EVS24
Stavanger, Norway, May 13-16, 2009

A Review of the Smart EV and an Analysis of the Required Developments in Battery Electric Vehicles in Order to Achieve Market Success

Timothy Moorin[1], Adrian Dickinson, Edward Moxey
[1] *University of Surrey, Guildford, United Kingdom, en41tm@surrey.ac.uk*

Abstract

This paper assesses the relative market success of battery electric vehicles that are likely to be developed over the next 3 years. It draws on the experiences of a sample of potential customers that have driven a prototype Smart EV and market research into the relevance of the product characteristics to a small sample of environmentally-concerned consumers when considering the purchase of a vehicle for urban use. Although the responses to the actual experience of driving the prototype Smart EV were better than prior expectations, many of the trial respondents still harboured concerns over the limited range and size of the vehicle. As such, no respondent wished to purchase the vehicle at the current price point. Naturally technology does not stand still and each generation of BEV will show significant improvements. Past experience with the automotive industry indicates that the design brief for each new model starts by taking up to 40% out of the cost of manufacture. This saving is typically used to fund enhancements to the vehicle design; such as ABS, air-conditioning, or increased performance. The authors have posited three different development paths that manufacturers could consider: a 35% reduction in price; a larger, more comfortable car; and a high performance two-seater. In order to understand how customers would respond, conjoint analysis was used on the major product characteristics being considered. A picture was built of consumer preferences that can be used to model the putative market shares of different urban compact vehicles when offered to the cohort of consumers typified by the sample of respondents to the research. This revealed that the next generation of BEVs could reach a combined 33% market share against the traditional models. The most potential, at 27%, was shown by the concept BEV with 4 seats and space to store shopping or luggage. Second was the sportier BEV with better driving performance and an estimated market share of 5%. Simply reducing the price is unlikely to increase the chances of market success as the low-cost BEVs with a characteristic profile similar to that of the current Smart EV gained < 1% market share.

Keywords: Market, Sales, BEV (Battery Electric Vehicle), Passenger Car, Optimization

1 Introduction

Electrically powered vehicles are often heralded as one of the major technical innovations that can be deployed to tackle climate change. However, past experiences of electric vehicles have often been poor and there are still a number of technological and customer perception challenges to overcome before a reasonable level of market success can be achieved.

Currently, most of the battery electric vehicles available for purchase are seriously constrained in terms of either their; driving performance, size, maximum range before recharge, or their high purchase price. Although a number of the major vehicle manufacturers are releasing, or developing, BEVs over the next 12 to 18 months, a significant number appear to be converting one of their existing compact vehicles using the best available technology within a distinct purchase price capping.

2 Smart EV Prototype

The Zytek prototype Smart EV is essentially a standard Smart Fourtwo that has been converted to a BEV by replacing the drive train with a 55KW (74bhp) neodymium permanent magnet brushless DC motor, operated at a reduced power output of 30kW (40bhp) and producing a maximum torque of 120Nm[1]. Unlike many EVs, the Smart is equipped with all the safety equipment that is standard on a regular Smart such as, ESP, ABS brakes, driver and passenger airbags and seatbelt pre-tensioners. The motor is powered by a ZEBRA (Liquid Sodium-Nickel Chloride) battery, via a 3-phase IGBT bridge, as shown in Figure 1, and can be operated as a generator during braking in order to recapture energy that would otherwise be lost. The conversion adds ~130Kg to the original 990Kg vehicle.

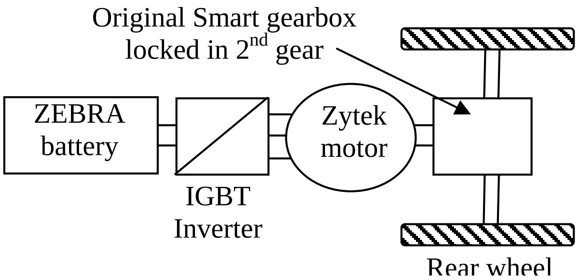

Figure 1: Prototype Smart EV Drive-Train Topology

2.1 ZEBRA battery Module

The ZEBRA battery module, Figure 2, has previously been utilised successfully in many applications, ranging from prototype electric vehicles, such as the BMW E1 and various electric/hybrid city buses, to military use in submersibles. At the time of the Smart EV development the ZEBRA battery module exhibited one of the highest energy densities, when comparing available and proven competing battery technologies. A typical ZEBRA battery has an energy density of 120Wh/kg, which is around 4 times that of an equivalent lead acid and 2 times that of a nickel metal hydride battery [2]. ZEBRA cells also demonstrate maintenance free operation, a high level of safety and are unaffected by ambient temperature. One key feature of the system is the ability to effectively bypass failed cells so that overall performance is left unaffected by component breakdown. However, they suffer from a low power density of 180W/kg and are unable to sustain a high discharge rate with a C-rating of 1.5 [2,3].

