Review of cost assumptions and technology uptake scenarios in the CCC transport MACC model

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1 Introduction

1.1 Background

In 2008, an AEA-led consortium was commissioned by the Committee on Climate Change (CCC) to develop a CO_2 marginal abatement cost curve (MACC) model for the transport sector, focusing on technology and efficiency options. The other contributors to this consortium included Ricardo, E4tech, Metroeconomica, IEEP, and CE Delft. AEA had overall responsibility for building the model, with our partners providing specific advice, expertise, and data on technology/fuel costs, abatement performance, and uptake scenarios.

This new study has been commissioned by the CCC to review the capital cost data for vehicle technologies currently included in the existing transport MACC model and to update these data where necessary. A separate report has been prepared as part of this study to investigate the market outlook to 2022 for plug-in hybrid electric vehicles (PHEVs) and pure electric vehicles (EVs), and to use the findings from this research to develop new uptake scenarios for these two technologies that can be used in the MACC model.

The transport MACC model is able to quantify the cost effectiveness of different technological options for reducing CO_2 emissions, using £/tonne of CO_2 abated as the cost effectiveness metric. Once the model has calculated the cost effectiveness of individual technology scenarios, they are automatically prioritised by the model in ascending order of cost effectiveness. As the cost effectiveness indicators are determined by the model using a combination of capital cost and operating cost data, the calculated outputs from the model are very sensitive to the cost values used by the model. It is therefore important, as far as is possible, for the cost data used in the model to be as robust and accurate as possible. This is challenging for a number of reasons – not least of which is the fact that the model has to be able to project changes in technology cost levels over the time period 2008 to 2022. CCC has used the model as it currently stands to inform the development of the UK's carbon budgets for the first three commitment periods to 2022. However, initial comparisons of some of the cost and learning rate data included in the model with other recently published research indicate that there may be differences between the data included in the CCC model as it currently stands, and the outputs from this other recent research.

1.2 Aims and Objectives

As the MACC model was developed over a very short period of time, significant effort was expended in making sure that the model's structure was robust, that the data on vehicle stock and activity levels were comprehensive, and that the model's functionality worked correctly. Data on technology costs were obtained from the existing literature, but given the CCC's time constraints, it was not possible to carry out a comprehensive review of all potential cost data available. Furthermore, in developing the individual technology scenarios used within the model, our approach was based on using a combination of market knowledge and the professional judgement of the whole project consortium to develop technology uptake scenarios to 2022. Therefore, the overarching aim of this study was to refine and improve the robustness of the cost and learning rate estimates included in the model.

1.3 Scope of the work

The focus of the study was electric and plug-in hybrid vehicles. The rationale for this was twofold. Firstly, it was acknowledged that in the original MAC curve, cost and learning rate data for electric and plug-in hybrid vehicles were less robust than the datasets for other technologies. This was largely due to the short timescales to develop the original MAC curve and the uncertainty regarding the future of these technologies. Whilst many vehicle manufacturers had announced they were developing electric

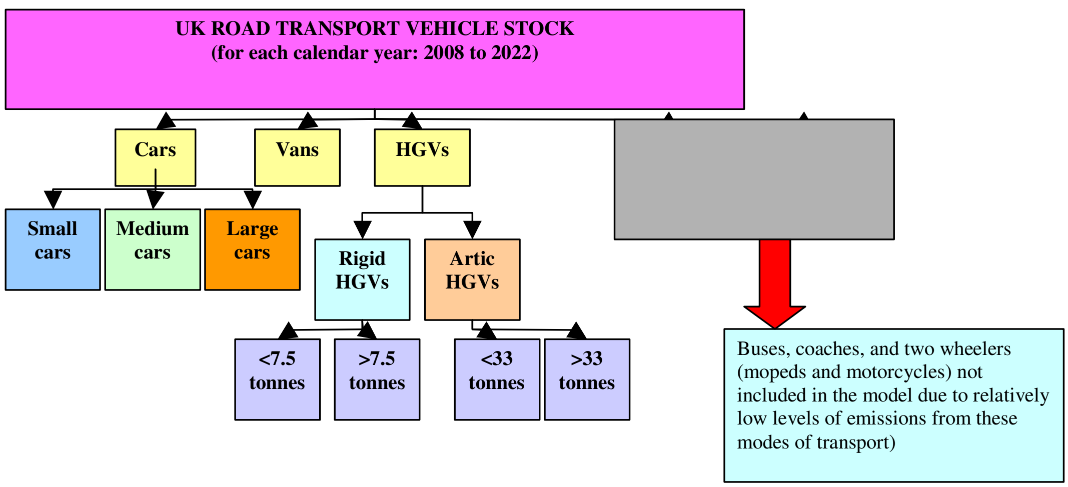
(EV) or plug-in hybrid vehicles (PHEV), the price, release dates and manufacture volumes were less clear and dependent on a number of factors such as Government incentives, the economic climate and public perception. Additionally, there has been a growing interest from the UK Government in the role that electric and plug-in hybrid vehicles could play in reducing CO_2 emissions from the transport sector, and hence it would appear timely to review the assumptions included in the transport MACC model. Whilst the focus of the study was on EV and PHEV technologies, the costs and learning rates for the other technologies in the transport MACC model were also reviewed and updated as appropriate.

2 Updating the vehicle capital costs used in the transport MACC model

2.1 Background

The CCC transport MACC model is a highly disaggregated technology-rich model that includes detailed datasets on vehicle stock levels, technology penetration rates, activity levels, costs, and emissions. In the model, the total UK vehicle stock has been broken down into passenger cars, light commercial vehicles (vans), and HGVs; buses, coaches and two wheelers have been excluded from the model due to the very minor contribution these modes make to UK transport sector CO_2 emissions. These vehicle categories have then been further disaggregated by size, as shown in the figure below.

Figure 1: Simplified schematic showing the structure of the vehicle stock model developed for the MACC model



Specific types of vehicles have been classified into each of the vehicle size categories, and representative base vehicle cost data have been allocated to each size category. For example, passenger cars have been split into small, medium, and large cars. The Society of Motor Manufacturers and Traders (SMMT) size/type classification system was used to allocate specific car types to each size category. Small, medium and large cars were defined in the MACC model as follows:

- **Small cars** were defined as vehicles in SMMT size categories A and B (category A refers to mini cars, and category B to superminis)
- **Medium cars** were defined as vehicles in SMMT size categories C, D, and I (category C refers to lower medium cars, category D to upper medium cars, and category I to multi-purpose vehicles (MPVs));
- **Large cars** were defined as in SMMT size categories E, F, G, and H (category E refers to executive cars, category F refers to luxury cars, category G refers to sports cars, and category H refers to sport utility vehicles)

It should be noted that this vehicle categorisation was used in the model for pragmatic reasons. In particular, the time and resource limitations available for developing the model meant that it was not possible to include more than three different passenger car size/type categories within the model.

However, it is recognised that the categories used in the model do not perfectly reflect real-world vehicle sizes and categorisations, and in particular it is acknowledged that the "large car" category used in the model actually consists of a combination of large conventional passenger cars (executive and luxury saloons), sport utility vehicles (4x4s), and sports cars. Whilst in practice these vehicles are quite diverse in nature and size, it was felt that given the small market share associated with new sales of vehicles in SMMT categories E, F, G, and H, it was not practical to separate these vehicles types any further. Data from the SMMT's latest CO_2 report (SMMT 2009[i]) indicates that in 2008 each vehicle category accounted for the percentages of sales listed below in Table 1

Table 1– 2009 market share and CO_2 emissions performance for vehicles in each SMMT category (source: SMMT)

SMMT category	MACC model classification	Market share – new car sales in 2008	Average new car CO_2 emissions performance in 2008
Category A (mini-cars)	Small car	1.3%	123.9 gCO_2/km
Category B (superminis)	Small car	34.1%	137.7 gCO_2/km
Category C: (lower medium cars)	Medium car	28.4%	153.7 gCO_2/km
Category D: (upper medium cars)	Medium car	16.0%	161.0 gCO_2/km
Category E: (Executive cars)	Large car	4.6%	185.9 gCO_2/km
Category F: (Luxury cars)	Large car	0.5%	266.1 gCO_2/km
Category G: (Specialist sports)	Large car	2.4%	214.7 gCO_2/km
Category H: (Sport utility vehicles)	Large car	6.4%	219.1 gCO_2/km
Category I: (Multi-purpose vehicles)	Medium car	6.4%	175.4 gCO_2/km

In developing the model, it was necessary to define base cost data for each vehicle size category against which the marginal costs of the different technological options for reducing vehicle emissions could be compared. The challenge here was to identify suitable figures that could be used to represent the retail prices of all vehicles within a size category. This was achieved by obtaining total annual sales data for each SMMT size category, identifying the best-selling vehicles in each of the SMMT size categories, obtaining actual retail price data (exclusive of VAT)[1] for each of these vehicles, and using all of this information to calculate a sales-weighted average price for each of the size categories (small cars, medium cars, and large cars) included in the model. This approach was used to generate estimates of the average prices for conventional petrol and diesel cars in each of the three passenger car size categories. A similar approach, again using actual retail price data for popular vehicle models was used to develop estimates of the average prices for light commercial vehicles and heavy goods vehicles.

Data on the costs associated with new low carbon technologies were obtained from a variety of sources, but for passenger cars, most (but not all) of these datasets were obtained from the TNO/IEEP/LAT report entitled "Review and analysis of the reduction potential and costs of technological and other measures to reduce CO_2 emissions from passenger cars" (TNO, 2006). Data for commercial vehicles were primarily obtained from various sources including the INFRAS study "Cost-effectiveness of greenhouse gas emission reductions in various sectors". These and other datasets were used to define the marginal capital costs associated with the various CO_2 abatement technologies included in the model.

[1] These data were obtained from Parkers Guide to New Car Prices

The model was set up to include two estimates for the capital costs associated with each vehicle technology included in the model. These figures are used to represent the upper and lower extremes of the range of marginal capital costs associated with each technology, and are not based on the estimates of the level of feasibility for achieving particular technology uptake scenarios. The marginal capital costs included in the model therefore relate to the change in total retail price of a vehicle when compared to the base representative vehicle in the same vehicle size/type category. The benefits of this approach are that the marginal capital costs associated with the new technology elements of the vehicle can be quantified separately from the basic vehicle elements - this allows the marginal capital cost of any of the new technologies included in the model to be altered independently of the basic vehicle cost (for example, when new data on technology costs becomes available). Secondly, the model includes learning rates that allow the marginal capital costs associated with individual technologies to be automatically modified as experience in manufacturing and deploying the technology of interest increases.

In developing the original marginal capital cost estimates used in the model, a broad range of literature were drawn upon, but in practice the data from TNO (2006) were found to be the most comprehensive and robust in terms of coverage of different vehicle technologies. Consequently, the majority of the cost data for passenger car technologies included in the CCC MACC model were taken from the TNO 2006 report. Table 2 provides a summary, for each **passenger car** technology, of the data sources used to populate the MACC model with marginal capital cost data.

