over to the Low drive inputs. The overlap in times gives the "off" states. This is covered in more detail in the motor controller manual.

To visualize the workings, let us simplify by considering a rotor with only two magnet poles 180° apart, and a stator with three coils 120° apart. The six states then occur over one rotation, 360°, with 60° per state.

The timing is then that the top coil "A" is off until a magnet pole is 30° past it. Then it turns on with the same polarity as that magnet for the next 120° (to 150°, states 0 and 1 of the table), repelling...
It then turns off while the other magnet goes by it from -30 to +30° and the first magnet goes from 150 to 210° at the opposite side (state 2).

Then, with the second magnet 30° past the top coil, it goes "on" with the opposite polarity for the second half cycle (states 3 and 4 from 210° to 330°, with state 5 again being "off" from -30 to +30°).

While the first magnet moves away from the top coil from 30° to 150°, the opposite pole is approaching the top coil and is attracted, going from -150° to -30° from our coil. Most of the repulsion of the first magnet is in the first 60° from 30° to 90°, then that magnet becomes rather distant from the coil. Most of the attraction of the second magnet is in the second 60° as it approaches our coil.

The other two coils do exactly the same thing, but 120° and 240° out of phase to the top one, between them providing continuous strong thrust at all points of rotation.

In the first 60° of the 120° swing (30° to 90°), phase "B" has been on, the magnet going -90 to -30 degrees from it, attracting the magnet "A" has been repelling. Thus the magnet is being strongly pushed by the coil just behind it and strongly pulled by the one just in front. The opposite magnet is also being weakly rotated by the same two coils, which are more distant as it is crossing over the third, "off", coil.

In the second 60° of the swing (90° to 150°), phase "B" goes off as the magnet goes by it and "C" comes on. Now "C" is pushing and "A" is pulling the opposite magnet immediately between them with the same strong forces, while the first magnet is weakly propelled as it passes by "B".

The 9 coils, 6 magnet poles machine, works exactly the same, but the six-state cycle repeats itself three times over 360 degrees, ie every 120 degrees. All the angles are 1/3 and three identical sets of coils are pushing three sets of magnets. So the timing is that the coil is off while a magnet pole passes over it from -10º to 10º past it, a 20º span (state 5). Then it turns on with the same polarity as the magnet for the next 40º (states 0 & 1). This repeats with opposite polarities for the other magnet in the second half of the cycle (states 2 (off) and 3 & 4).

**Mechanical Workings**

The car wheel's regular lug nuts are removed and replaced with long ones that stick out well past the lug bolts, to extend them as threaded sockets. I’m using around 30 mm long nuts. They’re from an auto wrecker (lying around everywhere) and I cut or ground the decorative outer end caps off. The magnet rotor is bolted onto the wheel via these sockets. From the center an axle protrudes. A trailer wheel rotor sits on this turning axle on regular trailer wheel bearings. The stator is bolted onto this and is thus centered on the wheel and rotor. Thus, the usually stationary axle turns with the car wheel, while the usually turning trailer wheel rotor is stationary. These automotive parts are almost ideal for the purpose - with even the holes in the right places - and avoid a lot of custom machined parts. (Finally I’ve found there’s almost no getting around drilling some lug bolt holes somewhere and I prefer shorter car axle/hub/bearing units.)

There are probably many types of suitable car wheel hubs & axle assemblies as well as the trailer hub & axle I used, with various spacers, rotors and hole drillings selected to suit. One I have from a Firebird could certainly be used (probably with an entirely flat magnet rotor), and I saw a picture of one that looked almost ideal in a Canadian Tire flyer, though at the store they couldn't show me one or tell me what model of car it was from. Most of these would be more compact than the trailer hub and axle. A drawback is that being pre-assembled, it will be harder to mount a slotted ring for the optical assembly - it will either have to fit over one end or be placed in two pieces. (Of course, it's little problem, if required, to cut an ABS piece in half and glue it back together around the axle.)

If I do a second motor myself, I will certainly try using a car axle. The first working prototype used the hub part of a rather hacked one. (Perhaps they'll get tried in the workshops.)

Two rectangular steel tube "brackets", upper and lower, bend around from behind the wheel just afront and behind the tire. They attach to the brake drum backing plate behind the wheel. Two arms, upper and lower, extend left and right from the stator to attach to the brackets. This somewhat springy mounting takes the torque and prevents the stator from spinning instead of the rotor and wheel. (If you are wondering about the strength of the brake drum backing plate for this purpose, recall that the brake shoes attach here and it takes all the force of squealing the brakes!)
Construction Principles

The motor is mounted on the wheel, which is unsprung, and although it is somewhat sprung by the flexible coupling and mountings, it is subject to levels of vibration not felt inside the car. Furthermore, if a roofrack comes loose, it is likely to be noticed and retightened, whereas the motor is down at the wheel and behind a cover. Many of the parts inside can’t be seen even if the cover is removed, and the whole motor has to be removed to retighten them. Even the brake drum has to be disassembled if the innermost stator bracket bolts come loose.

And there is more possibility to cause harm if something comes off the motor, wheel or brake assembly, or even comes loose, by losing power while driving, by having a loose part jam the wheel or cause a flat tire, or by dropping a chunk of metal on the road in front of the next car.

It is therefore critical to have a robust design, to install all the parts very securely, and to have scheduled inspections, frequently in the beginning stages. Fragile parts must be carefully situated and protected.

More on all this later.

Battery Power Supply

The electric Hubcap runs on 36 volts of batteries capable of supplying up to 100 amps continuous, situated where convenient in the vehicle. Generally it is desirable to locate them close to the motor controller(s) so the heavy leads are short, minimizing voltage drop and cost.

As I write this, generally the only practical, economical batteries for electric cars are lead-acid. These are rarely an environmental problem as they are normally recycled. With sodium sulfate added to the electrolyte, they can last for 10-20 years.

They are, however, heavy and bulky. The Electric Hubcap hybrid helps out by needing many fewer of them. Three large "size 27" "deep cycle" 12 volt batteries (50 pounds, $100 each) will run the car. Six of them (two parallel banks of three - 300 pounds), or six 6 volt "golf cart" batteries will do it with some driving range and longer life.

I will not here enter into speculation of what range is practical or the complex subject of lead-acid battery quirks. On any batteries, the Electric Hubcap will go farther than any other car drive. And because the car becomes a "hybrid" instead of an "electric car", whenever the batteries are considered "low", the driver will simply switch to gasoline driving until it is convenient to recharge them, or use "charge while driving" (on gas), with the advanced controller and switch back when they're recharged.

2. Motor Mechanical Components Selection

The structural components of the Electric Hubcap motor are:

* Axle & Hub, bearings ("spindle" herein)
* Stator
* Rotor
* Housing/Case
* Mounting Straps or Brackets

The motor can be made or configured with:

1. Rotating axle - rotor bolted to axle flange, stator on bearings.
2. Stationary axle - stator bolted to axle flange, rotor on bearings.
   These are in fact identical except the positions or the rotor and stator are reversed.
   There are two sub-versions:
   a. rotor (stator) welded to machined pipe-coupling bearing hub
   b. rotor (stator) bolted to standard trailer wheel bearing hub (no machining or welding, reversible)
3. Mechanical torque converter (MTC) ready.
4. Custom types, such as using a compact integrated car axle unit for axle, bearings, hub.
In the MTC version, the axle rotates independently of both the stator and the rotor, turning with the torque converter output drum. With two independently rotating units on one axle, the trailer wheel hub option is impractical and both units are welded to pipe-coupling hubs.

