The tzero Electric Sports Car – How Electric Vehicles Can Achieve Both High Performance and High Efficiency

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May 2000
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Abstract

In 1996, AC Propulsion began development of a high-performance electric sports car, the tzero. Now, tzero prototypes are undergoing in-use testing and safety certification development. In actual tests, the tzero accelerates from 0 to 60 mph in only 4.1 seconds, yet it is one of the most energy-efficient cars on the road. The rationale for the tzero is that a car with its unique technology and superior performance can be sold at a price high enough to cover the high costs of small-volume production. Once in production, the tzero may be the first electric vehicle to be sold at a profit. The expected market size for the tzero is small – less than 1000 units per year – but its technology and image are intended to build a larger market for other electric vehicles. This paper will provide a brief history of the development of the tzero, a status report on the progress in developing the production-certified version, and a comprehensive technical description of the car and its systems.

tzero Background

The tzero (shown in Figure 1) is a purpose-built electric sports car with world-class acceleration and handling performance. It was originally conceived by AC Propulsion in 1996 as a pathway to bringing a small-volume electric vehicle to market with a business case that could support the higher costs of small volume production.

Figure 1. The tzero electric sports car

Rationale for tzero

As a small company, AC Propulsion cannot subsidize the price of an electric vehicle offering the way the major automakers have. The company had previously made a few EV conversion vehicles (Hondas and Saturns) for auto manufacturers for evaluation purposes. No real market beyond these few vehicles was apparent, since the high costs of low volume conversion -- about $80,000 – priced such a vehicle outside of the range of any consumer interest. Even though these vehicles had better acceleration and driving feel than their gasoline-powered base cars, there was just no market for such a vehicle at a price that would cover the conversion costs.

The concept for the tzero was that a simple purpose-built EV that exhibited performance and driving feel superior to most, if not all, gasoline powered cars could be priced at a level consistent with the costs of low-volume production.

The tzero prototype

The first tzero was adapted from a kit car known as the Sportech, built by Dave Piontek. The Sportech was originally built around a highly tuned motorcycle engine with sequential shifting transmission. Its light weight and small size made it a good candidate for electric conversion. AC Propulsion acquired a Sportech, and the rights to the vehicle for EV applications in 1996. In making the first tzero, changes to the Sportech were few – mainly to accommodate the electric drivetrain. That first tzero, shown in Figure 2, was introduced at the Los Angeles Auto Show in January 1997. Performance was very good, with 0 to 60 mph in 4.9 seconds, with 100 miles range.

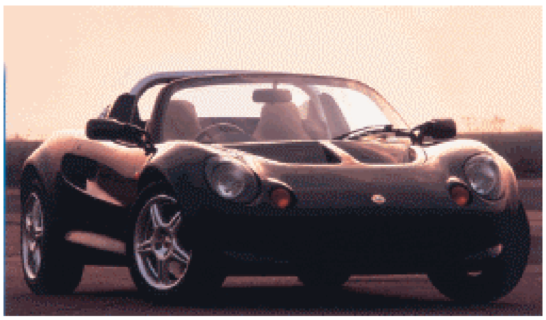
Figure 2. The prototype tzero based on the Piontek Sportech

Emergence of the Eco-Sports Car Market Category

The tzero is one of a new category of vehicle – the eco-sports-car. With electric drive, the eco-sports-car can offer better acceleration and pedal response than most premium IC powered sports cars – at speeds that are common and legal in the US. Figure 3 shows several other recent vehicles in this category. The tzero is the only one of these known to be driven on the roads on a daily basis and to be intended for production.

Suzuki EV Sport

Pinninfarina Ethos 2



Zytek Lotus Elise

Zero Sports EV (Subaru)

Figure 3. Examples of other recent eco-sports-cars

Powertrain

The tzero achieves superior acceleration performance and good range with low-cost lead acid batteries. Key attributes that enable this level of performance are a high battery mass fraction of 50%, powerful and lightweight electric drive components, and battery management that includes active thermal management (including battery heating), and pack balancing with module-level charging.

Motor

The tzero is powered by AC Propulsion's high-performance induction motor. For the tzero application it is operated at 37% higher peak current than allowed in our standard system. This is practical since the tzero is relatively light, and periods of peak power are limited to only a few seconds. Motor specifications are given in Table 1 and a photograph of the motor without the cooling shroud is shown in Figure 4. The motor is forced-air-cooled via fine-pitch fins located around the outer diameter of the motor housing. The cooling blower is run at variable speed depending on the temperature of the motor. In normal driving, the blower runs very little and the associated energy consumption is inconsequential.

The motor stator is constructed in a conventional 3-phase 4-pole configuration with 14-mil laminations. The rotor also has 14-mil laminations and is constructed with copper shorting bars and end rings. A Beryllium Copper ring is added for structural support on each end ring. The copper-based rotor increases both the efficiency and peak power capability of the motor.

AC Propulsion developed and patented the design and assembly process for this rotor.

Peak output power of the motor as installed in the tzero is about 150 kW (200 HP). Droop of the battery voltage under high current drain prevents achieving the full 177 kW output seen on the dynamometer. The peak torque is available in the vehicle; the battery droop only affects the motor speed to which peak torque is maintained.

Table 1. Motor Specifications.

Motor type	AC Induction w/copper rotor bars, 4 poles
Peak torque	246 n-m (181 ft-lb.)
Peak power (at 326V DC input)	177 kW (237 HP)
Base speed at 330V	5,000 rpm
Maximum speed	12,000 rpm
Peak current	687 A rms
Mass, include plenum and blower	50 kg (110 lb.)
Dimensions (less fins, termination, plenum)	213 mm dia by 257 mm long (8.4 in dia by 10.1 in long)
Dimensions of motor incl cooling plenum	305 mm dia by 305 mm long (12 in dia by 12 in long)
Maximum winding temperature	180 deg C (356 deg F)

Figure 4. tzero's 177 kW (237 HP) induction motor.

