Low-Emission Range Extender for Electric Vehicles

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ABSTRACT

Typical auto trips are within the driving range of efficient electric vehicles (EVs), but typical vehicle use also includes occasional trips that exceed EV range. EV users may face the necessity of maintaining a second car, or renting a car, for such trips. An alternative is the use of a range extending trailer (RXT), a trailer-mounted generator that, when towed behind an EV, effectively converts the EV to series-hybrid mode for long trips.

AC Propulsion Inc., with funding support from the South Coast Air Quality Management District (SCAQMD), has developed an RXT to evaluate commercial prospects for this concept. It incorporates a high specific output gasoline-fueled generator-set, engine and fuel controls for low emissions, and self-contained steering control to improve maneuverability. (See Appendix for RXT specifications). Successful series-hybrid operation is demonstrated. Emissions and fuel consumption from RXT operation are quantified.

INTRODUCTION

A trailer-mounted generator-set can extend the range and increase the utility of a battery-powered electric vehicle if it provides adequate power for sustained highway cruising and does not create unacceptable inconvenience for the user. At the same time, the emissions from the RXT must be controlled to avoid negating the emissions reduction benefit of the EV.

The purpose of the RXT is to reduce barriers to EV use caused by limited range and uncertainty about the availability of charging sites. The RXT is intended for use with EVs that have adequate range and acceleration capability using only their battery. Such EVs will require the use of the RXT only for long trips which may account for 10% to 20% of total vehicle miles. The remaining miles traveled will use battery energy drawn from the electric grid. The limited use-ratio for the RXT provides significant dilution of the overall emissions and fuel consumption of the RXT/EV combination.

The primary requirement for an RXT power unit is the ability to sustain battery charge continuously. The RXT power output must match the EV road load at the desired cruising speed. If output is below road load, the battery will eventually be discharged, necessitating a lengthy stop for charging. For efficient, small-to-medium size EVs, RXT output of 15 to 25 kW is necessary to provide comfortable freeway cruising.

Size and weight critically affect the usability of the RXT. Electric propulsion is well-suited for compact-size vehicles, so the RXT must be towable by such vehicles. It must also be easy to connect and easy to store if it is to provide acceptable convenience for the user. To achieve these objectives, a weight target of 150 kg was established. The resulting specific-power objective is not available from commercial generator-sets, (Fig 1.)

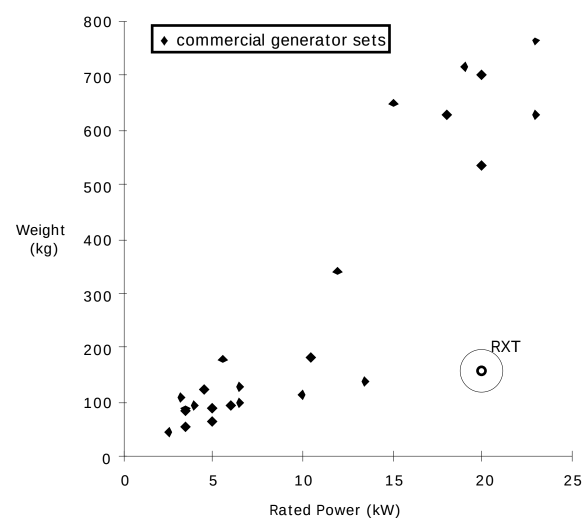

Fig. 1: RXT weight and output targets compared to commercially available generator-sets

DESIGN TARGETS The commercialization objective translates into specific targets for functionality, convenience, and environmental compatibility.

Functionality

- **output -** sufficient to operate EVs at typical freeway speeds of 100 - 130 kph (15 - 25 kW)
- **charging characteristic** - rated charging output over full range of operating voltage

Convenience

- **hookup** - one person hookup; simple, plug-in electrical connection
- **operation** - in-vehicle, driver-controlled, manual start/stop
- **backing** - when attached to the vehicle, the trailer will enable unrestricted backing maneuvers by the untrained driver
- **noise** - when operating at any condition up to maximum output, the trailer will not create objectionable in-car sound levels
- **vehicle handling** - the vehicle-trailer combination will not exhibit unexpected or unsafe handling under normal or emergency maneuvers
- **off-vehicle maneuverability** - when disconnected from the vehicle, the trailer will be maneuverable by one person

Environmental Compatibility

- **tailpipe emissions** - average emission rates at or below ULEV levels
- **refueling and evaporative emissions** - less than those for a conventional vehicle
- **generation efficiency** - fuel to battery energy conversion efficiency of 20-25%
- **vehicle combination efficiency** - vehicle-trailer combination highway energy consumption no more than 10% greater than vehicle without trailer

In pursuit of these objectives, the RXT program required three distinct development efforts — the charging system, the engine and emission control system, and the trailer chassis system.