Table 2: Data sources for the capital cost data used in the MACC model for passenger cars

Technology	Sources of capital cost data currently used in MACC model	Notes
1st generation advanced petrol engines	TNO 2006	Technologies included under this umbrella classification include direct injection, stratified charge, variable valve control, and variable valve timing technologies
2nd generation advanced petrol engines	TNO 2006	Second generation advanced petrol engines combine first generation technologies described above with engine downsize and boosting (i.e. turbocharging and/or supercharging).
Stop-start technology (petrol and diesel)	TNO 2006	
Micro-hybrid technology (petrol and diesel)	TNO 2006	Micro-hybrid technology consists of stop-start plus regenerative braking
Mild hybrid technology	TNO 2006	
Full hybrid technology	TNO 2006	
Plug-in hybrid technology	Average cost data estimated based on planned future vehicle models	
Battery electric technology	Average cost data based on vehicles currently on the market or planned for release in near future.	Capital cost data for light vans more robust than data for passenger cars, due to vehicles from Smith and Modec already being available on the UK market – retail price data were obtained from these manufacturers

Technology	Sources of capital cost data currently used in MACC model	Notes
		manufacturers.
Low rolling resistance tyres	TNO 2006	
Light weighting – mild weight reduction	TNO 2006	
Light weighting – mid weight reduction	TNO 2006	
Light weighting – strong weight reduction	TNO 2006	
Improved aerodynamics	TNO 2006	
Gearshift indicators	TNO 2006	

In using the TNO (2006) data in the MACC model, the cost data was converted from Euros to Pounds Sterling using an exchange rate of £0.711 to €1. The Treasury's GDP Deflator series was also employed to present the data in 2006 prices (the original TNO data was presented as 2002 prices).

As can be seen from Table 1, there are a small number of technologies where additional data from alternative sources were used to supplement the TNO data, and for electric vehicles, it can be seen that we did not make use of TNO data in the modelling. The TNO data were prepared as part of a service contract for the European Commission that was focused on analysing the costs and impacts of technologies that could be used to meet the proposed 2012 passenger car CO_2 legislation. As it had been assumed that there would be little or no contribution from electric vehicles towards meeting the proposed CO_2 reduction targets by 2012 (due to this technology being immature and costly), TNO's research did not include marginal capital cost data for these types of vehicles. For this reason, alternative data sources were used to estimate the costs of battery-electric vehicles for use in the MACC model. In particular, our research drew on published data for electric vehicles that are currently on the market and on estimates based on planned future vehicles not yet on the market, but for which estimated price data were available.

Given the very short timescales for developing what is a very complex MACC model, it was not possible during the model development phase to review in detail all available datasets and to develop the most comprehensive estimates for technology costs. Therefore it was recognised that further research was required to:

(a) Investigate whether more up-to-date marginal capital cost data was available to replace the TNO (2006) dataset;
(b) Review the TNO (2006) data and make any necessary amendments to improve its robustness;
(c) Identify the latest estimates on the marginal capital costs of hybrid and battery electric vehicle technology.

2.2 Methodology for Updating the Capital Costs

As described above, the transport sector MACC model considers three main vehicle types:

- Cars
- Light Commercial Vehicles (LCVs)
- Heavy Goods Vehicles (HGVs)

This section outlines the methodologies employed to update the capital costs for cars, LCVs and HGVs.

2.2.1 Cars – Selecting the dataset

The first element of Task 1 was to establish whether a more up-to-date dataset for the capital costs of low-carbon technologies for cars had become available in the time period since the development of the transport MACC model was completed. In making this assessment it was important to consider the robustness and consistency of the data collection. In the TNO (2006) study the data was collected using a detailed survey of car manufacturers, which ensured a high degree of consistency and robustness.

After undertaking desk based research and consulting stakeholders such as SMMT and ACEA we were unable to identify a more up-to-date dataset that satisfied our robustness and consistency criteria. Therefore, the decision was made to retain the TNO (2006) dataset for the car element of the updated marginal capital costs. In particular, the strengths of the TNO (2006) dataset are as follows:

- A consistent approach has been used throughout the TNO study to obtain data on a wide range of vehicle technologies for abating CO_2 emissions. Most other studies tend to focus on individual technologies or a restricted set of technology options;

- The TNO (2006) study built on a number of previous studies carried out by the same study team in the same area, and consequently there is a relatively high level of confidence in the robustness of the cost estimates;

- The main automotive trade associations representing the European vehicle manufacturers (ACEA), Japanese manufacturers (JAMA), and Korean manufacturers (KAMA) all provided marginal capital cost data that have been used by TNO in developing their cost estimates for the various vehicle technologies. The TNO (2006) study therefore has a relatively high level of buy-in from the automotive industry;

- The European Commission has used the outputs from the TNO (2006) study to inform the impact assessment process for the proposed passenger car CO_2 legislation, further reinforcing the level of buy-in attached to the study's results;

For these reasons, it was felt that the TNO (2006) study remains the most comprehensive and robust source of data on a wide variety of abatement options for passenger cars, and it is recommended that these data should continue to be used as the main source of marginal capital cost estimates for passenger car technologies. However, it should be noted that the TNO (2006) dataset does not cover electric vehicles (EV) or plug-in hybrid vehicles (PHEV). These costs have been updated separately as detailed in section 2.2.4.

2.2.2 Passenger cars – issues with the TNO (2006) dataset

Having made the decision to continue using the TNO data in the model, the next step was to review the manner in which these data had been used in the original MACC model. Initial investigations suggested there were some areas where improvements could be made. However, it is important to note that issues with the TNO (2006) data in the original MACC model were related to the manner in which the data had been manipulated by AEA and not any underlying issues with the data itself.

The main issues can be summarised as follows:

- **Use of data relating to the marginal capital costs to manufacturers as opposed to the marginal capital costs to society.** It should be noted that the data taken from TNO (2006) relates to the additional **costs to manufacturers** associated with incorporating new CO_2 abatement technologies into passenger cars. These marginal capital costs are not the same as the additional costs that would be experienced by consumers. TNO's research defines three potential sets of marginal capital cost data that can be used when carrying out cost effectiveness analysis for technological options for the transport sector. These are as follows:

    - **Manufacturer costs** (i.e. the additional costs to manufacturers associated with incorporating new CO_2 abatement technologies into vehicles);
    - **Costs to society** (defined as the impact of incorporating the technology on the vehicle's retail price, **excluding** any taxes, which are treated as transfer costs);
    - **Consumer costs** (defined as the impact on retail prices of incorporating the technology in a vehicle, **including** any relevant taxes).

  In the context of the CCC MACC model, the latter two types of marginal capital costs are of most interest, as the model has been designed to calculate cost effectiveness indicators from the point of view of total costs to society (including using a social discount rate) or from the point of view of private consumers (including using a private discount rate). Until this point in time, the marginal capital costs included in the MACC model have been the additional manufacturer costs, and with this in mind, it is necessary to convert the manufacturer costs presented in Table 3.12 and Table 3.13 of TNO (2006) into societal and/or consumer costs. In this context, societal marginal capital costs are assumed to be equivalent to retail prices exclusive of taxes, whilst consumers' costs are retail prices inclusive of taxes. To convert between manufacturer marginal capital costs and societal marginal capital costs, TNO estimated that the former should be multiplied by a factor of 1.16. These societal costs include the manufacturers' normal return on investment (profit) and apply equally to conventional and low carbon vehicles technologies. This means that the current cost data in the model for passenger cars are underestimated by 16%. This 16% is made up of the following elements:

    - 5% manufacturer profit
    - 10% additional dealer costs
    - 1% dealer profit

- **Implicit assumptions about deployment levels included in the TNO cost estimates.** The marginal capital cost data presented in TNO (2006) study assumes that all learning rate effects have already been overcome, and that the marginal capital costs experienced by consumers when purchasing each technology have already been minimised. The MACC model does not make implicit assumptions about learning rates in the same way, but rather learning rates are automatically applied to the cost data on the basis of technology deployment levels for any particular year in any particular MACC scenario. Assuming that the TNO costs are accurate, this means that in each model run the MACC model will currently systematically **underestimate** the marginal capital costs associated with each technology option where marginal capital cost data has been taken from the TNO report. Whilst the impacts of these underestimates are likely to be small (most of the technologies included in the MACC model have been set with a learning rate of 0.95 – i.e. costs reduce by 5% for each doubling of production), it is still important to address this issue.

- **Attribution of the marginal capital costs of technology to CO_2 reduction or to other goals.** In using the TNO cost data to populate the current MACC model, we did not take into account the fact that a small number of technological options will be used to achieve other goals apart from CO_2 reduction. For example, variable valve timing and variable valve control (part of the groups of first generation advanced petrol engine technologies) also have benefits in terms of reducing emissions of air pollutants, and TNO's research indicated that only 75% of the additional costs of these technologies should be attributed to CO_2 reduction. If these factors are taken into account, this means that the MACC model may currently overestimate the additional costs of first generation advanced petrol engine technologies and mild/full hybrid-electric technologies by 25%.

2.2.3 Passenger cars – addressing the issues with the TNO (2006) dataset

To address the issues with the TNO (2006) dataset that were highlighted in the previous sub-section the following steps were taken:

1. The TNO (2006) dataset was re-entered in full to correct some minor errors in the original MACC model.
2. A 5-year (2004 – 2009) average Euro-£ exchange rate was applied to the TNO dataset
3. The latest December 2008 Treasury GDP deflators were applied to the TNO data to 'inflate' the marginal capital cost estimates to 2006 prices and to ensure these datasets were consistent with the rest of the MACC model.
4. The marginal capital cost estimates obtained from the TNO (2006) study were multiplied by 1.16 to ensure the MACC model utilises the marginal capital cost to society as opposed to the marginal capital cost of manufacture.
5. The costs were converted to 2008 levels, as opposed to the cost at mass manufacture using the following formula (which is obtained by simply rearranging a standard learning rates formula – see Section 3.1):

$$C_{2006} = \frac{C_t}{(M_t \div M_{2006})^b} \quad \text{where} \quad b = \frac{\ln PR}{\ln 2}$$

Where		
	C_{2006}	= Marginal capital cost in 2006
	C_t	= Marginal capital cost at mass manufacture
	M_{2006}	= Estimate of production volumes in 2006
	M_t	= Estimate of annual production volumes at mass production
	PR	= Estimate of the learning rate
	ln	= Natural log

6. The attribution factors were set to 100% for each technology rather than the percentages stipulated in the TNO (2006) study

In reviewing and updating the existing datasets in the model, three sets of learning rates were developed in Task 2: low, central and high. In the calculations for Step 5 above the 'central' learning rates were employed. More details of the revised learning rates can be found in Section 3 of this report.

Step 6 above deviated from the approach stipulated in the TNO 2006 study by setting all the attribution rates to 100%. When a consumer purchases a vehicle they incur the full marginal cost of the low-carbon technologies with which the vehicle is equipped. Therefore, it was felt that the full marginal cost of each technology, rather than just the proportion that can be attributed to carbon savings, should be included in the MACC model. Whilst it was acknowledged that some vehicle technologies provide additional benefits over and above reducing CO_2 emissions, it was decided that attribution rates were not the best means of accounting for their impact. Indeed, identifying a suitable approach to appropriately account for these ancillary benefits may be a methodological issue for the CCC to consider in the future. This modification to the TNO 2006 approach was agreed with CCC.

2.2.4 Cars – Updating the Marginal Capital Costs for EV, HEV and PHEV

EVs and PHEVs are not covered by the TNO (2006) dataset so it was important to ensure that the marginal capital costs for those technologies were reviewed and, where necessary, updated. This was particularly important given the high number of announcements relating to electric vehicles in recent months and the potential these technologies have to deliver significant carbon savings in the transport sector. Simultaneously, retail price data were also collected for full hybrid cars, some of which are already in mass production. Whilst the TNO data covers full hybrid cars the decision was made to replace this with the latest retail price data since by definition it is significantly more up-to-date.

