27th Australasian Transport Research Forum, Adelaide, 29 September – 1 October 2004

Paper title: **Predicting the energy use of a solar-electric commuter car, and some implications for sustainable transport**

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Abstract (200 words):
The University of South Australia is developing a low-mass, energy efficient, solar-electric commuter car that can be powered entirely by non-polluting renewable energy.

To predict the energy that will be used by the solar-electric commuter car we need to know how the car is likely to be driven. Instantaneous power use will depend on speed v, acceleration a and gradient γ, and on the efficiency of the drive system. The energy required to recharge the car will also depend on the efficiency of the battery.

The Transport Systems Centre at the University of South Australia has instrumented an electric car and collected GPS data during urban driving. We use this data to calculate the proportion of time the car spent in each (v, a, γ) state. This new data can be used to model the performance of the car, and to predict the performance of the proposed solar-electric commuter car.

The energy required to run the proposed commuter car will be about 1/5 of the energy required to run a conventional car.

Introduction

Most commuter trips have only one person in the car. Furthermore, the car typically weighs 10-30 times the weight of the person being transported. Vast amounts of energy are required to propel these massive machines, and the conversion of fossil fuels into motion results in 8% of Australia's CO_2 emissions (Australian Greenhouse Office 2003).

Solar powered racing cars, powered only by sunlight, are able to travel 750km in a day at average speeds greater than 90km/h; yet we still drive around our cities in heavy, noisy, polluting cars.

Researchers at the University of South Australia (UniSA) are developing a low-mass solar-electric commuter car powered by non-polluting renewable energy. Rather than try to design a more efficient drive system for a conventional car, our approach is to take a solar racing car and make it practical. Figure 1 shows a preliminary design sketch.

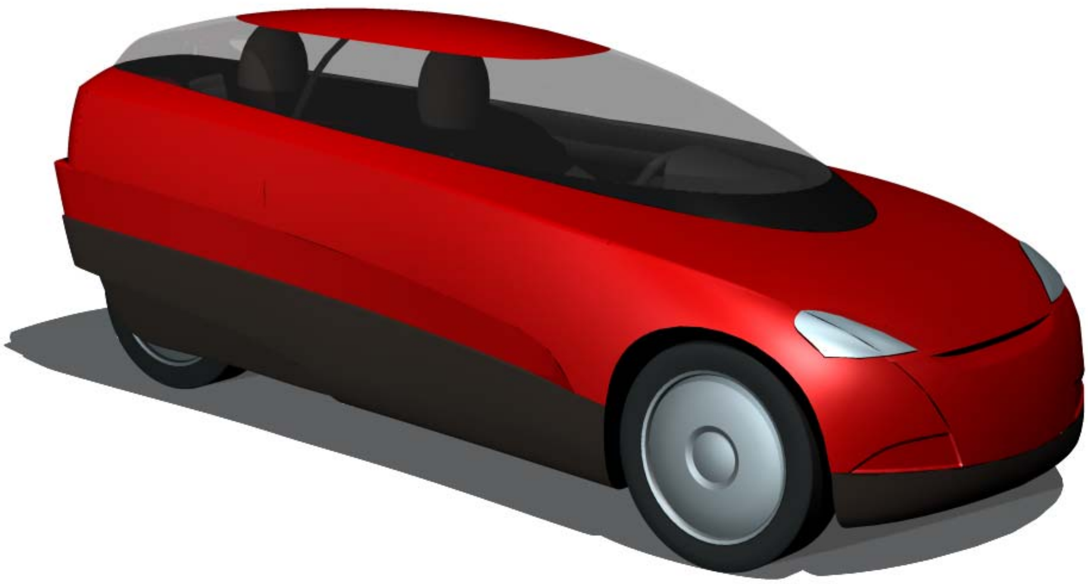

Figure 1 CAD model of the solar-electric commuter car.