Figure 2: ZEBRA Battery Module

The specified ZEBRA battery (Z21-Smart) is rated at 15.5 kWh, with a recommended maximum discharge of 80%, leaving 12.4 kWh usable. It is also recommended that a maximum of 6.3 kWh is withdrawn from the battery over a one hour period (Plus any recaptured energy from regenerative braking). The battery has a peak power output of 24kW [4], but must be heated to 260-330°C in order to maintain the nominal voltage of ~300VDC and the 3500 nameplate cycle life [2].

2.2 Driving Experience

In the period from August 2008 – February 2009 the authors regularly drove Smart EVs, covering a distance of over 2000 miles of mixed drive cycles and conditions, keeping a regular log of all distances travelled, time taken, charge consumed and ancillary usage. This was then analysed in order to evaluate the Smart EV and our experience is summarised in Table 1.

Table 1: Smart EV Performance

Top Speed	100kph
Acceleration, 0-50kph	~6.5 s
Acceleration, 0-100kph	< 15 s
Average Maximum Range	80Km
Total Battery Drain Time, from 100% SOC	~105 hrs
Full Recharge Time	6 – 8 hrs
Net efficiency	~3.5 Km/KWh

When a ZEBRA battery is not in use, ideally it should be left on charge, otherwise the battery utilises stored energy in order to maintain its internal temperature and prevent the molten electrolyte from freezing. If the battery temperature falls below the normal operating temperature, due to a prolonged period of discharge, then the battery must be brought back to its nominal SOC and temperature before effective use. This process may require up to two days, but will vary according to the initial battery pack temperature and the power available for reheating. During testing, a battery starting with an initial 0% SOC was charged for 48 hours, in which time it consumed 23 kWh of electricity, and reached a 74% SOC. To complete the recharge process took a total of 31.51 kWh.

It was also found that whilst plugged in, a ZEBRA battery registering 100% SOC, continues to draw a further ~0.15 kW every hour in order to maintain its optimum temperature and charge. However, when the vehicle is left unplugged, the battery discharges at an average of 0.13 kW/h, although this does vary considerably, depending upon the condition that the vehicle is left in. For example the Smart was left unplugged from an initial 100% SOC and monitored over a 12 hour period, in which time it used a total of 1.78 kWh (0.148 kw/h). On a different occasion the initial SOC was 32% and 12 hours later this had been reduced by just 1.3 kWh (0.11 kW/h).

By comparing two different sets of journeys, one in the autumn where no ancillaries were used, and the second, in the winter, it can be calculated that the combination of using the radio, heater (on full), windscreen wipers and lights can draw an extra ~2.8 kW per hour from the battery and significantly reduce the range of the car. It should be noted that the Smart EV does not contain an air conditioning system.

Over the accumulated 2000 miles, containing mixed conditions and drive cycle, the Smart EVs have exhibited a number of failures that ranged from reduced power output, to a full scale breakdown. On a number of occasions the battery appeared to be operating at a reduced power output, in a situation that could more commonly be described as a “limp-home” mode. It is the authors’ opinion that the selected battery is unable to maintain the Smart EV at top speed for extended periods of time, for example motorway cruising at 63 mph, without running an unacceptably high risk of battery failure. It appears that most faults occurred after the battery was heavily drained (70-80% DOD) on journeys where the car was travelling at higher speeds.

Whilst the Smart EV demonstrates great potential for an urban zero emission vehicle with adequate performance and range for most day-to-day driving, the battery and charging system caused a greater level of unreliability than is the norm for equivalent internal combustion vehicles.

More recently, Smart owners, Mercedes-Benz have announced the introduction of a second generation electric Smart. This will represent a major upgrade where the main vehicle shortcomings are addressed. The vehicle itself, will continue to use the reliable Zytek powertrain, but will be based on the newer Smart Fortwo model, and will use a lithium ion pack supplied by Tesla motors, a US based electric sports car manufacturer. The change to a lithium ion battery will allow for increased vehicle range, potentially higher performance, reduced recharge times, as well as the possibility to reduce the battery size and weight. The cars will be produced in the second half of 2009, in limited numbers, aimed for use in European city EV trails. If the trial proves successful, the aim is to refine the prototype before ramping up production in 2012 [5].

