**THE *ULTRACOMMUTER*: A VIABLE AND DESIRABLE SOLAR-POWERED COMMUTER VEHICLE**

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**Abstract**

The University of Queensland *UltraCommuter* project is the demonstration of an ultra-light weight, low drag, energy efficient and low polluting, electric commuter vehicle equipped with a $2.5m^2$ on-board solar array. A key goal of the project is to make the vehicle predominantly self-sufficient from solar power for normal driving purposes, so that it does not require charging or refuelling from off-board sources. This paper examines the technical feasibility of the solar-powered commuter vehicle concept, as it applies the *UltraCommuter* project.

A parametric description of a solar-powered commuter vehicle is presented. Real solar insolation data is then used to predict the solar driving range for the UltraCommuter and this is compared to typical urban usage patterns for commuter vehicles in Queensland. A comparative analysis of annual greenhouse gas emissions from the vehicle is also presented.

The results show that the *UltraCommuter*'s on-board solar array can provide substantial supplementation of the energy required for normal driving, powering 90% of annual travel needs for an average QLD passenger vehicle. The vehicle also has excellent potential to reduce annual greenhouse gas emissions from the private transport sector, achieving a 98% reduction in $CO_2$ emissions when compared to the average QLD passenger vehicle. Lastly, the vehicle battery pack provides for tolerance to consecutive days of poor weather without resorting to grid charging, giving uninterrupted functionality to the user. These results hold great promise for the technical feasibility of the solar-powered commuter vehicle concept.

## 1. INTRODUCTION

Since 1983, when Hans Tholstrup and Larry Perkins crossed Australia in *Quiet Achiever*, the dream of solar-powered cars has been a reality [1]. Solar vehicle technology has developed and matured through racing events such as the World Solar Challenge, and nowadays it is not uncommon for solar cars' performance to be limited by posted speed limits, rather than by the size and efficiency of their arrays.

Despite this, existing solar cars are a clear product of their race-bred history, and contain few of the features that might be expected in a practical vehicle. Awkward styling, limited seating, cramped conditions, no cargo capacity and a lack of accessories (especially air-conditioning!) are common traits in most solar cars, not to mention the limitation of being able to drive only in daylight hours. Few would argue that the solar cars of today represent a feasible means of transportation for the future.

### 1.1 The *UltraCommuter* Project

The University of Queensland *UltraCommuter* project is a demonstration vehicle that will change peoples' expectations about what is possible with a solar-powered car. Designed according to the Hypercar[SM] philosophy [2], the *UltraCommuter* will be an ultra-light weight, low drag, energy efficient, low polluting, series hybrid-electric commuter vehicle, optimised for Australian driving conditions, but with no compromises in vehicle performance, utility or comfort. More importantly, however, the *UltraCommuter* will be predominantly solar powered.

*Figure 1: A model of the UltraCommuter, currently being developed at The University of Queensland*

Researchers from the University's Sustainable Energy Research Group (SERG) are currently entering the construction phase of the project, intending to demonstrate the *UltraCommuter* in the World Solar Challenge in November 2003.

The purpose of this paper is to examine the technical feasibility of a solar powered commuter vehicle – a crucial aspect of the *UltraCommuter's* design.

## 2. ULTRACOMMUTER DESIGN AND TECHNICAL SPECIFICATIONS

Intended predominantly for use in urban commuting, the vehicle will be 3.8m long, 1.3m high and 1.6m wide, providing two comfortable seats with ample boot space for extra luggage. The interior will house intelligent electronic controls and displays, and the vehicle will feature full accessories, including climate control and entertainment systems.

### 2.1 Powertrain & Solar Array

Configured as a sports coupe with a mass of only 600kg, the *UltraCommuter* will be equipped with two 75kW high-performance wheel motors and a lightweight 75kg rechargeable lithium-ion battery pack. These will combine to give impressive performance – a 0-100km/h time of 8 seconds and 190km of driving range.

Parked in a sunny location, a 2.5m$^2$, 15% efficient, 375W solar array on the upper surface of the vehicle will store up to 3.0kWh of solar energy per day in the batteries, depending on conditions, supplementing the energy requirements for daily commuting. While it is possible to charge an electric vehicle from solar panels placed atop a garage or roof (this potentially allows a larger array area and reduces the mass of the vehicle), a primary aim of the *UltraCommuter* project is to design a predominantly self-sufficient vehicle that does not require charging or refuelling from off-board sources.