Rather than try to design a more efficient drive system for a conventional car, our approach is to take a solar racing car and make it practical. Figure 1 shows a view of our CAD model, this trike has two seats, one behind the other. Our design requirements are:

- two comfortable seats, luggage space, easy entry and exit, and good all-round vision;
- a small, aerodynamic body;
- mass, without occupants, less than 350kg;
- energy-efficient tyres, brakes and suspension;
- a non-polluting, efficient electric drive system, recharged using renewable energy;
- performance compatible with normal traffic;
- compliance with road safety and worthiness regulations;
- a commuting range of 100-150km; and
- electrical energy use less than 200kJ/km.

The car will have an electric drive system, with a high-efficiency, electronically controlled motor. The energy will most likely be supplied from a lithium ion polymer battery. The automotive industry seems to be relying on the development of fuel cells and hydrogen to power their future cars; the energy requirements of our car will be low enough that we can use existing battery technologies that are simpler and more efficient.

One of our most important requirements is that the car is non-polluting. Solar racing cars use photovoltaic cells on the upper surface of the car as a clean energy source. However, it is neither practical nor desirable to power a commuter car using only on-board photovoltaic cells:

the energy use of a practical commuter car in city traffic will be about three times that of a solar racing car on the open road (the Aurora solar car used about 50kJ/km during the 1999 World Solar Challenge);

the car will not have enough surface area to generate surface area to generate sufficient energy; and

photovoltaic panels are much more effective on the roof of a building, where they can be facing the sun and unshaded for much greater time intervals.

So our commuter car will be primarily a battery electric car, recharged using electricity generated from non-polluting renewable energy sources such as photovoltaic, wind and hydro-electricity. However, we will use some photovoltaics on the car, to extend the range and to keep the car cool when it is parked in the sunlight. In summer, a $1m^2$ photovoltaic panel will generate enough energy to drive the car 15–20km.

Predicting the energy required to drive the car is an important part of the project—as well as letting us assess the importance of various design parameters, it will help us determine the amount of energy storage required in the car. The rest of this paper shows how we can predict the energy use of our proposed car.

Modelling the drive system

The force required to move a car along a road is

$$F = m\frac{dv}{dt} + R(v) - G(x)$$

where t is time, x is position along the road, v is the speed of the car, and m is the mass of the car. The first term is the force required to accelerate the car. $R(v)$ is the resistive force acting against the car and $G(x)$ is the gradient force acting on the car.

The resistive force acting against the car can be modelled as

$$R(v) = mgc_{rr} + \frac{1}{2}\rho c_D A v^2.$$

The first term is rolling resistance, due primarily to the tyres; g is the acceleration due to gravity, and c_{rr} is a coefficient of rolling resistance. The second term is aerodynamic drag; ρ is the density of air, and $c_D A$ is the drag area of the body.

The force on the car due to the gradient is

$$G(x) = -mg\sin\theta(x)$$

where $G(x)$ is the angle of slope of the road at position x. Gradient force is negative on inclines, where θ is positive.

The drive system of the car comprises an electric motor, the motor control electronics, and a mechanical transmission. Electric motors are ideal for traction applications—they are able to generate high torque at low speed and over a wide speed range, and so a variable-ratio gearbox is not required.

The efficiency of the drive system depends on the efficiencies of each of the components, which in turn may depend on the speed of the car and the torque being generated or transmitted. For now we will ignore the details, and simply model the efficiency of the drive system as $\eta_D(v, F)$, where F is the drive force at the wheels of the car.

The power that must be supplied to the drive system to generate a drive force
F at speed v is

$$p = \frac{Fv}{\eta_D(v, F)}.$$

An electric traction system can implement regenerative braking—during braking, some of the kinetic energy of the car can be converted back into electrical energy and stored in the battery. We can model this in the drive efficiency function, η_D. For example, if the motor, controller and transmission have a combined constant efficiency η_m and the mechanical brakes dissipate a proportion ρ_B of the braking energy then

$$\eta_D(v, F) = \begin{cases} \eta_M & F \geq 0 \\ \frac{1}{\eta_M(1-\rho_B)} & F < 0 \end{cases}.$$

If we assume that the battery has constant energy efficiency η_B then the rate of change of the battery energy use Q can be modelled by the differential equation

$$\frac{dQ}{dt} = \begin{cases} p & p \geq 0 \\ \eta_B p & p < 0 \end{cases}.$$

Commuting requirements

Commuting requirements, and the associated fuel consumption or energy use, are usually derived from data collected in instrumented cars. Instrumenting a conventional petrol car to measure instantaneous power use is quite difficult. Instead, we used a Solectria electric car loaned to UniSA by Gerard Industries. The advantage of an electric car is that drive power can be calculated from simple measurements of battery voltage and current.

