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CAN ELECTRIC VEHICLES ADDRESS IRELAND'S CO_2 EMISSIONS FROM TRANSPORT?

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ABSTRACT

In the period 1990-2007, CO_2 emissions from Ireland's Transport sector increased by 181%. It has been proposed that a transition to electrically-powered vehicles (EV) – either battery-powered (BEV) or plug-in hybrids (PHEV) – offers the potential for significant reductions in these emissions. However, the benefits of PHEV – and of plug-in vehicles generally – accrue because some fraction of the fossil fuel normally consumed by the vehicle is displaced by electricity extracted from the national grid. The net benefit therefore depends on many factors, including the characteristics of the electricity generation and distribution system, and the proportion of vehicle-kilometres (vkm) completed under electric power.

This paper examines these factors in an Irish context. On the basis of individual vehicles, it is found that electrification yields substantial and immediate reductions in greenhouse gas emissions for urban-type driving cycles. For inter-city travel, however, the percentage reduction attainable is much smaller, and the technical difficulty of achieving this capability is much greater. Unless that challenge can be overcome, it is shown, 50%-75% of CO_2 emissions from private cars will remain beyond the reach of electrification.

KEYWORDS: electric vehicles, emissions, CO_2, transport

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ABBREVIATIONS:

AER ..... all-electric range
BEV ..... battery-electric vehicle
CV..... conventional vehicle
EU..... European Union
EV..... electric vehicle
GHG ..... greenhouse gases
HGV ..... heavy goods vehicle
ICE..... internal combustion engine
ISG..... integrated starter-generator
NCT ..... national car test
NEDC ..... new European drive cycle
PC ..... private car
PCkm ..... private-car kilometres
PER..... primary energy requirement
PHEV..... plug-in hybrid electric vehicle
POWCAR ... Place-Of-Work Census of Anonymised Records
STW..... socket-to-wheel
TTW ..... tank-to-wheel
UDDS ..... Urban Dynamometer Driving Schedule
UNFCCC .... United Nations Framework Convention on Climate Change
VCA..... Vehicle Certification Authority
vkm ..... vehicle kilometres
WSER ..... wall-socket energy requirement

1 INTRODUCTION

Since 1990, Ireland has experienced a surge in growth of the transport sector. The primary energy requirement (PER) of transport increased by 177% between 1990 and 2008 [1], resulting in a corresponding increase in greenhouse gas (GHG) emissions [2]. Although the growth rate was highest for road freight, the largest absolute increase in GHG from the sector was attributable to private cars [1].

Over the same period, the GHG emissions index ($g.kW^{-1}h^{-1}$) of the Irish electricity system has steadily improved, from 896 $gCO_2.kW^{-1}h^{-1}$ in 1990, to 582 $gCO_2.kW^{-1}h^{-1}$ in 2008 [1]. Nonetheless, Ireland needs to further reduce national GHG emissions if it is to meet emissions targets for both the 2008-2012 Kyoto period, and for the EU 2020 deadline [3]. This led the government in 2007 to set ambitious targets for electricity generation from renewable sources [4]. These targets were subsequently increased, and now require that 15% of electricity be derived from renewable sources by 2010, and 40% by 2020 [5]. If met, these targets will reduce CO_2 emissions from the electricity sector to approximately 520 $gCO_2.kW^{-1}h^{-1}$ in 2010, and to ~330 $gCO_2.kW^{-1}h^{-1}$ in 2020 [6, and Appendix 1].

In this context, electrification of the private car fleet appears tempting, since it might reduce GHG emissions from that source. Moreover, significant collateral benefits would accrue, including reduced oil-dependence, improved air quality in urban areas, and increased sustainability of personal transport. However, the magnitude of the ensuing benefits is dependent not only on the efficiency and Carbon-intensity of the electricity supply system, but also on the efficiency with which electric vehicles (EV) exploit that electricity, and the fraction of private-car-km (PCkm) completed under all-electric power. The quantification of these latter factors is a primary focus of this paper.

2 ELECTRIC VEHICLES VERSUS CONVENTIONAL VEHICLES

2.1 Advantages of electric vehicles

On a tank-to-wheel (TTW), or socket-to-wheel (STW) basis, EV are generally more efficient than conventional vehicles (CV). Three primary factors drive this increased efficiency:

- greater efficiency of the prime mover – especially at low vehicle speeds and when starting from cold
- elimination of engine idling, and

- regenerative braking

The first of these is of fundamental importance. The internal combustion engine (ICE) – petrol or diesel – has a minimum rotational speed at which it can supply shaft power. Even at this minimum speed, the shaft power needed to overcome internal friction in the engine itself is typically of the order of 5 kW, and this requirement increases with rotational speed. At low vehicle speeds, the shaft power required to propel the vehicle may often be much less than that required to overcome engine friction, so that the mechanical efficiency of the engine ranges from 0% (at idle) to perhaps 80% at the optimum operating point.

Furthermore, the shape of the torque-speed curve for ICE requires the use of a gearbox in order to maintain acceptable performance across a broad range of vehicle speeds. The net result is that engine speed generally does not correlate with vehicle speed except under open-road conditions – low vehicle speeds still require moderately high engine speeds, and necessarily, therefore, low engine output torque. Hence, when vehicle speeds are low the mechanical efficiency of ICE is generally very poor.

Overall engine efficiency is a product of its mechanical and thermodynamic efficiencies; the latter is constrained by the Second Law of Thermodynamics, and is typically of the order of 50% for a modern design. Overall engine efficiency therefore ranges from about 40% at the optimum operating point (50% x 80%), down to 0% at idle.

The efficiency disadvantage of the ICE is compounded when starting from cold. Gasoline engines require mixture enrichment to be employed in order to attain acceptable operation, even under mild ambient temperatures. All CV also suffer from the increased viscosity of lubricating oil at low temperatures, which increases the frictional losses in the engine and transmission from a cold start. Although EV may also suffer from this effect, the frictional loads in CV are far

greater than in EV (as discussed above), and the penalty of increased oil viscosity is weighted accordingly.

The above characteristics are in marked contrast with those of electric motors, which have high (75%-90%) overall efficiencies across most of the speed and load map, and can deliver maximum torque at zero shaft speed (e.g.[7-9]). The latter characteristic obviates the requirement for a gearbox, so that an EV can maintain high mechanical efficiency down to zero road speed. The thermodynamic losses of an EV are associated primarily with the generation and transmission of the electricity that is used to drive the motor. Additional electrical losses occur between the electrical wall socket and the driven wheel but, as will be seen, these losses are generally smaller than the upstream losses. Hence, the overall efficiency of the EV depends on the efficiency of the electrical generation and transmission system, as well as on that of the motor and on-board electrical system.