CHARGING SYSTEM

Unlike a conventional generator-set, the RXT must provide rated output over a range of voltages consistent with the battery charging voltage. The charging voltage varies according to battery state-of-charge (SOC). To recover and maintain high SOC at freeway speeds, the RXT output cannot drop off as battery SOC and voltage increase. To maintain rated output almost up to 100% SOC requires active voltage regulation, (Fig. 2).

Note that both charging characteristics shown are rated at 20 kW output, but without active voltage regulation, rated charging output is achieved at only one point, corresponding to a discharged battery condition. As shown, active voltage regulation provides a broad region of constant power charging, the flat region of the output curve, and a very sharp high voltage cutoff to protect system electronics. Generators without active voltage regulation are unable to maintain rated outputs as battery SOC increases, so high SOC cannot be sustained. Since it is necessary to maintain batteries near full charge to provide reserve power for hill climbing and passing, generators without active voltage regulation must be oversized to provide sustainable cruising capability.

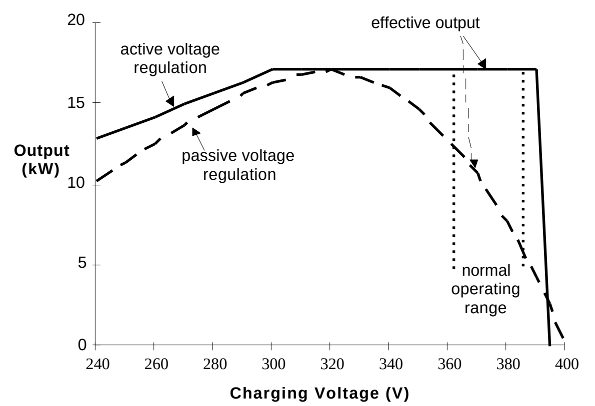

Fig. 2: Charging output characteristics

The specific output target for the alternator requires high operating speed. Alternators from jet aircraft are designed to operate at 8000 rpm and produce 15 to 25 kW depending on the design and application. Surplus aircraft alternators used in previous RXT development efforts performed well. The efficiency of the aircraft alternators is 85% to 90%, and they are designed for light weight and high reliability.

Aircraft alternators cannot meet the cost constraints imposed on an automotive application. The aircraft design includes features for light weight and reliability that are not cost-effective in automotive applications. To achieve high specific output and low cost, an alternator based on the AC Propulsion AC-induction traction motor was evaluated. This motor is well-proven as a power unit for electric vehicles. It offers the advantages of simple and robust construction, high specific output, high efficiency, and air cooling, all desirable characteristics for the RXT application. In EV applications, the motor generates power during regenerative braking, so its capability as a generator is established.

As a motor, the AC-150 is rated at 70 kW continuous so it is oversized for the range extender application. Use of the basic motor architecture will allow generators of varying speeds and outputs to be developed by changing the length and field windings for different applications. The generators would share basic dimensions and components such as end plates, housings and rotor shafts (except for length), and laminations. By sharing these components, economies of scale and reduced costs can be approached more rapidly. Using the motor as a generator in the range extender application, however, requires innovation in the control system in order to avoid the size and complexity of the inverter used to control motor/generator function on an EV.

Based on examples in the literature of the use of self-excitation of AC-induction motors and the use of switched capacitors for phase shifting, a laboratory control system was developed for feasibility testing on the dyno. The control system uses low-frequency zero-current switching of the capacitors at the synchronous frequency (typically a few hundred Hz), so component costs are limited and undesirable EMI is not generated. A starter circuit initiates field excitation at startup, but the field is self-exciting during operation.

An off-the-shelf AC Propulsion traction motor used for the initial tests demonstrated satisfactory levels of output, efficiency, and control authority. The first prototype alternator was designed and fabricated in-house using shortened traction motor components. The alternator uses the same materials and construction methods as the traction motor. It also uses an external air-cooling system similar to that employed for the traction motor, allowing cooling air flow to be tailored closely to the system's actual needs.

The alternator was dyno tested using a laboratory control system. In the initial test, output and efficiency were met design targets. Based on the established feasibility of the control concept, prototype control systems for the generator-set were developed. The complete prototype charging system achieves 20 kW DC output at 7000 rpm with efficiency over 90%. Compared to the aircraft alternator, design cost is lower and weight is the same.

ENGINE AND EMISSION CONTROL

The engine development program was divided into three phases: engine selection, engine adaptation, and engine control system.

ENGINE SELECTION Commercialization objectives require the use of an engine for which production feasibility is proven. For this reason, only production engines were considered as range extender powerplants. Engine selection required identification of an engine that would meet the stringent power, efficiency, and emission performance requirements.