The authors logged 57 hours (2300 kilometres) of commuting in a Solectria electric car. Figure 2 shows a map of where the electric vehicle travelled on the Adelaide road network. The points on the map represent data captured at one-second intervals by the logging system. The "Info Tool" dialog box shows the attributes that are associated with each point: data from a Global Positioning System (GPS) receiver, which includes time, position and speed of the vehicle, and measurements of battery current and voltage (Pico channel A and B).

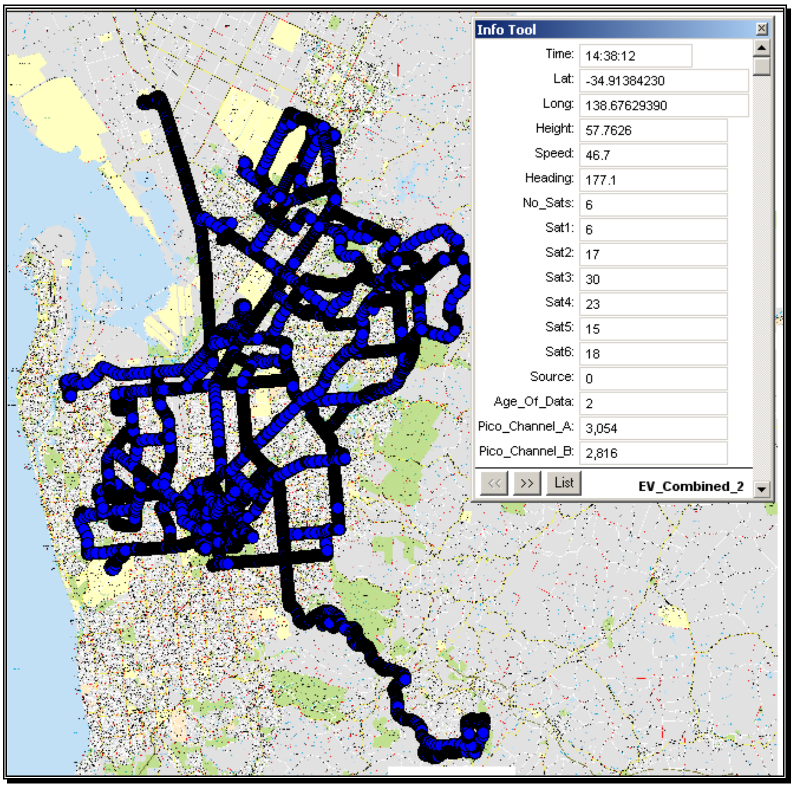

Figure 2 GIS plot of trips made in the Solectria electric car

One way we could predict the energy use of our solar-electric commuter car would be to extract sequences of speed, acceleration and gradient from the logs, and then calculate the power required for the car to follow these sequences, second by second. But the power requirement at state (v, a, θ) is independent of time it does not depend on how the car got to that state or on what it will do next. Instead of calculating power for long sequences of journey states, we can instead approximate the density of the journey state space by a histogram, and calculate energy use from the histogram.