Gear Reduction Unit and Drive Shafts

Drive power is delivered to the rear wheels through a single speed gearbox with a 9:1 reduction ratio. The gearbox is based the Honda Civic manual transmission, with all the first-stage gears removed and replaced with a new gear set sized for the increased torque (Figure 5). The final drive gear and differential are stock Honda parts. The gearbox input shaft is connected to the motor through an electrically isolated coupling. (Electrical isolation of the motor is a requirement for the integrated charging system.)

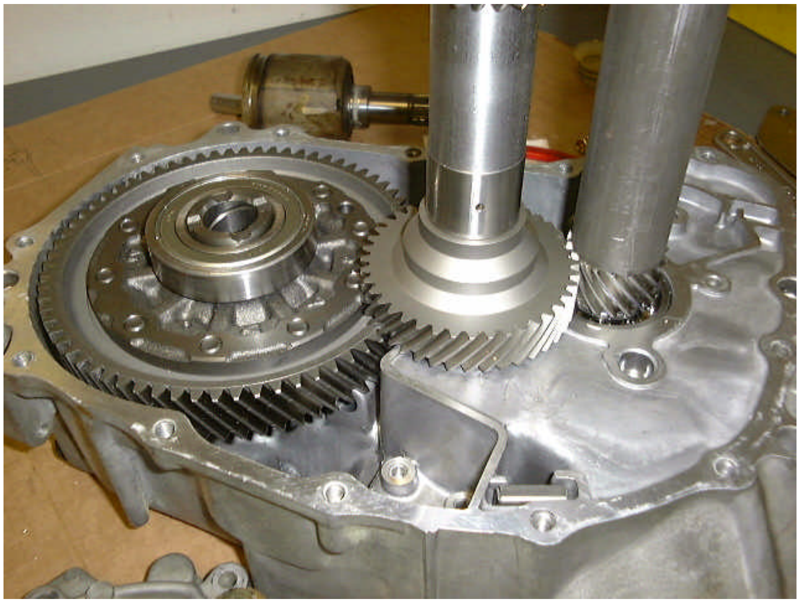


Figure 5.   Gears installed in transmission. Small and medium gears are new. Differential at left is stock.

Power Electronics Unit

The power electronics unit (PEU) contains the traction inverter, charger components, and 12V auxiliary power supply in one enclosure. The system is air cooled with a speed-controlled squirrel-cage blower. Cooling air is forced past fine-pitch cooling fins on the bottom of heat sink plates. Outside air does not flow through the electronics. Air inside the electronics enclosure is circulated internally with a small fan. An air-to-air heat exchanger removes heat from this closed volume. The specifications of the PEU are given in Table 2.

Traction Inverter

The traction inverter power stage is based on three bipolar IGBT-based ‘smart poles’ switches. Unlike most other traction inverters, the switches are made up of paralleled discrete IGBTs in TO220 packages. This approach allows the heat load to be spread over a larger area, making air cooling possible.   Additionally, the cost per kVA for discrete IGBTs is currently about half that for packaged IGBT modules.

Control of the phase current is through discrete analog circuits, with a lookup table for optimum slip speed. Patented techniques are employed for high speed stability and for maximizing the motor output in the voltage-limited (high speed) portion of the operating region. A map of efficiency over most of the speed and power range is shown in Figure 6.

Table 2. PEU Specifications (Generation 2)

Voltage	336V nominal 240 min, 450 max
Motor Current	687 A rms max tzero only 500 A rms (other applications)
Max input power	206 kW (tzero only)
Dimensions	760 mm x 313 mm by 186 mm 29.9 in x 12.3 in x 7.3 in
Weight	30 kg (includes cooling blower)
Charger	20 kW max
Auxiliary supply	100 A at 13.5 V

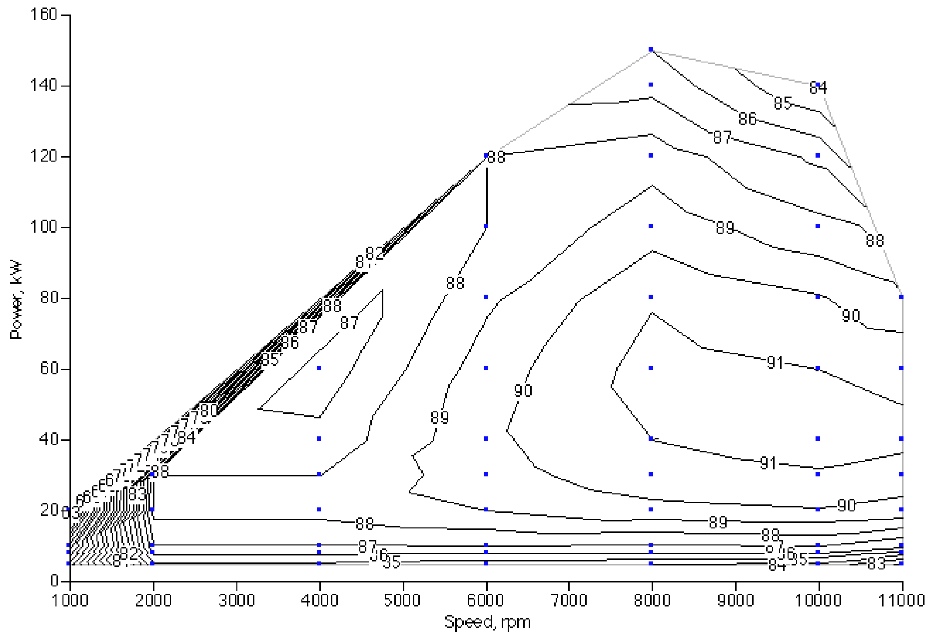


Figure 6. Efficiency map (combined motor and traction inverter). Standard AC150 drivetrain. With the tzero fixed-ratio gearing, 8000 rpm corresponds to 60 mph.