<u>Power</u> - The range extender power objective of 20 kW continuous electrical output required a thermal engine with considerably higher net shaft output. Generator losses would add 10% to the power requirement. Altitude compensation, required to maintain full output to 2200 m altitude added an additional 25% to the rated power requirement. Finally, emission tuning and durability considerations would require de-rating from peak rated output, so an additional 20% was added to the power requirement target. Engine power of 35 kW was considered ideal and the engine search concentrated on engines in the 30 to 40 kW power range.

<u>Efficiency</u> - Since the range extender is towed behind an EV, evaluation of its net efficiency must consider both generation losses and towing losses.

Towing losses figure more prominently than generation losses in the overall vehicle/trailer combination efficiency because they affect efficiency whenever the trailer is being towed even if the engine is not running. Towing losses are caused by trailer weight, size, and shape. Since the engine is the largest and heaviest component of the range extender, minimizing engine size and weight is important for towing efficiency. (Size and weight are also critical for convenient storage and hookup.) For a given output, engine size is primarily determined by operating speed. Engine weight is determined both by size and by design and material use. Compact, high-speed, aluminum intensive designs are favorable. The operating speed target was set in the 6000 - 9000 rpm range, consistent with the speed target for the alternator.

From the engine perspective, generation losses can be minimized by improving thermal efficiency and reducing engine friction. Both considerations favor fewer cylinders. In the 30-40 kW power range, engines are available with one to four cylinders. A higher number of cylinders increases friction, and also increases thermal losses due to the higher surface to volume ratio of the cylinders. For these and size reasons, more than two cylinders was considered undesirable.

<u>Emissions</u> - Range extender engine emissions are to be controlled to a level equivalent to current automotive engine emission levels. This requires use of automotive-style fuel injection and exhaust aftertreatment systems to replace the fuel and exhaust systems fitted as standard equipment to candidate RXT engines. Since engine-out emissions data are not widely available to identify lower emitting engines, engine emission data were not used for engine selection, but inherent engine characteristics were used to eliminate some types of engines.

Two-stroke engines are unfavorable for emissions. Reducing exhaust emissions of two-stroke engines requires techniques such as direct injection to control HC and ultra-lean operation or lean catalysis for control of NOx. These techniques are under development by engine manufacturers, but are not yet readily available. For this reason, two-stroke engines were ruled out for the range extender application.

Air-cooled engines present emission control challenges because of the difficulty controlling engine temperature. Air-cooled engines require either a cooling airstream from vehicle movement, which is not available in an enclosed range extender, or engine-driven fans which cannot be as easily controlled. No air-cooled engines were considered suitable for the range extender application.

The power, efficiency, and emission objectives for the range extender power plant and other considerations relating to user-friendliness determined the criteria for candidate engines (Table 1).

Table 1**:** Engine selection criteria

Criteria	**Requirement**	**Comment**
cycle	spark ignition, 4-stroke	commercial diesel engines too heavy, 2-stroke engine emissions too high, turbines insufficiently developed
cooling	liquid-cooled	emissions and durability
power	30 - 40 kW	requirement for 20 kW electrical output up to 2200 meters altitude
operating speed	6000 - 9000 rpm	desirable for size and weight considerations
weight	less than 70 kg	consistent with overall weight target of 150 kg
size configuration	small and compact	rotary, inline, vee and opposed considered
number of cylinders	one or two	desirable for size and mechanical efficiency
availability and cost	mass produced	representative of a design that can be mass produced at reasonable cost

An exhaustive survey of available power plants for the range extender identified four categories of candidate engines based on their original application: utility power, snowmobile, watercraft, and motorcycle. The California Air Resources Board provided valuable assistance in the form of listings of small engine specifications from certification documentation.

Utility power - Engines for use in small power equipment such as generators, welders, compressors, pumps, mowers and other equipment come in a broad variety of configurations. None of the engines in this category that we identified offered specific output (kW/kg) at the level required for the range extender application. Weight sensitive applications such as chain saws gave high specific output but were invariably two-stroke designs.

Snowmobiles - Most snowmobile engines exceed the power requirements of the range extender. No suitable, 4-stroke, snowmobile engines were identified.

Watercraft - Many outboard motors and personal watercraft use small high-speed engines in the 30-40 kW range, but only one line of 4-strokes is available in the US at this time. Honda offers a range of 4-stroke outboards ranging from 37 - 67 kW. The 37 kW unit uses a 3-cylinder, 800 cc engine that operates at 5500 rpm. This unit was included on the list of engines investigated in more detail.

Motorcycles - Numerous motorcycle engines offer potential size and output combinations suitable for a range extender. Even after screening for the necessary 4-stroke cycle and liquid-cooling, engines from BMW, Honda, Kawasaki, Suzuki, and Yamaha were available at the required power levels. These engines were investigated in more detail.