In addition to the efficiency advantages outlined above, EV benefit from the elimination of engine idling and from the ability to exploit regenerative braking. Because of the efficiency gains associated with their use – particularly in urban-type certification drive cycles – both of these technologies are beginning to appear on modern CV. However, neither can achieve the same level of performance obtained with EV. The “stop-start” technology employed on CV requires driver intervention every time the vehicle stops, and its effectiveness is therefore completely dependent on the degree of driver engagement. A degree of regenerative braking on CV is usually achieved using either the engine alternator or, at greater expense, an Integrated Starter Generator (ISG). Whichever device is employed, the maximum power transfer is heavily constrained by the 14-volt electrical system employed on CV, and is limited in practice to about 3-4 kW (200-300 A). These characteristics are in stark contrast to EV, where the regenerative absorption capacity is roughly equal to the electric motor power.

The net result of the above is that, at low vehicle speeds and/or where there is significant potential for regeneration, the TTW efficiency of EV significantly exceeds that of CV. Collateral advantages include a reduction in oil-dependence for the transport sector, zero tailpipe emissions and, given an appropriate electricity generation and transmission system, reduced GHG emissions and energy consumption. It is important to note, however, that intercity travel normally implies high vehicle speeds, and low potential for regenerative braking; the advantage of EV over CV is therefore significantly reduced in that application.

2.2 Disadvantages of electric vehicles

The primary drawbacks of EV derive from the on-board battery packs required to drive the electric motor and to store the regenerative energy recovered during braking. There is an inherent trade-off between energy-density ($Wh.kg^{-1}$) and power-density ($W.kg^{-1}$) for all battery technologies developed to date [10-15]. For EV, high energy flow rates are required to achieve performance comparable to CV, and to maximise the recovery of energy under braking. However, high energy storage capacity is also required to achieve acceptable all-electric range (AER). The cost, size, durability, and thermal management of battery packs impose further stringent limitations on the capability of pure EV [10,12,14].

The amount of time required to recharge the battery constitutes another significant – though rarely discussed – limitation on the applicability of EV. The wall-socket energy requirement (WSER) of an EV depends heavily on the characteristics of the vehicle and of the drive cycle, as shown below. For motorway, or long-distance, travel however, estimates in the literature range from 150-250 $Wh.km^{-1}$ [11,15-17]. Taking the mean of these values, an inter-city trip of 200 km would require 40 kWh of electrical energy from a wall socket for travel in each direction. If supplied using a standard 3 kW domestic socket, the EV would require over 13 hours of charging time to travel each way – compared to about 2 hours for the trip itself.

Some BEV, such as the Nissan Leaf, incorporate "rapid-charge" sockets with a power transfer capability up to 50 kW. This author's discussions with electricity suppliers suggests that they are very reluctant to exceed this rating for charging points that will be operated by the general public, so it is unlikely that charging rates above this value will become widespread. However, even the use of a 50 kW, dedicated EV charging point would require almost an hour of charging time in each direction – assuming that a charging point is available on demand. In practice, with recharge periods of this duration, the availability of charging points might quickly constitute a significant constraint.

The charging requirement is exacerbated by the fact that battery storage is expensive, heavy, and bulky (eg [10]), so that the range achievable under all-electric operation is very limited. The recently-announced Nissan Leaf, a pure BEV, has a battery storage capacity of 24 kWh, of which 16 kWh is likely to be usable. Whereas this might be adequate for the claimed 100 miles (160 km) of AER on an urban drive cycle such as the US UDDS, the AER is likely to fall to about 60 miles (100 km) on the motorway-style drive cycle associated with inter-city travel – see for instance [17]. Nissan itself is quoted [18] as stating that the range could drop as low as 77 km (48 miles) if the car is driven hard on a motorway with the air-conditioning on. On that basis the vehicle will need to stop <u>at least</u> once to recharge during each 200 km leg of the proposed trip, as well as at each end. Even assuming the availability of a 50 kW charger at an appropriate location, this will add at least 30 minutes to each two-hour trip; in practice the time penalty is likely to be considerably longer. Consequently, the AER of mass-market, light-duty vehicles such as private cars (PC) is heavily constrained, and the use of EV for long-haul or heavy-duty goods vehicles is completely precluded for the foreseeable future.

Finally, it is worth noting that the CO_2 embedded in batteries and other EV components – associated with the energy required for their manufacture and distribution – is not necessarily

negligible. However, it *is* difficult to quantify with confidence. Moreover, these emissions are not considered to be part of the Transport inventory when compiling data for the UNFCCC and Kyoto Protocol. For these reasons, and in order to maintain a coherent narrative, it is omitted from the analysis presented in this paper.

3 ENERGY REQUIREMENT AND CO_2 EMISSIONS

From the above, it can be concluded that EV offer very significant benefits in an urban context (with low vehicle speeds, low power requirement, short trips), but that the benefits decrease dramatically on extra-urban journeys. A thermodynamic vehicle and drive-cycle model developed by the author [19] has been used to estimate the energy required for vehicles to follow a range of prescribed drive cycles, and the results are summarised in Figure 2. The vehicles modelled are from the "VW Polo", "VW Golf", and "VW Passat" classes, which constitute about 94% of the Irish passenger-car fleet [20], and which correspond roughly to "sub-compact", "compact", and "sedan" classes in US terminology.

3.1 Outline description of vehicle and drive-cycle model

The model developed by the author is a spreadsheet-based, backward-facing model. An outline description and list of equations is presented in Smith [19], but the principal features may be summarised as follows:

The vehicle is "driven" through a prescribed time-speed trace, and the tractive effort required at the tyre-road interface is computed for each time-step based on the vehicle characteristics (mass, drag coefficient, etc.). A schematic diagram of the energy flows in the model is shown in Figure 1.

Figure 1

By assuming energy conversion efficiencies for the various components linking the driven wheels to the battery (and ultimately to the wall socket), the corresponding energy and power flows can be determined. In practice, the efficiency of energy conversion and transfer between components is a function of the energy flow rate. This subtlety is ignored in the current model, and representative "typical" efficiency values are employed, as deduced for instance from [7-9]. The actual values employed in the model are listed in Table 1.

Table 1

From the values listed in Table 1, it can be seen that the overall socket-to-wheel efficiency assumed for operation in EV mode is 74%, with the remaining 26% being accounted for by losses in the battery, inverter, motor and transmission.