Charger

The tzero's Reductive™[1] charger uses the motor and power switches from the drive system to serve as the power elements of the charger. The Reductive charger is conductively coupled to the power grid, and operates with standard J1772 conductive wall boxes and can be directly plugged in to 110- to 240-V outlets. Since the Reductive charger is based on a powerful drive system, it can charge at higher power levels than standard chargers. The Reductive charger in the tzero can charge at up to 20 kW compared to 4-7 kW for conventional chargers and, with minor modifications, can be configured to charge at 40 kW.

[1] Reductive is a trademark of AC Propulsion.

In the tzero, a 60% charge can be completed in as little as 30 minutes. An inherent feature of reductive charging is nearly silent operation when running at less than 10 kW, since the cooling blowers need only to run at a very low speed.

There are significant cost savings with integrated charging. The cost of the additional components needed to allow the drive system to function as a 20 kW charger is only $300. Conventional EV chargers cost $2000 or more, and high-power EV chargers cost $10,000 and up. The charger will operate on 50 or 60 Hz power at any voltage between 110 and 240V. The architecture of the system is shown in Figure 7.

Integrated charging inherently allows for power flow from the vehicle to the power grid. This reverse power flow capability has been implemented in AC Propulsion's new second generation drive system. It operates in two modes: grid-connected or stand-alone. In a vehicle like the tzero, this capability is useful in several areas:

- Battery diagnostics. Automated capacity checks or conditioning can be run overnight by discharging the battery into the power grid then recharging it. Since most EV drivers rarely use the full range capability of their vehicles, this is very useful for tracking the capacity and health of the battery pack.

- Backup power. With the addition of a transformer and utility disconnect switch, such a system can function as a residential scale uninteruptible power supply (UPS). The 20 kW rating is adequate for virtually all houses.

- Mobile power. In the stand-alone mode, the charger can supply up to 10 kW of 120V power, or 17 kW of 208V single phase power. The system installed in the prototype tzero has provided power to run air compressors and a MIG welder.

- EV to EV energy transfer. The system allows an EV equipped with this system to transfer charge to another EV if it is equipped with an onboard charger. This feature could be used to 'rescue' an EV driver that has run out of charge. If the vehicle being rescued has the same type of charge system, the transfer can be accomplished at up to 16 kW at 208V.

Auxiliary Power Supply and 12V Battery

The PEU houses a 100A auxiliary power supply to provide power to for the vehicle's electrical loads. A small 12V 7-Ah battery is also incorporated to provide peaking for short loads above 100 Amps and to provide unswitched accessory power when the vehicle is turned off.

Recharge Interface

The tzero is fitted with the standard SAE J1772 conductive charging inlet from Avcon/Meltric. In order to enable high-power charging, a means has been developed which enables the high-current pins of the AVCON receptacle to be used for transferring high-current AC. Previously, these pins had been earmarked for high-current off-board DC charging. The new approach, called Level 2+, allows these same pins to be safely used for both DC and AC power transfer. The new standard is backward and forward compatible – level 2 vehicles are compatible with level 2+ interface boxes, and level 2+ vehicles are compatible with existing level 2 wall boxes. The system has been presented to the SAE charging standards committee, and may be adopted by the end of 2000. A block diagram of the Level 2+ system is shown in Figure 8.

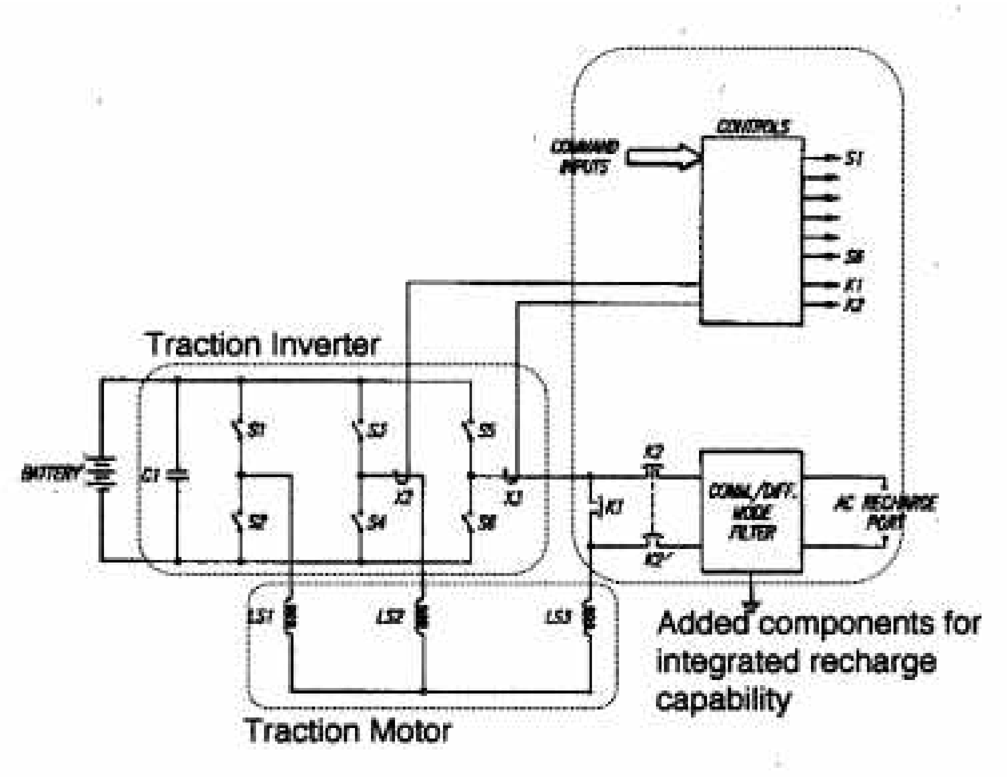


Figure 7. Architecture of the integrated charging system.