The battery range of 190km allows for tolerance to consecutive days of poor weather without resorting to grid charging. Should charging be required, the 8.6kWh capacity could be completely recharged by a standard 240V 10A wall outlet in approximately four hours.

Further developments to the powertrain of the *UltraCommuter* will include the possible addition of a hydrogen- or natural gas-fuelled range extender for clean and efficient longer trips (up to 500km range).

## 3. TECHNICAL FEASIBILITY OF THE *ULTRACOMMUTER* AS A SOLAR-POWERED COMMUTER VEHICLE

To determine the feasibility of the *UltraCommuter* as a solar-powered commuter vehicle, we must determine to what extent solar power can supplement the daily energy needs of the vehicle for driving purposes. This issue is most easily addressed by calculating what solar-powered driving range (SDR) is provided by the on-board solar panel each day.

A parameterised description of a solar-powered vehicle is presented to calculate the daily SDR. Following this, the specific energy consumption (in watt-hours per kilometre) of the *UltraCommuter* is predicted for a characteristic driving schedule. Then, by using realistic solar insolation data, a prediction is made of the daily variation in SDR, thus determining the extent to which solar power can supplement the energy needs of the vehicle.

### 3.1 Parameterised Description of a Solar-Powered Commuter Vehicle

In determining the solar-powered driving range (SDR) of the vehicle, a number of parameters are relevant as shown in Table 1:

| Parameter | Symbol | Units |
|---|---|---|
| Global solar insolation | $G_{solar}$ | MJ/m$^2$ |
| Area of solar array | $A_{array}$ | m$^2$ |
| Efficiency of solar array | $h_{array}$ | % |
| Efficiency of charging circuitry | $h_{charge}$ | % |
| Energy (in-out) efficiency of battery | $h_{batt}$ | % |
| Specific energy consumption of vehicle | $\bar{E}_{vehicle}$ | Wh/km |

*Table 1: Relevant parameters for a solar-powered commuter vehicle*

These parameters may be used to calculate the SDR of the vehicle with the following expression:

$$SDR(km) = \frac{G_{solar} A_{array} h_{array} h_{charge} h_{batt}}{\bar{E}_{vehicle}} \qquad (1)$$

In using this expression, care must be taken to ensure that the flat-plane orientation of the solar array coincides with that of the measuring equipment for the solar insolation data. Typically, the standard reference for these measurements is a horizontal flat plane.

### 3.2 Specific Energy Consumption of the *UltraCommuter*

To determine the daily SDR for the *UltraCommuter* with equation 1, an estimate is needed of the specific energy consumption of the vehicle.

Estimating the energy consumption of an electric vehicle is not a simple task. An electric vehicle is a complex system, with numerous loss components that may be modelled. Furthermore, the vehicle must be modelled in operation over realistic driving schedules. However, for the purposes of this study, complicated analysis of vehicle losses is not required. The authors have devised a simple technique that is sufficiently accurate for predicting the energy consumption of the vehicle, based upon a set of typically-known vehicle parameters [3].

This technique considers the four main components of energy consumption in an electric vehicle:

- Tractive energy requirements at the wheels of the vehicle (aerodynamic drag and rolling losses)
- Braking losses
- Losses in the electric drive train (motor and controller) of the vehicle
- Battery losses

To determine the specific energy consumption of the vehicle, we require the average power consumption due to these four components, which may be summed to determine the total average power consumption of the vehicle. The specific energy consumption of the vehicle is then calculated as follows

$$\overline{E}_{vehicle} = \frac{\overline{P}_{total}}{v_{avg}} \quad (2)$$

where $\overline{P}_{total}$ is the total average power consumption of the vehicle, in watts (W), and $v_{avg}$ is the average speed of the vehicle, in kilometres per hour (km/h).