The first step in updating the marginal capital costs for electric and plug-in electric cars was to select representative electric vehicles for each of the three car categories in the MACC model. Where possible two representative vehicles were selected for each market segment (or three in case of small EVs). This approach mitigated the risk that an unusual pricing strategy by one manufacturer might unduly influence the marginal costs. The rationale for selecting each vehicle is given in Section 2.2.5.

Once the retail price estimates for the representative vehicles had been gathered the marginal capital cost was calculated by subtracting the price of an equivalent conventional petrol vehicle, where one existed. Where there was no obvious equivalent vehicle, the representative vehicle's price was compared to the 'base cost' data for a conventional vehicle in that size category (the origins of base cost data are explained in detail in Section 2.1). The marginal retail costs were then converted to societal costs by subtracting VAT. Next the societal costs were converted to 2006 prices by applying the Treasury's latest December 2008 GDP deflators. Finally, the low and high values for the marginal capital cost of each technology were determined by taking the two extreme values from the two representative vehicles as illustrated in Table 3. For example, for small EVs the marginal capital costs for the i-MiEV, Th!nk City and Citroen C1 ev'ie were calculated to be £11,200 to 20,400, £16,300 and £6,300 to £7,000 respectively. Therefore, the two extreme values are £6,300 and £20,400 so these are the values that will be inserted in to the updates MACC model.

It is important to note that the relative marginal capital costs for each vehicle category may have been influenced by the cost and choice of the comparator vehicle. This is because the marginal capital costs were calculated by subtracting the capital cost of the comparator vehicle from the capital cost of the representative electric vehicle. To mitigate this potential issue every effort was made to select the most appropriate comparator vehicle. For instance, the non-electric version of the Mitsubishi i-MiEV was used as the comparator vehicle for small EVs. That said, care should be exercised before drawing any firm conclusions regarding the relative marginal costs of different vehicle categories.

Table 3 – The marginal costs for the representative EVs and PHEVs that will feed into the MACC model

	Retail Price (2006 prices, less VAT)		Marginal cost	
	LOW	HIGH	LOW	HIGH
1st representative small EV: Mitsubishi iMiEV	£18,500	£27,600	£11,300	£20,400
2nd representative small EV: Think! City	£23,500	£23,500	£16,300	£16,300
3rd representative small EV: Citreon C1 ev'ie	£13,300	£13,300	£6,300	£7,000
'Representative' marginal cost for small EVs			**£6,300**	**£20,400**
1st representative vehicle: Scaled up Mitsubishi i-MiEV*	£22,400	£33,400	£11,300	£22,200
2nd representative vehicle: Scaled up Think! City*	£28,400	£28,400	£17,300	£17,300
'Representative' marginal cost for medium EVs			**£11,300**	**£22,200**
1st representative large EV: Tesla Roadster	£71,700	£72,500	£49,700	£50,500
2nd representative large EV: Liberty Land Rover (Conversion)	£74,800	£98,400	£29,600	£39,500
'Representative' marginal cost for large EVs			**£29,600**	**£50,500**
1st representative medium PHEV: Chevrolet Volt	£28,200	£28,200	£13,900	£13,900
2nd representative medium PHEV: Toyota Prius Plug-in (Conversion)	£20,100	£20,100	£8,400	£8,400
'Representative' marginal cost for medium PHEVs			**£8,400**	**£13,900**
1st representative PHEV: Fisker Karma	£62,000	£62,000	£12,100	£29,100
'Representative' marginal cost for large PHEVs			**£12,100**	**£29,100**

* Note: Due to an absence of data on 'medium' electric cars the sale price and hence marginal cost were estimated by scaling up two small representative vehicles. This is described in more detail in Section 2.2.5

The values in Table 3 form part of the updated marginal capital cost dataset, which is the main output from Task 1 of the study. A full list of the revised values that will be inserted into the updated MACC model can be found in Section 2.3.

As explained earlier in this section it is important for this review that the marginal capital costs of electric and plug-in hybrid electric cars are as accurate as possible. To that end price estimates for these technologies were also calculated using the latest estimates of battery prices from the Arup/Cenex report[2]. These calculations served as a check for the retail price estimates gathered via the desk research. The two approaches complement each other since the retail price approach uses a 'top down' methodology for estimating prices, whilst the battery price approach is 'bottom up'.

The marginal capital costs of the representative electric cars were calculated by taking the price of an equivalent conventional petrol car, then subtracting the average estimates for the price of the engine and transmission (obtained from the TNO (2006) report) before adding the price of the electric motor and Li-ion batteries. In a similar vein, the marginal capital costs of the representative plug-in hybrid cars were calculated by taking the price of an equivalent conventional petrol car and adding the price of the electric motor, energy controller and Li-ion batteries. Whilst this was a fairly simplistic assessment of the respective prices of EVs and PHEVs it does take account of the key components that impact upon the price.

[2] Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug in Hybrid Vehicles, Cenex/Arup, 2008

Table 4 – Key assumptions for bottom up calculations of EV and PHEV prices

Assumption	Low Cost	High Cost	Data Source
Cost of **SMALL** engine + transmission for conventional vehicle (Euro)	1,800	1,800	AEA estimate based on cost of medium engine + transmission
Cost of **MEDIUM** engine + transmission for conventional vehicle (Euro)	2,310	2,310	TNO 2006, p147
Cost of **LARGE** engine + transmission for conventional vehicle (Euro)	2,800	2,800	AEA estimate based on cost of medium engine + transmission
Cost of electric motor for EV ($/kW)(cost for 2010 onwards)	19	25	Prosopects for Hydrogen and Fuel Cells, Energy Technology Analysis, OECD/IEA, 2005
Cost of energy controller ($/kW)	11	19	Well-to-wheels analysis of future automotive fuels and powertrains in the European context, Well-to-wheels report, Version 2a, December 2005, EC JRC, Concawe, EU CAR
Cost of Li-ion batteries for EV ($/kWh of battery capacity)	1,000	2,000	Cenex/ARUP study, p33 - $250/kWh is the consensus for the lowest long term Li-ion battery price and $1000/kWh is the consensus for the current lowest price

Table 5 gives the marginal capital cost of electric and plug-in cars calculated by both means – the 'top down' marginal societal capital cost and the 'bottom up' cost calculated by estimating the price of the batteries. The low and high estimates of the top down costs were based on the range of 'representative' prices quoted for each representative vehicle in Table 3. The low and high estimate of bottom up marginal capital costs were based the range of technology costs listed in Table 4. The bottom up marginal capital cost was calculated for both representative vehicles listed in Table 3. In a similar vein to Table 3, the two extreme values were then utilised for this comparison.

Table 5 – Comparison of 'top down' and 'bottom-up' estimates of marginal cost

Vehicle type	LOW 'top down' marginal capital cost (dervied from anticipated sale price)	HIGH 'top down' marginal capital cost (dervied from anticipated sale price)	LOW 'bottom up' marginal cost of (derived from estimating the price of batteries and other key components)	HIGH 'bottom up' marginal cost of (derived from estimating the price of batteries and other key components)
Small EV	£6,300	£20,400	£9,300	£31,000
Medium EV	£11,300	£22,200	£9,300	£19,900
Large EV	£29,600	£50,500	£28,400	£57,500
Medium PHEV	£8,400	£13,900	£10,400	£19,800
Large PHEV	£12,100	£29,100	£16,900	£31,300

* Note: Due to an absence of data on 'medium' electric cars the sale price and battery capacity were estimated by scaling up a small car. This is described in more detail in Section 2.2.5

Table 5 illustrates that overall the two sets of 'low' marginal costs are broadly similar for EVs. In the small electric vehicles segment the lower values from the top down and bottom up analyses are well aligned at £11,326 and £9,295 respectively. In the medium EV segment there is also a gap of around £2k whilst in large EVs the gap is less than £800.

In contrast, there is a greater discrepancy between the 'high' marginal capital costs for EVs. The wide range of battery cost estimates could be the explanation for this. The cost estimates for Li-ion batteries, which were taken from the Arup Cenex Report, ranged from $1,000 per kWh to $2,000 per kWh. Many commentators would suggest the price is nearer the lower bound, which would suggest the high value for the bottom up analysis is overly conservative. We attempted to verify this assertion with the battery trade associations but unfortunately they were not able to supply us any up to date price estimates.

The discrepancy between the values for PHEVs is more sizeable for both the high and low values. There are several potential explanations for this variation. Firstly, there is significant variability between PHEVs in terms of their battery capacity. Different manufacturers are choosing to 'select' different electric-only ranges. For instance the Chevrolet Volt will have a maximum all-electric range of 40 miles where as it will be just 6 miles for the Toyota Prius PHEV[3]. When combined with different marketing strategies and different views on where to position their PHEV brand this can create a disconnect between the cost of the vehicle and its retail price.

An extension of this argument can be applied to Fisker Karma which is a luxury saloon car. Given that it will only ever be produced in relatively small volumes there will always need to be a greater difference between the variable production cost of the vehicle and its price, compared to a mass-market vehicle, to allow Fisker to recoup its fixed costs and make a normal profit. Hence by taking as a starting point the price of an equivalent conventional petrol car the bottom-up methodology is likely to underestimate costs.

While the Fisker Karma is an extreme case, manufacturing volumes are likely to be a general factor in the disparity between the top-down and bottom-up marginal capital costs. Significant economies of scales will be achieved as production volumes are increased and manufacturing processes are improved through learning by doing. Several manufacturers who are launching vehicles in the next couple of years (e.g. Mitsubishi and GM) are quoting a price for the first tranche of vehicles, which is significantly higher than the price they anticipate even a year or two later. This approach to pricing could create a further disconnect between the cost and price of each vehicle which might resolve itself in the medium term.

2.2.5 Rationale for selecting representative vehicles

This sub-section details the rationale for selecting the representative vehicles for the following vehicle technologies:

- EV (small, medium and large cars)
- PHEV (medium and large cars)

Small PHEVs were not included in the original MACC model since car manufacturers were of the opinion that they would not be able to recoup the cost of including an engine, batteries, and an electric motor in a vehicle in that segment. This is because small cars, with the exception of high performance sports cars, are generally perceived to be 'budget' vehicles. Therefore, consumers looking to purchase a small car tend to be particularly price sensitive.

Whilst this argument could also be applied to small electric vehicles there is one important difference; electric vehicles are inherently simpler than conventional vehicles. Were it not for the low manufacture volumes and high battery prices they would be cheaper to manufacture than conventional vehicles. Consequently, if there is a substantial fall in battery prices, there is a possibility that electric vehicles could become price competitive with conventional vehicles in the small cars segment.

Small EVs
The Mitsubishi I-MiEV, Th!nk City and Citroen C1 ev'ie were chosen to represent the small EV segment. The Mitsubishi I-MiEV and Th!nk City were selected because they are likely to be the first two small EVs, and amongst the first EVs of any size, to be launched in the UK. The i-MiEV, which is the electric version of the existing Mitsubishi i, will be launched in the UK in autumn 2009[4]. As a result, there is good data available on its likely price both in the short term when just 200 will be made available for lease in the UK, and in 2010/11 when manufacture volumes will increase and the price is likely to fall[2]. In contrast, the Citroen C1 ev'ie was selected due to the price at which it will be sold (£16,850). This equates to a significantly lower marginal capital cost than either the I-MiEV or Th!nk City. However, this comes at a price since the range is only 70 miles (compared to 112 for the I-MiEV and 100 miles for the Th!nk City) and the top speed is just 60mph.