Note that the MTC version could also be good for electric aircraft (with the great manganese-salt batteries). Like the car wheel, it's usually desirable that the propeller turn more slowly than the motor. I'm not sure how large a plane one motor and MTC of this size could power, but it would replace a considerably larger gasoline engine. (Then there's two props, or multiple units on one longer axle - there's a light electric aircraft in here somewhere.)

Many motor configurations are possible for uses where no torque converter is needed. If a spinning axle is required, a trailer wheel hub can hold the non-rotating stator, and the rotor is bolted onto the axle flange.

For some applications, possibly the spindle may be an independent axle car wheel assembly. Or, 1" axle trailer wheel bearings will fit on a 1" bolt or 1" threaded rod. If no flange is needed a bolt is less expensive than a trailer axle. Custom parts may be an improvement if multiple motors are to be produced. Flat steel disks can be made to order complete with all holes, with a CNC abrasive waterjet cutter, of which there are a growing number doing custom work. Pipe couplings can be turned on a lathe to make bearing hubs. The possibilities here are limited mainly by the imagination and time spent figuring out a "best solution".

The car and trailer parts remain the simplest for making one or two motors.

These common items may be found at trailer supplies stores, automotive supplies stores, or auto wreckers. The most suitable ones I've found so far are described below. Especially, of a myriad of choices, the 6129R (cross references below) seems to be the best rotor for both stator and rotor.

With most motors, the rotor is inside and the stator is outside - radial flux. With the EH, the rotor and the stator are two disks of similar and unusually large diameter, eg 9 to 11 inches, and the electromagnetic elements face each other like two dinner plates (or whatever) - axial flux.

I was using "10.5 inches nominal" as the diameter when I was hoping to drive the wheel directly, but with the 6129 rotors (250mm, 9.85" diameter), I've picked 10.25", which leaves the magnets sticking out 1/8" and the coils out that much farther. It also doesn't leave a lot of room between the coils for messy or oversize windings. But the light rotors reduce the weight somewhat, and perhaps with larger car wheels, it might clear curbs for easier parallel parking. I recommend a plate thickness of about 3/8" (10mm) to provide mechanical strength and to carry the magnetic fields.

### A Magnet Rotor - N black, S - yellow. 11" diameter disk brake rotor with no fins, shallow hub rise. (Buick Gran Sport rear wheel rotor?) Magnets to 10.5", leaving 1/4" outside lip. A "skip tooth" configuration was employed, for sharp transitions between N and S. 18 magnets would be really too many - the rotor is brutally magnetic. The 100mm, 4 lug bolt holes pattern had to be drilled (before adding the magnets!) to fit the wheel and hubs used.

The stator has 9 coils, three sets of three, spaced 40º apart. The coils for a given phase are 120º apart from each other - the same spacing as the magnet pairs. Each coil is a disk about 1" thick and almost 3" in diameter, and has holes through it for two 1/4" diameter mounting bolts. The magnetic core is a 50mm diameter circle. With the 10.5 inch rotors, the nine coils just fit on the backing plate/disk with little space between them. (Coil details are described fully later.)
For a smaller diameter rotor, the coil cores will have to be reduced from 50mm to a lesser figure, or a bit can be "cut off", flattening two points on the sides to make it slightly pie shaped. The pie pieces will fit in a smaller circle while retaining a maximum of core material, but are a bit more complex, and of course will have - very slightly - higher copper losses. Aim to have an inch (25mm) between coil cores at all points to allow sufficient space for the windings.

Prototype stator with clamped on coils. 10.25" rotor (Honda, 4 lug holes/100mm pattern, finned), with the copper wire of the coils overhanging outside for 10.5" core outsides to match magnets on rotor. (Well, actually this is the 10.25" O.D. sized prototype. The coils are too close together, and would be better at 10.5", and the connection wiring didn't quite fit in the center area (it's around the outside instead), so I changed the spec to 10.5". The magnets on the rotor for this actually are at 10.5".)

The housing or case protects the motor from dirt, mud and rocks. I used a 3-1/2" inch length of turquoise colored 12" I.D. PVC plastic culvert pipe (from which part the name "Turquoise Energy" originally sprang).

A nice cover can be placed over the end of the motor. Mine is a stainless steel "wok lid" of the right diameter. (Alternate choice was a mixing bowl.) With a car axle, a much shallower dish should fit.

The upper and lower rear mounting arms reach from the brake drum housing behind the wheel (which takes the torque of screeching brakes) around the front and back of the wheel. They connect to the arms attached to the stator and prevent the stator from rotating. 1/2" x 1" rectangular steel tubing does nicely for the rear arms, giving the rotor assembly a bit of spring. 1/4" x 3/4" flat steel could perhaps work well for the front arms. I used the 1/2" x 1" tube and connected front and rear with 1/8" x 3/4" angled (bent) joining pieces, "strapping", threaded for 1/4" bolts.

Most of the motor fabrication consists of drilling holes and bolting ready made parts together. Other items are making the coils (unless purchased), glueing the magnets to the magnet rotor and spray painting the metal parts. (eg, rust paint the rotors.) The optics parts and the coils can certainly be made, but are more time consuming. If you choose to buy them, making the motor is an easy project -- much easier than installing the overall system in the car to complete the hybridization.

Creating a set: Center Hub & Axle Assembly + Rotor + Stator
The center hub assembly mounts the whole motor onto the center of the car wheel. OLD- PRESUSPENSION

It consists of a standard small trailer wheel axle and hub with trailer wheel bearings. The axle turns with the magnet rotor and car wheel while the hub, attaching the stator, remains stationary. The 6 inch long, 1-1/16 inch diameter (untapered) axle size is suitable. (A shorter axle such as various car hub/axle assemblies would protrude less. All will be a custom fit.) The trailer hubs/axes can be purchased with a mounting base conveniently having four mounting holes that fit a car wheel having four lug bolts. (4 -100mm.) The magnet rotor and the axle base attach by means of long coupler nuts and extension bolts on the car wheel lug bolts.
top: Long nuts on wheel. (from auto wrecker; with decorative endcaps cut or ground off.) These provide about 3/8" to 1/2" of free thread on the outer ends. Be sure to get nuts whose threads run the full length - some only go a short distance.

Bottom: Magnet rotor and trailer axle, showing use of extension on socket wrench to keep hands and tools away from the magnets while doing up the bolts. (I haven’t had anything crushed doing up bolts (so far) but I’ve had my fingers cut by lug wrenches that grab hold suddenly, dragging my hands across the magnets.)

Also of note, I had originally planned to put 18 magnets on the rotor, hence the uneven spacings - which are probably an advantage anyway. Souths are right next to norths with the gap being in the middle of each pole. (12 magnets is already brutally magnetic and 18 didn’t seem to add any notable thrust to the first working prototype anyway.)

Instead of the trailer axle and hub, there are any number of car axle/hub assemblies (which I’ll call "spindles" herein), made mostly for cars with front wheel drive and/or independent rear wheel suspension. On some, the hub/bearings and axle components are separate, on others they are a single combined unit. I used a combined Firebird spindle for the wave power. There are many different sizes and designs, and one must find rotors that can end up being a good fit for the spindle chosen. One GM combined spindle that is perhaps worthy of note is one with a triangular inner end (3 bolts) that happens to mount the rotors about 44mm apart, Canadian Tire # 013-0500-0. This is a good width for using two entirely flat rotors cut from, say, 5/16" steel plate. This would make the thinnest possible motor, 60mm or 2-3/8" disregarding protruding nuts and bolts.