3 Future Vehicle Development Paths

Whilst some development in the overall performance of motors and power electronics may occur, the major developments are likely to continue to be seen in the development of battery technology and the integration of components.

The new generation of lithium based batteries have demonstrated a significant increase in specific energy density and reduced risks of over-heating [6]. By comparison lithium solid polymer batteries have at least twice the maximum energy and power densities of the ZEBRA battery, used in the current Smart EV, at less than half the operating temperature [7].

At the same time, motor industry engineers are continuing to redesign the vehicles and electric systems to improve reliability and drive out cost. The extent to which this is possible is outside the scope of this paper and the authors have simply assumed a standard 40% reduction in the base cost of the vehicle for the next generation of BEVs.

In order to evaluate how a selected sample of potential customers (drawn largely from people who are would be categorised as interested in the environment and from socio-economic factor C and above) would likely to respond to future developments in BEV technology and hence the postulate improvements in future product characteristics, an experimental dataset was constructed by comparing the prototype Smart EV with other popular compact vehicles and three trajectories for development of concept EVs with; improved driving performance, or increased size/seats, or a lower purchase price. It was also assumed that all future developments would use the next generation of lithium based batteries with improved characteristics.

3.1 Improved driving performance

In this situation the cost of the vehicle is assumed to rise by £3000. The development looks at giving the vehicle an improvement in performance by reducing the vehicles mass, increasing aerodynamic efficiency, installing a more powerful motor, and an enhanced battery pack.

3.2 Increased size/ seats

One of the major limitations with the prototype Smart EV is seen to be its size. This assumed trajectory increases the overall size of the vehicle to accommodate 4+ passengers with additional luggage volume. The base line vehicle