[3] http://crave.cnet.co.uk/cartech/0,250000513,10001656,00.htm
[4] http://www.verdictoncars.com/jsp/vocmain.jsp?lnk=211&featureid=990&pageid=-1

The Th!nk City had been due to launch in the UK in early 2009[5]. However, financial difficulties caused manufacture to cease so it isn't expected to be available in the UK until 2010. The best price data available for the Th!nk City was gathered from an interview with Th!nk's UK Market and Sales Director which was published online[3]. However, it is important to note that this interview was before Th!nk suffered its financial difficulties in December 2008. Consequently, there is a possibility that their UK pricing strategy may have changed in the interim period. No new announcements have been made regarding the UK price. That said, the original price of £14k plus battery rental remains consistent with the latest price announcements in the US (circa $20,000) where Th!nk is hoping to build a new assembly plant[6].

Medium EVs
Unfortunately, the research could not identify the retail price for a medium sized battery electric car, as no vehicles in this size category are currently on the market, and none are planned for market release in the immediate future. To overcome this absence of data for medium EVs the price and marginal capital cost were estimated by scaling the small electric car retail price using energy consumption per km data from Ricardo that were used during the original development of the transport MACC model. We believe that this is a realistic and pragmatic approach to estimating the theoretical costs for medium-sized battery electric passenger cars. The figures from Ricardo, which were used in the original MACC model are given in Table 6.

Table 6 – Energy consumption per km provided by Ricardo for the original MACC model

Size of vehicle	Energy consumption in MJ/km
Small car	0.595
Medium car	0.72
Large car	0.994
Vans	0.91

Large EVs
The Tesla Roadster and Liberty Range Rover conversion were chosen to represent the large EV sector. The Tesla Roadster was selected because it is already on sale and hence reliable prices and specifications were available directly from the Tesla's website. However, there was some concern that it may not be representative of the large car segment which also includes SUVs, large saloons etc. Therefore, the Liberty Range Rover was also considered when calculating the marginal cost of large EVs.

It is important to note that the Liberty Range Rover is a 'conversion' electric vehicle. In other words Liberty are purchasing standard petrol/diesel Range Rover bodyshells and will convert them into electric vehicles by installing an electric motor / batteries and making various other changes. Whilst this is Liberty's sole focus (they do not manufacture electric vehicles from scratch) the converted Range Rover would not be the same as its purpose-built equivalent, were such a vehicle to be launched. That said, given that the marginal cost of EVs is largely determined by the battery capacity, it seems fair to assume that the Liberty Range Rover conversion will be a reasonable representation of an EV of that type.

Medium PHEVs
In a similar vein to the representative vehicles for the EV market segments, the Chevrolet Volt has been selected because it is likely to be first to market in the medium PHEV segment. In Europe, the Volt will be sold as the Vauxhall/Opel Ampera, which is almost identical save for branding and minor modifications to the vehicle's styling. Given this situation, the price estimates for the Volt was thought to be a good guide as to the likely price of the Ampera.

However, it was thought preferable not to rely on the price estimates for a single vehicle when estimating the marginal capital cost of medium PHEVs. Unfortunately there is not any other medium

[5] http://www.businessgreen.com/business-green/analysis/2212579/interview-think-bring-electric
[6] http://www.thedetroitbureau.com/2009/03/first-drive-think-city-ev/

PHEV close enough to market for reliable price estimates to have been made. Consequently, the Toyota Prius converted plug-in PHEV was used as a second representative vehicle. The Prius' that are currently available are conventional hybrid electric vehicles, which is only able to travel very short distances in electric-only mode. By adding a larger battery pack and a charging socket the conventional Prius can be converted to a plug-in Prius. Toyota is planning to launch a volume manufactured Prius PHEV within the next 5 years and some vehicles are already on trial in the UK[7].

Large PHEVs

The large PHEV segment is represented by the Fisker Karma, which is a luxury four-door sports saloon. As discussed in the previous sub-section this raises some questions regarding its suitability in terms of being representative of the of the whole large car segment, which is very diverse. Unfortunately there is little scope to make use of a second vehicle because no data is available. Whilst large PHEVs such as the Ford Escape SUV and the Jeep Patriot are being developed for the US market they are not close enough to market for any kind of price information to have been released.

However, it is also important to note that as described in 2.1, the vehicles that make up the large cars segment are actually more similar than might be expected in terms of CO_2 emission per km and hence fuel consumption. It is acknowledged that a second representative vehicle would have improved the robustness of the marginal capital cost estimate; it is recommended that when further data becomes available these estimates should be revised.

2.2.6 Light commercial vehicles (LCVs) and Heavy Goods Vehicles (HGVs)

Data for the marginal cost of low-carbon technologies tends to be more difficult to find for LCVs and HGVs. This is because low-carbon technologies for LCVs and HGVs are produced in lower volumes and by fewer manufacturers than the car market. Furthermore, the development of policies for controlling CO_2 emissions from these types of vehicles is less well developed than for passenger cars, and consequently, there has been less research focused on these modes of transport. In addition, new models/technologies for LCVs and HGVs tend to receive less media attention than the car market. The existing cost data included in the MACC model were obtained from a variety of data sources, including the following:

- The Landscape of Global Abatement Opportunities up to 2030 (Vattenfall, 2007);
- Cost effectiveness of greenhouse gas emissions reductions in various sectors (INFRAS, 2006);
- Measuring and preparing CO_2 reduction measures for N1 vehicles (TNO/IEEP/LAT, 2004 for the European Commission);
- Retail price data from selected vehicle manufacturers;
- Data from the US Environmental Protection Agency

Significant desk research was undertaken during the course of the project to locate new sources of marginal capital cost data for LCVs and HGVs. Electric vehicle manufacturers Modec and Smith Electric Vehicles provided fresh datasets for their vehicles. Modec provided retail price data for their electric van whilst Smith Electric Vehicles provided retail price data for their van and 7.5 tonne truck. This data was used to calculate the marginal retail cost of electric vans and 7.5tonne trucks by subtracting the price of the appropriate conventional diesel vehicle. The marginal retail costs were then converted to societal costs by subtracting VAT. Finally, the societal costs were converted to 2006 prices by applying the Treasury's latest December 2008 GDP deflators.

For 3.5 tonne to 7.5 tonne category both the low and high costs are derived from retail price data from Smith Electric Vehicles. Two battery technologies (Li-ion and Zebra) and two battery sizes (4 battery packs and 6 battery packs) are available. The low price estimate utilised the prices for 4 Zebra battery

[7] http://crave.cnet.co.uk/cartech/0,250000513,10001656,00.htm

packs and the high price utilised prices for 6 Li-ion battery packs. The marginal capital costs in 2006 prices were calculated for both options in the same manner as previously explained.

In addition to the data from Modec and Smith Electric Vehicles, detailed comments on the interim updated marginal capital costs from Iveco, Volvo's HGV division and the external experts retained by CCC ensured the final values were as robust as possible.

2.2.7 Rounding up of marginal capital costs

Retail prices for vehicles and the TNO dataset were manipulated in a variety of ways to generate the correct marginal capital costs. This included subtracting VAT, deflating from 2009 prices to 2006 prices and back calculating current costs from the TNO 2006 dataset. Once these operations were completed the resulting figures consisted of multiple decimal places.

If the marginal capital costs were quoted in such a precise form it would have implied a greater degree of accuracy that was actually the case. Whilst the project team are confident that the marginal capital costs are as robust as possible, some uncertainly is inherent in the numbers. For instance, uncertainty arises from the fact that some of the datasets are based on assumptions or cost estimates.

Therefore, to avoid misrepresenting the accuracy of the data the decision was made to 'round' the marginal capital costs according to the following criteria:

- For marginal capital costs less than £200 the numbers were rounded to the nearest £10
- For marginal capital costs greater than £200 the numbers were rounded to the nearest £200

By structuring the rounding in this manner the 'detail' of the marginal capital costs was retained for the lower numbers, where it was relevant and appropriate.

2.2.8 Exchange rates

The exchange rates employed in the analysis to calculate marginal capital costs had a significant impact on the results. This is because the TNO (2006) dataset quoted marginal capital costs in Euros. Consequently, all these figures were converted to Pounds Sterling both in this study and the original MACC model.

In addition, some of the retail price estimates for technologies not covered by TNO (2006) were quoted in other currencies. For example, prices for the Chevrolet Volt medium PHEV, Toyota Prius conversion medium PHEV and the Fisker Karma large PHEV were only available in US Dollars.

The exchange rates employed in the analysis were an average of the exchange rates for a 5-year period between 1st January 2004 and 31st December 2008:

- US$0.537 = £1
- Euro0.705 = £1

By taking an average over a five-year period it was hoped that any fluctuations in value of currencies would be smoothed out. However, it is acknowledge that Sterling has weakened significantly in recent times so there may be an argument for employing exchange rates that reflect the current situation. That said, due to need to employ 'pricing to market 'strategies the impacts of exchange rate fluctuations may not fully translate into variations in retail price.

2.2.9 Seeking comments from vehicle manufacturers

Right from the outset of the project we sought to open a dialogue with SMMT and ACEA with the aim of securing their time to review the updated marginal capital costs and learning rates. In addition, we also approached an existing contact at Volvo's HGV division to canvas his opinion on the updated marginal costs and learning rates.

SMMT and ACEA took different approaches to the consultation. SMMT forwarded the datasets straight onto their members for them to comment as they saw fit where as ACEA preferred to agree a common position with its members before responding on their behalf.

Unfortunately, despite some initial interest and much prompting we only received detailed comments back from Iveco and Volvo. Some manufacturers such as General Motors (GM) chose to participate via ACEA whilst others cited more pressing priorities related to the economic downturn. That said, ACEA did make the comment during telephone conversations that they were happy (paraphrasing) with the TNO 2006 dataset. Given that detailed comments were received on the HGV data and the TNO 2006 covers many of the technologies for cars, the overall coverage of the comments is relatively good.

2.3 Limitations and caveats

2.3.1 Price vs cost

Intuitively, many lay people believe there is a close relationship between the cost of car and price at which it is sold. However, right from the project's inception the project team were aware that at times there was a tenuous link between the price of certain vehicles and their cost. This was reinforced during a stakeholder workshop hosted by CCC where representatives from the automotive manufacturers confirmed that there was a complex relationship between the cost and price of vehicles. For instance, vehicles are often heavily discounted when they are first launched to ensure the model gains a foothold in the market.

This issue has implications for certain parts of this study. Some of the marginal capital costs were calculated by taking the retail price of the vehicle or technology in question, subtracting VAT, converting to 2006 prices and subtracting the cost of the baseline vehicle or technology. This approach contains the implicit assumption that there *is* a relationship between cost and price since it relies on retail prices as the starting point for the analysis.

Whilst it is acknowledged this is a shortcoming of the approach it should be noted that it only applies to data that was derived from the price of vehicles. Most of the data used in the study did not originate from that type of source. For example, the vast majority of the car data came from the TNO 2006 study that obtained its information from a comprehensive survey of manufacturers.

The main vehicle types that will be affected by this issue are EVs and PHEVs. This is because actual or projected retail price data is the only information available that relates in any way to the cost of the vehicle. Manufacturers, guard the data on the true production costs of these vehicles very carefully since it is highly commercially sensitive. Therefore, other than drawing attention to this point and taking care not too place too much emphasis on the precise figures quoted for marginal capital costs, there is little else that can be done within the scope of this study.