It is frustrating shopping for these automotive items as the stores know nothing about them and keep them in boxes out of reach at the back, indexed only by the model of car they were originally for. A Canadian Tire flyer showed one that looked very promising, but when I went there they couldn’t tell me which one it was to show it to me! Taking tools, tape measure and measuring calipers to an auto wrecker may give better results - that’s how I got the Firebird unit - and you might also find rotors to fit the spindle you pick. You want to end up with about 44mm (1-3/4") spacing between the inside faces of the two rotors. If it’s somewhat narrower, washers can be added to move the rotors apart. If it’s a bit wider washers under the coils can ‘expand’ the coil widths, but if it’s more than a couple of typical 1/4" washer thicknesses extra it’s probably not a good match. Don’t forget to take larger "torx" bits - they’re common for holding the spindles onto the car! (I’d be glad to hear of spindles & rotors that seem to make good sets, to post to the web for all.)

Onto the center of the axle base, a plastic "tuna tin" with slotted vertical sides is affixed to alternately interrupt and pass the light between three LEDs and their associated phototransistors as the wheel turns. It’s just an ABS plumbing pipe cap that needs some cutting and fitting. With a unitary spindle assembly, you may need to cut it in half or thirds and glue it together again around the axle. However, the angles need to be pretty close for good motor operation.
Firebird (or was it Sunbird?) hub/axle assembly, shown with 12" x 1/4" flat rotor (a bit big but could work or be turned down - 3/8" thick would be better) and Honda (?) rotor. The spacing is too close - not enough room for coils (1"), magnets (1/2") and air gap (1/4") (= 1-3/4" = 44mm) - so some spacers would be required, eg to move the flat rotor down. Also required would be a number of custom holes for bolts. For a small 5-stud car wheel, perhaps the hub/axle should be reversed as the other end already has the right holes for that wheel (with its own stud bolts hammered out - they're usually a press fit) and would bolt right on.

**Best Rotors?**
(latest recommendations as of March 31 2010)

Amidst the vast array of possibilities from a zillion models of cars, one might well wonder "What are the best options?" I wouldn't call any of the available disk brake rotors or other hardware for motors "ideal" for Electric Hubcap motor systems, but there are some "good enoughs" here and there. Of the things now available "off the shelf", here are my current favorites.

These 'favorites' are now somewhat fine-tuned: In an auto parts store, I found a "Raybestos" catalog with all disk and drum rotors indexed by diameter, with useful info about each one and a picture of each one. Some I asked about were out of production, but I came up with the rotor below.

*Stator:* The "optimum" rotor for both the rotor and the stator seems to be: Raybestos 6129R, AKA AS6129. The identical Gren version from Canadian Tire says on the box: 016-9719-2 (the Cdn.Tire #), 636801/5485, Replaces BD125108, 52-125108.) Diameter is about 250 mm (9-7/8") and it only weighs about 6 pounds, pretty much the lightest one going in this sort of diameter. The low weight is because it's a solid (unfinned) rotor just 9 mm (3/8") thick, which is pretty much ideal - just thick enough magnetically and for strength without extra metal. It has the desired 4 bolt 100mm (or 4") bolt circle.

Some places can't cross reference rotors by part numbers. Here's a list I found of cars the '6129' is supposed to fit (whether front or rear wheels I'm not sure). It's welcome to see there are quite a few, some fairly recent, so it's not likely to become unavailable - especially not once people start buying them for motors. (Also they might be readily found at an auto wrecker):

* 1991-2003 Ford Escort
* 1994-2005 Mazda Miata
* 1990-1998 Mazda Protege
* 1991-1999 Mercury Tracer

If this had a low center hub rise (or none at all), I would call it almost an "ideal" part. As it is, the one inch rise forces the 'pancake' motor to be thicker. On the other hand, it makes the hub longer, and if the hubs were much shorter, there could be too much wobble anyway.

The biggest drawback to this rotor is that the smooth surfaces for mounting the coils and the
magnets are only 1-1/2" wide instead of 2". For bolt-ons that's okay, but for glue-on magnets, I turned the surface down until it was flat for 2", which took off about 1/16" leaving 5/16" thickness. Okay but minimal.

**Axle/hub/bearings:** Dexter 6" x 1-1/16" or 6" x 1" straight trailer axle with flange, 1 or 1-1/16" I.D. trailer bearings.

* For NON torque converter motors, one rotor disk can be bolted to a matching Dexter 4 bolt - 4" circle trailer hub and bearings can be used to avoid the need for machining anything on a lathe. However, the fitting is awkward because the hub doesn't fit into the center of the rotor disk. *Precautions must be taken not to crush your fingers between the magnets and the coils when putting this unit together.* Also the lug bolts on the trailer hub are spaced to 4" diameter (101.6mm) instead of 100mm, and the holes in the rotor have to be filed out a bit to match them.

* For the motor with the torque converter, there are three separate pieces on the axle instead of two:
  * Stator
  * Motor rotor
  * Torque converter drum

The axle and torque converter drum are attached and turn together, at the speed of the car wheel. The stator doesn't rotate and the motor rotor rotates at a different rate of speed than the torque converter. Therefore, both the stator and the rotor have to be attached to the shaft on bearings. It is of interest that the rotor and the stator parts are virtually identical, except for a mutual bearing seal piece between them.

I found that a 1-1/2" cast steel pipe coupling makes a good hub, welded to the 6129 rotor. It has to be shaped on a lathe:

* The outside of one end is turned to fit squarely in the center hole of the rotor.
* A tenon is made on the inside of that end to fit a 1" or 1-1/16" trailer bearing outer race, extending in about [try] 15mm (19/32").
  - A bearing seal or cap, as well as the bearing race, goes in that tenon.
* A similar tenon is made on the other end, but only [try] 8mm (5/16") deep.
  - Only the bearing race goes in this tenon, and it sticks out a bit.
  - These tenons determines the spacing between the rotor and the stator, which should be about 1-15/16".
* The outer face of that side is turned smooth to accept an axle seal (one side) or a pipe or tube to hold the seal piece (the other one)

**Further Rotors:**

Before the '6129' I considered a number of other rotors

Here are a couple of disk rotors with center hubs wide enough to fit over the trailer hub. Unfortunately, they have wide 5-bolt hole patterns and the proper mounting holes would have to be carefully drilled:

1993 Chevy Lumina (Z-34 car, not van), *rear* wheel rotor. "Gren" brand replacement has these numbers on the box:
C16-9575-2, 682301/5567 "Replaces BD61851, 52-61851", Canadian Tire # 016-9575-2.

I thought this one would be great because the center hub is only 1/2" tall, so the magnets could be mounted on the hub side. However, the center hub is so wide that the magnets would stick out to 10.5" diameter if thus configured.

Another pretty good rotor is the "Pontiac Gran Sport" *rear* wheel rotor disk. This rotor is shown above - it seems to be used in a number of GM cars, but I haven't sourced out part numbers. This 11 inch rotor would have more metal around the coils, but still it would probably have coil wires sticking out unprotected a bit. It's a solid rotor (no fins), 11" in diameter with a hub about like the Lumina's except 3/4" tall - still quite short but taller than 1/2" magnets.
There may be better choice(s), but I’ve looked extensively now and I have yet to find them.

Ideally, I envision disks specially cut from 9 mm (3/8") plate steel by (eg) CNC waterjet cutting. (or maybe pulsejet?) The center holes would be sized to securely weld in the short 1-1/2" pipe coupling, machined at both ends to fit bearing races. The stator disk might be about 11.5" instead of 10", or have semicircular projections, protruding out far enough to protect the coil wires during handling if the motor is set on edge, and with the mounting strap/bracket mounting holes near the outer edge, protruding bolts positioned between the coils or in the center area. Ventillation holes would be strategically drilled through the plates as seemed appropriate, with the magnets acting as fins to provide the air moving power. Of course, this vision has not been put to the test.