The data logged in the instrumented car includes GPS speed and altitude at one-second intervals. We approximate the acceleration of the car at time ti by the central difference

$$a_i \approx \frac{v_{i+1} - v_{i-1}}{2\Delta t}.$$

Road gradient is more difficult to calculate, since GPS altitudes are not accurate enough for a direct calculation. To estimate gradients, we first use the time and altitude data to constructed an altitude profile (*x, h*) where x is the distance travelled since the beginning of the trip, calculated by integrating the speed of the car, and h is the measured altitude. We then smooth this altitude profile by setting the smoothed altitude at distance *x* to be the weighted mean of nearby altitudes. The gradient of the road at time ti is then approximated by the change in smoothed altitude during the time interval $[t_{i-1}, t_{i+1}]$, divided by the distance travelled during the same time interval:

$$\gamma_i = \sin\theta_i \approx \frac{h_{i+1} - h_{i-1}}{x_{i+1} - x_{i-1}}$$

If the distance travelled during the interval is zero then we set $\gamma_i = 0$.

Our histogram uses bins centred on states $\{(v, a, \gamma) \mid v \in \{0, 1, \ldots, 35\}, a \in \{-10, -9.5, \ldots, 10\}, \gamma \in \{-0.10, -0.09, \ldots, 0.10\}\}$, where v is in ms^{-1} and a is in ms^{-2}.

Figure 3 shows speed, acceleration and grade histograms for the 57 hours of city driving in the Solectria electric car. In Figure 4, colour indicates the position of each histogram bin and opacity indicates the relative number of samples in each bin. The histogram in Figure 5 shows the time of day during which the data was collected.