The final engine candidates and their specifications are shown in descending order of suitability based on specifications and other considerations (Table 2). The Kawasaki EX500, a 2-cylinder, 500 cc motorcycle engine was judged to be the best-choice, and it was selected as the range extender power plant.

Table 2: Candidate Engine Specifications

Mfr	**Disp (cc)**	**Power (kW)**	**Max RPM**	**Cyl**	**Comments**
Kawasaki	498	45	9800	I2	best size/power combination, known design
Yamaha	849	40	7500	I2	size concerns
BMW	740	52	8200	I3	cost, size, and weight concerns
Honda	808	37	6500	I3	marine engine, marginal on speed
Kawasaki	592	63	11000	I4	four cylinder
Honda	600	69	11500	I4	four cylinder
Yamaha	599	62	10000	I4	four cylinder
Suzuki	600	70	11500	I4	four cylinder
Suzuki	805	46	6500	V2	size, speed concerns
Honda	583	30	6500	V2	speed, power concerns
Kawasaki	651	26	6500	I1	marginal on power

ENGINE ADAPTATION Modifications to adapt the Kawasaki EX-500 engine to the generator and trailer include minor machine work to both engine side covers and a drilling and tapping operation to the crankshaft to adapt the coupling hardware. All other necessary adaptations are accomplished by installing fabricated components on the engine with standard disassembly and assembly procedures. The motorcycle gearbox internals are removed. The integral gearbox casing is retained because it houses the oil pump and serves as one of the engine mounting structures.

Compact trailer packaging helps achieve size and weight objectives. The engine/generator unit is mounted transversely in order to minimize length, accommodate trailer suspension and steering motion, and achieve good balance. The cooling system, sized for the road-load needs of a compact car, includes a rear-mounted radiator. In this position, it benefits from airflow ducted up from under the trailer that is then evacuated in the aerodynamic wake of the trailer. A pusher fan has been mounted to the radiator to aid cooling at low speeds.

EMISSION CONTROL The RXT engine operates in four constant-speed modes controlled by the combined engine and alternator management system.

- **Startup** Startup mode operates at every engine start. It includes the engine start routine and a timed, no-load, 3500 rpm operating point designed to achieve engine warmup and catalyst lightoff. Throttle operation and fuel calibration are programmed for consistent starting and modified according to ambient and coolant temperature.
- **Purge** A canister purge cycle is activated after engine startup in response to specific battery, temperature, and canister status indicators. The purge cycle operates at 7000 rpm and light-load in closed-loop mode until canister purge is complete.
- **Idle** The idle mode provides a no-load, reduced-speed operation. It can be activated by the driver to reduce noise and heat load during short periods of urban or congested conditions without necessitating a start/stop cycle.
- **Power** The power mode operates at 7000 rpm and delivers 20 kW at up to 380V. The servo-controlled throttle maintains constant speed but controls output to prevent over-voltage conditions such as during regenerative braking.

<u>Exhaust Emission Control</u> Specific emission control strategies are required for each of these modes. The RXT engine operates under conditions significantly different from those encountered over typical emission test driving cycles, and these conditions present unique opportunities and challenges for the control of emissions. The engine and emission control system developed for the RXT provides precise control of fuel and ignition as well as tuning flexibility to accommodate the particular engine control requirements.

The automotive-style port fuel injection system comprises individual throttle bodies mounting pintle-type fuel injectors fed by an in-tank pump. A servo motor actuates the throttles in response to engine mode and speed signals. An intake airbox and air filter housing mounts directly to the throttle bodies. A commercially available retrofit engine management system controls fuel injection pulsewidth and timing. The control settings are derived from lookup tables and interpolation routines that define engine control calibrations based on engine speed and load. In closed-loop mode, fuel quantity (pulsewidth) is trimmed to maintain programmed mixture ratios according to input from a single exhaust gas oxygen sensor mounted at the catalyst inlet.

The exhaust system follows the tuning and silencing performance of the original motorcycle exhaust system as closely as possible. Two tuned lengths empty to an expansion chamber in front of the first catalytic converter, a 90 mm diameter 400 cell metallic substrate Pt/Rh catalyst mounted ahead of the trailer axle, 700 mm downstream from the exhaust ports. A second 70 mm diameter converter is mounted to the rear of the trailer axle. The dual catalysts package more efficiently and improve tuning flexibility. Auxiliary air is introduced between the two catalysts during some operating modes. From the rear converter the exhaust flows to a motorcycle muffler mounted transversely under the rear of the trailer.