2.3.2 Learning and technological effects vs supply side effects

Section 3 of the report describes the approach to updating the learning rates in the transport MAC model. Learning rate theory is one of the key building blocks of the MAC model. However, relying on the concept of technology learning in this manner entails making the fundamental assumption that costs *will* reduce as manufacture volumes increase.

Under 'normal' circumstances, when other variables remain benign, this is a perfectly reasonable assumption to make. Of course, in the real world a complex mix of factors determines the cost of vehicles and technologies. These factors include supply side effects such as the cost of materials.

The marginal capital cost of EVs and PHEVs is driven by the cost of li-ion batteries, which in turn are heavily influenced by the price of electrode materials.

It is very difficult to predict how much influence these supply side effects will have the cost of EVs and PHEVs. On the one hand the price of lithium cobalt oxide cathodes (the most common cathode material for li-ion batteries) may rise as demand for cobalt and lithium (and hence their price) increases. Alternatively, these changes could bring forward research to reduce their cost or initiate a switch to another cathode material such as lithium iron-phosphate or a manganese based alternative. The study by Arup/Cenex suggests that the price of the active materials in electrodes is likely to fall over time. This view is supported by the recent NAIGT report.

A detailed analysis of these issues is beyond the scope of this project. However, the impact of supply-side effects is certainly worth bearing in mind when considering how the marginal capital costs will change over time.

2.4 Revised Capital Costs and Learning Rates

This sub-section lists the interim updated marginal capital costs and learning rates for small cars, medium cars, large cars, LCVs and HGVs. As described in sections 2.1 and 2.2 some costs have been updated whereas others remain as per the original MACC model. The following marginal capital costs have been updated:

- All the costs for cars originating from the TNO (2006) study
- Electric cars
- Plug-in hybrid cars
- Full-hybrid cars
- Electric LCVs
- Electric 3.5 - 7.5 tonne trucks

The changes that have been made to the learning rates are described in Section 3 of the report. Tables 7 to 11 list the full suite of interim updated societal marginal capital costs and learning rates.

Table 7 – Marginal societal capital costs and learning rates for small cars

	Technology	Marginal Cost					Learning Rate			
		Original Values		Updated Values		Source for Updated Values	Original Values	Updated Values		
		Low	High	Low	High		Central	Low	Central	High
Powertrain technologies (petrol)	Conventional petrol engine	£0	£0	£0	£0	Parkers Guide	1.00	1.00	1.00	1.00
	1st Generation advanced petrol engine	£89	£391	£90	£400	TNO (2006)	0.95	0.96	0.95	0.94
	2nd Generation advanced petrol engine	£199	£345	£200	£400	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 1st gen petrol engine	£194	£496	£400	£700	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 2nd gen petrol engine	£305	£451	£500	£700	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 1st gen petrol engine	£545	£847	£700	£1,000	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 2nd gen petrol engine	£655	£802	£900	£1,100	TNO (2006)	0.95	0.96	0.95	0.94
	CAI - petrol engine	£400	£600	£400	£600	AEA estimate	0.90	0.95	0.90	0.85
Powertrain technologies (diesel)	Conventional diesel engine	£355	£355	£400	£400	Parkers Guide	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£514	£460	£600	£600	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£776	£776	£900	£900	TNO (2006)	0.95	0.96	0.95	0.94
	HCCI - diesel engine	£755	£955	£800	£1,000	AEA estimate	0.90	0.95	0.90	0.85
Other	Electric	£8,861	£13,292	£6,300	£20,400	C1 ev'ie, iMiEV, Think! City	0.85	0.96	0.92	0.87
	LPG conversion	£1,000	£0	£1,000	£1,400	AEA estimate	1.00	1.00	1.00	1.00
Non-powertrain "additive" technologies	Low rolling resistance tyres	£11	£20	£10	£20	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£19	£20	£20	£20	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Medium weight reduction	£50	£58	£80	£90	TNO (2006)	0.95	0.96	0.95	0.94
	Light weighting - Strong weight reduction	£188	£205	£700	£700	TNO (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£60	£60	£100	£100	TNO (2006)	0.95	0.96	0.95	0.94
	Gearshift indicators	£54	£54	£20	£30	TNO (2006)	0.95	0.96	0.95	0.94

Table 8 – Marginal societal capital costs and learning rates for medium cars

		Marginal Cost					Learning Rate			
	Technology	Original Values		Updated Values		Source for Updated Values	Original Values	Updated Values		
		Low	High	Low	High		Central	Low	Central	High
Powertrain technologies (petrol)	Conventional petrol engine	£0	£0	£0	£0	TNO (2006)	1.00	1.00	1.00	1.00
	1st Generation advanced petrol engine	£133	£354	£140	£400	TNO (2006)	0.95	0.96	0.95	0.94
	2nd Generation advanced petrol engine	£266	£399	£300	£400	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 1st gen petrol engine	£354	£576	£500	£700	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 2nd gen petrol engine	£487	£620	£600	£800	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 1st gen petrol engine	£664	£886	£900	£1,200	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 2nd gen petrol engine	£797	£930	£1,100	£1,200	TNO (2006)	0.95	0.96	0.95	0.94
	Mild Hybrid - petrol engine	£1,417	£1,417	£1,700	£1,700	TNO (2006)	0.85	0.90	0.85	0.80
	Full hybrid - petrol engine	£3,100	£3,909	£3,200	£3,200	Toyota Prius	0.85	0.90	0.85	0.80
	Plug-in hybrid - petrol engine	£7,257	£12,000	£8,400	£13,900	GM Volt, Toyota Prius Plug-in (conversion)	0.85	0.98	0.92	0.86
	CAI - petrol engine	£400	£400	£400	£400	AEA Estimate	0.90	0.95	0.90	0.85
Powertrain technologies (diesel)	Conventional diesel engine	£737	£737	£700	£700	Parkers Guide	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£914	£914	£1,000	£1,000	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£1,224	£1,224	£1,500	£1,500	TNO (2006)	0.95	0.96	0.95	0.94
	Mild Hybrid - diesel engine	£2,154	£2,154	£2,200	£2,200	TNO (2006)	0.85	0.90	0.85	0.80
	Full hybrid - diesel engine	£3,837	£4,646	£3,900	£3,900	TNO (2006)	0.85	0.90	0.85	0.80
	Plug-in hybrid - diesel engine	£7,994	£12,737	£9,200	£14,600	GM Volt, Toyota Prius Plug-in (conversion)	0.85	0.98	0.92	0.86
	HCCI - diesel engine	£1,137	£1,137	£1,100	£1,100	AEA Estimate	0.90	0.95	0.90	0.85
Other	Electric	£14,347	£21,521	£11,300	£22,200	AEA Estimate	0.85	0.96	0.92	0.87
	LPG conversion	£1,200	£2,300	£1,500	£1,700	AEA Estimate	0.95	1.00	1.00	1.00
Non-powertrain "additive" technologies	Low rolling resistance tyres	£27	£27	£30	£30	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£25	£27	£30	£30	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Medium weight reduction	£80	£89	£120	£140	TNO (2006)	0.95	0.96	0.95	0.94
	Light weighting - Strong weight reduction	£260	£295	£900	£1,000	TNO (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£66	£66	£100	£100	TNO (2006)	0.95	0.96	0.95	0.94
	Gearshift indicators	£54	£60	£20	£30	TNO (2006)	0.95	0.96	0.95	0.94

Table 9 – Marginal societal capital costs and learning rates for large cars

		Marginal Cost					Learning Rate			
	Technology	Original Values		Updated Values		Source for Updated Values	Original Values	Updated Values		
		Low	High	Low	High		Central	Low	Central	High
Powertrain technologies (petrol)	Conventional petrol engine	£0	£0	£0	£0	Parkers Guide	1.00	1.00	1.00	1.00
	1st Generation advanced petrol engine	£177	£354	£190	£500	TNO (2006)	0.95	0.96	0.95	0.94
	2nd Generation advanced petrol engine	£112	£452	£130	£500	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 1st gen petrol engine	£283	£460	£600	£800	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 2nd gen petrol engine	£218	£557	£500	£900	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 1st gen petrol engine	£784	£961	£1,100	£1,400	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - 2nd gen petrol engine	£719	£1,058	£1,100	£1,400	TNO (2006)	0.95	0.96	0.95	0.94
	Mild Hybrid - petrol engine	£1,367	£1,771	£1,400	£1,800	TNO (2006)	0.85	0.90	0.85	0.80
	Full hybrid - petrol engine	£2,151	£3,720	£2,600	£18,300	Lexus RX and LS	0.85	0.90	0.85	0.80
	Plug-in hybrid - petrol engine	£15,000	£18,000	£12,100	£29,100	Fisker Karma	0.85	0.98	0.92	0.86
	CAI - petrol engine	£400	£600	£400	£600	AEA Estimate	0.90	0.95	0.90	0.85
Powertrain technologies (diesel)	Conventional diesel engine	£565	£565	£600	£600	Parkers Guide	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£565	£760	£900	£900	TNO (2006)	0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£1,119	£1,119	£1,400	£1,400	TNO (2006)	0.95	0.96	0.95	0.94
	Mild Hybrid - diesel engine	£2,336	£2,336	£2,400	£2,400	TNO (2006)	0.85	0.90	0.85	0.80
	Full hybrid - diesel engine	£4,285	£4,285	£3,200	£18,800	TNO (2006)	0.85	0.90	0.85	0.80
	Plug-in hybrid - diesel engine	£15,565	£18,565	£12,700	£29,700	Fisker Karma	0.85	0.98	0.92	0.86
	HCCI - diesel engine	£965	£1,165	£1,000	£1,200	AEA Estimate	0.90	0.95	0.90	0.85
Other	Electric	£21,987	£32,981	£29,600	£50,500	Tesla Roadster, Liberty Land Rover	0.85	0.96	0.92	0.87
	LPG conversion	£0	£0	£2,000	£2,400	AEA Estimate	0.95	1.00	1.00	1.00
Non-powertrain "additive" technologies	Low rolling resistance tyres	£31	£48	£30	£50	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£30	£34	£30	£30	TNO (2006)	0.95	1.00	1.00	1.00
	Light weighting -Medium weight reduction	£102	£120	£150	£180	TNO (2006)	0.95	0.96	0.95	0.94
	Light weighting - Strong weight reduction	£370	£477	£1,300	£1,700	TNO (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£66	£67	£100	£100	TNO (2006)	0.95	0.96	0.95	0.94
	Gearshift indicators	£54	£60	£20	£30	TNO (2006)	0.95	0.96	0.95	0.94