**Magnet Position Sensing: Optics or Hall Effect Magnetic Sensors**

In order to supply the correct power signals to the coils at the right times in the sequence of magnet rotation, the rotor position must be made known to the motor controller.

The original means I created for doing this is a slotted cylinder wall that turns with the rotor. This alternately interrupts and opens the light path between three LEDs and their three partner phototransistors.

A second technique that I used later was to use three "Hall Effect" solid state magnetic switches, mounted on the stator between coils. These switch state with the polarity of the magnets going by. (I used Allegro Microsystems A1213LUA-T) These look like a small plastic transistor. Another package looks like a small IC chip. They are simpler to mount and not subject to problems with ambient light if the cover is off the motor.

First we'll detail the optical system (historical precedence?), then the (preferred) magnetic switches.

There are three slots and three "walls" the same length between them, 60º, which rotate with the magnet poles: solid at the north magnets and slots for south (or vise versa), changing where the magnet poles switch. Each pair occupies 120º, the angle occupied on the stator by one set of three coils, phases A, B & C. The three optical LED - phototransistor pairs are set 40º apart, the angle between the individual coils. (According to my theories, they should line up directly with the centers of three consecutive coils, but this isn't giving good results and has been keeping the motor off the road this last week. I'm writing up and putting this manual on-line anyway, fully knowing this section will want revision in a few days.) There will be found one angle where the motor runs fastest and draws the least current, as found by a clamp-on "ampprobe" meter on one of the three drive lines (and perhaps a tachometer). If you're not familiar with these interesting meters, they work by magnetism with no actual electrical connection. Again, magnetism is proportional to current flow. Just "clamp" the probe around the wire. There are AC (common) and DC (less common) meters or meter ranges. A DC meter lets you read the total current in the main battery wire. The AC current in each phase of the motor, if it's turning, should read 2/3 of the total supply current. At the right angle, each state in the six-state drive sequence is timed perfectly by the transitions of the phototransistor outputs. (As I write, I'm about to install a "ligature", a clamp that can be turned, to mount the optics on so their position can be adjusted. That's what I used to good effect on the original prototype.)

Accuracy of the slots and optic component angles is important for best operation, and I'm beginning to think three curved plates forming the "solids" mounted out at the inner edge of the north magnets, with an expanded optics mounting to suit may be better than the small "tuna tin" arrangement, but have not yet come up with an arrangement.

**That's the optical system. Now we'll describe the magnetic switch system.**

Although theoretically less precise than the optical system, the three switches are simpler to mount and not subject to potential problems with dust, or with ambient light if the cover is off the motor.

The first cause of reduced precision is magnetic hysteresis: they don't switch until a requisite strength in the opposite magnetic polarity has been reached, rather than switching at the zero point. This was a particular problem when using a magnet rotor with six 2" x 2" magnets rather than
twelve more uniformly spaced magnets. At the outer rim there were wide gaps between magnets, and instead of switching near the mid point, they waited until the next magnet was almost there. I had to re-mount the sensors on the inside side. There was little room there and I had to "miniaturize" the posts and circuit boards. I discovered that using steel mounting posts instead of aluminum helped, doubtless concentrating the magnetic field just under the sensors.

The hysteresis would be less problem with 12 evenly spaced 2" x1" magnets, and still less problem with the "skip tooth" magnet arrangement shown herein.

The second theoretical cause of reduced precision is interference from the magnetic fields of the stator coils. However, I placed the sensors between coils rather than on coil centers, and I made no attempt to measure the effects. It seemed to work well, so I was happy.

Special Installations

Double motor:
For fitting two motors onto one shaft to get more power in one place, the trailer hub bolts are long enough to hold two stators facing opposite directions. One magnet rotor is mounted to the axle base location as usual, while the other must be fitted with a center hub of 1-1/16" diameter to fit on the other end of the axle, and a keyed slot or other non-slip alignment device must be used. An 8" or 10" long trailer axle would be used to gain the extra shaft length, with some sort of cotter pin and washer or shaft collar arrangement to hold the bearings and hub (made for 6" axle) in place. If a splined center vehicle axle for front wheel drive is used as the motor axle, the motor could possibly fit right onto a splined front wheel drive shaft in place the transmission/differential box, for an all-electric vehicle with a hidden motor(s).

Concentric Motors:

The general use for these would be for counterrotating propellors for boats or submarines. A solid axle must pass through a hollow one. As with the double motor the two stators could be mounted back-to-back. The shafts would no doubt requires some extra shaft machining with outer and inner shaft bearings (trailer wheel bearings are available).

Larger or Smaller Motors:
The 10.5 inch rotor diameter that I've used holds nine 2" core diameter coils and six 2" across magnet poles, for an average magnet and coil radius of about 4.25 inches.

Scaling up the design could be accomplished by either increasing the size of each component - stator, rotor, coils and magnets (or doubling up magnets), or by using more of them. 14 inch rotors would give 6 inches radius with four sets of phase elements (12 coils and 8 magnet poles) instead of three (9 coils and 6 magnet poles). This would provide a torque ratio of \( \frac{4}{3} \times \frac{6''}{4.25''} \), or 188% of the torque, would draw 133% as much current to start rolling, and would use four electromagnetic cycles per one wheel revolution. It might well need triple mosfet drivers instead of double - a bigger motor controller, and of course #6 wire instead of #8. With the coils in parallel, it would still be 36 volts. It would probably be suitable for some heavier vehicle than is typical (You would have to find such big rotors, and they would have to fit on the car wheel without extending beyond the rims.)

I'm assuming that Turquoise Energy will be supplying the "standard" size coils, making them, and two magnets per pole, a "simpler" choice.

Nine larger coils - whose cores, wire gauge and number of turns and characteristics would have to be figured out anew, and six somewhat larger magnet poles (18 magnets?) would cover more of the larger rotor's total surface area and provide more force, optimal for the larger size.

Each coil as described herein occupies about 3.3 linear inches, about an inch in from the outer diameter. A 8.5" rotor has 20.4 linear inches, \( \frac{6}{3.4} \), for a six coil stator (and hence 4 magnet rotor) -- if all the components can be fit in. Again these will still be 36 volt motors, but of course the 6 coil version will have somewhere in the vicinity of half the power, 1/4 the torque, and twice the RPM of the 12 coil one, and will draw half the current from the batteries. With the coils in series, the motors could be nominally 72, 108 and 144 volts respectively for 6, 9 and 12 coils and would draw 1/2, 1/3 and 1/4 as much current, respectively. Voltages above 36 volts are recommended only in dry locations, ie, indoors, and will require driver MOSFET transistors with higher voltage ratings. As always, wiring between the controller and the motor should be as short as possible.
Beyond 14", a lot of rotor area will be "going to waste" with relatively "tiny" elements around the rim and a lot of blank center, and so the coil and magnet sizes will definitely benefit from an increase.

Going smaller, it will get hard to fit the shaft, hub and optics without decreasing the size of the coil and magnet elements.

In fact, the production prototype was based on 10.25" instead of 10.5", and I had to turn down the trailer hub outer diameter a bit to get it past the insides of the coils freely, make some of the coils a bit smaller to fit them all on, and connect the coils around the outside instead of the inside (where the lead lengths would be shorter). Indeed, 10.75" or 11" would probably be an easier fitting choice if the rotors are available.