Because the RXT engine does not directly drive the vehicle, its operation can be optimized for emission reduction without concern for driveability. For example, the startup mode calibration achieves rapid lightoff by maximizing heat rejection to the exhaust stream. Purge and idle modes operate in closed loop to maintain mixture control. Power mode calibration operates rich of stoichiometry to control NOx generation. In power mode, load transients may occur as the controller throttles output to avoid exceeding the voltage limit. These load reductions must sometimes occur rapidly necessitating rapid throttle closure. Conversely, load recovery rate is not critical. For this reason the two transient modes can be calibrated differently.

<u>Evaporative Emission Controls</u> The evaporative control system developed for the RXT relies on the closed fuel injection system to control running and hot-soak losses. A sealed fuel system capable of withstanding full fuel vapor pressure eliminates evaporative losses due to diurnal cycling. This is of particular importance for this application because RXTs may often be parked for days or weeks at a time without opportunity for canister purge. The gas tank is pressure-tight except during refueling. Before removing the gas tank cap for refueling, the tank must be vented to the charcoal canister with a manual valve. The canister is then purged upon engine restart.

To prevent opening of the tank without venting, the gas cap top, or handle, spins freely whenever the tank is pressurized. Only after the pressure is released does the cap handle engage the cap itself so that it can be unscrewed. This gas cap fits standard gas tank filer necks, and appears the same as conventional gas caps. The pressure and vacuum relief functions of conventional gas caps are fulfilled with separate check valves incorporated into the fuel tank vent lines.

In order to withstand the full range of pressure variations, a cylindrical fuel tank with curve-formed ends is necessary. With this construction, a tank with over 34 liter capacity packages conveniently and mounts directly to the frame at the front of the trailer. Externally, the tank includes mounting provisions for the evaporative emissions control hardware.

TRAILER CHASSIS SYSTEM

A major objective of the range extender development program is to improve commercial prospects by minimizing the inconvenience and difficulties associated with trailer use including storing, hitching, and backing the trailer. Backing will be especially difficult with the range extender because other objectives require that the trailer be short and low making back-up almost impossible if a conventional ball-hitch is used. A system to limit or control trailer yaw with respect to the tow-vehicle is necessary to allow the range extender to fulfill its mission.

Consideration of yaw-control trailer design approaches yielded a total of six different concepts.

- Dual-hitch designs — two horizontally disposed hitch points prevent yaw mechanically but allow the trailer to pitch up and down
  - non-steering, close-coupled trailer to reduce tire scrub
  - trailer lift in reverse
  - caster systems
  - trailer steering linked to tow-vehicle steering
  - self-steering systems with electronic control of steer angle
- Single-hitch designs — conventional ball hitch
  - self-steering systems with electronic control of steer angle

These approaches were all considered from customer convenience, functionality, and design feasibility perspectives.

The concept of a dual-hitch, non-steering, close-coupled trailer offered the least complex trailer design. It would simply allow the tires to scrub, a workable concept as long as trailer weight was kept low and the vehicle-axle to trailer-axle distance was kept short. Although trailer design can keep the trailer short, vehicles with long rear overhangs could cause undesirable levels of scrub.

A variety of increasingly complex dual-hitch designs was considered to address handling and tire scrub concerns, but all suffered from what increasingly came to be seen as two serious shortcomings - 1) the need to engineer a special dual-hitch for every range extender vehicle application, and 2) the difficulty in aligning and connecting a dual hitch trailer, especially on uneven ground, compared to a single-hitch design. These shortcomings could significantly compromise the range extender's commercialization potential. For this reason, a single hitch trailer with steering control was selected for feasibility evaluation.

As conceived, single hitch design with steering control will remain straight behind the tow vehicle, within close limits, under all types of vehicle maneuvers, with no input from the driver. The control system is designed to steer the wheels in response to deviations from zero-yaw, so as to maintain the trailer directly behind the tow-vehicle (Fig. 3). This system allows the use of conventional hitches on any car. The single hitch trailer is much easier to connect and does not interfere with tow-vehicle roll motion as a dual-hitch design would. The key components of such a system are the mechanical steering system and the steering control unit which uses signals from a yaw transducer and speed and direction sensors to generate steering commands.