The average power consumptions due to the four loss components are expressed as follows:

$$\overline{P}_{wheel} = \tfrac{1}{2} r C_d A v_{RMC}^3 + C_{rr} m g v_{avg} \quad (3)$$

$$\overline{P}_{brake} = \left(1 - k_{regen}\right) \tfrac{1}{2} m v_{avg} PKE \quad (4)$$

$$\overline{P}_{loss-drive} = \frac{1-h_{drive}}{h_{drive}} \left(\overline{P}_{wheel} + \tfrac{1}{2} m v_{avg} PKE\right) + \left(1 - h_{drive}\right) k_{regen} \tfrac{1}{2} m v_{avg} PKE \quad (5)$$

$$\overline{P}_{loss-batt} = \left(1 - h_{batt}\right) h_{drive} k_{regen} \tfrac{1}{2} m v_{avg} PKE \quad (6)$$

$$\overline{P}_{total} = \overline{P}_{wheel} + \overline{P}_{brake} + \overline{P}_{loss-drive} + \overline{P}_{loss-batt} \quad (7)$$

where $r$ is the density of air, $C_d A$ is the coefficient of aerodynamic drag times frontal area, $C_{rr}$ is the coefficient of rolling resistance, $m$ is the total vehicle mass, $g$ is the gravitational acceleration, $k_{regen}$ is the fraction of regenerative braking, $h_{drive}$ is the electric drive train efficiency and $h_{batt}$ is the energy (in-out) efficiency of the battery. In addition to average speed, $v_{avg}$, the other driving cycle parameters are $v_{RMC}$, the root-mean-cubed velocity, and $PKE$ (m/s$^2$), the positive acceleration kinetic energy per unit distance, which is a measure of the acceleration work required in a driving pattern [4]. For equations 3-7, the average and root-mean-cubed speeds must be expressed in metres per second (m/s).

For the prediction of the specific energy consumption of the *UltraCommuter*, driving cycle parameters for the intensified (x1.2) Urban Dynamometer Driving Schedule (UDDS) were used [4]. Figure 2 shows the intensified UDDS cycle, and the cycle parameters are presented in Table 2.

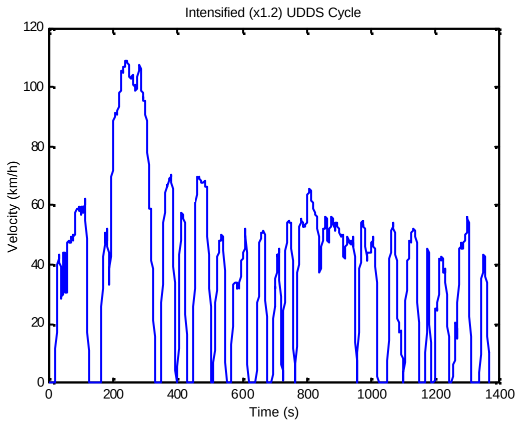


*Figure 2: The intensified UDDS cycle*

| **Driving Cycle Parameter** | **Value** |
|---|---|
| Average velocity | 37.7 km/h (10.5 m/s) |
| RMC velocity | 53.5 km/h (14.9 m/s) |
| PKE | 0.34 m/s$^2$ |

*Table 2: Descriptive parameters for the intensified UDDS cycle*

Vehicle parameters for the *UltraCommuter* used in the prediction of specific energy consumption are presented in Table 3, along with the calculated values for specific energy consumption. For comparison, specific energy consumption is also calculated for a Daihatsu Mira electric vehicle – another (crude) example of a 2-seat electric commuter vehicle also housed at The University of Queensland. Note the extraordinary difference in specific energy consumption between the two vehicles.

| **Vehicle Parameter** | **UltraCommuter** | **Daihatsu Mira EV** |
|---|---|---|
| $m$ | 680kg | 1050kg |
| $C_d A$ | 0.35m$^2$ | 0.75m$^2$ |
| $C_{rr}$ | 0.0075 | 0.01 |
| $k_{regen}$ | 1.0 | 0.0 |
| $h_{drive}$ | 90% | 70% |
| $h_{batt}$ | 90% (Li-Ion) | 70% (Pb-acid) |
| $\overline{E}_{vehicle}$ | **44.9 Wh/km** | **166.3 Wh/km** |

*Table 3: Vehicle parameters and predicted specific energy consumption for the UltraCommuter and Daihatsu Mira EV*

### 3.3 Solar Insolation Data

Real global solar insolation data was obtained from the Bureau of Meteorology [5] for Brisbane, the location of The University of Queensland St Lucia campus and likely area of operation for the *UltraCommuter*. Data was obtained for the ten year period 1985-1994, and a sample of this data (1990-1994) is shown in Figure 3. Note the observed maximum in insolation values (~30MJ/m$^2$) during the summer months, and corresponding minimum in peak insolation values (~15MJ/m$^2$) during winter months. Also note the scatter of insolation data due to varying weather conditions throughout the year.