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**Section 3. Making the Stator Coils**

Nine coils are required per motor. The easiest way to get the coils is to buy them, but I was unable to find any suitable coils commercially available. Naturally, Turquoise Energy Limited plans to make them for sale. It's not difficult to wind good coils, but it is somewhat time consuming. It may be worthwhile to wind your own if you're on a budget, or if you wish to make your motor before our coils are in production.

The materials required for each coil are:

- about 275 grams/9.5 oz/12.5m of #14 magnet wire (pref. 150ºc+ insulation)
- about 310g/12.5 oz of 1.0" nail gun finishing nails strips
- two 1/4" x 2" or longer bolts with 1"+ smooth sides before threads (hex heads)
- Motor Varnish or Casting Epoxy that will withstand high temperatures (150ºc+)
- Hi temperature flat black enamel paint for heat transfer to the air (stove paint?).
- Small cable ties

Also required is a coil winder jig (see picture) and a jig/plate to put the cores in on.

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**Winding the Coils**

A coil winder on an axle with a two inch/50mm diameter spool, 7/8" wide, and a handle to turn it is fast, easy and does a neat job. Minimally, a cylinder of that size with side walls can wind coils for one motor by hand if care is taken to wind them neatly. If they're not neatly wound, they might not fit on the stator without touching each other, which could cause a short circuit.

Other options: A car spindle from an auto wrecker might work... even the one you buy for the motor shaft... if you figure out some way to mount it and attach the spool. Or, you could make the spool roughly as shown and mount its center rod in a chuck on a wood lathe or a drill press (turn by hand) - whatever it takes to be able to turn it smoothly while feeding the wire in continually.
Coil winding jig. The bearing spindle (left) can be had, eg, at a motor shop. The drill chuck with the same threads was a separate purchase. The spool is a piece of plastic (turned on a wood lathe with indents for the big washers) on a 3/8” threaded rod. A nut holds the inner end while the threaded handle holds the outer. Turning backwards winds the handle off, and the outer washers are removed to release the coil of wire. Later, the rear washer was faced by a 'washer' of metal cut to fit on the spool, which is pulled to push the coil off the winder from behind - that works better.

The coils shouldn't stick out above or below the nails, so the 7/8" width is chosen for 1" nails. Leaving around 30cm of lead wire, wind 60-63 turns of #14 magnet wire onto the spool. (Don't lose count.) I come to the end of the fifth layer at about 61-62 turns. I stop at 61 in order not to further increase the diameter of the spool. That would make the coils hard to fit on the rotor.

Readers of previous editions will note that I have changed this from 70 turns to 60. The number of turns was derived empirically, by making motors and measuring the currents. 70 turns was derived from high currents in an earlier prototype, which had 60. But I also increased the core size, and so there's more wire in each turn. Doing 70 turns was thus compensating twice, and I made a motor that would really run better at 42 volts than 36. With the increased core size, the length of 60 turns goes from about 9.5-10 meters of wire to 11.5-12, which was the desired increase. It's also better to not have to wind the additional layer of wire, so the nine coils fit in the desired 10" diameter (to the outside of the cores), instead of 10.5". The maximum phase currents I was reading of 80 amps with 70 turns should increase to 90 amps with 62 turns. That's 30 amps per coil, which is the maximum desirable amount for an air cooled coil of #14 wire according to a calculator I used on the web. It's all approximate, based on heat and how fast it is dissipated. The heat increases with the square of the current though, so it rises fairly rapidly above the maximum current density. If the currents are too high, the coils will overheat and burn out. 60 to 63 turns is in range - don't start a sixth layer of windings to get an extra turn or two.

#15 wire is too light for the motor currents. #13 wire probably won't fit unless the stator diameter is increased. (If you have trouble getting #14 wire, you can try two strands of #17, soldered together at each end. That gives the same cross section of wire. I’ll try it soon because I got a bunch of surplus wire with more #17 than #14. It's almost bound to be a bit bulkier, but I hope it will fit.)

Give the outer lead 1/2 turn wrap around the inner one so it doesn't unravel, cut it off the spool to length, then wrap the coil with a strip of packaging tape or "magic transparent" tape to help hold it together while you take it off the spool.

Slip a small nylon cable tie on so that both leads are held from unwrapping by it. Remove the tape and put on a second tie, to hold the shape of the coil until it's cast solid.

Wind all nine coils the same way. (Ie, don't reverse directions, start from the opposite side, or whatever.)
The nine wound coil wires in position on the 10" (actually 9-7/8") stator disk ("6129" rotor). Note that there isn’t a lot of free space between coils. If the coils take much extra space for any reason, it may be hard to fit them on. When I was doing 70 turns of wire (6 layers) instead of 60-63 (5 layers), I had to increase the motor diameter (at the outer edge of the coil cores) from 10" to 10.5".

I plan to make all the connections in the inside area rather than around the outside (shorter leads, neater), but leaving plenty of space at the center to get the axle flange in and out.

Finishing Nail Strip Coil Cores

If solid iron cores were used, the magnets spinning past would generate electricity into the iron. It would be one big short circuit, causing heat, drag and very low efficiency. Today's standard practice is to make the entire stator out of die-cut sheet iron pieces, varnished to insulate them from each other and laminated together. You can see these laminates in motors and transformers everywhere.

One might liken this to damming a stream with multiple dams, one after another. They stop the stream from flowing. Putting the laminates the wrong way is like putting dams parallel to the stream: the water will run between them and keep flowing.

The die cut laminate technique isn't very accessible at home, and it's not even the best way to do it. For us, wanting the strips all one inch tall, strips of one inch insulated nail gun finishing nails solve the problem. They can be spray painted or varnished for insulation and broken apart to any desired length.

The coils are put together on a piece of metal with two 7/32" holes, 1.5" apart and threaded for 1/4" bolts. The bolts reserve space for the coil mounting bolts that hold the coil onto the stator. A piece of aluminum foil or high temperature plastic is placed over the bottom sheet to keep the varnish or epoxy from sticking to the base metal. The protruding bolts fit in the holes in the scrap of yew wood so it can sit flat while working on it.
The iron alloy used in motor coils needs certain specific characteristics. One is that they shouldn't magnetize. Take a magnet (eg, one of the supermagnets) and rub it along the nails in one direction. If the nails become magnetized and will attract to other steel objects, they're not good. Try a different brand. The ones I've tried so far have all been good: they don't magnetize. Perhaps they're specifically made to be non-magnetizable for some obscure but fortuitous reason. (Easier to handle?)

Another good characteristic is if the nails don't conduct electricity very well along the strip. This should reduce any remaining stray eddy currents a bit. Instead of laminates, individual short iron wires minimize stray currents. Some brands are better than others. The main thing, though, is to insulate between the strips.

(BTW: Don't try sanding or grinding the heads and points off the nails: the filings get in and increase the electrical conductivity between nails within the strip. Breaking the strips apart or bending them too far reduces connectivity but weakens the strip. Generally it's best just to leave them alone.)

Paint (at least) one side of the nail strips with polyurethane insulating spray paint. This insulates the rows electrically from each other. I found this paint at an electric motor repair shop. (I don't see why automobile engine enamel wouldn't be fine... If it seems thin, insulate both sides.) Allow it to dry.

I'll made a "jig" with a stainless steel plate. (I was hoping motor varnish won't stick to stainless, but no such luck!) It has two holes 1.5" apart, threaded for 1/4" N.C. bolts.

Two bolts are threaded through until the smooth part of the shaft, 1-1/2 to 3 inches long, meets the plate. The protruding threaded ends were cut short.