When modelling regenerative braking, a similarly simplified approach was adopted. In practice, the degree of energy recovery that is possible depends on the efficiency of the components listed above, but is also constrained by the power transfer capabilities of these components, and by the fact that friction braking is generally employed on the non-driven wheels. Therefore, not all of the kinetic energy that might theoretically be recovered passes through the vehicle electrical system, and a smaller fraction is finally stored in the vehicle battery. In calculating the results presented here, a recovery factor of 65% was assumed for all cycles.

3.2 Selected results from the model

Seven different drive cycles were analysed using the model above, and summary results are presented below. The "NEDC" cycles (New European Drive Cycle) are those used for vehicle certification within the European Union. The NEDC comprises an "urban" and an

“extra-urban” component, with certification based on the emissions measured over a “combined” cycle comprising four “urban” plus one “extra-urban” cycle. “UDDS / LA4” denotes the “Urban Dynamometer Driving Schedule” used for certification purposes in the United States. “US06” is a more aggressive, higher-speed cycle introduced in 2006, amid concerns that the certification fuel consumption (and emissions) data obtained using the UDDS and “Highway” drive cycles under-estimated real-world values. The “Dublin” cycle is a real-world measurement obtained by the author for a vehicle travelling from Dublin city centre to Dublin airport, and comprises a 10 km combination of urban and motorway driving in dense traffic. The “ARTEMIS” cycles were developed under the EU ARTEMIS programme, which was established to determine, via direct measurement, drive cycles representative or real-world driving conditions in the EU. “ARTEMIS urban” denotes urban driving; “ARTEMIS motorway 130” represents motorway driving with a peak vehicle speed of 130 $km.h^{-1}$. The speed-time traces for all cycles except “Dublin” were obtained from [21].

Figure 2 Wall-socket electricity requirement versus drive cycle, for a VW Golf-class EV

The wall-socket electricity requirement (WSER) calculated by the model, for each of the three vehicle classes, is presented in Figure 2. It can be seen that, for all vehicle classes, the WSER is highest under motorway-type driving cycles, and lowest for low-speed, urban-type cycles. The magnitude of the effect is very substantial: energy requirement per km travelled is, on average, 2.5 times higher for “ARTEMIS motorway 130” than for the “NEDC urban” cycle. It is this variation in WSER with drive cycle that makes discussion of AER for EV somewhat moot. The key point to extract from the data is that AER under open-road conditions is likely to be significantly shorter than under urban stop-start operation. Since inter-city travel typically involves open-road or motorway-type driving, achieving inter-city capability for EV will therefore be doubly difficult.

Taking the Golf-class vehicle as broadly representative of an "average" passenger car, the CO_2 emissions for EV can be calculated as a function of the CO_2-intensity of the electricity system. As previously stated, the CO_2-intensity of the Irish electricity system (including transmission losses) was 582 $g.kWh^{-1}$ in 2008 [1]. A WSER of 118 $Wh.km^{-1}$ on the "NEDC combined cycle" therefore translates to vehicle CO_2 emissions of 69 $g.km^{-1}$. This can be compared with the certification value of 129 $g.km^{-1}$ for the corresponding diesel vehicle – emissions from the Golf EV are roughly half those of the conventional vehicle. The benefit of EV is even more apparent when only the urban component of the NEDC is considered: a WSER of 85 $Wh.km^{-1}$ for the Golf EV translates to CO_2 emissions of just 49 $g.km^{-1}$ when powered by the Irish grid; the urban fuel consumption for the diesel Golf is 6.4 $l.100\ km^{-1}$, which translates to CO_2 emissions of 168 $g.km^{-1}$ – over 3 times higher than for the corresponding EV.

Figure 3 presents the CO_2 emissions per km from both a diesel Golf (CV) and a Golf EV, for each of the drive cycles analysed. To indicate the impact of a "greener" electricity system on emissions, data are presented for both the true, 2008 Irish grid mix (582 $g.kW^{-1}.h^{-1}$), and for the projected 2020 system mix (330 $g.kW^{-1}.h^{-1}$). It is clear that the CO_2-intensity of EV is lower than that of CV for all drive cycles analysed, particularly using the projected 2020 generation mix.

Figure 3

However, whereas the percentage reduction is very significant for low-speed, urban cycles, the savings obtained on higher-speed cycles – though still significant – are much less impressive, particularly when based on the 2008 generation mix. This is an important point, and its implications are discussed in the following section.

4 HOW MUCH CO_2 REDUCTION COULD EV DELIVER?

It is evident from the foregoing that EV are best suited to urban-type drive cycles, from the perspectives of performance and of range. It is also in an urban context that they deliver the greatest reduction in CO_2 and other tailpipe emissions – *per km travelled*. On the other hand, although EV are most effective in an urban-type drive cycle, the majority of Irish private-car km (PCkm) are extra-urban as shown below. Therefore, in order to make a reliable calculation of the total potential for EV to deliver CO_2 savings, it is necessary first to estimate the proportion of Irish PCkm that are completed in "urban mode", *i.e.* with low average and peak speeds, modest accelerations, and a significant proportion (>15%) of time spent with the vehicle stationary.

4.1 Estimation of urban versus extra-urban travel

Unfortunately, there is no Irish data set from which the required information can be directly extracted. Conversely, although no empirical data are available to directly support this assertion, the circumstantial evidence is strong. The primary support in this respect is the POWCAR data set compiled by the Irish Central Statistics Office from the 2006 National Census [22]. The relevant data is plotted in Figure 4. It shows the cumulative percentage of trips made to their place of work by drivers of passenger cars, as a function of the distance travelled (upper curve). It is easy to see that about 75% of such trips are of 20 km or less, and that almost 50% are of less than 10 km. Using the data from that upper curve, it is possible to compute the cumulative percentage of vehicle-kilometres (vkm) associated with trips of a specified distance or less (lower curve). It is clear from Figure 4 that, although 75% of these trips are of 20 km or less, those trips account for only 40% of total vkm associated with trips to work by drivers of private cars.

Figure 4 Summary of POWCAR data from the Irish Central Statistics Office

Comparison of the total vkm accounted for in the POWCAR data, with vkm gathered independently as part of the Ireland's National Car Test (NCT) programme, indicates that the data in Figure 4 accounts for only 30% or so of all vkm associated with private cars. The assumption that the distribution of trips with distance, shown above, can be extrapolated to the remaining 70% of private car km (PCkm) is somewhat speculative but, in the absence of better empirical data, this author felt obliged to make that assumption. It is comforting to note, however, that when the much more comprehensive data from the UK [24] and USA [25] is plotted on the same basis, circumstantial support for this assumption is found. It is clear for all three data sets that, although two thirds of all car trips cover a distance of 15 km or less, these trips account for less than one third of PCkm travelled.