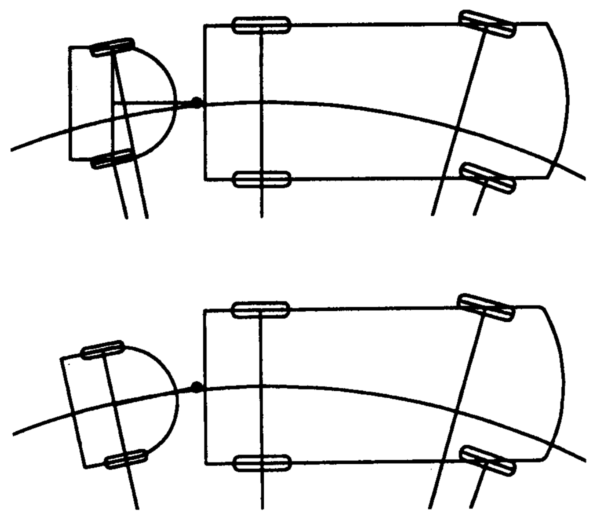

Fig. 3: Trailer steering concept vs. conventional trailer

The steering system was developed for the torsion arm suspension fitted to the RXT, but it will adapt to beam-axle suspension as well. To accommodate the steering action, the original trailing arms were replaced with purpose-designed weldments that hold fabricated steering spindles. The spindles, with integral steering arms, pivot on sealed bearings and accommodate standard 27 mm diameter trailer hubs and bearings. The steering arms are oriented to minimize bump steer. The left-hand hub and spindle are modified to provide wheel speed and direction signals for use by the steering control system.

To match the steering capability of typical cars, the steering mechanism provides maximum steering angle of 40˚. Ackerman effect has been designed into the steering linkage to reduce scrub while turning. An electrically powered steering rack developed to the size and load requirements of the application has demonstrated sufficient power to steer the wheels lock-to-lock under full trailer weight in under three seconds.

The steering control operates from signals for trailer yaw, vehicle direction, and vehicle speed. These signals are generated entirely on the trailer itself. This design approach is important for commercialization because it requires no interaction or connection with the tow-vehicle steering system, thus simplifying installation and eliminating the need for any tow-vehicle-specific hardware.

Speed and direction signals are derived from a pair of pulse generators positioned in the left-side trailer wheel hub. Speed is derived directly from pulse frequency. Direction is derived from the relative phasing of the signals from the two sensors.

The yaw sensor design is fundamental to the steering control function. Originally, the yaw sensor was planned as a mechanism that would derive yaw from linear displacement of a linkage between the trailer and vehicle. Although this would have been a straightforward approach, the necessity of attaching a link point to the vehicle bumper, calibrating the linkage for each application, and the potential for damage to the linkage appeared to be potential drawbacks.

An integrated system that directly senses yaw of the trailer tongue with respect to the ball hitch was thought to be preferable. The sensor elements are contained entirely in the trailer tongue and ball, an arrangement that allows accurate determination of yaw angle with little sensitivity to pitch and roll. With the integrated yaw sensor, the only modification to the tow vehicle is installation of the ball equipped with the energized coil and its associated wiring. Calibration is a matter of aligning the ball in the straight ahead position and tightening the ball nut. The sensor ball is compatible with non-steering trailers.

For both forward and reverse, the required steering input is opposite to that of the front wheels of the tow vehicle. For example, for a right turn, front wheels will be turned to the right, trailer wheels turned to the left. The yaw response of the trailer to a vehicle steering input depends on whether the vehicle is traveling forward or backward. The trailer will yaw to the right when the vehicle is steered to the right while moving forward, but it will yaw to the left if the vehicle moves backward. Consequently, the trailer steering control requires a vehicle direction input to provide the proper trailer steering response to a yaw signal. Vehicle speed information is used to vary the response sensitivity to assure trailer stability at all speeds.

Short trailers can exhibit instability or intermittent oscillation at high-speeds. To improve stability on the highway, the steering controller includes algorithms that effectively damp high-speed oscillations with steering control inputs.

Early tests using drivers unfamiliar with the self-steering concept revealed that some driver actions, such as large steering inputs while the vehicle is stationary, or excessive speed in reverse, can overwhelm the steering system's range of control and result in potential jack-knife situations. As a result, the control system now includes adjustable threshold switches that trigger audible warning indicators for excess yaw and excess speed in reverse.

OPERATING TEST RESULTS

The RXT has been operated over more than 5,000 kilometers in urban and long-distance service behind two different EVs since January 1997. It has been emission tested at CARB and independent test labs, and it has been demonstrated to and driven by a wide variety of users. The results provide a valid basis from which to evaluate the development program with respect to the original design objectives.

FUNCTIONALITY The alternator control system operates correctly. At high battery state-of-charge levels, it limits output and controls voltage to specified levels. Under regenerative braking, it properly gives priority to regenerative energy. With regen it limits output in a rapid and stable manner, allowing the full regen current to be absorbed before any alternator current is added. This control function is critical in order to avoid voltage spikes that can damage the vehicle control electronics.

The RXT provides continuous output of 20 kW DC at output voltages from 280 - 380 V. This output has sustainably propelled a 4-seat compact size EV at 120 kph and a smaller 2-seat EV sports car at 130 kph. At such speeds, the RXT can efficiently maintain battery SOC at near 80%. Higher SOC can be maintained but some efficiency is lost because of frequent engine throttling. With the EVs tested, 80% SOC would provide sufficient battery energy reserve to crest any interstate mountain pass in the United States without dropping below the speed limit.