The coil of wire is placed, centered, around the bolts. The leads should be directly between the two bolts, not near one of them.
strips parallel to the rotation. The copper coil wire will stick out beyond and inside the (~2") mounting face.

Then start filling in the coil center with rows of nails, heads alternately up and down, and the insulation paint separating each row electrically.

The rows go left to right, in line with the bolts (NOT inside to outside of the stator diameter - that's the direction eddy currents will flow).

Fill the core space, but stop without the core putting pressure on the copper wire, which might rub through the thin insulation on the wire and cause a short circuit.

This isn't really a precision operation. Efficiency isn't affected by a bit less iron, though maximum magnetism and power is. If the core is 90% full of nails, spending a lot of time filling tiny gaps and perfecting every detail can't help much more. The motor controllers are set up to accommodate a bit of slack. (You will save a bit of epoxy, and-or the coil may be a bit physically stronger - again presumably minor points.)

With the bolts almost at the wire at both ends, it's probably best not to fill in the few nails that would fit on the outside of the bolts - they're too likely to break loose, which might cause problems. (This was found out during prototyping. Epoxy held them better than varnish.)

Avoid having nails sticking out beyond the others top or bottom.

A coil ready to dip in motor varnish.
I used a piece of telephone hook-up wire to make a "handle".
There should be aluminum foil, or perhaps high temperature plastic, covering the metal plate.

Left: a coil (#15 wire, oops!)
Right: A finished prototype coil cast in epoxy. (A second coat of epoxy on top wouldn't hurt - much of it ran down and pooled at the bottom before it hardened.)

Epoxy Casting or Varnishing the Coils
Motor coils are subject to being vibrated back and forth not only by mechanical motion but by
magnetic forces. They must be immobilized or the thin insulation will soon be worn off somewhere and they'll burn out. Traditionally coils are dipped in motor varnish and baked in an oven for some hours at 240ºC/475ºF. With these coils, multiple dippings and bakings are advisable as they are simply "glued" together by the varnish.

Left: Soaking a coil in motor varnish while bubbles come out. Right: The coil raised above the can while excess drains off.

They need to be baked for about 40 minutes. After 20 only minutes, all the nails will slide out when you try to pick it up and it'll be a gooey mess. After an hour, they look a little crisp. The baking should be done OUTDOORS, eg, in a toaster-oven. The fumes are powerful and noxious. I'm sure the stench would last a long time in a house. (Try a second-hand shop for a toaster oven - plug it in and make sure it works.)

Casting them in high temperature epoxy is another good technique, which I used on the prototype. Good epoxy is probably easier to come by in small quantity than motor varnish, which is doubtless bought in five or forty-five gallon pails by typical motor repair shops. With some home-brew wind power generators the entire stator with the coils is cast as a solid donut of polyester resin. This would quickly overheat in this application.

Epoxied coil, epoxied core with no wire.

Finally, daub on some thick, flat black, high temperature enamel such as might be used for wood stoves or solar panels. Flat black radiates and transfers heat to the air best.

**Nanocrystalline Ceramic Coil Cores**
I feel it should be possible to make superior coil cores with very low 'iron losses' from ceramics. They would also simplify the coil making, eliminating the time spent inserting strips to make up the cores. I've been trying to do make them from various 'strategic' ceramic materials, but they have all given poor results so far.

Someone must know how these things are done, but if so the knowledge doesn't appear to have spread to the internet.

**Section 4. Assembling the Stator**

**Coil Bolt Holes & Template**

The nine coils are attached at 40º angle intervals around the rotor. The bolt holes are all in-line about 0.9 inches in from the outer edge, so at 9.6" diameter. Select one lug bolt hole as "north" and center one coil on it. The bolts are 1/4" diameter, so drill 1/4" holes. If the coils don't attach easily, drill one hole of each coil a little bigger, eg, 9/32" or 5/16". The distance between holes is the same as that used for the bolt spacing in the coils, 1.625".

Use 2" long bolts. If they fit, put flat washers under each coil. If there is still room, put lock washers on the 18 bolts. Take a coil and bolt it on with two bolts, leads facing the center. Do the other 8. Do the bolts up tightly, but not so as to crush the cores, which are only glued together with motor varnish. (Torque spec: 20 foot pounds?)

A picture of the "production prototype" stator with the coils clamped on is shown on page 17 ("Stator with clamped on coils.") I am not satisfied with the clamps. They have few threads and might strip, are metal and will pick up eddy currents, and they magnetize. These metal clamps are the second attempt. First, regular nuts were embedded into the coil cores. They proved inadequate in varnished coils -- one pair pulled right through and the coil jumped up against the magnets. (They might be okay for epoxy cast coils.) I'd like to try "hacked" (IIRC the name right) "collar nuts", holding down (eg) flat nylon clamp strips. I might use #10 - 24 bolts and collar nuts instead of 1/4", at least on the prototype. The #10 collar nuts shanks will fit in the 1/4" coil holes. To use 1/4" bolts and collar nuts on future units, the coil holes would be increased to 5/16".

Only the wide gap between rotor magnets and stator coils (1/4"?), gives the clearance and leeway to permit clamps on top of the coils, and bolts that stick through just a bit!

TE plans to make and sell solid stator hole templates, and to put PDF ones on line. And a good coil clamping system... once one is figured out!

**Wiring up the coils**

It is preferable to face the leads inwards and do the wiring in the center if your hub leaves enough room. This both keeps lead lengths shorter and leaves more empty space for cooling airflow around the outside.

The coils of each phase are wired in parallel and the phases are "Y" connected, therefore one side of all nine coils is connected together. On the other side, the three coils of each phase, 120º apart from each other, are connected together and to a heavy lead (#6 if it fits, else #8) that will connect to the cable from the motor controller.

There are a number of ways to bare the end of the wire for connection. The insulation can simply be sanded off, but that's usually pretty tedious. One popular wind plant maker prefers to burn it off the ends of the coil wires with a propane torch and then clean them off with sandpaper. That works well. I prefer to scrape it off with a small sharp knife (eg: pen knife, paring knife, not exacto knife), and clean it up with sandpaper. (Somewhat more tedious, but I've never burned myself yet!)

Make a ring of about #10 wire to attach the "center point" coils ends to. This should be soldered to all the wire ends going clockwise into the coils (or the opposite, as long as they're all the same). I strip some insulation off the end, then I cut the insulation the spacing for of each coil and slide it down until there are nine bare spots the right distance apart. Wrap with electrical tape - the awkward shape leaves few options but tape unless you can manage to slip some sleeving on to cover each join.

A piece of small diameter soft copper pipe (eg 3/16" I.D., used for oil or propane tank connections) is
about right to stuff in three coil wires in one side and the heavy lead (#8) in the other. These are then crimped and insulated. (pieces of large diameter insulation or sleeving, electrical tape. Forget heat shrink as the wires may get quite warm - heat shrink isn't generally used in motors.)

Crimping the leads: The three coils on one side, the lead on the other, using a piece of copper propane pipe as a large crimp connector. (Two wires are the #14 coil leads; the third is a #10 wire - the coil’s lead was too short.) A piece of sleeving is then slipped over the bare copper

On the ends of the heavy leads, use Anderson Power Products 75 amp Power Pole connectors. These are the only physically compact suitable plugs I've found. You can buy single connector units and stack three, or get a three position plug and socket. The plugs and sockets of the single units are identical - you just turn one over and they mate. There are different colored plastic bodies to identify the three phase wires. I found the Power Pole connectors at an electronics store, not at any electrical supply. Marette connectors ("wire nuts") can of course be used, but leave the possibility of bare wire ends shorting and perhaps blowing the motor controller during installation or later maintenance.