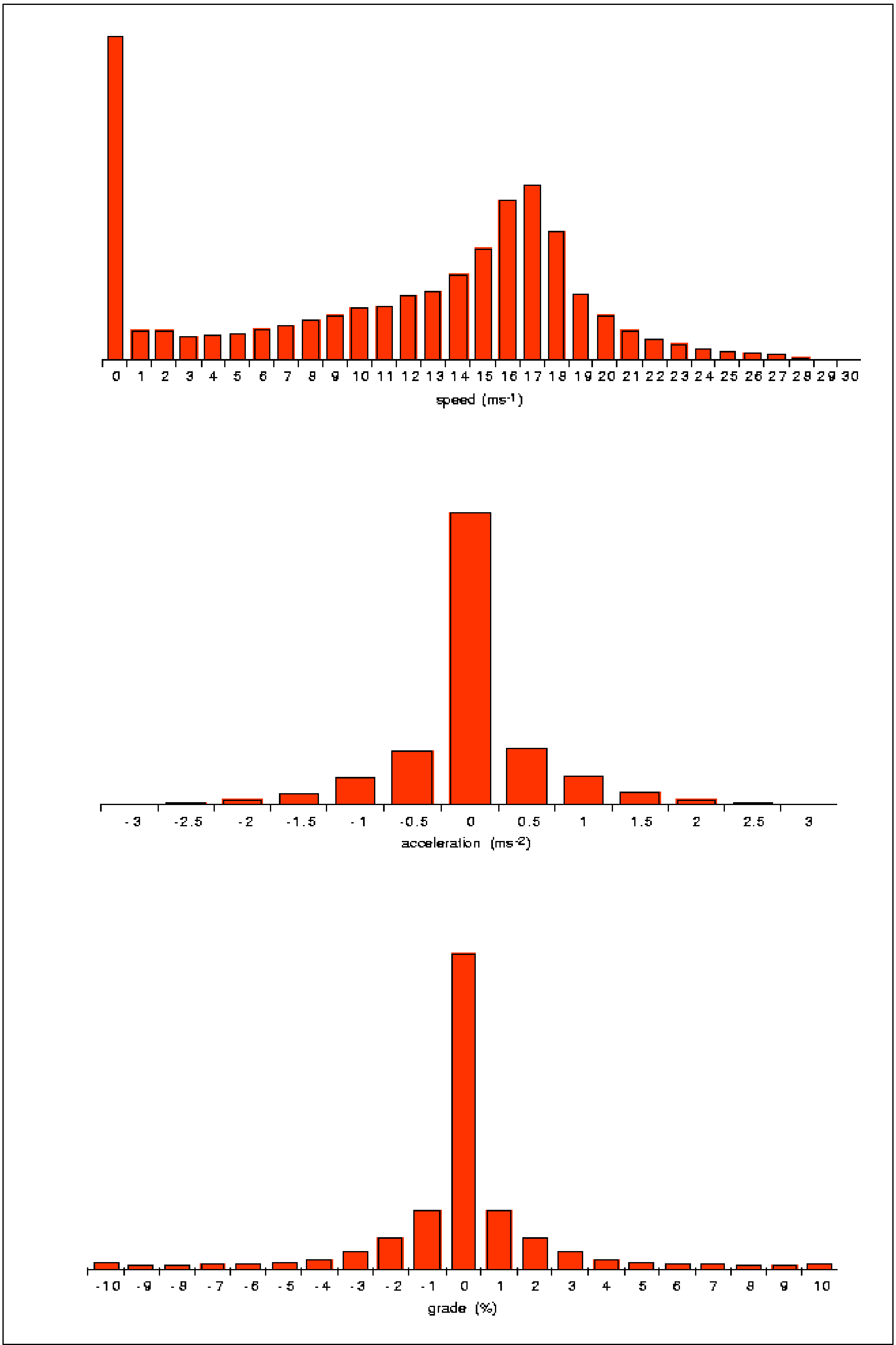

Figure 3 Speed, acceleration and gradient histograms for city driving

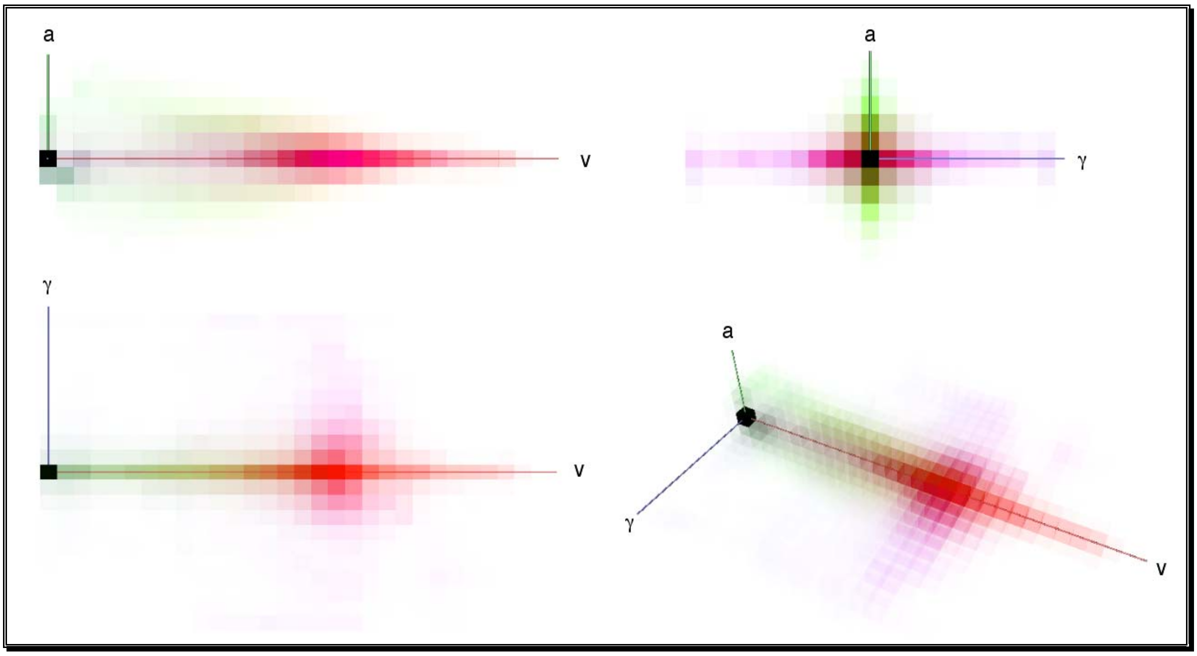

Figure 4 Four views of a 3D(v,a,γ) histogram for city driving. Colour indicates the position of each bin; opacity the number of samples in each bin