The RXT is intended for use with pure EVs that have battery-only range of 80 km or more. Such EVs, typically do not require range extension in strictly urban driving, but in such driving, the RXT can sustain battery charge in efficient EVs while operating at about 20% - 30% duty cycle. That is, the RXT need operate only 20 - 30 km out of every 100 urban km driven in order to maintain battery SOC. This duty cycle factor allows EV/RXT combination emissions to remain low even if none of the driving energy is supplied by electricity from the grid.

For most long-distance trips, manual control of the RXT facilitates driver involvement in management of battery SOC. Faced with a low SOC and an extended ascent, the driver may anticipate the energy requirements, running the RXT and slowing the vehicle in order to build battery charge. Conversely, approaching a destination, the driver may elect to consume the battery charge rather than operate the RXT, knowing that charging will be available at the destination. Automatic control of the RXT cannot achieve this kind of optimal operation unless route, topographic, and driver intention information are provided for the RXT control algorithm.

The RXT, as developed, meets the highway power requirements of a wide range of EVs (Fig. 4). The 20 kW RXT output will propel large or less efficient EVs at a sustainable 100 kph. Smaller or more efficient EVs can sustain speeds of 130 kph or higher.

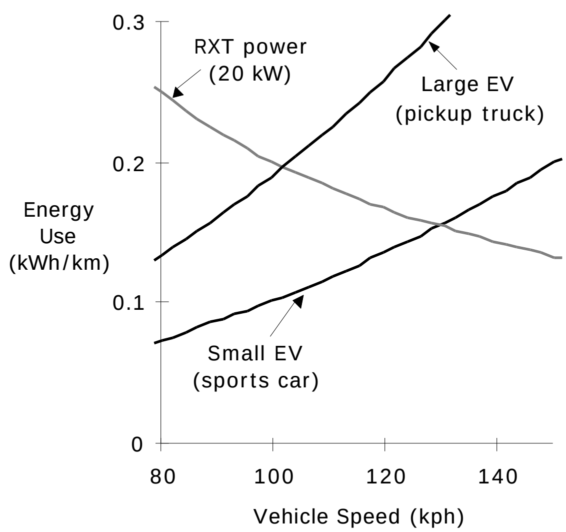

Fig. 4: EV energy consumption at highway speeds

CONVENIENCE Total RXT weight of 160 kg without fuel, and overall length of 1220 mm make the RXT easy to maneuver when it is off the vehicle. One person can attach the RXT to an EV and connect its wiring harness in less than two minutes. Once connected to an EV, the RXT is operated from within the cockpit. Start and stop are controlled manually by the driver. Output control is automatic. The driver may also manually select the no-load idle setting from within the car

Driving an EV with the RXT in tow requires only slight adjustments to driving technique. Around town, curves and sharp turns present no concerns because the narrow width and tracking of the trailer eliminate the possibility of clipping corners. Lane change maneuvers require only awareness of the added length due to the trailer. On the highway, the tracking and stability of the trailer eliminate wander, sway, and oscillation. Lane changes, including emergency avoidance maneuvers at speeds as high as 140 kph can be performed as easily as without the RXT.

The weight of the RXT reduces acceleration somewhat. With the RXT operating at full output, the change is negligible. With the trailer not operating, acceleration is reduced about 10%, not critical unless the tow vehicle has a marginal power-to-weight ratio.

At speeds up to 10 kph in reverse, the trailer reliably maintains its orientation straight behind the vehicle. This allows reversing without requiring specific driver inputs to guide the trailer. The trailer reverses correctly over straight, serpentine, and circular paths. The most challenging maneuvers involve reversals and large steering inputs such as three-point-turns in confined areas, or parallel parking. The trailer steering system allows such maneuvers to be successfully completed if the driver employs a technique that avoids large steering inputs while the vehicle is stationary and makes smooth steering transitions during reversal of driving direction. With these techniques in mind, the EV/RXT combination can be driven and parked in the same manner as a non-articulated vehicle of equal length.

At maximum output, the RXT is almost inaudible from within the car at highway speeds. Stationary or at low speeds, at the current state of development, the RXT noise level may be objectionable to nearby drivers or pedestrians. Under these conditions the operator may turn off the RXT or select the idle mode.

When disconnected from the vehicle, the RXT can be easily moved by one person due to its light weight and good balance. A control on the trailer allows centering the steering to the straight-ahead position manually so that it can be maneuvered most easily. The compact, box-like shape of the trailer, made possible by its short tongue, allows it to be stored in locations that would not accommodate normal trailers.