4.2 Calculation of potential CO_2 emission savings from EV

Given the above, it is now possible to estimate the potential reductions in CO_2 emissions that could be achieved if: a) all urban-mode PCkm, and b) all PCkm, were completed using EV rather than conventional vehicles. CO_2 emissions are estimated for conventional vehicles in each mode, and for EV in each mode using both the 2008 and the 2020 generation mix. The estimates for CV are calculated as follows:

1. National statistics are used to determine annual PCkm and PC energy requirement
2. Trip-distance data is used to estimate the fraction of PCkm completed in urban mode
3. Vehicle certification data is used to estimate the fuel consumption in urban mode relative to that in extra-urban mode.
4. Hence total energy requirement and CO_2 emissions for each mode can be found

Howley et al [1] report the total energy consumption of the Irish PC fleet in 2008 as 2,181 ktoe. Based on analysis of National Car test (NCT) data, they further estimate the average distance travelled by private cars at 16,708 km per annum in 2008. The Irish Bulletin of Vehicle and Driver Statistics 2008 [20] states that the private car fleet number 1,924,281 in 2008. Combining these two numbers yields an estimate of total annual vkm for private cars in 2008 of 3.22×10^{10} vkm. Combining this figure with the 2,181 ktoe of energy consumed by PC yields an estimate of the energy intensity per vehicle km: 2.84 $MJ.km^{-1}$.

The second major assumption required for the calculation is that short trips are more likely than long ones to possess "urban" drive cycle characteristics. To simplify the calculations, this author extended that assumption by assuming that *all* trips of 15 km or less, *and* the first 15 km of all longer trips, were completed in "urban" mode. Referring to Figure 4, this implies that about 27% of all PCkm are completed in "urban" mode, with the remaining 73% having the characteristics of "extra-urban" drive cycles. Sensitivity to this parameter was examined by reducing the "urban" fraction of vkm to 20% and then by increasing it to 40%; this roughly equates to assuming that the first 12 km or first 20 km, respectively, of each trip is completed in "urban" mode.

The final piece of information required is the ratio of fuel consumption per km in "urban" drive cycles to that in "extra-urban" driving. Again, no empirical data set is available and so a somewhat oblique approach is adopted. Examination of fuel consumption data measured during vehicle certification [26] reveals that fuel consumption on the urban portion of the NEDC is, on average, 1.68[2] times higher than on the extra-urban portion (standard deviation <13%). Using this ratio, the following table can be constructed (see Appendix 2 for calculation method):

[2] To establish sensitivity to this parameter, the effects of using 1.50 and 1.85 were also examined. The resulting impacts on absolute values were small, and on the overall trends negligible. Hence, only the results obtained using the value of 1.68 are presented in this paper.

Table 2 CO_2 emissions from conventional vehicles (CV)

It can be seen from Table 2 that, because the fuel consumption of the PC fleet in 2008 is a fixed quantity, the total CO_2 emissions from the PC fleet are fixed. By varying the fraction of PCkm that are considered to be completed in "urban" mode, however, the proportion of CO_2 emissions associated with that mode is also altered. In order to match the total fuel consumption recorded for that year, the assumption of a larger fraction of "urban" PCkm implies a reduction in energy consumption per km travelled in urban mode – and since the ratio of urban:extra-urban energy consumption is fixed, an increase in vehicle efficiency on extra-urban cycles also.

In order to calculate CO_2 emissions from EV, the WSER for urban and for extra-urban driving must be estimated. Based on the modelling results presented in Figure 2, values of 105 $Wh.km^{-1}$ and 180 $Wh.km^{-1}$, respectively, were chosen. Knowing the CO_2-intensity of electricity generation, the CO_2 emissions associated with completing <u>all</u> urban-mode PCkm in EV mode are easily found. The same calculation is done for the extra-urban case although, as previously stated, transferring a significant fraction of extra-urban PCkm to EV will not be a realistic proposition in the short to medium term. The results of these calculations are presented in Table 3, assuming the 2008 Irish generation mix, and in Table 4 for a 2020 generation mix ("White Paper Plus") proposed in [5].

Table 3 CO_2 emissions from electric vehicles (EV), 2008 electricity generation mix

Table 4 CO_2 emissions from electric vehicles (EV), 2020 electricity generation mix

First, consider a scenario where all "urban-mode" PCkm are completed under electric power, and all extra-urban PCkm are powered by ICE. Figure 5 indicates that, for this scenario, annual reductions in passenger car CO_2 emissions of between 1,500 kt and 2,600 kt are potentially achievable using the 2008 generation mix. The reductions are seen to be quite sensitive to the proportion of PCkm completed in urban mode.

It is surprising, however, to notice that the use of the "green" generation mix projected for 2020 results in a relatively small additional saving. That is because the bulk of the CO_2 emissions in this scenario are associated with the non-electric PCkm; reducing CO_2 emissions from that portion of drive cycles will require improvements in ICE or other improvements in conventional vehicle technology. This is an important point since, as discussed previously, using electricity to power extra-urban drive cycles is unlikely to be a realistic proposition for at least a decade. It is clear therefore, that for any realistic distribution of PCkm between urban and extra-urban modes, the major CO_2 reductions are associated with electrification of the urban component.

Figure 5 CO_2 emissions from the Irish passenger car fleet. Brown bars denote actual 2008 emissions (no EV). Blue bars denote case where *all urban* PCkm are completed under electric power, and electricity is supplied using the Irish 2008 generation mix. Green bars denote case where electricity is supplied using the "green" generation mix projected for 2020.

Figure 6 presents data for an alternative, more ambitious, scenario, in which *all* PCkm are powered by electricity from the grid. Examining the results for the 2008 generation mix, CO_2 reductions of 52%-58%, or about 3,600 kt per annum, are obtained. Obviously these reductions

are greater than those obtained for scenario 1. Moreover, switching to the 2020 generation mix yields very substantial additional reductions. For either generation mix, the savings are relatively *insensitive* to the fraction of PCkm completed in urban mode.

Figure 6 CO_2 emissions from the Irish passenger car fleet. Brown bars denote actual 2008 emissions (no EV). Blue bars denote case where *all* passenger cars are pure EV, and electricity is supplied using the Irish 2008 generation mix. Green bars denote case where electricity is supplied using the "green" generation mix projected for 2020.

It should be remembered that the data presented in Figures 5 and 6 represent an upper bound on what is physically achievable. It is assumed in each scenario that all PCkm in a particular mode are completed under electric power only. Amongst other challenges, that would require the replacement of every vehicle in the current fleet, a process that might be expected to take 15 years or more even if all vehicle sales in that period were EV.

Nonetheless, it is equally clear that very substantial reductions in CO_2 emissions from the PC fleet are theoretically possible – up to 70% using a realistic estimate of the 2020 electricity generation mix.