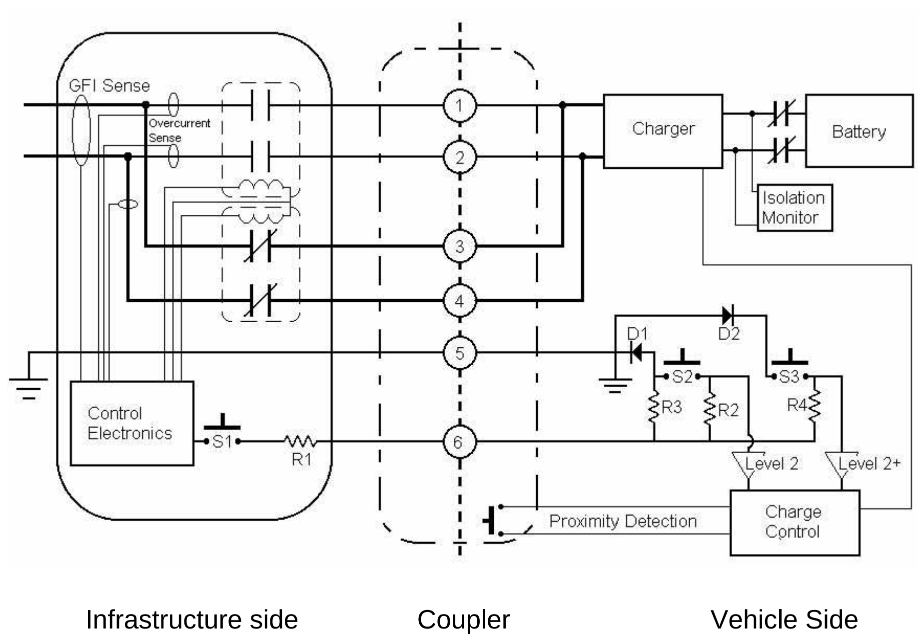


Figure 8. Block diagram of proposed Level 2+ charge standard, which allows high-current AC power transfer to the vehicle with a simple wall box

Battery Pack

The battery pack consists of 28 series-connected 12V lead acid batteries. Two rows of 6 batteries are packaged along each side of the vehicle between the front and rear wheels (Figure 9), and the remaining 4 batteries are packaged just ahead of the motor. There are no separate or removable battery 'packs'. For packaging volume efficiency and light weight, each battery is mounted individually to the vehicle chassis. The side mounted batteries are supported on light-weight sheet-steel mounts welded to the frame, and secured with tension rods and aluminum right angle brackets. The rear batteries mounted to the chassis bottom with shaped delrin blocks and tension rods. Battery interconnects are custom-made with braided copper. The battery pack fuse is in the electrical center of the pack. A manual disconnect or contactor is not needed or provided. The battery pack is electrically isolated from the chassis. Charging is inhibited if battery to chassis impedance drops below 2 MOhms.

Figure 9. Battery packaging in side pods. The duct on the left is for battery pack cooling air.

Battery Modules

The battery modules are a deep-cycle spiral-wound recombinant lead acid type made by Optima Batteries. The module is commonly known as the "yellow-top". When new, these batteries deliver 44 Ah on typical driving cycles. In the tzero application, these batteries deliver up to 600A discharge current for brief periods. Variants of these batteries are also marketed as premium automotive starting, lighting, and ignition (SLI) batteries. A deep cycle yellow top battery that has reached the end of its service life as an EV battery will still function quite satisfactorily as an SLI battery. AC Propulsion has implemented a very successful secondary market for spent yellow top batteries. They are sold for SLI application at $25 each – about 25% of the original cost – with a two-year warranty. Several of these are still going strong after 5 years of SLI service.

Battery Management System

The tzero is fitted with AC Propulsion's BatOpt battery management system. This system consists of a BatOpt module mounted to each battery (Figure 10) and a central controller called the BatOpt computer. The BatOpt modules are interconnected on a 4-wire bus; two wires for digital communications, and two for connection to the full voltage of the battery pack. The functions of the BatOpt module are:

- Voltage measurement - The voltage is sensed across the battery terminals and communicated to the control computer.

- Temperature measurement - A thermistor senses the temperature on the side of the battery.. The measured valued is communicated to the control computer

- Balancing and weak module support - Each BatOpt module contains a 5-A switching power supply powered by the full pack voltage. This supply can be switched on and off by the BatOpt computer for purposes of balancing the pack or bringing up a weak module. This function is available while driving as well as while charging.

- Battery Heating - The BatOpt module can control a 3-A heater load to enable each battery to be individually heated to the optimum temperature. The heaters are individually controlled by the BatOpt computer. In the tzero, the battery temperature is usually set to 40 deg C (104 F). There is a thin-film heater blanket installed in each of the two central cavities in the battery. The heaters are powered with 12V directly from the battery being heated. In order to preclude charge imbalance due to varying levels of heating in different modules, the 5A power supply in each BatOpt unit is cycled on and off to provide an average of 3A, such that the heating energy for individual modules is effectively shared uniformly across the whole pack.

Figure 10. Optima 'yellow-top' battery with BatOpt unit mounted.