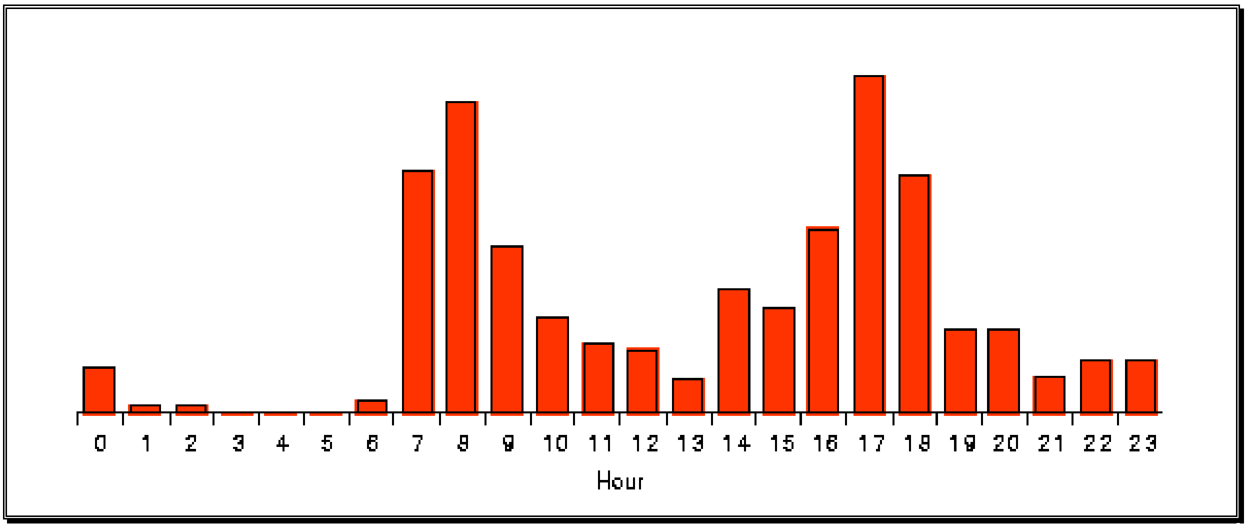

Figure 5 Histogram showing the time of day when data were collected

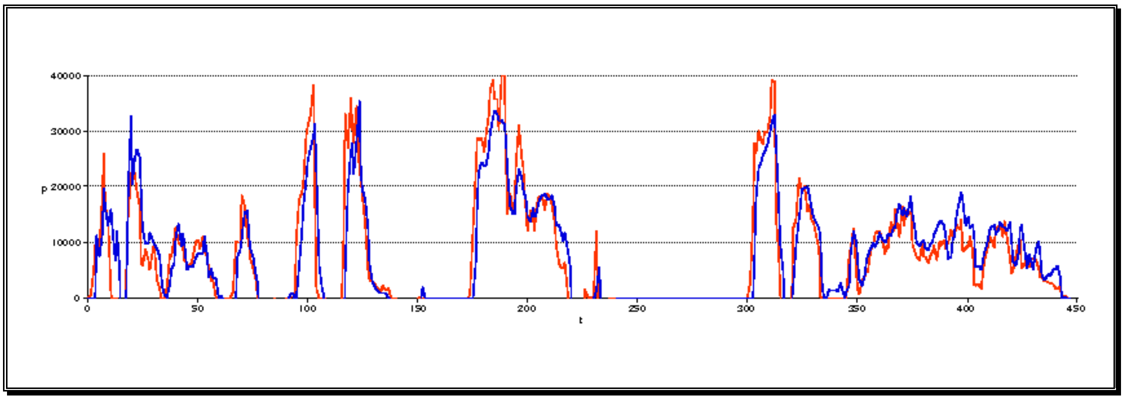

Figure 6 Measured power (red) and predicted power (blue) for part of a trip

Modeling the Solectria electric car

The Solectria electric car was originally a conventional petrol car a Daewoo Cielo but has been converted to electric drive by Solectria Corporation. The car has the following features:

mass	1270kg
motor	48kW AC induction motor
transmission	13:1 reduction, front wheel drive
battery	240V, 90Ah Nickel metal hydride (NiMH) battery
charger	240V, 20A or 15A, single phase
other features	electric brake vacuum pump, resistive heating, electric air conditioning motor