Table 10 – Marginal societal capital costs and learning rates for LGVs

		Marginal Cost					Learning Rate			
	Technology	Original Values		Updated Values		Source for Updated Values	Original Values	Updated Values		
		Low	High	Low	High		Central	Low	Central	High
Powertrain technologies (petrol)	Conventional petrol engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	1st Generation advanced petrol engine	£133	£354	£200	£400	TNO (2006)	0.95	0.96	0.95	0.94
	Stop/start - 1st gen petrol engine	£155	£271	£150	£300	Mercedes Sprinter	0.95	0.96	0.95	0.94
	Micro-hybrid - 1st gen petrol engine	£923	£958	£900	£1,000	Vattenfall (2007)	0.95	0.96	0.95	0.94
Powertrain technologies (diesel)	Conventional diesel engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£155	£271	£150	£300	Mercedes Sprinter	0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£923	£958	£900	£1,000	Vattenfall (2007)	0.85	0.96	0.95	0.94
	Mild Hybrid - diesel engine	£2,000	£2,300	£2,000	£2,300	US EPA	0.85	0.90	0.85	0.80
	Full hybrid - diesel engine	£3,522	£3,522	£3,500	£3,500	US EPA	0.85	0.90	0.85	0.80
	Plug-in hybrid - diesel engine	£7,500	£10,000	£7,500	£10,000	AEA Estimate	0.85	0.90	0.85	0.80
	HCCI - diesel engine	£400	£600	£400	£600	AEA Estimate	0.90	0.95	0.90	0.85
	Electric	£33,724	£37,245	£38,200	£43,000	Smith EV and Modec	0.85	0.90	0.85	0.80
Non-powertrain "additive" technologies	Low rolling resistance tyres	£24	£106	£20	£110	US National Research Council	0.95	0.96	0.95	0.94
	Light weighting -Mild weight reduction	£40	£40	£40	£40	US National Research Council & IEA	0.95	0.90	0.85	0.94
	Light weighting -Medium weight reduction	£146	£146	£150	£150	US National Research Council & IEA	0.95	0.90	0.85	0.80
	Light weighting - Strong weight reduction	£500	£500	£500	£500	US National Research Council & IEA	0.95	0.90	0.85	0.80
	Improved aerodynamics	£68	£176	£70	£180	Vattenfall (2007)	0.95	0.96	0.95	0.94
	Gearshift indicators	£60	£60	£60	£60	AEA Estimate	0.95	0.96	0.95	0.94

Table 11 – Marginal societal capital costs and learning rates for rigid HGVs

	Technology	Marginal Cost					Learning Rate			
		Original Values		Updated Values		Source for Updated Values	Original Values	Updated Values		
		Low	High	Low	High		Central	Low	Central	High
	Rigid Truck 3.5 - 7.5 t									
Powertrain technologies (diesel)	Conventional diesel engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£1,200	£1,200	£300	£400		0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£1,800	£1,800	£1,800	£1,800		0.95	0.96	0.95	0.94
	Mild Hybrid - diesel engine	£2,400	£2,400	£50,000	£50,000	Imperial college	0.85	0.90	0.85	0.80
	Full hybrid - diesel engine	£5,400	£9,400	-	-	-	0.85	0.90	0.85	0.80
	HCCI - diesel engine	£800	£1,000	£600	£800	AEA Estimate	0.95	0.96	0.95	0.94
	Electric	£83,868	£120,159	£76,100	£102,900	Smith EV	0.85	0.90	0.85	0.80
Non-powertrain "additive" technologies	Low rolling resistance tyres	£161	£161	£160	£160	Infras (2006)	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£2,066	£2,066	£2,100	£2,100	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting -Medium weight reduction	£4,132	£4,132	£4,100	£4,100	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting - Strong weight reduction	£10,330	£10,330	£10,300	£10,300	Infras (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£1,550	£1,550	£1,500	£1,500	Infras (2006)	0.95	0.96	0.95	0.94
	Gearshift indicators	£60	£60	£60	£60	AEA Estimate	0.95	0.96	0.95	0.94
	Specific long-distance vehicles	£0	£0	£0	£0	AEA Estimate	0.95	0.96	0.95	0.94
	Rigid Truck > 7.5 t									
Powertrain technologies (diesel)	Conventional diesel engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	Stop/start - diesel engine	£1,200	£1,200	£1,200	£1,200	AEA Estimate	0.95	0.96	0.95	0.94
	Micro-hybrid - diesel engine	£1,800	£1,800	£1,800	£1,800	AEA Estimate	0.95	0.96	0.95	0.94
	Mild Hybrid - diesel engine	£2,400	£2,400	£50,000	£50,000	Imperial college	0.85	0.90	0.85	0.80
	Full hybrid - diesel engine	£5,400	£9,400	-	-	-	0.85	0.90	0.85	0.80
	HCCI - diesel engine	£400	£600	£800	£1,000	AEA Estimate	0.95	0.96	0.95	0.94
Non-powertrain "additive" technologies	Low rolling resistance tyres	£136	£161	£300	£300	Volvo Estimate	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£3,263	£3,263	£3,300	£3,300	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting -Medium weight reduction	£6,525	£6,525	£6,500	£6,500	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting - Strong weight reduction	£16,314	£16,314	£16,300	£16,300	Infras (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£2,447	£2,447	£2,400	£2,400	Infras (2006)	0.95	0.96	0.95	0.94
	Gearshift indicators	£100	£100	£100	£100		0.95	0.96	0.95	0.94
	Specific long-distance vehicles	£3,263	£3,263	£3,300	£3,300		0.95	0.96	0.95	0.94

Table 12 – Marginal societal capital costs and learning rates for articulated HGVs

Articulated Truck < 33 t

Powertrain technologies	Conventional diesel engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	HCCI - diesel engine	£400	£1,500	£800	£1,000	AEA Estimate	0.95	0.96	0.95	0.94
Non-powertrain "additive" technologies	Low rolling resistance tyres	£409	£409	£300	£300	Volvo Estimate	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£4,230	£4,230	£4,200	£4,200	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting -Medium weight reduction	£8,460	£8,460	£8,500	£8,500	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting - Strong weight reduction	£21,150	£21,150	£21,100	£21,100	Infras (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£3,172	£3,172	£3,200	£3,200	Infras (2006)	0.95	0.96	0.95	0.94
	Specific long-distance vehicles	£4,230	£4,230	£4,200	£4,200	Infras (2006)	0.95	0.96	0.95	0.94
	Teardrop trailers	£2,500	£2,500	£2,500	£2,500	Don-Bur Bodies and Trailers Ltd	0.95	0.96	0.95	0.94

Articulated Truck > 33 t

Powertrain technologies	Conventional diesel engine	£0	£0	£0	£0	N/A	1.00	1.00	1.00	1.00
	HCCI - diesel engine	£1,000	£1,500	£1,000	£1,500	AEA Estimate	0.95	0.96	0.95	0.94
Non-powertrain "additive" technologies	Low rolling resistance tyres	£614	£614	£500	£500	Volvo Estimate	0.95	1.00	1.00	1.00
	Light weighting -Mild weight reduction	£5,493	£5,493	£5,500	£5,500	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting -Medium weight reduction	£10,986	£10,986	£11,000	£11,000	Infras (2006)	0.95	0.90	0.85	0.80
	Light weighting - Strong weight reduction	£27,464	£27,464	£27,500	£27,500	Infras (2006)	0.95	0.90	0.85	0.80
	Improved aerodynamics	£4,120	£4,120	£4,100	£4,100	Infras (2006)	0.95	0.96	0.95	0.94
	Specific long-distance vehicles	£5,493	£5,493	£5,500	£5,500	Infras (2006)	0.95	0.96	0.95	0.94
	Teardrop trailers	£2,500	£2,500	£2,500	£2,500	Don-Bur Bodies and Trailers Ltd	0.95	0.96	0.95	0.94
	Increased weight limit (60t)	£19,225	£19,225	£19,200	£19,200	Infras (2006)	0.95	0.96	0.95	0.94

3 Updating the learning rates used in the transport MACC model

3.1 Background

The costs associated with technological options for reducing CO_2 will evolve as a direct consequence of the scale of application (economies of scale and learning effects) and time (innovation). Decreases in the costs of technology arise due to a combination of factors including:

- Improvements in production processes (i.e. over time, and with increases in the scale of manufacturing, production processes can become more efficient, thereby reducing costs);
- Technological or manufacturing innovations may lead to reductions in unit costs (e.g. new materials or production processes);
- A move to mass production from low-volume production.

Decreases in the marginal costs of technology due to these effects can be quantitatively described using learning rate theory. Learning rate theory enables changes in the costs associated with a particular technology to be quantified in relation to levels of deployment in the market. The theory is based on the application of assumptions for each of the above elements in order to estimate cost trajectories for individual technologies. The approach has been employed in the existing CCC transport MACC model using learning rate data identified by AEA and our consortium partners (Metroeconomica and CE Delft) when developing the model in 2008.

The application of learning rate theory is not straightforward in practice, because there are a number of unknown factors that cannot be foreseen with absolute accuracy. In particular, it is difficult to predict future innovations and, with respect to vehicle technologies, the rate at which costs will decrease is highly dependent on the levels of activity and investment in research and development made by vehicle manufacturers. This latter point is itself closely tied into the policy framework – for example, if there is a strong regulatory mandate to reduce vehicle CO_2 emissions, then manufacturers are more likely to rapidly invest large amounts of money into developing and commercialising abatement technologies. This in turn will alter the learning rates that might apply to a particular technology.

Also, it should be noted that while in its quantitative formulation learning rates link costs to production volumes, the drivers of cost reduction mentions above go beyond pure economies of scale and some take time in order to be realised. In other words there is an implicit time dimension in learning rate theory that needs to be taken into account when applying learning rate equations, as very rapid growth in production volumes (which in itself may be unlikely due to logistic and market reasons) may not be accompanied by a quick reduction in cost.

Lastly, depending on the assumed production volumes learning equations for the relevant technology may be extended well beyond the move from niche to mass production over which they were originally estimated. In practice beyond certain levels of production it is possible that learning relationships may ‘flatten out’ unless some technology breakthrough is achieved (e.g., for battery technology, learning on Li-ion batteries that are currently being introduced in the market may eventually stop and be superceded by a move to a new generation of batteries, based on a different chemistry).

The learning rates in the existing transport MACC model, as well as in this study are presented as decimal numbers between 0 and 1. A learning rate of 1 indicates a technology is in mass manufacture and there will not be further decrease in cost with increases in production levels. A learning rate of 0.95 for a particular technology indicates that the marginal cost of a vehicle equipped with that technology will reduce by 5% every time production levels double; a learning rate of 0.60 indicates that the marginal cost will decrease by 40% each time production levels double.

The formula used to calculate the learning rates is as follows:

$$C_t = C_o \times \left(\frac{M_t}{M_o}\right)^b \quad \text{and} \quad b = \frac{\ln PR}{\ln 2}$$

Where C_{2006} = Marginal capital cost in 2006
C_t = Marginal capital cost at mass manufacture
M_{2006} = Estimate of production volumes in 2006
M_t = Estimate of annual production volumes at mass production
PR = Estimate of the learning rate
ln = Natural log

In the original MACC model a single learning rate was used for each technology. One of the key aims of this study is to generate ranges for the learning rates to reflect the level of certainty in respect of the cost reductions that can be achieved for each technology. Some of the more mature technologies such as first generation advanced petrol engines are at or close to mass-production, and so the range of learning rates will be small. In contrast, EVs and PHEVs are some way from mass production so there is far more uncertainty regarding the rate at which costs will reduce. As a result the range of learning rates will be significantly greater.

Finally it should be noted that technology learning is a global phenomenon that is ultimately linked to global production volumes. For reasons of expediency in the existing transport MACC model learning rates are however related to UK sales. This implicitly assumes that the increase in UK sales is a proportionate reflection of global trends, and may also quickly and implicitly result in an extension of learning rates to large global production volumes (if for instance a UK production volume of 100,000 corresponds to a global production volume which is likely to be an order of magnitude bigger).

3.2 Methodology for updating learning rates

A twin-track approach was employed in updating the learning rates in the original MAC model:

1. Desk research was undertaken in an effort to identify appropriate studies or other sources of learning rates for low-carbon technologies for cars, LCV and HGVs.

2. More detailed consideration has been given to the technologies where learning rates are likely to be least certain (EV, HEV and PHEV).