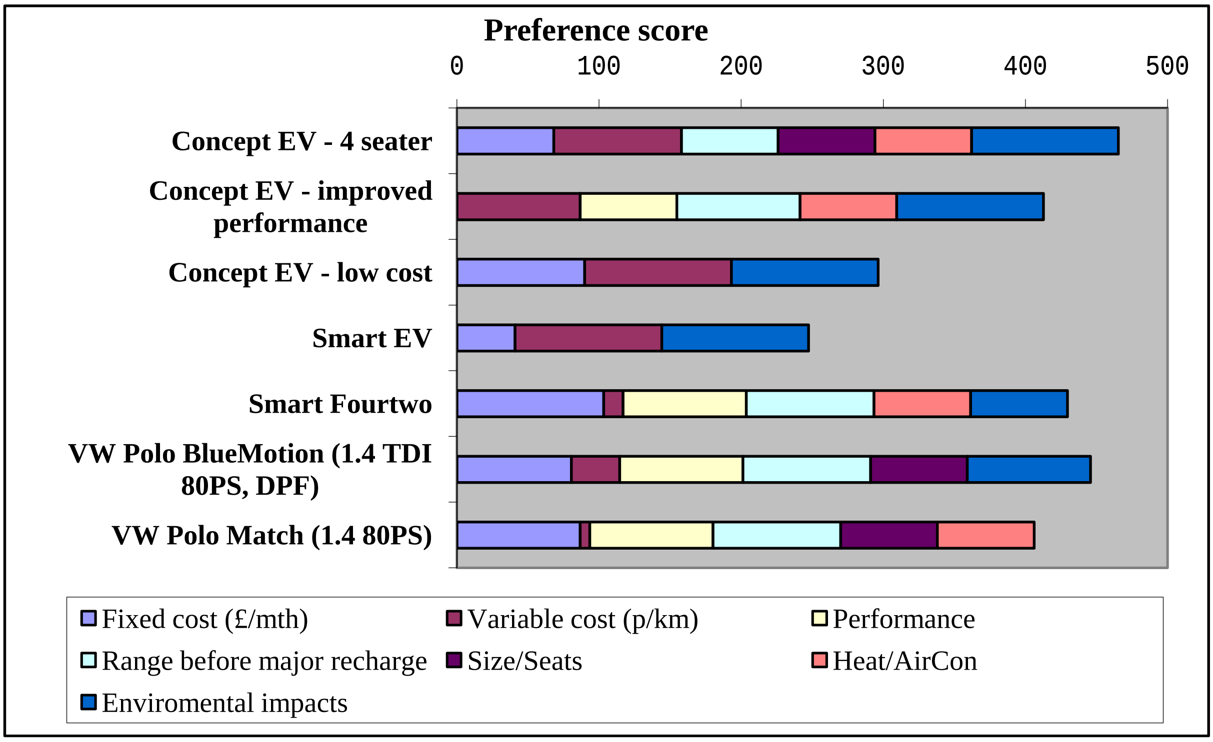

Figure 3: Example of customer preference for the Smart Fourtwo where the utility weighting for the low fixed costs and low environmental impact have been selected above the other product attributes.

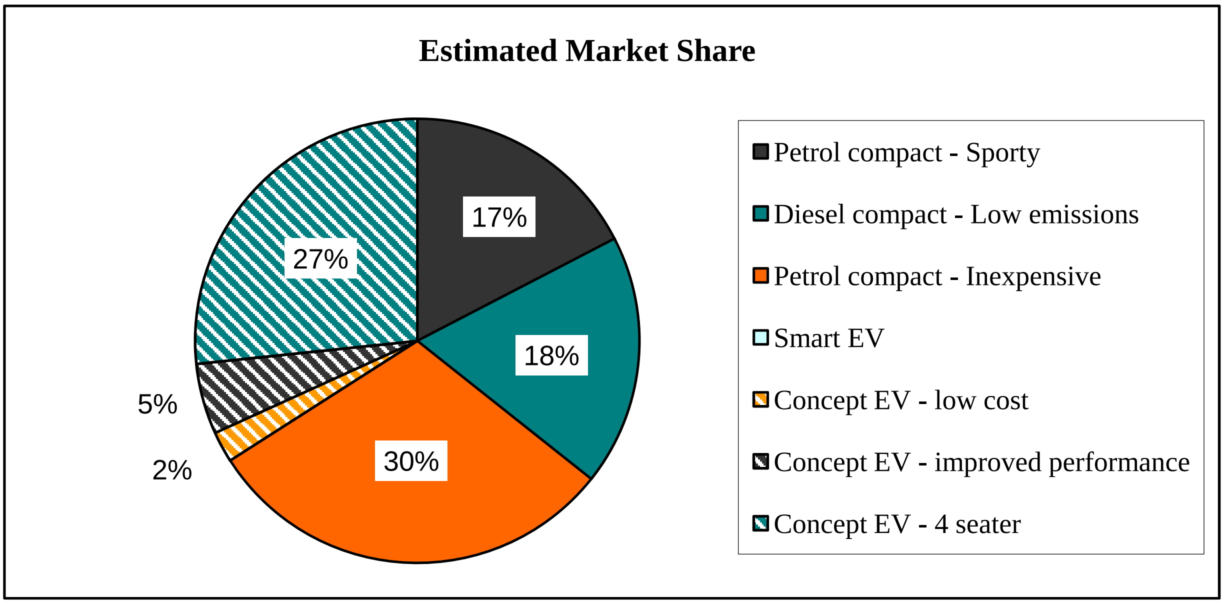

Figure 4: Pie chart of estimated market share for three concept BEVs, compared to the Smart EV and popular petrol and diesel versions of compact vehicles.

performance is slightly increased in line with the vehicle size.

3.3 Lower purchase price

In order to achieve a lower purchase price it was assumed that a 35% cost saving could be made to the existing Smart EV prototype. This is thought to be possible through mass production and the inclusion of cheaper dedicated components, instead of ones selected for conversion purposes. The vehicle is expected to have an improvement in performance due to utilising lithium ion batteries, but all other aspects of the vehicle are to remain constant.

3.4 Methodology

The methodology chosen for evaluating the consumer preferences was conjoint analysis [8]. Conjoint analysis techniques are part of a larger tool kit of 'trade-off' based analysis tools that are used for the systematic analysis of decisions. It is also commonly referred to as multi-attribute compositional modelling, or stated preference research. The objective of trade-off based analysis is to discover the combination of attributes that are the most influential on a respondent's choice during decision making. In order to be appropriately assessed the respondent must be limited to a small number of attributes where each choice is sufficiently similar to allow for close consumer comparison, but dissimilar enough to allow for a clear preference to be determined and weighted.

In addition to basic information (age, gender, size of household, length of commute and approximate annual mileage), each potential customer was asked to rank the following seven product characteristics in order to estimate their preference scores.