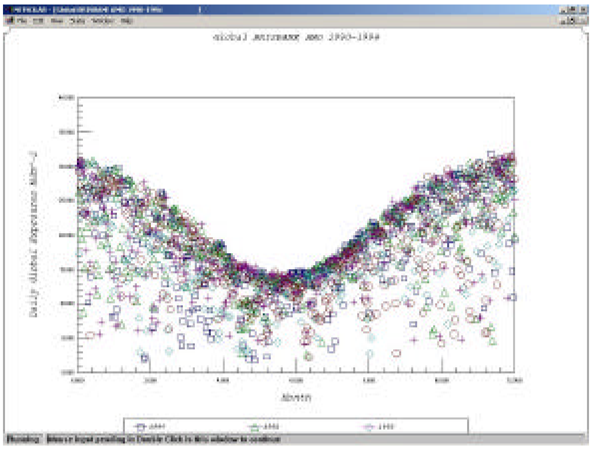

*Figure 3: Global insolation data for Brisbane during the period 1990 - 1994*

Further insight into the variation in solar insolation can be obtained from the histograms for summer and winter presented in Figures 4 and 5 respectively. For these graphs, "summer" represents the months November – January and "winter" represents the months May – July.

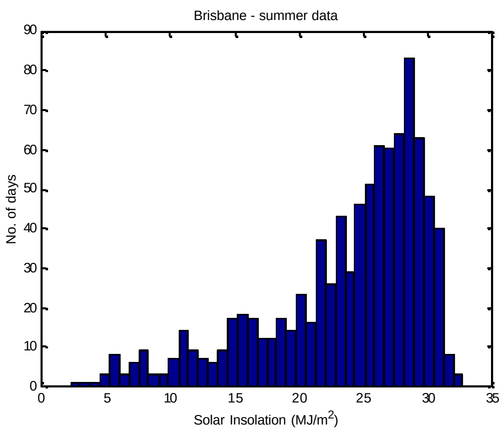


*Figure 4: Distribution of daily global insolation for Brisbane in summer*

While a detailed statistical analysis is beyond the scope of this paper, it is clear that both distributions are left-skewed, with the majority of days showing higher insolation values. This is beneficial to the feasibility of the solar-powered commuter vehicle. Also note that the general overall "shape" of both distributions is quite similar, suggesting similarities in the scatter of insolation data in both summer and winter.

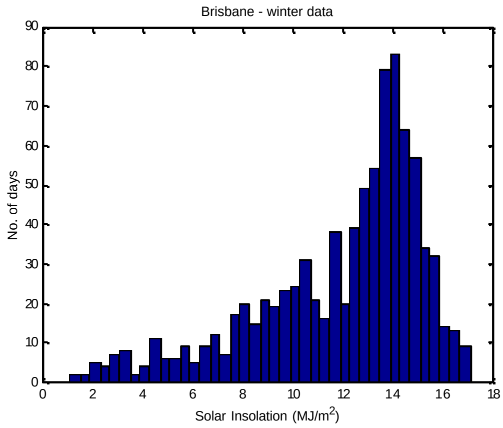


*Figure 5: Distribution of daily global insolation for Brisbane in winter*

In the following analysis, calculations of solar driving range are made using both the summer and winter data sets to allow further comparison. No account has been made for solar energy losses that may occur through shading (from trees, buildings, etc…) although, in the case of the *UltraCommuter*, researchers will ensure than the vehicle is parked in a sunny location.

### 3.4 Solar-Powered Driving Range

Using equation 1, the specific energy consumptions in Table 3 and the solar insolation data presented in section 3.3, the variation in daily solar driving range (SDR) was predicted for the *UltraCommuter*. These calculations assume a flat plane array area of 2.5m$^2$, an efficiency of 15% and a charger efficiency of 95%. For comparison, calculations were also performed for the Daihatsu Mira EV, assuming an identical on-board solar array. The distribution of daily SDR for the *UltraCommuter* in summer is shown in Figure 6.