CONCLUSIONS

In the period 1990-2008, GHG emissions from the transport sector in Ireland increased dramatically, with the largest absolute increase associated with private cars. At the same time, the CO_2-intensity of the Irish electricity sector decreased substantially, and that trend is set to continue for the next decade at least. In that context, electrification of the Irish PC fleet would

appear to yield significant GHG benefits, in addition to increasing security of supply, and improving urban air quality.

However, absent a quantum leap in battery technology (and perhaps even if that occurs) it is unlikely that pure EV (BEV) will offer a realistic option for high-speed, open-road travel where, in any event, their efficiency and CO_2 advantage over conventional vehicles (CV) is much reduced. Conversely, in urban-type driving cycles, characterised by low average and peak speeds and relatively short trips, EV operation is realistic and offers very substantial benefits per km travelled.

This paper provides a scoping analysis, for the Irish situation, of the potential magnitude of those benefits. It is found that transfer of <u>all</u> <u>urban-mode</u> PCkm from conventional engines to electric power would realise annual CO_2 savings of 1,500 – 2,600 kt, reducing CO_2 emissions from Irish passenger cars by ~25%-40% from current levels. Preliminary examination of travel data for the UK and US suggests that this conclusion may apply there also. This finding remains true even if electricity is delivered with a very low intensity of CO_2.

Reductions beyond this level will not be possible, however, unless a practical solution is found to the problem of extra-urban travel. Reducing CO_2 emissions for extra-urban travel will require either a revolutionary breakthrough in electrical energy storage, significant improvements in the tank-to-wheel (TTW) efficiency of conventional engines, a substantial uptake of low-Carbon 2nd or 3rd generation biofuels, or – most likely – some combination of these factors. In the short term (to 2020), improvements in ICE offer significant hope and, in combination with progressive electrification of urban PCkm, useful reductions in CO_2 emissions are possible.

Finally, it is worth reiterating that the analysis presented here addresses private cars (PC) only, because electrification of HGVs and other large vehicles is currently unrealistic both

technically and economically. In Ireland, however, PC are responsible for less than 40% of PER and GHG from the Transport sector. Solving the remaining 60% of the problem remains, for the moment, a significant – and separate – challenge.

APPENDIX 1 CALCULATING THE CO_2 INTENSITY OF IRELAND'S 2020 ELECTRICITY GENERATION MIX

This calculation is based on the "White Paper Plus" scenario proposed in [5]. The projections for that scenario are presented in the following table, along with CO_2 emission factors for each fossil fuel as derived from [1]:

Fuel source	Fuel input (ktoe)	Electricity Generated (GWh)	CO2 emission factor ($kt.ktoe^{-1}$)	CO2 emissions (kt)
Coal	373	1,596	3.961	1,477
Oil	345	1,367	3.069	1,059
Gas	2,397	15,773	2.382	5,710
Peat	338	1,398	4.886	1,651
Biomass	500	2,132		
Hydro	91	1,053		
Ocean	118	1,367		
Wind	718	8,347		
Gross	4,879	33,033		9,898

The CO_2 intensity of gross generation is then calculated: $i_{CO2} = \frac{9{,}898 \times 10^3}{33{,}033} = 299.6$ $g.kW^{-1}.h^{-1}$

Allowing for 9% losses for house load, and Transmission & Distribution losses, this translates to 330 $g.kW^{-1}.h^{-1}$ at the wall socket.

APPENDIX 2 CALCULATION OF ENERGY INTENSITY OF IRISH PC IN URBAN AND EXTRA-URBAN MODES

The average energy intensity of the Irish PC fleet (E_{fleet}) has been calculated from Energy balance and NCT data. This can be disaggregated as follows:

$$E_{fleet} = (E_u \times f_u) + (E_{xu} \times f_{xu})$$

where E_u = energy intensity on an urban cycle (MJ.km^{-1})

f_u = fraction of PCkm completed in urban mode

E_{xu} = energy intensity on an extra-urban cycle (MJ.km^{-1})

F_{xu} = fraction of PCkm completed in extra-urban mode

Rearranging and expanding:

$$E_{fleet} = E_{xu}\left[\left(\frac{E_u}{E_{xu}} \times f_u\right) + (1 - f_u)\right]$$

Since E_{fleet} is known, specification of any two of the three remaining variables allows the equation to be solved.

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FIGURE CAPTIONS

Figure 1

Figure 2 Wall-socket electricity requirement versus drive cycle, for a VW Golf-class EV