Pack Cooling

The pack is cooled with ambient air ducted in from a variable-speed squirrel cage blower in the nose section of the car. A close-fitting cover is fitted over the side-mounted batteries to assist in directing air flow over them. The space between this cover and the body side pod forms part of the air ducting that delivers air to the pack. The air enters the pack at the center of each side battery pack. The flow path splits, with some air moving forward and out at the front wheel well and some moving rearward. The rearward-moving air passes over the rear side batteries and the 4 batteries in front of the motor before exiting through the rear wheel wells.

Powertrain Control

Control of torque delivery of the powertrain is primarily through the accelerator pedal, subject to several limit conditions for parameters such as motor temperature, PEU temperature, upper and lower battery voltages, and to limit wheel slip.

Traction Control

With rear-wheel drive, high power, and short wheelbase, the tzero could be expected to be prone to wheel spin and/or loss of traction of the drive wheels, resulting in a vehicle spin. To reduce this possibility, the drive system incorporates a traction control system that prevents the drive wheels from spinning or slipping under acceleration or regenerative braking. The system operates in all quadrants: forward and reverse direction, and acceleration torque and regeneration torque. The system works by limiting the slip of the rear (driven) wheels with respect to the front (un-driven) wheels. The speed of each front wheel is sensed, and the average of these is used in the traction control system. The system allows for different slip limits in motoring and regeneration. The slip fraction has been empirically determined to provide optimum motoring traction and safe regeneration. The motoring slip limits are set higher than the regeneration limits. This approach allows the traction control to be set up such that there is enough wheel slip to achieve maximum acceleration , but with slightly diminished directional stability. Drivers are generally familiar with the potential for loss of traction while accelerating and its effects on vehicle stability. The natural instinct is to back off on the accelerator if the car starts to get ‘sideways’. Because there is not a comparable driver instinct for potential loss of traction while slowing with strong regenerative braking, regeneration traction is set up with more margin - there should be no possibility for regeneration to upset the stability of the vehicle.

The overall effectiveness of the traction control system was demonstrated recently in a staged drag race in the rain against an all-wheel-drive Porsche Carrera 4. The tzero handily out-accelerated the Porsche without a hint of wheel spin, and at the end of the run, transitioned to full regenerative braking at 90 mph on the rain-slick runway without any loss of traction or directional instability.

Regenerative Braking

Strong regenerative braking is provided and is crucial to the high overall energy efficiency of the tzero. Driver control of the level of regeneration is through the first quarter of the accelerator pedal travel, with a slider control on the instrument panel to set the maximum regeneration level when the pedal is all the way up. The feel is like that of engine braking, but with a continuously-variable gear ratio to set the level. No regeneration is mixed in with the service brakes. In this way, the driver always knows which type of braking is being used, and quickly adopts a driving style that almost completely eliminates the use of friction brakes. At its maximum level, the regenerative braking will slow the tzero at about 0.3 G, adequate for virtually all normal driving. The ‘zero torque’ point of the accelerator pedal travel varies with vehicle speed, such that at zero speed there is no regeneration commanded, and hence no ‘dead zone’ in the pedal travel when starting up from rest.

Under very hard cornering, any significant levels of motoring or regenerative braking can potentially exceed the traction margins in the rear tires, resulting in a spin. Traction control alone is not enough to eliminate this occurrence. Driver experience and instinct usually result in judicious application of power when cornering. In regeneration, the goal is to preclude any possibility of having regenerative braking induce a spin while cornering. This is accomplished by attenuating the maximum level of regeneration allowed as the cornering load increases. Regeneration tapering starts at 0.3G and is down to zero at and above 0.5-G cornering level -- if regeneration alone is applied. If the service brakes are also applied, then regeneration is allowed in proportion to brake pedal pressure, since the front/rear balance of the service brakes is somewhat front-biased to accommodate the regenerative braking that is usually present when the service brakes are applied. If regeneration were not enabled in this fashion, application of the friction brakes while cornering leads to an undesirable level of understeer or 'plowing'.

Chassis Systems

The underpinnings of the tzero evolved from the original Piontek Sportech chassis. Many changes have been made to the structure and suspension for the tzero application.

Frame

The tzero has a triangulated space frame built with square and rectangular 304 stainless steel tubes (Figure 11). The frame of the first prototype tzero was made of mild steel. Stainless steel was chosen for its higher strength (and hence ability to use thinner wall sections) and because painting or other corrosion protection would not be required. All frame joints are TIG-welded, with special attention paid to minimizing warpage and carbon embrittlement.

Figure 11. Frame looking forward from driver's side. Note battery hanger brackets

Suspension

The suspension system is a classical double-wishbone arrangement front and rear. Hard polyurethane bushings are used all around except for the upper front arms, where rubber is used. Double-adjustable coil-over shocks are fitted for the development vehicle. The suspension arms are tzero specific and are fabricated in-house. Adjustments to camber and toe (front and rear) can be made without any disassembly. A tubular steel sway bar is fitted at the front. The right rear corner is shown in Figure 12.