- Fixed Cost: including finance, maintenance, insurance and tax over a 36 month period.
- Variable Cost: as fuel/electric cost per Km, or mile
- Driving Performance: Top speed and Acceleration
- Range before Recharge
- Number of Seats and Size
- Climate Control/Air Con
- Environmental Impact of Vehicle: in terms of GHG emissions, noise and other pollutants.

These estimates were then refined by posing a series of eight tradeoffs which compared vehicles that only differed in three respects. Each respondent chose between two partially-described vehicles and recorded the strength of their preference on a scale from 1 to 9. The software selected the most informative tradeoffs by considering the degree of current knowledge about the respondent's preference for each specific attribute (e.g. 2 seats) and the estimated relative attractiveness of that attribute. The preference scores were updated after each trade-off to align with the recorded preference. Once all eight trade-offs had been completed, an iterative routine was run that made small changes to the discrete preference scores, selecting the change that minimised the sum of squared errors between the respondents actual answers and those predicted by the model.

In order to calibrate and validate the analysis, the recorded preferences for each individual respondent were considered in two stages. Firstly, the implied preference for the Smart EV was computed and contrasted with three alternative vehicles; a petrol Smart Fourtwo, a diesel VW Blue Motion 1 and a petrol VW Polo Match[1], as listed in Table A. The respondent ranked the four alternatives to confirm that the imputed preference score matched their actual choices. Once the preference scores had been validated, it was possible to test a range of potential vehicle developments without incurring perception bias or respondent fatigue [9].

The result of our conjoint analysis ranks the three concept BEVs, the current Smart and the fossil fuel vehicle options in terms of potential market share for a cohort of the general population that is similar to the pool of individuals that trialled the Smart EV. An example of the individual results is given in Figure 3.

As a final step in our analysis, the preferences were used to propose the most cost effective developments that would be necessary for the electric car to be the vehicle of choice for the majority of these potential customers. The estimated market share is depicted in Figure 4.

4 Conclusion

The Smart EV was driven by a range of individuals who were all pleasantly surprised at the performance in terms of acceleration, speed, ease-of-use and simplicity of charging for urban driving. At this stage of the lifecycle, there is a price premium to be paid for innovative products such as the Smart EV that makes it uncompetitive against the traditional alternatives given the compromises that need to be made in range and carrying capacity. During the trial period, a number of reliability issues came to light primarily associated with the battery and charging system. The ZEBRA was selected for their proven track record but may have been overstressed during the trial. Most of the failures followed extended periods of high power demand when the battery was at a low state of charge.

Naturally technology does not stand still and the next generation of lithium ion batteries offer greater performance and energy densities. At the same time, re-engineering the current designs will allow substantial reductions in cost and/or increases in specifications.

We have considered three alternative development paths for the next generation of urban BEV. Our conjoint analysis suggests that in general customers from socio-economic group C and above would appear to accept a higher purchase price and running costs for the advantage of having four seats and storage space in future BEVs. High driving performance does not appear to be considered important in compact vehicles for urban use.

[1] There is no particular bias toward the inclusion of these particular fuelled vehicles. They are simply a popular example of a compact car on sale in the UK.

References

[1] *Zytek Electric Drivetrain Enters Production for smart EV*, http://www.worldcarfans.com/2060718.001, accessed 15-11-08

[2] O'Sullivan T,M. El al, *Zebra Battery Technologies for the All Electric Smart Car*, International Symposium on Power Electronics, Electrical Drives, Automation and Motion (2006)

[3] Cord-H. Dustmann, *Advances in ZEBRA batteries*, Journal of Power Sources 127 (2004), 85-92

[4] *MES-DEA ZEBRA Z21 Datasheet*, http://donau.kicms.de/cebi/easyCMS/FileManager/Files/MES-DEA/batteries/Zebra_Z21.pdf, accessed on 03-03-09

[5] *Mercedes-Benz and Smart electric vehicles coming in 2010*, http://www.motorauthority.com/mercedes-benz-and-smart-electric-vehicles-coming-in-2010.html, accessed on 03-03-09

[6] Shukla A.K. and Kumar T.Prem, *Review Article: Materials for next-generation lithium batteries*, Current Science, Vol 94, no.3 (2008)

[7] Westbrook M.H., *The Electric Car: Development and future of battery, hybrid and fuel-cell cars*, ISBN 0-8529601-3-1 The institution of Engineers and Technology, Power and Energy Series (2001)

[8] Green and Srinivason, *Conjoint analysis in consumer research: Issues and outlook.* Journal of Consumer Research, v5 (1978), 103-123

[9] Orme B., *Getting Started with Conjoint Analysis: Strategies for project design and pricing research*, ISBN 0-9727297-4-7 Research Publishers, 2006

Authors

Timothy Moorin graduated from the University of Surrey in 2008 with a degree in Mechanical Engineering. He has since undertaken an Engineering Doctorate (EngD) in Environmental Technology at the same institution which is supported by the EPSRC. His main area of research is in the field of electric vehicles, focussing on how they can be utilised in the delivery sector.