We used the car for our normal commuting for about three months. Each time the car was recharged we measured the energy supplied to the charger. The results were:

total distance (km)	4326
total recharge energy (MJ)	3176
kJ/km	734

The overall CO_2 emissions intensity of electricity supplied in Australia in 1999 was 0.985kg/kWh (Australian Greenhouse Office 2001). A coal-fired power station generates about 1kg/kWh (Geoscience Australia 2001). A gas-fired power station has about half the emissions of a coal-fired station. If we assume the average emissions for Australian power stations, the emissions for the electric car would be about 200g/km.

The original Daewoo Cielo would have had a fuel efficiency of about 8l/100km, and so the CO_2 emissions from the original car would have been 180g/km (Greenfleet 2001). This figure probably does not include the emissions associated with producing the petrol and delivering it to the car, which would add another 20-30g/km.

The CO_2 emissions for the electric car would be about the same as those of the original petrol car if the electricity is sourced from an average Australian power station. If the electricity is sourced from a gas-fired power station, the emissions for the electric car drop to about half of the emissions of the original car. *But the electric car can also be recharged using renewable energy, in which case there are no emissions.*

We collected detailed data for about 2300km of urban driving in the Solectria car. The data collected included the battery voltage and battery current, from which we calculated the instantaneous battery power. The measured power during traction is predicted reasonably well by

$$p(v, a, \gamma) = \frac{1}{\eta_D}[mav + mgc_{rr}v + 1/2\rho c_D A v^3 + mg\gamma v]$$

with the parameters

mass with one occupant (kg)	$m = 1380$
rolling resistance coefficient	$c_{rr} = 0.015$
aerodynamic drag area (m^2)	$c_{DA} = 0.70$
drive efficiency	$\eta_D = 0.85$
acceleration due to gravity (ms^{-2})	$g = 9.8$
density of air (kgm^{-3})	$\rho = 1.2$

These parameters were obtained by estimating values for the rolling resistance coefficient and the efficiency of the AC induction drive, and then calculating the drag area using a least-squares fit to power measurements taken during a journey on a relatively level road. The calculated drag area is not unreasonable for the size and shape of the car. Figure 6 shows measured power (red) and predicted power (blue) for part of a trip.

We can use the car model and our histogram data to predict the energy use of the Solectria car, and compare it to the measured energy use. We assume that the drive efficiency is

$$\eta_D(F) = \begin{cases} \eta_M & F \geq 0 \\ \frac{1}{\eta_M(1-p_M)} & F < 0 \end{cases}$$

with $\eta_M = 0.85$ and $\rho_B = 0.3$ and that the battery efficiency is $\eta_B = 0.75$.

The histogram data is a set of tuples $\{(v, a, \gamma, t)\}$ where t is the total time spent in state (v, a, γ). The total energy taken out of the battery is predicted by

$$Q = \sum t \frac{dQ}{dt}(v, a, \gamma).$$

The total energy required to recharge the battery is

$$E = \frac{Q}{\eta_B}.$$

The total distance travelled is approximated from the histogram data by $X = \Sigma tv$; the energy use for the car is the total energy required to recharge the car, divided by the total distance travelled.

The energy use predicted for the Solectria electric car is 738kJ/km; the measured value was 734kJ/km.

Energy use for the solar-electric commuter car

We can use the same method to predict the energy use of our proposed solar electric commuter car. The car will have the following features:

Low mass: The chassis will be build from aluminium honeycomb panels and clad with foam and a plastic skin. Windows will be polycarbonate. Every component will be designed to minimise mass. The target mass of the car, without occupants, is 350kg.

Low rolling-resistance: The car will use low rolling-resistance tyres, with c_{rr} less than 0.1. The suspension will be designed to minimise tyre scrub due to toe-in and lateral movement of the tyres during suspension movements. Brake pads will be retracted away from the disks when the brakes are released.