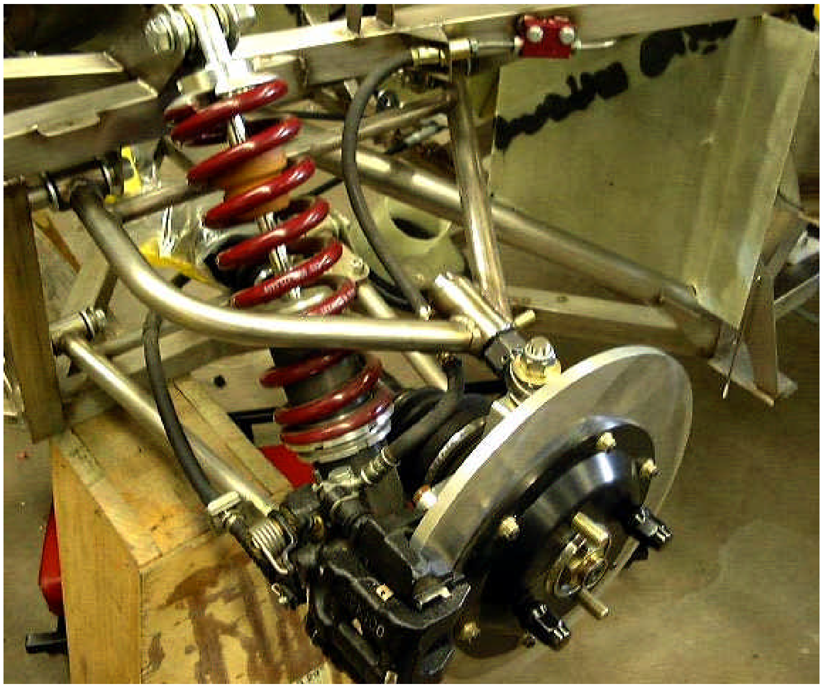


Figure 12. Right rear suspension.

Steering

The steering system is a conventional unboosted rack and pinion setup, with the rack ahead of the front axle centerline. The rack from the Mazda Miata is used and is shortened for the tzero application. The rack features an internal roller support, lessening friction and improving driving feel. The kingpins are also adapted from Miata kingpins. The caster angle and trail are selected to provide good steering feel.

Brakes

The brakes in the tzero are normally used only for slowing the last two or three mph before stopping. Wear is virtually non-existent. Even with so little use, the brakes must still be fully capable in times when regeneration is not present or when slowing is desired at a rate faster than regeneration can provide – such as in autocrossing or other hard driving. Additional requirements are that there should be little or no drag of the brake pads when they are not applied.

In order to save space and weight, and reduce complexity, the tzero uses unboosted brakes. In order to have acceptable pedal force, large-diameter rotors are desired, along with high mechanical advantage in the hydraulic system.   The brakes are split into separate front and rear circuits, with an adjustable front/rear balance. The front calipers are of a fixed type, with four pistons. The rear calipers are of a floating type, with one piston as well as an integral mechanical parking brake mechanism. The brake rotors remain a development item.   To save weight, metal-matrix-composite rotors were fitted – ventilated in front, and non ventilated in the rear.   While these are very suitable for daily use – since they are almost not used normally – there are concerns that MMC rotors may not have adequate capability to meet the testing required by the Federal Motor Vehicle Safety Standards. Both prototype tzeros are now fitted with vented and drilled MMC front rotors and conventional solid iron rear rotors.

Tires

The choice of tires is always very important for an electric vehicle. Rolling resistance can represent a substantial fraction of the total energy consumption. Tire manufacturers have developed excellent special low rolling resistance tires for electric vehicles. The main elements of a low rolling resistance tire are: silica tread filler compound, thin sidewalls, and tall sidewalls (i.e. not low profile). Unfortunately, none of these tires are suitable for the tzero (none even fit). Because of the tzero's 57% rear weight bias and high-power, considerations other than optimizing rolling resistance enter in. In order to provide safe and satisfying handling, the rear tires must be substantially wider than the front tires. The front tires must fit 15-in wheels (to clear the large brakes), but are very limited in outside diameter. The rear tires also have a limited outside diameter, but can be larger than the front tires. Taken together, these requirements are only met with low-profile high performance tires. Unfortunately, high performance tires generally have the highest rolling resistance.

Typical high performance tires have about 2.5-times-higher rolling resistance than the best EV tires. However, not all high performance tires have the same rolling resistance, so an extensive search was performed to find performance tires in the sizes needed with the lowest rolling resistance. The search ultimately led to tires made by Continental General Tire. For the front wheels, a nearly-ideal tire was available – it is a moderately-low-rolling-resistance model from the EcoContact line, and is an OEM application on the rear wheels of the DaimlerChrysler Smart car. For the rear, the choice is from the SportContact line. Two rear tire sizes (16 and 17-in) have been tested, with good handling results for both.

Rolling resistance data is defined and tested differently at different tire companies. Reported data is not directly comparable between companies. A very simple low speed coast down test was developed to measure rolling resistance of a complete vehicle. The test is nothing more than measuring deceleration rates in a low-speed parking lot coast down. Initial speed is typically 7 mph. The test is run in both directions to remove the effect of slope and in multiple repetitions to reduce random error. Representative rolling resistance test data from a number of different vehicles and tires is given in Table 3. The tzero has the highest rolling resistance of the vehicles measured (but it would have been much worse with other high performance tires). For the tzero rolling resistance typically accounts for 35 to 43 percent of the total energy consumption. If the tzero tires were as good as the best EV tires, range would increase by 22 to 30 percent.

Table 3. Summary of tire rolling resistance coefficients

Vehicle	Tire	Rolling Resistance (as % of weight)
4 passenger EV prototype	Michelin Proxima, 205/60 R15	0.54%
EV1 (worn tires)	Michelin Proxima	0.59%
EV1 (new tires)	Michelin Proxima	0.65%
Honda Insight	BF Goodrich Potenza RE92	0.68%
Honda Evplus	Dunlop	0.72%
tzero	Conti EcoContact/SportContact	1.14%

Body

The tzero body is non-load bearing, and is made of fiberglass/epoxy composite material. The parts are built with hand layup in female molds. Foam core and carbon fiber reinforcements are added for stiffening in the larger parts. The inner fenders and belly pans are made of Kevlar/epoxy composite. There are just six major pieces to the body – front body, rear body, two side pods and two doors. The front body is bolted on to the frame and does not open. The rear body is hinged for access to the trunk, suspension, electronics box, and rear batteries. Ingress and egress are aided by small doors and a tilt-up roof panel. Doors, rear body, and roof are shown in the open position in Figure 13.