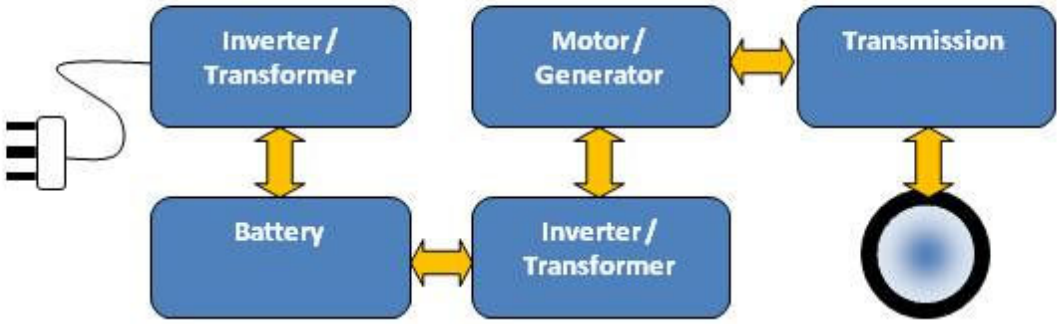
Figure 3

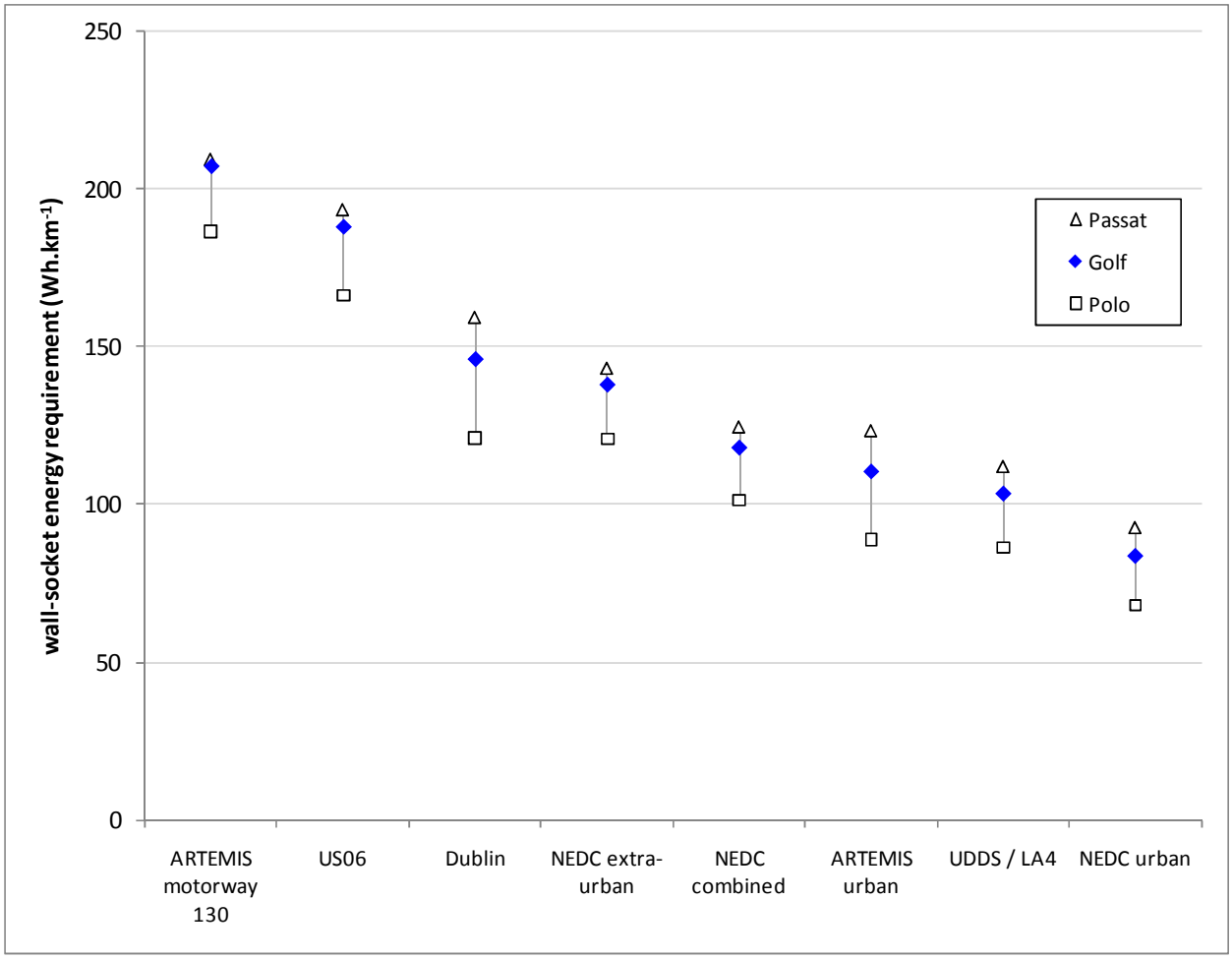
Figure 4 Cumulative fraction of car trips, and cumulative fraction of PCkm, as a function of trip distance for three distinct data sets: Ireland (POWCAR) [20], UK [23], and US (NHTS) [24]

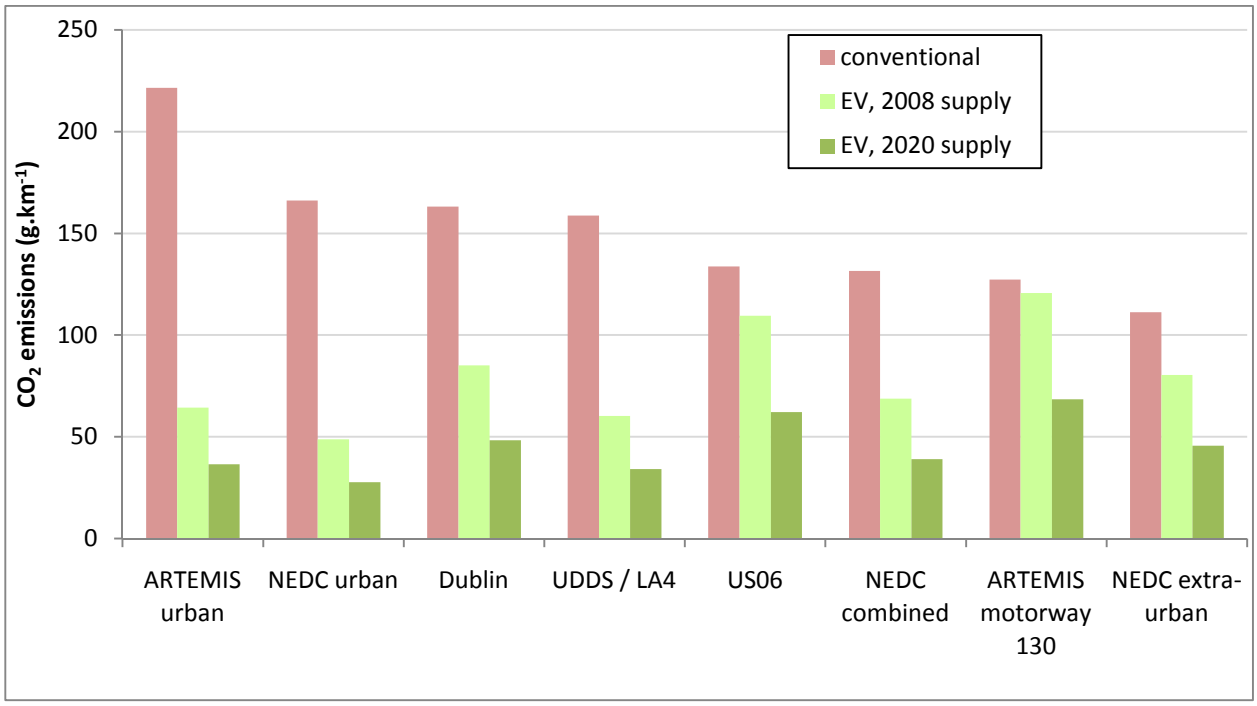
Figure 5 CO_2 emissions from the Irish passenger car fleet. Brown bars denote actual 2008 emissions (no EV). Blue bars denote case where *all urban* PCkm are completed under electric power, and electricity is supplied using the Irish 2008 generation mix. Green bars denote case where electricity is supplied using the "green" generation mix projected for 2020.