Low aerodynamic drag: The car will have a small streamlined body, with covered rear wheels, smooth underside, and low frontal and surface areas. The target drag coefficient is 0.20, with $c_D A = 0.26$.

Efficient drive: The car will use a rare-earth permanent magnet, brushless motor and an efficient transmission. The overall drive efficiency will be greater than 90%.

Low mass: efficient battery. The battery will be a lithium ion polymer battery with an energy efficiency greater than 95% and a total mass less than 50kg.

The parameters for our energy model are:

mass with one occupant (kg)	$m = 420$
rolling resistance coefficient	$c_{rr} = 0.01$
aerodynamic drag area (m^2)	$c_D A = 0.26$
drive efficiency	$\eta_D = 0.90$
battery efficiency	$\eta_B = 0.95$

Using the same (v, a, γ) data as for the Solectria car, the predicted energy use for the solar commuter is 151kJ/km; this is about 1/5 of the energy required for the Solectria car.

Sustainable transport

The high energy density of petrol has allowed the development of vehicles that are incredibly inefficient. The automotive industry is tackling the problem of dwindling oil supplies and increasing greenhouse gas (GHG) emissions by developing more efficient drive trains. Hybrid vehicles have also become available for retail sale in recent times and are claimed to have about 70% of the fuel consumption of conventional cars. By turning off the petrol engine while the car is stationary, emissions can be reduced to as low as 20% of the emissions of a conventional car.

Converting a conventional car to battery-electric drive does not reduce GHG emissions if the electricity used to recharge the batteries is sourced from a coal-fired power station. Furthermore, the range of the battery-electric car will be about one quarter that of the conventional car, and the electric car takes many hours to recharge.

If electricity is sourced from gas-fired power stations then GHG emissions from a battery-electric car are about half those of a comparable petrol car. If electricity is supplied from a renewable energy supply then there are, of course, no emissions.

Hydrogen fuel cells are being touted as the solution to our energy and emissions problems. However, there are significant problems to be overcome. Current technologies for the on-board storage of hydrogen must be improved to in order to be safe and provide the vehicle with a suitable driving range. More importantly, the power plant to wheel efficiency of a hydrogen car is not significantly better than modern diesel or hybrid cars (Bossel, 2003). If the hydrogen fuel is not produced with renewable energy then GHG emissions from fuel cell cars are no better than those from a diesel or hybrid cars.

Our approach is to design a commuter car that has much smaller energy requirements than a conventional car. By designing a small, aerodynamic car with a mass of 350kg and an efficient electric drive system, our predicted energy use is one-fifth that of a conventional car. With such a low energy use, the car can be powered using motor and battery technologies similar to those used in solar racing cars.

The safety of such a small, low-mass vehicle is, of course, a concern. Our initial approach is to ensure that the car accelerates, brakes and handles well. We have also designed the car without ‘A’ pillars and placed the passenger behind the driver, so that the driver has an unobstructed view of the surrounding traffic. One advantage of a low-mass car is that it will inflict less damage in a crash. Protecting the occupants of a low-mass vehicle in a crash with a heavier vehicle is a challenge, but not an insurmountable one. It is an area of research that the authors are exploring.

Conclusions

The authors have used an electric car to measure the instantaneous power requirements for commuting around Adelaide. Commuting requirements are then characterised by the proportion of time spent in each (v, a, γ) state.

We have then developed a mathematical energy-use model of the electric car. The energy use predicted by our model agrees remarkably well with the observed energy use.

Finally, we have used the same mathematical model to predict the energy use of a proposed low-mass solar-electric commuter car, which is based on the technologies used in solar racing cars. The proposed car will have an energy use of about 1/5 of that of a conventional car. Furthermore, when it is recharged using renewable energy, the car can be operated without producing any emissions, hence provide a pathway to sustainable transport.

Acknowledgements

The authors would like to thank our anonymous reviewer for some useful suggestions.

The authors would also like to thank John Packer for his design and modelling of the commuter car body.

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