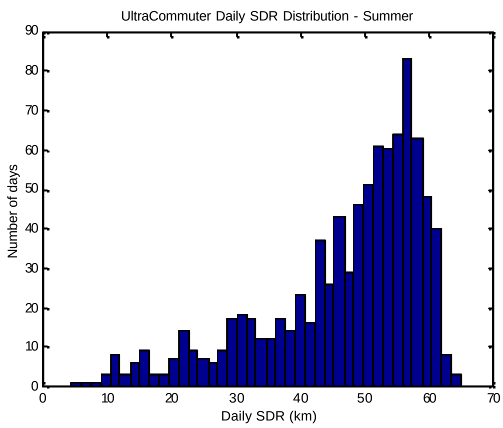


*Figure 6: Summertime distribution of daily SDR for the UltraCommuter in Brisbane*

More meaningful results can be obtained by converting the distribution in Figure 6 into a cumulative probability distribution for daily solar driving range (Figure 7). This allows an estimate to be made of the probability that the daily SDR will be greater than a given distance.

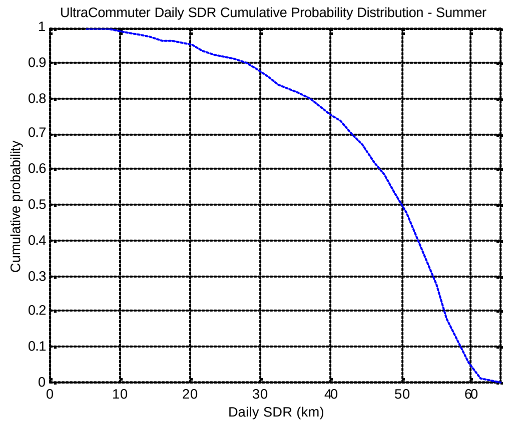


*Figure 7: Cumulative probability distribution of summertime daily SDR for the UltraCommuter*

Table 4 summarises the results from the prediction of daily solar driving range (SDR) for both the *UltraCommuter* and Daihatsu Mira EV. The results are quite promising for the *UltraCommuter*, suggesting that the on-board solar array could provide significant supplementation of the energy needs for daily driving. The results for the Daihatsu Mira are quite poor in comparison – a direct consequence of the Mira's drastically higher specific energy consumption. It is quite clear that the *UltraCommuter* would be the better solar-powered commuter vehicle of the two.

| | **UltraCommuter** | | **Daihatsu Mira EV** | |
|---|---|---|---|---|
| | Summer | Winter | Summer | Winter |
| Maximum SDR | 64.9 km | 33.8 km | 13.6 km | 7.1 km |
| Average SDR | 50.0 km | 25.4 km | 10.5 km | 5.3 km |
| 80th percentile SDR | 36.6 km | 17.9 km | 7.6 km | 3.8 km |
| 95th percentile SDR | 20.4 km | 8.9 km | 4.3 km | 1.9 km |

*Table 4: Summary statistics for the distribution of daily SDR for the UltraCommuter and Mira EV*

### 3.5 Urban Usage and Emissions Comparison

Ideally, the distribution of daily solar driving range should be compared to distributions for daily vehicle usage (in km) to predict how many days driving each year could be performed solely on the power of the sun. Unfortunately, at the time writing, such data has not been obtained (the authors are not aware if it exists at all) preventing this comparison from being made.

Fortunately, anecdotal evidence provided by staff at Queensland Transport suggests that the technical feasibility of the *UltraCommuter* as a solar-powered commuter vehicle is quite promising. A quoted rule-of-thumb for Queensland Transport staff is that 10% of trips are less than 1km, 30% are less than 3 km and 50% are less than 5km [6]. Also, the 1992 South East Queensland Household Travel Survey showed that more than 80% of trips are less than 10km and over 90% are less than 20km [6]. While these figures do not translate directly to daily travel distances, they do suggest that the *UltraCommuter* could perform a substantial number of these trips each day purely on solar power.

On an annual basis, the figures are also promising. The average daily solar insolation for Brisbane is 18MJ/m$^2$ [5], which translates to an average daily solar range of 35.7km for the *UltraCommuter*. This equates to 13 000km of annual solar-powered travel. From the 1999 Australian Survey of Motor Vehicle Use [7], the average annual travel of Queensland (QLD) passenger vehicles was 14 300km, making for a very favourable comparison.

It is also important to realise that the battery pack range of 190km provides an excellent tolerance to consecutive days of poor weather. The average daily travel distance for a QLD passenger vehicle is approximately 40km, meaning that the *UltraCommuter* could operate for roughly 4 days of poor sunlight without resorting to grid charging.