Figure 13. Doors, roof, and top opened. The trunk volume is 5.1 cu-ft – the same as that of a Mazda Miata

Doors

The original tzero body, based on the Piontek Sportech had no doors at all. Getting in required stepping over the high sill. Small doors were incorporated in the next prototype tzero. In addition to slightly easing ingress/egress, the door allows a side window to be fitted which moves up and out of the way as the door is opened.

Interior

Instrument Panel

A complete set of driver displays is provided to communicate the status of the drivetrain components. The instrument panel is shown in Figure 14. The main elements of the instrumentation are listed below:

Speedometer	Standard analog unit with trip odometer
Volt/Amp meter	Replaces tachometer. Shows instantaneous battery current (charge and discharge) and voltage
Pack LED display	On center in pod above steering column. One LED for each battery. Each LED lights with increasing brightness if module voltage is between 14V to 16V or between 9V and 11V. Above 16V or below 9V, the LED is on at maximum intensity. This display gives the driver a direct real-time visual indication of the status of the battery pack.
Motor and PEU temp	Indicates temperature of motor and power electronics unit.
Energy status display	User configurable display. Can show Ah, Wh, regenerated Ah, Wh, average speed, trip distance, trip Wh/mile. There is no indication of miles remaining, as such an indication is an estimate based on future driving, which is strongly influenced by future hills and speed, both of which are not known to the system. In place of miles remaining, the energy status is indicated as simply net Amp-hours discharged. The driver becomes well aware of the capacity of the battery pack in the course of everyday driving, and uses the net Amp hour discharge vs. the capacity to remain informed.
Battery status display	User configurable display and battery and recharge control center. Screens with multiple bar graphs for battery voltage or temperature, module detail, BatOpt 5A charger manual control, Recharge control for line current, battery current, battery voltage lid, battery heating temperature, cooling blower-on temperature, maximum battery temperature for charging.

The overall approach to instrumentation on the tzero is to provide detailed battery data in real engineering units, rather than the ‘dumbed-down’ displays found in most other electric vehicles. Many early-adopter electric vehicle drivers have expressed a desire for more detailed energy status information. Several EV1 drivers have incorporated supplementary PalmPilot or lap top computer displays of serial data available from the diagnostic port.

Figure 14. Instrument panel.

Seats

The compact seat shells are of molded fiberglass. The seats are not adjustable for and aft (pedals move). They are thinly padded and upholstered in leather. An inflatable air bladder is fitted in the lumbar area of the driver's seat.

Pedals

The brake and accelerator pedals are mounted to a movable frame to allow for adjustment for different leg lengths. Pedal movement is accomplished with an electric motor and lead screw. The accelerator pedal has longer than normal travel to prevent the car from feeling too 'jumpy' -- with so much power available it is not desirable to have a short throw pedal.

Heating and Defogging

The heating/defogging system has two sources of heat. The primary source is waste heat from the drive motor.   If this is insufficient or the motor is cold, two PTC heaters are mounted in the air ducts near the windshield. Air is delivered through slots at the base of the windshield and through openings in the ducts aimed at the foot well area. The system has fresh and recirculate positions, and also a setting for recovering waste heat from the motor. In this mode, fresh air is drawn through the motor cooling fins and then passed through ducts behind the seat and forward along the side walls of the interior to the windshield area for discharge. Return air for the recirculate mode goes through openings on the forward edge of the seat. All fresh air for ventilation and powertrain cooling is drawn through two inlets near the front edge of the rear deck.

Performance

Acceleration

The tzero exhibits superior acceleration performance. Very few street cars can match it.

In testing at the Pomona, California drag strip using Road and Track Magazine's radar timing system, the tzero accelerated from 0 to 60 mph in 4.36 seconds (raw data). When corrected to remove the first foot of travel (for comparison to all auto magazine test data), the time is only 4.07 seconds. The speed vs. time trace is shown in Figure 15. This performance is substantially above that of the first prototype tzero, which registered 4.9 seconds to 60 mph. Reasons for the improvement are a 45-kg (100-pound) weight reduction (now 1106 kg, 2440 lb), and a 25% boost in the motor drive inverter current rating.

Corrected elapsed times to distance were as follows:

1/8 mile	8.51 sec	86.4 mph
1/4 mile	13.24 sec	90.0 mph

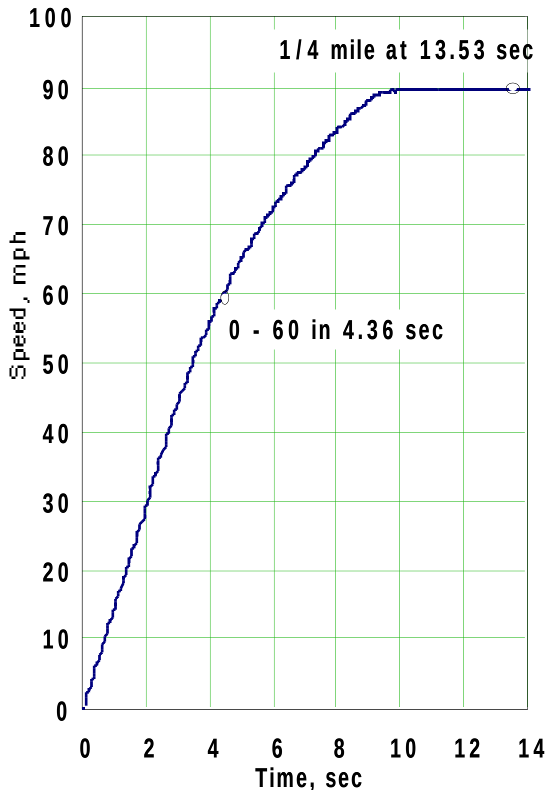


Figure 15. Acceleration profile.