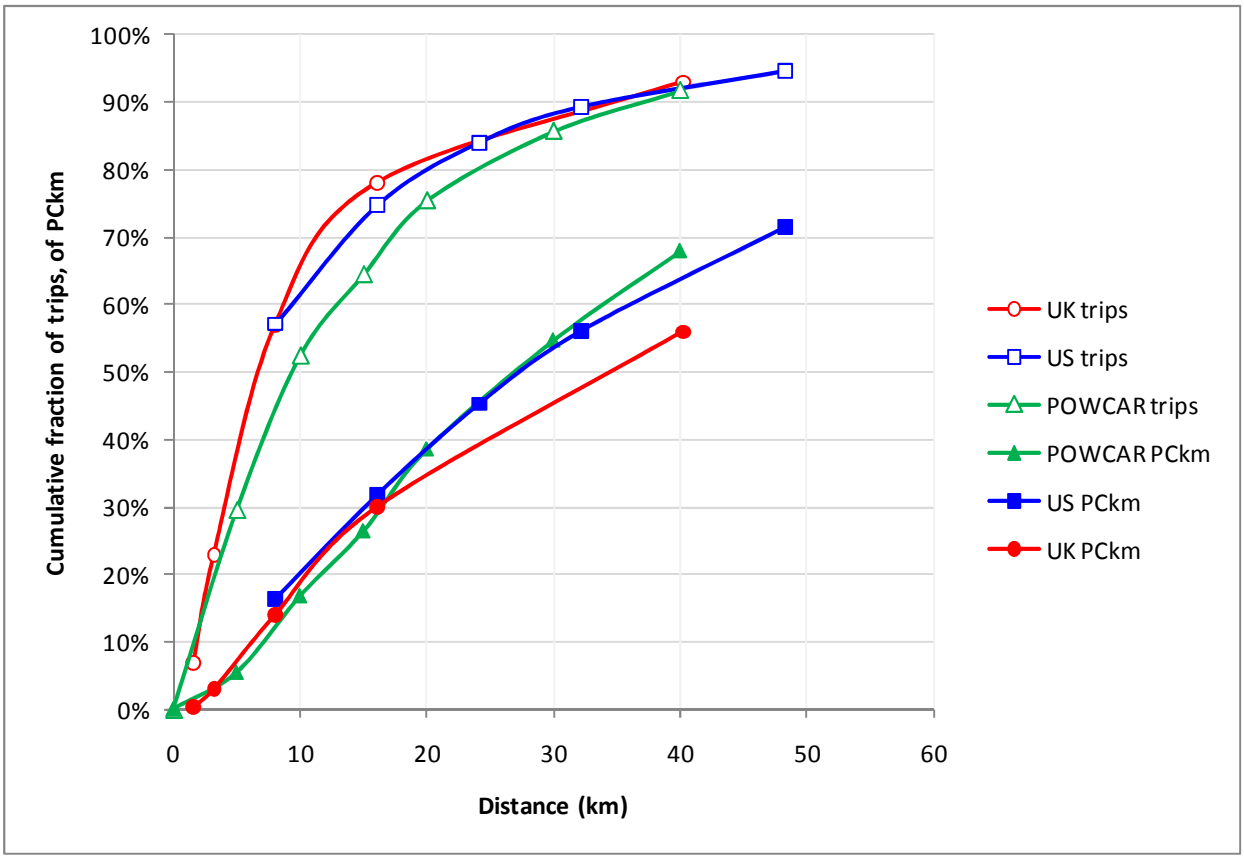
Figure 6 CO_2 emissions from the Irish passenger car fleet. Brown bars denote actual 2008 emissions (no EV). Blue bars denote case where *all* passenger cars are pure EV, and electricity is supplied using the Irish 2008 generation mix. Green bars denote case where electricity is supplied using the "green" generation mix projected for 2020.

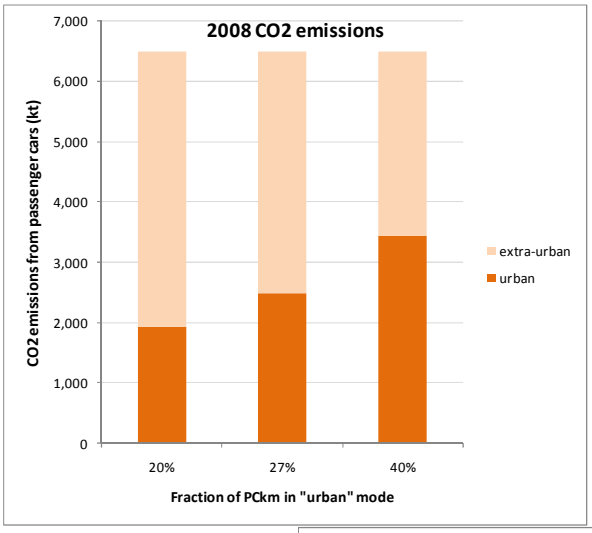
FIGURES

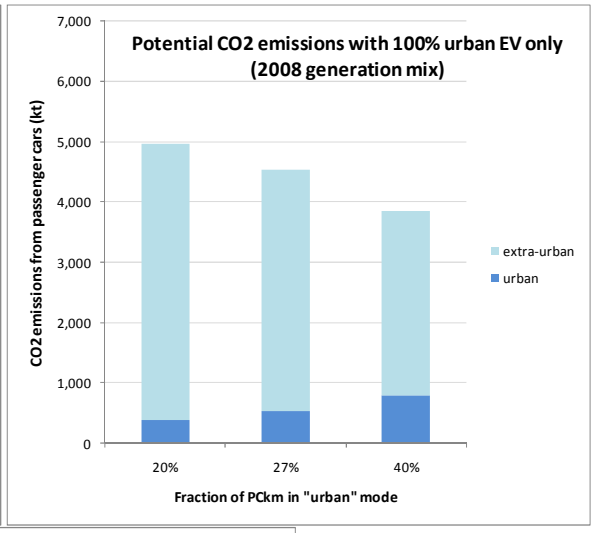

Inverter / Transformer
Motor / Generator
Transmission
Battery
Inverter / Transformer

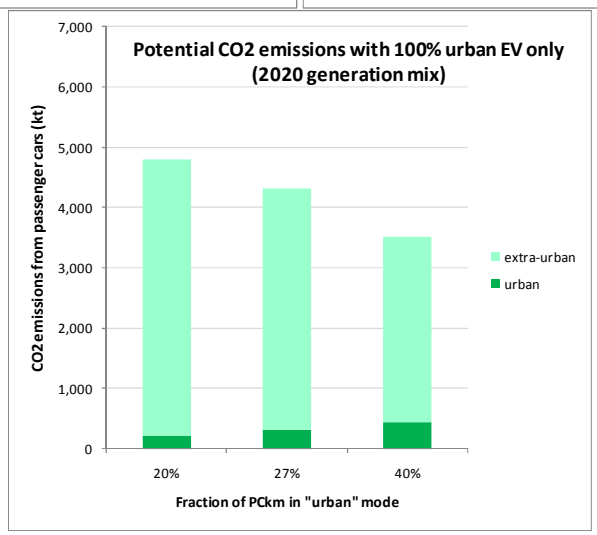

wall-socket energy requirement (Wh.km-1)
250
200
150
100
50
0
Passat
Golf
Polo
ARTEMIS motorway 130
US06
Dublin
NEDC extra-urban
NEDC combined
ARTEMIS urban
UDDS / LA4
NEDC urban