#### 3.5.1 Greenhouse Gas Emissions

It is also interesting to examine the potential for a vehicle such as the *UltraCommuter* to reduce greenhouse gas emissions from the private transport sector. Table 5 presents specific energy consumption, equivalent fuel consumption and annual $CO_2$ emissions for the *UltraCommuter* with and without solar supplementation, the Daihatsu Mira EV without solar supplementation (its current status) and the average QLD passenger vehicle [7]. These figures are calculated for 14 300km of annual travel. For the UltraCommuter and Mira, the energy for non-solar travel is provided through charging from the national grid. These calculations assume $CO_2$ emission values of 0.92kg$CO_2$/kWh for grid electricity [8, 9] and 2.3kg$CO_2$/L for passenger vehicle fuel [10] and a grid transmission efficiency of 90% was also assumed.

Table 5 shows the reduction in $CO_2$ emissions that is achieved through solar supplementation of the *UltraCommuter*'s energy needs for driving. It also confirms the potential for a vehicle such as the *UltraCommuter* to reduce greenhouse gas emissions from the passenger vehicle fleet. The annual $CO_2$ reduction from the solar-powered *UltraCommuter* compared to the average QLD car is 3.65 tonnes $CO_2$ per car, which represents a 98% saving.

| Vehicle | Specific energy/fuel consumption | Average daily solar driving range (km) | Annual $CO_2$ emissions (tonnes) |
|---|---|---|---|
| UltraCommuter | 44.9 Wh/km ($0.55L/100km_{eq}$) | 28.5 | 0.07 |
| UltraCommuter – no solar | 44.9 Wh/km ($0.55L/100km_{eq}$) | N/A | 0.77 |
| Mira EV – no solar | 166.3 Wh/km ($2.04L/100km_{eq}$) | N/A | 3.66 |
| Average QLD passenger car | 11.3 L/100km | N/A | 3.72 |

*Table 5: Comparison of specific energy consumption, equivalent fuel consumption and annual $CO_2$ emissions for the UltraCommuter, Daihatsu Mira EV and the average QLD passenger vehicle*

Even if a vehicle such as the *UltraCommuter* could only achieve 1% penetration in the QLD vehicle fleet of 1 751 895 registered passenger vehicles [7], the annual reduction in greenhouse gases would still amount to 64 000 tonnes of $CO_2$ each year.

It is also interesting to note the limited reduction in $CO_2$ emissions achieved by the Daihatsu Mira EV as compared to the average typical QLD vehicle, despite its relative advantage in equivalent fuel consumption. The predominant use of high carbon intensity fuels (such as brown and black coal) in Australian power generation can be attributed to this result.

## 4. CONCLUSION

The *UltraCommuter* project will demonstrate an energy efficient and low polluting electric commuter vehicle, predominantly powered by an on-board solar array for its normal driving needs. Based upon the analysis of the solar driving range of the vehicle, a number of conclusions can be made:

1. A $2.5m^2$ solar array on the vehicle will provide substantial supplementation of the energy required for normal driving needs. On an annual basis, the solar array will collect enough energy to power the *UltraCommuter* for 13 000km of travel, or 90% of the annual travel of the average QLD passenger vehicle.

2. Furthermore, the *UltraCommuter* can also expect substantial solar supplementation on a daily basis. In summer, the average daily solar driving range (SDR) is 50.0km, with 80% percent of daily SDR being greater than 36.6km. In winter, the corresponding values are an average of 25.4km and an 80% percentile of 17.9km.

3. The battery pack in the *UltraCommuter* provides a good tolerance to consecutive days of limited solar charging. Based on average usage, the vehicle could operate for 4 consecutive days of poor weather without resorting to grid charging.

4. Solar supplementation of the *UltraCommuter* achieves an excellent (91%) reduction in $CO_2$ emissions below what would normally be achieved by powering the vehicle solely from grid electricity.

5. A vehicle such as the *UltraCommuter* has excellent potential to reduce greenhouse gas emissions from the private transport sector. In comparison with the average QLD passenger vehicle, the *UltraCommuter* achieves a saving of 3.65 tonnes $CO_2$, or 98%, per vehicle.

These results hold great promise for the technical feasibility of the solar-powered commuter vehicle concept and the *UltraCommuter* project.

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