Our initial desk research has found that published sources of learning rates for low carbon technologies are very limited. This point was reinforced during an email exchange with Socrates Kypreos who is Head of the Energy Modelling and the Systems Analyses Group in the General Energy Department at the Paul Scherrer Institute (PSI), in Switzerland. Mr Kypreos had been contacted in relation to his project: 'Modelling the Global Transportation Sector', which utilized a range of learning rates. It transpired that the learning rates used in the work were purely estimates and in his view no reliable information on learning rates exists for cars or vans.

That said, further sources of learning rates were identified as part of the desk research, including the following:

- The CE Delft Note on the potential and costs for further CO_2 reduction beyond 2012 – development of indicative future cost curves, prepared for DfT in June 2008

- AMG (Analysis and Modelling Group). Canada's Emissions Outlook: An Update. Ottawa: AMG, National Climate Change Process, December 1999.

- US Department of Energy's Transport Sector Model, Washington, DC: Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy, 1998

In view of the fact that the North American studies are at least nine years old, care was taken not to put too much weight on the learning rates it contained for "high efficiency" petrol and diesel cars/vans, electric cars and hybrid electric cars. In contrast the learning rates for Internal Combustion Engines, HEVs and advanced light weighting in CE Delft note have been used in this study to inform the updated learning rates. A full list of the updated learning rates can be found in section 3.3.

In terms of the more detailed consideration of EVs, HEVs and PHEVs attention has focused on the battery technologies. Our initial research showed that the batteries are by far and away the most important component in terms of determining the marginal costs of these types of vehicles. This has been reflected in the interim analysis (see Section 2.2). In particular, the choice of electrode materials and the price of the materials on the commodity markets are a key factor in determining the price of batteries. For instance, the price of cobalt peaked in March 2008 at around $50 per lb (or $125 per kg) and has since fallen to around $15 per lb. This illustrates the extent of the volatility in the price of key materials.

The study team engaged with the trade associations EUROBAT and EUCAR, with the aim of securing a more detailed insight in to the specific components or processes that dictate the marginal cost and learning rate for each of the battery technologies. Unfortunately neither organisation was able to assist us. Therefore, the main source of price estimates for batteries was the recent Arup/Cenex report and the papers it referenced. As described in detail in Section 3.3 these figures were used to estimate the learning rates for Li-ion batteries and hence the learning rates for EVs and PHEVs.

Using the interim results from the research undertaken to date, three sets of revised learning rates have been compiled:

- The **high** learning rate is defined as a conservative estimate of the learning rate where less progress is made in reducing costs than had been expected. This could occur for a number of reasons but perhaps the most likely cause in the current climate would be the global economic downturn. It is not difficult envisage a situation where car manufacturers reduce investment in developing new technologies in order to conserve funds. Alternatively manufacturers may decide to focus their development efforts on other technologies such as advanced diesel.
- The **central** learning rate is defined as the most likely learning rate based on anticipated levels of technological advancement. In other words this would entail existing technology development programmes progressing as planned.
- The **low** learning rate is defined as an optimistic estimate of the learning rates based on the best possible outcome in terms of the rate at which costs are reduced.

As has already been stated, estimating learning rates is a difficult process, which relies on a combination of professional judgement and as much evidence as is available. This is because in estimating learning rates, it is necessary to make judgements about possible known and unknown technological innovations and improvements in manufacturing processes; clearly it is not possible to have perfect foresight in these areas. Therefore, it is important to bear in mind that the learning rates listed in Section 2.3 are the study team's best estimates based on the best available data. The learning rates have also been reviewed by ACEA and SMMT's members as well as CCC and its external experts.

The updated learning rates can be found in section 2.3 alongside the update marginal societal capital costs.

3.3 Estimating the learning rates for EVs and PHEVs

Given that EVs and PHEVs are a particular focus of this study it was important to consider the learning rates for those technologies in particular detail. However, as described in Section 3.2 the data on learning rates for EV and PHEV, and indeed any automotive technology, is limited. In view of these data limitations it was decided to investigate the learning rates associated with li-ion batteries, which are largely responsible for the marginal capital cost of EVs and PHEVs compared to conventional vehicles. These battery learning rates were then used to estimate the learning rate for the overall electric or plug-in hybrid vehicle.

As illustrated in the learning rate formula in Section 3.1 there are two key sets of information required to calculate a learning rate:

- The current manufacture volume and cost (in practice 'current' can be taken to mean any date so long as the manufacture volume and cost are available)
- The future manufacture volume and cost.

For the purposes of this study estimates of costs and manufacture volumes for li-ion batteries were taken from the following studies:

- Axsen J, Burke A, Kurani K, Institute of Transportation Studies, University of California (2008): Batteries for Plug-in Hybrid Electric Vehicles (PHEVs): Goals and the State of Technology circa 2008
- Sanjay Rishi, Benjamin Stanley and Kalman Gyimesi, (2008), Automotive 2020: Clarity beyond the chaos, IBM Global Services
- Fritz R. Kalhammer, Bruce M. Kopf, David H. Swan, Vernon P. Roan, Michael P. Walsh (2007), Status and Prospects for Zero Emissions Vehicle Technology, Report of the California Air Resources Board Independent Expert Panel
- Matthew A. Kromer and John B. Heywood (2007), Electric Powertrains: Opportunities andChallenges in the U.S. Light-Duty Vehicle Fleet, Sloan Automotive Laboratory, Massachusetts Institute of Technology
- Anup Bandivadekar, Kristian Bodek, Lynette Cheah, Christopher Evans, Tiffany Groode, John Heywood, Emmanuel Kasseris, Matthew Kromer, Malcolm Weiss (2008), On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions, Laboratory for Energy and the Environment, Massachusetts Institute of Technology
- Benjamin K. Sovacool, Richard F. Hirsh (2009), Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition, Energy Policy 37 (2009) 1095–1103

These reports considered a range of vehicle sizes and hence a range of battery sizes. That said, it is thought that battery size does not have a significant impact on 'per kWh' battery cost. This is because an EV or PHEV 'battery' is made up of several 'battery packs', which in turn consist of a large number of 'cells' in which the reversible chemical reactions to generate a current actually take place.

The reports also reflect a range of assessments of costs at very different levels of production, including very small/ prototype volumes, niche market production volumes and mass production volumes. Consequently, this allowed the project team to estimate learning rates for various battery sizes, and in turn EVs and PHEVs. A summary of the most useful data extracted from these studies can be found in Table 12.

It is worth noting that the figures presented in Table 12 are broadly consistent with the New Automotive Industry Growth Team's (NAIGT) projected battery prices[8]. For instance, the NAIGT

[8] An Independent Report on the Future of the Automotive Industry in the UK, 2009

foresee energy storage for vehicles costing $200/kWH in the long term, which is defined as being 10 to 20 years from production.

Table 12 – A summary of cost and manufacture volumes for Li-ion batteries

Source	Battery Capacity (kWh)	For Vehicle	Manufacture Volumes (units/year)	Battery Cost Estimate (2007 USD)	Cost per kWh (2007 USD)
Bandivadekar (2008)	8	PHEV-20	100,000 [1]	2,560	320
Kalhammer (2007)	7	PHEV-20	100,000	4,025	575
Kalhammer (2007)	7	PHEV-20	20,000	5,190	741
Kromer (2007)	8	PHEV-30	100,000 [1]	2,080	260
Kromer (2007)	8	PHEV-30	100,000 [1]	2,560	320
Axsen (2008)	14 [2]	PHEV-40	100,000	3,400 [3]	243
Kalhammer (2007)	14	PHEV-40	100,000	5,585	399
Kalhammer (2007)	14	PHEV-40	20,000	8,350	596
Kromer (2007)	16 [2]	PHEV-60	100,000 [1]	3,440	215
Kromer (2007)	16 [2]	PHEV-60	100,000 [1]	4,320	270
Kalhammer (2007)	25	Small EV	100,000	8,150	326
Kalhammer (2007)	25	Small EV	20,000	11,875	475
Kromer (2007)	48	Full Spec EV	100,000 [1]	9,600	200
Kalhammer (2007)	40	Full Spec EV	100,000	8,395	210
Kromer (2007)	48	Full Spec EV	100,000 [1]	12,000	250
Bandivadekar (2008)	48	Full Spec EV	100,000 [1]	12,000	250
Kalhammer (2007)	40	Full Spec EV	20,000	12,240	306
Arup / CENEX (2008)	-	All	500	-	1,000
Arup / CENEX (2008)	-	All	500	-	2,000

1. Where mass production volumes are not explicitly stated in the source material, they are assumed to be 100,000 units per year.

2. Battery capacities are not given in this study but have been assumed based on the standard capacity for the given PHEV range supplied in Kalhammer (2007)

3. USABC cost goal for batteries for this vehicle type, considered in the literature to be an optimistic mass production cost estimate.

A suite of learning rates for batteries was calculated using different combinations of data from Table 12. For example, a learning rate was calculated for medium PHEVs using rows 1 and 2 from Table 12. A second learning rate for medium PHEVs was then calculated using rows 2 and 3, a third using rows 1 and 3 and so on. Each potential combination was calculated in this manner. The range of learning rates for each vehicle size is presented in Table 13 although it should be noted this was merely a convenient way of presenting the data. As discussed earlier in Section 3.3 there is not thought to be a link between battery size and per kWh cost.

It is important to note that the ‘outliers’ (i.e. values that are out of sync with the rest of dataset and therefore likely to be erroneous) have been excluded (learning rate values lower than 0.7, indicating a very rapid decrease in cost with increases in production volumes have been excluded).

Table 13 – High and low learning rate estimates

	Estimate	Data Source	Production volumes (units/year)	Cost per kWh (2007 USD)	Calculated Learning Rate
Battery for medium PHEV	Low	Arup / CENEX (2008)	500	2,000	0.766
		Kromer (2007)	100,000	260	
	High	Arup / CENEX (2008)	500	1,000	0.930
		Kalhammer (2007)	100,000	575	
Battery for large PHEV	Low	Arup / CENEX (2008)	500	2,000	0.747
		Kromer (2007)	100,000	215	
	High	Arup / CENEX (2008)	500	1,000	0.887
		Kalhammer (2007)	100,000	399	
Battery for small EV	Low	Arup / CENEX (2008)	500	2,000	0.789
		Kalhammer (2007)	100,000	326	
	High	Arup / CENEX (2008)	500	1,000	0.864
		Kalhammer (2007)	100,000	326	
Battery for large EV	Low	Arup / CENEX (2008)	500	2,000	0.740
		Kromer (2007)	100,000	200	
	High	Kalhammer (2007)	20,000	306	0.917
		Bandivadekar (2008)	100,000	250	

Table 13 shows that the learning rates for both EV and PHEV batteries range from around 0.75 to 0.93. This information was used to estimate the learning rate for electric and plug-in hybrid electric vehicles.

The project team estimated the overall EV and PHEV learning rates by applying the learning rates in Table 13 to the cost of battery whilst assuming a learning rate of 1 (i.e. zero learning) for the remainder of the vehicle. Whilst this latter assumption may seem rather crude, aside from the batteries, the learning rate for the rest of the vehicle is likely to be very modest. For instance, electric motors are mature technologies in mass production for other applications. Furthermore, many other elements of an EV or PHEV will bear a close resemblance to a conventional vehicle – tyres, interiors, windscreen wipers etc will all be very similar if not identical.

To generate a range of learning rates the two extremes of battery learning rates and costs were considered:

1. The most aggressive learning rate for batteries + the 'high' initial battery price
2. The most conservative learning rate for batteries + the 'low' initial battery price

These two learning rates were then applied to battery proportion of the total vehicle cost to arrive at the 'high' and 'low' learning rates for the overall EV and PHEV. The 'central' learning rate was assumed to be the mid-point between the high and low learning rates. The three sets of learning rates for EVs and PHEVs are presented in Table 14.