**Optics Circuit Board & Cable**

The optics board is a somewhat custom mounting job. It needs to be able to shift around the axle until the correct timing angle is found, preferably while the motor is running. (I thought I had that angle worked out, but the timing is obviously not close enough to "right" on the production prototype as I write this preliminary manual. Perhaps some other "correct" angle will be found, the same in all EH motors, then stationary mounting can be considered.)

Optics board wired on PWB: 3 pairs of LEDs/Phototransistors around the axle at 40º spacings. The five connections are made via the five wire trailer plug: 1-Ground, 2-LED current supply, 3, 4, 5, - FotoA, B, C phototransistor outputs. The three LEDs are in series and their supply resistor is on the motor controller board.

The board as shown above is on the original fixed mounting, but the timing is not optimum. A silver
"ligature" clamp around the hub for a rotatable optics board mounting (just made, from a flattened piece of #6 nickel-brass wire/rod) is also visible. I then silver soldered a long, flat handle and #4 mounting nuts to it. I put machine screws into the nuts and added electronics supply standoffs to get the right height. I drilled new mounting holes in the board and clamped it onto the top ends of the bolts with nuts.

If the hub is a continuous taper and no metal lathe is available (I confess to turning this indent on a lathe), holes for about three machine screws, to be screwed in above the clamp to prevent it from sliding towards the rotor, can be drilled and threaded.

The board mounted on the ring. A thin temporary handle that I hope won't hit the magnets sticks out beyond the rim to where it can be adjusted while the motor is running for best performance. Naturally, the complete, wired optics board with mountings, and the slotted cylinder it works with, is a component Turquoise Energy hopes to offer to builders.

Section 5. Assembling the Magnet Rotor

OLD WAY (PRE HALL SENSORS, PRE TORQUE CONVERTER)

Shallow Hub Magnet Rotor. 11" rotor ("Gran Torino") with supermagnets at 10.5", leaving 1/4" outer lip. Black is north, yellow south. An ABS slotted optics interrupter cylinder is mounted on the axle plate.

Also note: 5 hole hub was drilled to fit 4 lug car; "skip tooth" magnet pattern; and that the (trailer) axle is screwed to the rotor for magnet safety.
Supermagnets

The neodymium, iron and boron supermagnets (Nd:Fe:B or NIB magnets) are very powerful. It is easy to get nonchalant, but one or two magnets can do serious injury. Never get your finger between two of them! A rotor with a dozen could be deadly. If two magnets get stuck together, there is a special jig to get them apart safely. One of the reasons I chose the 1/2" x 1" x 2" magnet size for hand-made motors is that I would want a machine to handle supermagnets any bigger than that. Also they're the most common and cheapest large size to buy... perhaps for the same reason.

When the rotor is assembled, put on gloves and place a couple of layers of thin (flexible) sheet steel over the magnets as a safety measure, and put it in a box with some styrofoam over it as well.

Two 1" thick foam safety cutouts. The pieces of sheet metal magnetically clamp it to the magnets. The second one has a large center cutout to permit bolting it to the car wheel without removing it. Once one bolt is well started, the guard may be removed if desired, but less bolts and socket drives end up stuck to the magnets if it's left on.

That this seemingly innocuous rotor is a very dangerous piece of equipment can hardly be overstressed. The magnet rotor may be thought of as something of the nature of a loaded rat trap (or maybe a leg-hold trap for larger animals!): Working with it is a case when simply moving slowly and deliberately won't protect you from sudden and perhaps very serious violence from a single misstep.

Holes in the Rotor

All holes in the rotor should be drilled to fit and checked for fit before putting the magnets on the rotor:
* Lug bolt holes, if the ones on the rotor aren't right for the car wheel.
* Holes to hold the axle to the rotor.
* Any holes required in the rotor for mounting the slotted "optical commutator" ring.
* Hole for the magnet bolts if using screw-on magnets.

For safety, it is recommended that the motor axle be bolted (or welded?) to the magnet rotor separately from the lug bolts used to hold them on the car wheel, and then kept on the rotor. The presence of the protruding axle will reduce (not eliminate) the chance of having all the magnets clamp flat onto a large flat magnetic object with potentially deadly force. A specific place the protruding trailer axle won't help is one attempts to install the stator with the center hub missing. DON'T GO THERE! (Always remember to hold the stator only by its arms when putting it on, then you'll only have a mechanical disaster instead of a crippling or deadly one.)
Magnet Bolt Holes

Supermagnets can be ordered as simple glue-ons or with two holes for flat head screws to also bolt them onto the rotor. The ones I got with bolt holes would fit #10 machine screws, but I used #8, and I needed the bit of play that allowed for inexact hole positions. I drilled and tapped the rotor for that size. Again, a template would have been helpful and I expect TE will be making them.

In principle I prefer the bolt-ons, but I did the car motor rotors just with "epoxy steel" glue. It's after 10 or 20 years that the glue is likely to give way, as I found out on a used electric lawn mower.

Magnet Placement, handling the magnets, magnet placing jig

Up to six magnets can be placed without too much danger, but as more are added between, things get very scary without a safety and placement guide. Here is the latest magnet placement template, top and bottom views:

![Magnet placement template, top and underside views. (The pacific dogwood (oiled) was just too beautiful to put ugly screws into from the top!)](image)

It's set up for the 10.5" diameter rotor size with 18 magnet positions. But I actually only put on 12 magnets, skipping the middle one of each polarity. The template fits over the magnets already on the rotor (if they are correctly placed), while helping to guide the current magnet into place in spite of very strong forces trying to flip it and pull or push it aside, and protecting the worker from getting his fingers crushed between two magnets.

The black mark at the entrance to the slot is some of the "epoxy steel" glue. As you can imagine, it's impossible at some point in the insertion to keep the magnet from snapping down onto the rotor.

(*Somewhere*, I had pictures of actually putting the magnets on the rotor with this jig. Now I can't find them!)

"Epoxy Steel" epoxy glue

This is great glue for the magnets! I got it at Rona hardware.

Optics Interrupter "Can" (Optical sensor system)

This little rotor tidbit is the base of the control system. Its slots and solids spinning by three LED/phototransistor pairs indicate the magnet positions to dictate the phasings of the motor controller's drive signals.

In the prototype shown, a 2" ABS plumbing pipe end cap had most of its end removed to fit around the axle, and the "south magnet" slots were cut out with a hacksaw. It was then bolted onto the axle plate with machine screws.

Operation of the optics system is described in the theory chapter.
When I mounted the board on the new adjustable ring, I sanded the end, the "solids", a little shorter so they wouldn't hit the mounting nuts or the wires on the slightly raised board. One little piece was glued back on (methylene chloride or plumber's ABS solvent cement) where a slot was cut a bit too wide. Adjustments are simple with ABS!

The "slotted tuna tin" shape is preferred over a flat slotted rotor because the stator and rotor can be pulled apart freely without the phototransistors hitting anything, and because only a flat circuit board with normally mounted parts is required.

## Section 6. Mounting the Motor

(I plan to write another whole manual about electrifying a car with the Electric Hubcap system. This section, which obviously needs a major update, will stay with the motor making instructions until that's done.)

### Brake Drum Housing Attachments

The mounting arms attach to the back of the brake drum housing behind the wheel. At its center, the stator is firmly attached to the wheel by its axle, but the arms are needed to prevent the stator from turning. They absorb the rotational torque of the motor's thrust and braking. The brake drum housing is strong enough to handle this force. Consider: the brake cylinder mounts on it and it must be able to absorb the torque of screeching tires. There are two pairs of arms, upper and lower. The trickiest and most "customized" part of the whole installation is securely mounting and placing these arms so they are out of the way of all moving parts as the suspension rides up and down from the top of its travel to the bottom.