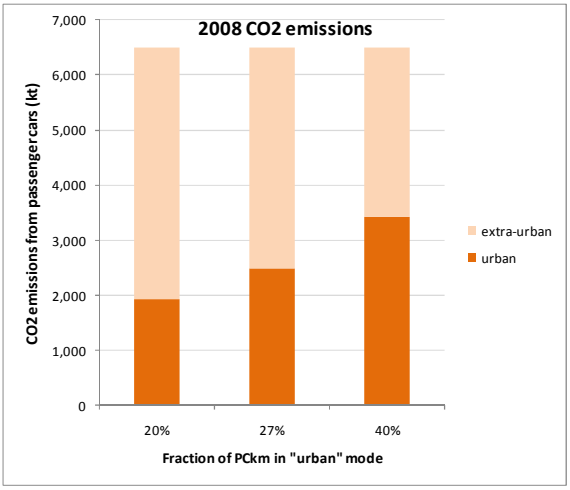

250
200
150
100
50
0
CO_2 emissions (g.km^{-1})
conventional
EV, 2008 supply
EV, 2020 supply
ARTEMIS urban
NEDC urban
Dublin
UDDS / LA4
US06
NEDC combined
ARTEMIS motorway 130
NEDC extra-urban

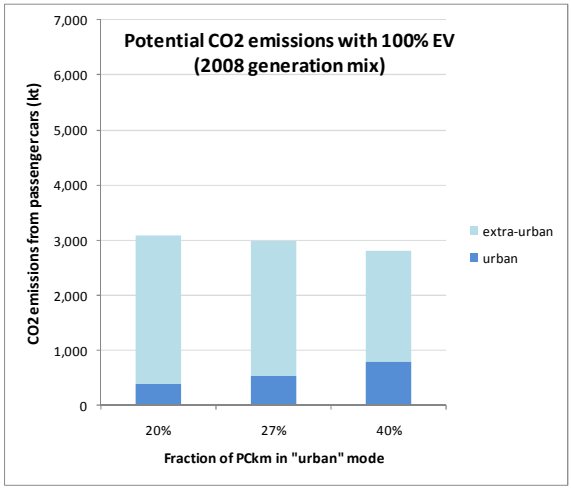

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative fraction of trips, of PCkm
0
10
20
30
40
50
60
Distance (km)
UK trips
US trips
POWCAR trips
POWCAR PCkm
US PCkm
UK PCkm

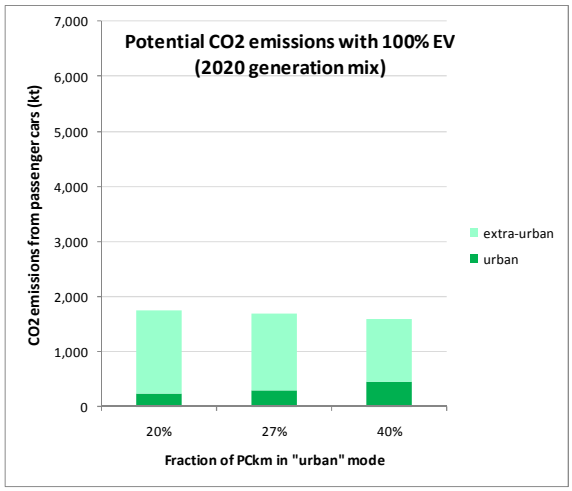

2008 CO2 emissions
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban


Potential CO2 emissions with 100% urban EV only
(2008 generation mix)
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban


Potential CO2 emissions with 100% urban EV only
(2020 generation mix)
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban


2008 CO2 emissions
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban


Potential CO2 emissions with 100% EV
(2008 generation mix)
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban


Potential CO2 emissions with 100% EV
(2020 generation mix)
CO2 emissions from passenger cars (kt)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
20%
27%
40%
Fraction of PCkm in "urban" mode
extra-urban
urban

TABLES

Socket-to-battery transformer efficiency	96%
Battery input efficiency	96%
Battery output efficiency	95%
Inverter efficiency	96%
Motor efficiency	90%
Generator efficiency	85%
Transmission efficiency	98%
Battery-to-wheel supply efficiency	80%
Socket-to-wheel supply efficiency	74%

Table 2

2008 energy consumption of the Irish PC fleet	2,181			ktoe
Urban:extra-urban fuel consumption ratio	1.68			
Fraction of PCkm completed in urban mode	20%	27%	40%	
Implied urban-mode energy intensity	4.2	4.0	3.8	$MJ.km^{-1}$
Implied urban-mode energy consumption	645	836	1,152	ktoe
Associated urban-mode CO_2 emissions	1,923	2,491	3,434	kt
Implied extra-urban-mode energy intensity	2.50	2.40	2.23	$MJ.km^{-1}$
Implied extra-urban-mode energy consumption	1,536	1,345	1,029	ktoe
Associated extra-urban-mode CO_2 emissions	4,578	4,009	3,066	kt
Fraction of CO_2 emissions associated with urban mode	29.6%	38.3%	52.8%	
Total PC CO_2 emissions	6,500	6,500	6,500	kt

Table 2 CO_2 emissions from conventional vehicles (CV)

EV WSER, urban mode	105			$Wh.km^{-1}$
EV WSER, extra-urban mode	180			$Wh.km^{-1}$
Fraction of PCkm completed in urban mode	20%	27%	40%	
EV urban-mode CO_2 emissions	393	530	786	kt
EV extra-urban-mode CO_2 emissions	2,695	2,459	2,021	kt
Total EV CO_2 emissions	3,088	2,989	2,807	kt

Table 3 CO_2 emissions from electric vehicles (EV), 2008 electricity generation mix

EV WSER, urban mode	105			$Wh.km^{-1}$
EV WSER, extra-urban mode	180			$Wh.km^{-1}$
Fraction of PCkm completed in urban mode	20%	27%	40%	
EV urban-mode CO_2 emissions, 2020 generation mix	223	301	406	kt
EV extra-urban-mode CO_2 emissions, 2020 generation mix	1,528	1,394	1,146	kt
Total EV CO_2 emissions, 2020 generation mix	1,751	1,695	1,552	kt

Table 4 CO_2 emissions from electric vehicles (EV), 2020 electricity generation mix