Both the high and low learning rates for PHEVs presented in Table 13 are closer to 1 than EVs. This reflects the fact that the battery, where the vast majority of technology learning is likely to take place, is significantly smaller for PHEVs. In turn this means it will make up a smaller proportion of the overall cost for PHEVs and hence the overall price of a PHEV is likely to reduce at a more modest rate than EVs.

Table 14 – Learning rates for EVs and PHEVS

	EV	PHEV
Low learning rate	0.87	0.86
Central learning rate	0.92	0.92
High learning rate	0.96	0.98

The tables in Section 2.3 illustrate the updated marginal capital cost and learning rates for each technology and Section 3.4 illustrates the impact of these learning rates on the future costs of an EV and PHEV.

3.4 Illustrating the impact of learning rates

Learning rates are a relatively simple concept; they describe the fall in costs of a technology when manufacture volume doubles. However, they are not always easy to visualise, particularly when manufacture volumes are set to increase many times from a low base. Therefore, this section will seek to illustrate the impact of different learning rates through two examples: an illustrative small EV (taking likely launch cost information for the Mitsubishi i-MiEV) and an illustrative medium PHEV (taking likely launch cost information for the Chevrolet Volt). Table 15 lists the assumed launch prices/production volumes and learning rates, which are consistent with the learning rates for EVs and PHEVs in Section 2.3.

It should be noted that the learning rates presented are for the complete EV or PHEV not just the battery. It is also worth emphasising that Table 15 presents the likely launch ‘cost to society’ (deflated to 2006 prices) rather than launch ‘prices’ i.e. VAT has been removed. This change was made in light of stakeholder comments that learning rates should be applied to costs rather than prices. However, it is also worth noting that this modification does not address the circumstances where new models are launched at below cost price in order to establish a foothold in the market. The project team are aware that such practices are commonplace amongst manufacturers but a detailed consideration of that issue is beyond the scope of this study.

Table 15 – Prices, production volumes and learning rates for an illustrative small EV and medium PHEV

	Small EV	Medium PHEV
Likely launch cost (Price less VAT and deflated to 2006 prices)	£27,600	£28,200
Likely production volume at launch	2,000	10,000
Low learning rate	0.84	0.85
Central learning rate	0.92	0.92
High learning rate	0.95	0.96

Note: Likely launch cost and production volumes reflect information available on the first models of small EV and medium PHEV expected to be introduced in the market, respectively the Mitsubishi (-MiEV and the Chevrolet Volt)

The data in Table 15 was used to calculate the cost to society for each vehicle at various annual production volumes. The results are presented Tables 16 and 17 and Figures 2 and 3.

Table 16 – The cost of an illustrative small EV at various manufacturing volumes when the low, medium and high learning rates are applied.

Small EV production volume	**2,000**	**4,000**	**8,000**	**16,000**	**32,000**	**64,000**	**128,000**
LOW learning rate (0.96)	£27,600	£23,100	£19,400	£16,300	£13,700	£11,500	£9,600
CENTRAL learning rate (0.92)	£27,600	£25,300	£23,100	£21,100	£19,300	£17,700	£16,200
HIGH learning rate (0.87)	£27,600	£26,172	£24,800	£23,500	£22,300	£21,100	£20,000

***Figure 2** - The price of an illustrative small EV at various manufacturing volumes when the low, medium and high learning rates are applied.*

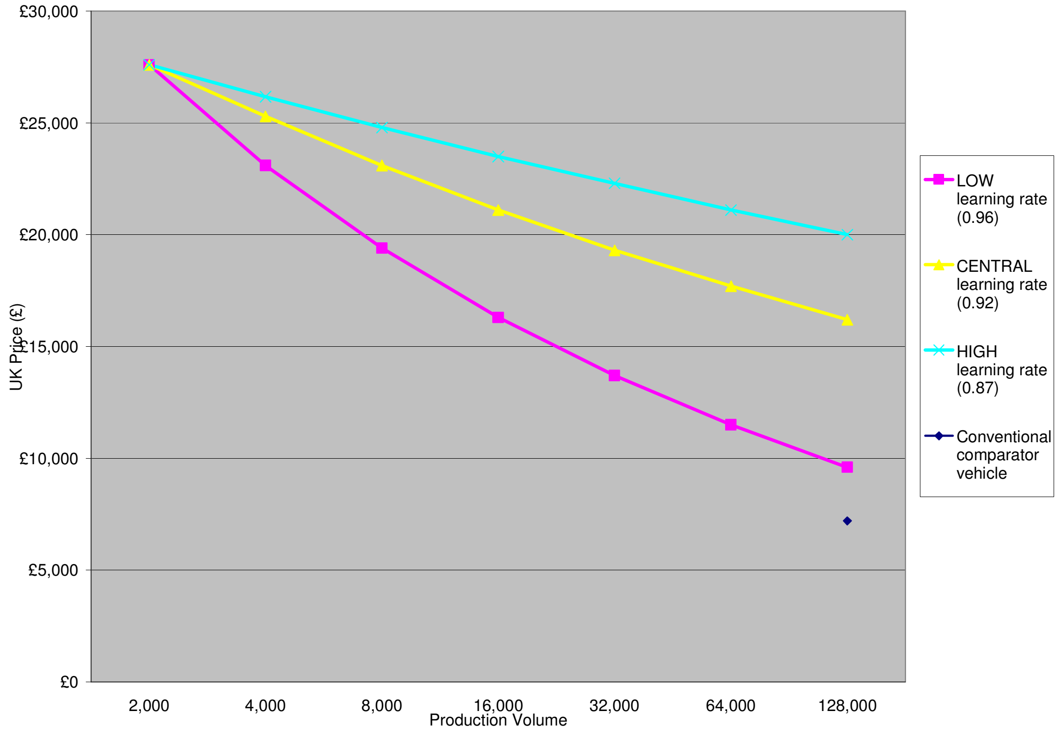
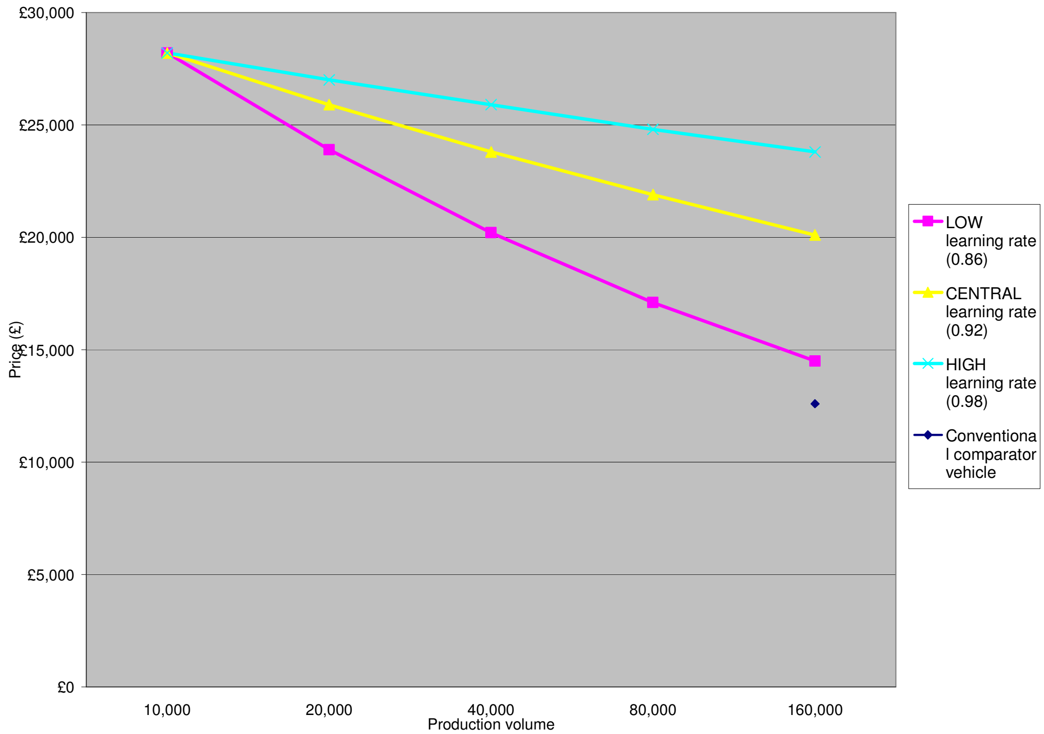


Table 17 – The price of an illustrative medium PHEV at various manufacturing volumes when the low, medium and high learning rates are applied.

Medium PHEV production volume	**10,000**	**20,000**	**40,000**	**80,000**	**160,000**
LOW learning rate (0.86)	£28,200	£23,900	£20,200	£17,100	£14,500
CENTRAL learning rate (0.92)	£28,200	£25,900	£23,800	£21,900	£20,100
HIGH learning rate (0.98)	£28,200	£27,000	£25,900	£24,800	£23,800

Figure 3 – The price of a medium PHEV at various manufacturing volumes when the low, medium and high learning rates are applied.



The results presented in this section illustrate that the learning rates for EVs and PHEVs produce costs to society that are broadly in line with expert opinion. This is best illustrated when considering the price of small EVs and medium PHEVs at or around so-called 'mass production'. TNO (2006) states that mass production for vehicles occurs at a manufacturing volume of 100,000. This volume of productions is also often taken to represent mass production in studies looking at battery costs.

Using this definition the illustrative small EV would be well into mass production at a manufacture volume of 128,000, which is the last column in Table 16 and the final series of points on Figure 3 (in fact battery learning is likely to spillover across different types of vehicles and battery sizes, so in applying learning rates vehicle production volumes within the relevant vehicle class this analysis is likely to introduce a conservative assumption). At this point the range of vehicle costs across all three learning rate scenarios is £11,800 to £21,300 compared to a base cost for a conventional small petrol car[9] (the Mitsubishi i) of £7,200. This seems reasonable since most commentators agree that the price of EVs will remain above conventional vehicles for the foreseeable future. In the long term (i.e. post 2025) there may come a time when EVs become cheaper than conventional vehicles, although this will depend on whether li-ion battery costs can be reduced significantly. That said electric vehicles are inherently simpler than conventional vehicles (they have around half the number of moving parts) so they certainly have the potential to be cheaper.

The cost of the illustrative medium PHEV ranges from £17,700 to £26,400 at a production volume of 80,000, which is approaching mass production. At a production volume of 160,000 the cost ranges from £15,200 to £25,800. This compares to a base cost for a conventional medium petrol car (Vauxhall Astra) of £12,600. In a similar vein to the illustrative small EV this projected costs seem very reasonable. PHEVs are likely to retain a price premium over conventional vehicles since they require two power trains – electric and conventional petrol or diesel.

[9] The Mitsubishi i was selected as the conventional 'small' comparator vehicle because it is the vehicle on which the Mitsubishi i-MiEV is based and hence it is a similar size and shape to the Mitsubishi I-MiEV.

In summary, the learning rates for EVs and PHEVs seem to produce a plausible cost trajectory between launch and mass production when applied to the expected initial costs of illustrative EVs and PHEVs. In addition, whilst this simple analysis is certainly not definitive, it also suggests there is merit in applying li-ion battery-specific learning rates to batteries and assuming a learning rate of 1 for the remainder of the vehicle.

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