First, the tire wall generally sticks inwards past the housing, so I bolted two thick steel plates to the brake drum housing to extend it beyond the tires. Alternatively, the stand-off blocks could be welded to the rectangular tubing, or the tubing could be bent to fit. (I had to cut the rear block and do some bending of the lower arm anyway, to get it past the shock absorber.)
For mounting, the brakes must be disassembled and holes drilled through the housing. Care must be taken to ensure the heads of the bolts are clear of the brake shoes and mechanism, and don't interfere with operation of the brakes in any way.

(In fact, the front mounting block here pushed on the parking brake cable and the right side parking brake didn't work well, if at all.)

1" x 2" tubing wouldn't have fit in. I wanted 0.5" x 1.5" tubing, but local stores only had the 0.5" x 1". I used that. It probably flexes a bit more than is desirable.

To bend the elbows, first I mashed in the flat center section with a hammer along the area to be bent, from both sides. Then I C-clamped them to something roundish. I can't remember what it was, except that it had a straight section and I used two big C-clamps, clamping the short arm end, which left the longer center portion to push on.

I did it out at my "anvil": a flat solid rock sticking out of the ground in the garden, with a 24 oz hammer. It was tough going with nothing to really hold that short end, and I'm sure a very big vice would have been most handy, or a really skukum work table that would have held those C-clamps solid while I pounded.

**Fitting and vehicle suspension considerations**

*(up-down travel of wheels with weight, bumps and potholes)*

The bracket should be tested to make sure it doesn't hit the car at any point in the travel of the suspension.

Jacking up the car on the body near the wheel will cause the wheel to drop down relative to the car until the suspension "tops out". But that usually moves the bracket into more open space. It's the other direction where things usually get tight.

To push the car down one must add weight, and perhaps "jump" up and down on the bumper. It should be ascertained that even when the suspension "bottoms out" the brackets don't hit anything.

**Around-the-wheel Arms**

Once the arms have been attached, they must be fine-adjusted - again bent - to meet up with the stator arms for easy attachment. The best way to do this is with a piece of rectangular steel that fits inside the tubing, eg a 1/2" x 3/4" x 3' long steel rod. Stick it in the end and move it around until the arm ends where you want it.

**Stator Arms - Strapping**

The stator is held on by strapping, eg, 1/8" x 3/4" mild steel bars. These wrap around the outer end of the motor stator and the ends insert into the wheel bracket arms coming around the wheels. They are held by bolts. I drilled 1/4" holes in the arms, and matching 7/32" holes in the strapping, threading them for 1/4" bolts. The bolts go through the outer hole, thread into the strapping, and come out the other hole. Then a nylock nut goes over the end.

End of stator strap to connect it to the wheel bracket. [fix: Needs image]

**Nyloc Nuts & avoiding things that fall off while driving**

Just a final safety reminder that the motor should be solid. "Nyloc" nuts can be valuable for keeping bolts from falling out even if they come loose. So can lock washers and "loc-tite".

Check everything carefully before enclosing it, and before taking the car on the road. Listen for anything unusual as you start to drive and for the first while.

Check again after 1, 5, 25, 100 and 500 Km.

The one-piece coil casting on my first prototype fell partway off after some tens of kilometers, when some of the bolts came loose. (The design was quite different from later versions.) Amazingly, it did it in a parking lot. I stopped at once and removed it. No harm was done. Potentially, it could have been on a busy highway with nowhere to pull over. It would probably have broken right off and been a serious hazard for cars behind!

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**How Long Does it Take to Build?**
I can hardly undertake to divine how long it will take to go to stores and get on line to order all the needed pieces, nor how long it will take to put together a coil winder or a magnet alignment tool.

However, it might well be useful to know how long actual construction operations are likely to take, and I can offer the following:

Winding coils. Winding nine coils took me about an hour and a half, including staring over a couple of times after losing count or a coil seeming to get "messy". I've wound coils before. Someone doing it for the first time might be expected to take perhaps three hours.

I hope to add the time expectations of more operations as I make another motor and keep track of the time it takes.

Putting in the coil cores:
Varnishing the coils:
Drilling the stator holes:
Making coil clamps:
Mounting the coils on the stator:
Wiring the coils & power plug:

Glueing the magnets to the rotor face:

Making the

**Electric Hubcap Specs.**

*approximate nominal specs*

**Volts:** 36 (battery voltage)
**Amps:** around 127 (~90 amps max in each phase * sqrt of 2 = 132)
**Watts (in):** around 4570
**HP (out):** around 5.2
  - Note: HP at estimated 85% efficiency. Efficiency should be higher when operating below max. power.
**RPM:** 0 - 2000

Cooling: Fan (magnet 'fins') - moving air & convection; exposed coil surfaces.
  - Air is drawn in at central vent holes near axle, is blown outwards across the coils by the magnets - "cooling fins" - and is expelled through air gap at stator rim.
  - Note: permanent magnet rotors don't get warm. Only the stator needs cooling.

Overall diameter (with 12" I.D. "culvert pipe" PVC plastic cover): 13"
Rotor & Stator nominal Outer Diameter: 10" (The outer sides of the coil wires protrude beyond 10".)
Overall Motor Length: Varies by spindle & rotors chosen.
Practical minimum length: $8 + 13 + 8 + 25 + 8 = 62$mm or 2-1/2" (Magnet rotor thickness + magnet width + air gap + coil width + stator "rotor" plate thickness) -- excluding protruding nuts and bolts
  - Note: this excludes the thickness of the torque converter.

**Coil Size:** 1" thick circular disc, 2.65" outer diameter
**Coil Wires:** 60-63 turns of #14 AWG magnet wire wound on 2" diameter cylindrical former, about .95" across.
**Coil Cores:** Strips of 1" long nail gun finishing nails, spray painted (insulated) on one side and broken to length to create laminated cylinder, 1" tall x 2" diameter. Two voids are left for 1/4" diameter mounting bolts.
**Coil Iron:** The nails should not become magnetized when rubbed with a supermagnet. (ie, they should not be able to pick up other metal objects.)
**Inductance:** I measured 0.60 mH on a single coil, and 0.60 mH across any two phases of the assembled motor stator. (Neither figure is a misprint.)
"Glue": Finished coils are cast in high temperature epoxy or dipped in motor varnish and baked.
Stator: nine coils around rim facing magnet rotor magnets, spaced 40º apart. Three phases. Each set of three coils 120º apart is wired in parallel. Motor is wired in “Y” configuration, so one side of each coil (eg the CCW lead in) goes to the center point while the other ends (eg the CW ends) tie to the three supply wires, #8 or #6 AWG.

Gap, stator coils to rotor magnets: 3/8" to 1/2" (10-12mm) nominal. (There is an optimum somewhere around here... a gap that is too small makes excessive vibration and WORSE motor performance instead of better.)

Rotor Magnets: twelve - 2" x 1" x 0.5" Nd-Fe-B (“NIB”) or other supermagnets, nominal strength 35 - 45. They should be magnetized through the thickness; ie, the large (2" x 1") faces should be the poles. (Other sizes to make a similar magnetic field would also work fine.) Note that these magnets double as the cooling fan fins.

Bare Motor Weight: 31-33 pounds
(with 6129r disks, two machined & welded-on 1-1/2" pipe coupling bearing hubs, no mountings or covers, ready to fit torque converter onto.)

Electric Hubcap is a trademark of Turquoise Energy Limited.