Equally significant is the accessibility of this performance. No special driving skill is needed to achieve these numbers. Response to the accelerator pedal is better than virtually all other street cars. Maximum torque or power is almost instantly available at any speed – no downshifting is needed. Top-gear rolling acceleration performance (as is often reported in Car and Driver magazine) is a good indicator of how responsive a car feels. A comparison with several other performance cars is listed below.

Vehicle	Top gear acceleration 30-50mph	50-70 mph
tzero	1.7 sec	2.5 sec
BMW Z8	7.2	5.1
Honda S2000	10.3	10.2
McLaren F1	7.0	3.7
Porsche Carrera 4	9.6	9.6

Maximum Speed

The maximum safe speed is limited by the 12,000 rpm motor maximum speed and the gearbox ratio. The gearbox ratio of 9:1 has been selected with the aim of optimizing performance at normal speeds in the United States. The maximum speed of 90 mph is more than enough for almost all normal freeway or highway driving in the US. If a lower numerical gear ratio were selected to achieve a higher maximum speed, efficiency and acceleration would suffer in everyday driving. If fitted with a multi-speed gearbox with appropriate ratios, the power-limited top speed would be in excess of 160 mph.

Handling

The tzero suspension and tires have been tuned for good driving feel and safe handling at the limits. Ultimate cornering limits were not the goal. Considerable testing has been performed on a skid pad to develop the vehicle dynamics at the cornering limits. Limit behavior is moderate understeer. Applications of regeneration or motoring torque while cornering at the limit produce benign results due to the traction control and limits on regeneration while cornering.

Energy Efficiency and Range

The energy efficiency of the tzero suffers when compared with most other electric vehicles due to its high tire rolling resistance. However, its light weight, small size, strong regenerative braking, and very low tare loads combine to deliver very good overall efficiency. Overall energy consumption in everyday driving is typically between 160 and 200 Wh/mi. With an earlier generation of tires, which had lower rolling resistance but unacceptable handling, 145 Wh/mi. was often achieved. At a constant 64 mph, energy consumption is 171 Wh/mi, which is only slightly higher than an EV1.

A real-world example of the range capability is an 85-mile trip. Composed of freeway and highway driving, this trip included climbing to the top of a local 1500-m (5000-ft) mountain (starting from 275m (900 ft)).

How Tzero Compares with Two-Seat Cars with Highest and Lowest Fuel Economy

The Honda Insight is the top mileage car sold in the United States. The Ferrari 550 Maranello claims the worst fuel economy. Table 4 provides a comparison of key efficiency and performance attributes of the tzero with both of these vehicles. (The Honda Insight fuel economy shown is based on real-world driving tests by AC Propulsion.)

In order to compare with the tzero, the efficiency for each vehicle is quoted in BTU/mile.

(For the tzero, the BTU consumption is based on the amount of natural gas (or other fuel) needed to generate the energy to charge the battery. For the others, a value of 115,000 BTU/gallon of gasoline was used.)

The tzero has the efficiency of the car with the highest fuel economy and 0-60 performance better than the car with the worst fuel economy.

Table 4. Efficiency comparison with Honda Insight and Ferrari 550 Maranello

	tzero	**Honda Insight**	**Ferrari 550 Maranello**
Fuel economy	180 wh/mi DC	56 mpg	10 mpg
Energy efficiency, fuel BTU/mile	2,032	2,050	13,350
0 to 60 mph	4.1 sec	12.3 sec	4.2 sec
Lateral acceleration	0.88 G	0.77 G	0.94 G
Emissions certification level(g/mi)	ZEV	ULEV	Tier 1
hydrocarbon	0.0	0.055	0.25
CO	0.0	2.1	3.4
NOx	0.0	0.30	0.4
Evaporative	0.0	2g/test + 0.05 g/mi	2g/test + 0.05 g/mi

Commercialization Plans

AC Propulsion intends to produce the tzero and offer it for sale as a complete certified vehicle. The production volume is expected to be on the order of 100 per year. The price point has not been determined, but it will be comparable to other low-volume high performance vehicles.

Future Changes and Improvements

There are a number of changes that need to be made prior to commencing production. These fall into three general areas: (1) general improvements, (2) cost reduction, and (3) changes needed for compliance with motor vehicle safety standards.

Manufacturing Approach

In its current configuration, a very high fraction of the total content is manufactured in-house by AC Propulsion. This general approach will continue for the first year or two of manufacturing as the process is developed and any bugs worked out. Local job shop vendors will be used for minor parts fabrication. Eventually, major subassemblies such as the body or chassis might be built outside.

Marketing and Support

Because of the small market size, it will not be financially feasible to purchase advertising. Instead, AC Propulsion's internet web site will be the main conduit for information on the vehicle. Media articles and personal referrals will be the means by which prospects learn about the car.

Distribution will be direct rather than through dealers. Test drives will be available in target market areas – initially Southern California and the San Francisco Bay Area. Cars will be shipped in enclosed trailers by companies specializing in individual vehicle transport.

Service will be handled with a combination of approved service centers and AC Propulsion travelling technicians.

Conclusions

The tzero is an electric vehicle intended to be sold without subsidy. Its superior performance and driving feel will justify the price point that will be required to sell without subsidy. Niche vehicles such as the tzero may lead the way to more mainstream electric vehicles that can be a real business for their manufacturers.