ENVIRONMENTAL COMPATIBILITY

The emissions and energy consumption of the EV/RXT combination merit considerable attention because the objective of commercializing RXTs must not come at the expense of the environmental benefits of EVs. At its present state of development, the RXT demonstrates the promise of matching or improving upon the emissions and fuel efficiency of conventional cars, <u>when in use</u>. Considering the projected RXT usage pattern of 10% to 20% of total EV miles, the combination would thus be 5 to 10 times better than the conventional car overall.

<u>Emissions</u> The emissions attributable to an EV depend on the emissions rate of the power generating source per unit of electrical energy, and on the energy consumption of the EV itself. Grams of pollutant per kWh of energy generated and kWh of energy used per mile of travel resolve to gm/mi of emission. Unlike a conventional vehicle, the equivalent emissions rate of an EV depends directly on its energy efficiency.

In a similar manner, the emissions of the EV/RXT series hybrid combination depend primarily on the specific emissions of the power unit and the energy efficiency of the vehicle/trailer combination. The third factor that determines overall emission output from the EV/RXT combination is the ratio of fuel energy to battery energy used over a given driving period.

At the current level of development, RXT specific emissions at the primary operating point have responded well to fuel control and catalyst strategies. Computed for an EV operating with a battery-to-wheel energy consumption of 125 Wh/km (200 Wh/mi), the rates are near or below current standards (Table 3). This puts average emission rates at well below ULEV standards.

Table 3: RXT Emissions at 20 kW output

	HC	CO	NOx
Specific emissions (gm/kWh) (preliminary)	0.13	23	1.5
RXT emissions rate for EV @ 125 Wh/km (gm/mile)	0.03	4.6	0.3
250 km round-trip emissions with 15 kWh battery depletion (gm/mi)	0.016	2.4	0.16
Overall emission rate @ 15% RXT use (gm/mi)	0.005	0.7	0.007
ref: ULEV standards (gm/mile)	0.04	1.7	0.2

Fuel Consumption As with emissions, fuel consumption of the EV/RXT combination depends on the energy consumption of the vehicle combination, the specific fuel consumption of the RXT, and the ratio of fuel energy to battery energy consumed.

Because emission rates and fuel consumption vary directly with vehicle energy consumption, the energy cost of towing the RXT is critical. At the present level of development, efforts to reduce size and weight have limited the towing energy penalty to less than 10% at highway speeds. Small changes can be significant. A switch to radial tires for the trailer reduced energy consumption by 2%, even though the radial and the original bias ply tire measured nearly identical rolling resistance. The benefit derived from the shorter profile of the radial that tucked the trailer lower in the aerodynamic wake of the low-slung EV sports car that was towing the RXT.

The fuel efficiency and overall energy conversion for the RXT, including the alternator losses, have achieved the original development objectives at the present level of development (Table 4).

Table 4: RXT fuel consumption at 20 kW output

	SI units	US units
RXT specific fuel consumption (preliminary)	0.37 kg/kWh	0.13 gal/kWh
Conversion efficiency (fuel tank to battery)	22%	22%
Equivalent fuel economy @ 125 Wh/km	5.5 l/100km	38 mpg
250 km round-trip fuel economy with 15 kWh battery depletion	2.9 l/100km	80 mpg
Overall fuel consumption @ 15% RXT use	0.8 l/100km	280 mpg

Towing the RXT behind a high-performance electric sports car yields fuel consumption of 5.9 l/100km (40 mpg) at 100 kph and 7.4 l/100km (32 mpg) at 120 kph. These values reflect the efficiency of the EV as well as the RXT.

The EVs used with the RXT for these tests store 15 -16 kWh of dischargeable energy in their batteries. Using that energy over the course of a day's driving reduces the operating time and fuel consumption of the RXT. Over a 250 km round-trip, returning with depleted battery, the EV/RXT combination will consume the same amount of gasoline as a conventional vehicle, or a hybrid that cannot charge from the grid, that achieves 2.9 l/100km (80 mpg).

Over the course of typical operation, if the RXT is used for 15% of miles driven, gasoline consumption will be the same as if the EV/RXT combination achieved 0.8 l/100km (280 mpg).

CONCLUSIONS

The vehicle/trailer combination demonstrates series-hybrid operation including excellent acceleration, highway capability, high speed hill-climbing ability, good fuel economy, and low emissions. Series-hybrid functionality is established without use of unproven energy storage devices or exotic powerplants.

The RXT demonstrates how the range extending trailer concept can achieve acceptable levels of convenience and eliminate the functional compromises necessary to package series-hybrid componentry within a vehicle.

For people who want to drive an EV, the RXT provides an alternative to the ownership of a gasoline vehicles for occasional long trips. It can offer significant advantages in terms of size, fuel consumption, overall emissions, and potential cost.