Adrian Dickinson studied Mathematics at Cambridge University. Adrian has had wide experience in market research and product development and has used a range of techniques to develop innovative strategies for companies in the healthcare, drinks, travel, finance and logistics sectors.

Dr Edward Moxey is engineering consultant currently involved in developing technologies for reducing the carbon footprint of buildings and vehicles. Edward has been an academic at the Universities of Surrey and Essex, researching and teaching electro-mechanical systems and automation. Edward has worked in a number of industries including; electronic testing and measurement, electricity distribution and metering, and the defence industry.

Appendix

Table A: The vehicle selection for conjoint analysis of the major product characteristics

	Concept Electric Vehicle	Concept Electric Vehicle	Concept Electric Vehicle	Smart Electric Vehicle
				
Model	Four Seater	Improved Performance	Low Cost	Electric Smart
Maximum Power	40kw (54 BHP)	80kw (108 BHP)	30kw (40 BHP)	30kw (40 BHP)
Seats	4+	2	2	2
Maximum vehicle speed	70 mph	100 mph	60 mph	60 mph
Acceleration (0-40mph)	8 Seconds	5.5 Seconds	9 Seconds	9 Seconds
Acceleration (0-62mph)	----	10 Seconds	----	----
Combined fuel consumption	0.17kWh/km	0.20kWh/km	0.14kWh/km	0.15kWh/km
Range	80 miles	170 miles	50 miles	50 miles
Battery size	20kWh (Li-Ion)	30kWh (Li-Ion)	15kWh (Li-Ion)	15kWh (Zebra)
Air-conditioning	No	Yes	No	No
CO2 Emissions (Tail pipe)	0 g/km	0 g/km	0 g/km	0 g/km
VED (Tax) Band	A	A	A	A
UK purchase cost	£17,500	£22,000	£12,000	
Insurance group	3	4	2	2
UK fixed costs (£/month)	£390	£505	£282	£436
UK variable costs (p/km)	1.7 p	2.0 p	1.4 p	1.5 p

	Smart Fourtwo	VW Polo BlueMotion 1	VW Polo Match	Smart Electric Vehicle
				
Model	1.0 Petrol 71BHP	1.4 TDI 80PS 3dr DPF	1.4 80PS Petrol 3dr	Electric Smart
Maximum Power	53kw (71 BHP)	60kw (81 BHP)	60kw (81 BHP)	30kw (40 BHP)
Seats	2	4+	4+	2
Maximum vehicle speed	90 mph	109 mph	109 mph	60 mph
Acceleration (0-40mph)	6.7 Seconds	6.5 Seconds	6.4 Seconds	9 Seconds
Acceleration (0-62mph)	13.3 seconds	12.8 Seconds	12.2 seconds	----
MPG Urban	55.4	57.6	34	
MPG Extra Urban	70.6	88.3	54.3	
MPG Combined	64.2	74.3	44.8	
Combined fuel consumption	4.345 l/100km	3.8 l/100km	6.3l/100km	0.15kWh/km
Range	Fuel Tank	Fuel Tank	Fuel Tank	50 miles
Battery size	----	----	----	15kWh (Zebra)
Air-conditioning	Yes	No	Yes	No
CO2 Emissions (Tail pipe)	105 g/km	99g/km	150g/km	0 g/km
VED (Tax) Band	B	A	C	A
UK purchase cost	£9,000	£12,355	£10,575	
Insurance group	2	5	4	2
UK fixed costs (£/month)	£185	£336	£300	£436
UK variable costs (p/km)	5.2 p	4.7 p	5.4 p	1.5 p

Note: Pictures are for reference only
Note: Current prices based on MRP and include maintenance and insurance for 30 year old driver with 50% no claims bonus
Disclaimer: Concept cars are projections of potential electric cars on sale in 2011