The definitive, peer-reviewed and edited version of this article is published and can be cited as:

Liu, J. and G. Santos (2015), 'The Plug-In Hybrid Electric Vehicles Potential for Urban Transport in China: the role of energy sources and utility factors', *International Journal of Sustainable Transportation*, Vol. 9, N°2, pp. 145–157. DOI: 10.1080/15568318.2012.738776

The Plug-In Hybrid Electric Vehicles Potential for Urban Transport in China: the role of energy sources and utility factors

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Key words

Plug-in Hybrid Electric Vehicles (PHEV), Off-Grid Hybrid Electric Vehicles, Lifecycle Analysis, GREET, Utility Factor, Battery Charging, carbon emissions road transport, electric driving range, battery range, charging behaviour, GHG emissions, driving distance

Abstract

To investigate the energy consumption and emissions of Plug-in Hybrid Electric Vehicles (PHEVs) in China in 2020, we undertake a "Well-to-Wheel" lifecycle energy consumption and carbon emission analysis using the 'Greenhouse Gases, Regulated Emissions and Energy Use in Transport' model from the US Argonne National Laboratory. We find that PHEVs would reduce energy consumption by 37.5% and GHG emissions by 35% when compared to current gasoline vehicles under the predicted 2020 electricity generation mix. These savings would be higher under cleaner electricity generation mixes. These benefits are not substantially affected by changes in travel distances, battery ranges or charging frequencies.

1. Introduction

As the car stock in China grows, so does the contribution of transport CO_2 emissions, the dependence on imported petroleum, and urban air pollution. Indeed, since the late 1990s these issues have been "a focus of interest for many research institutions" (Wang et al., 2006, p.3). With a vehicle fleet forecast to increase by 10% per year until 2020 (Wang et al., 2006, p.35) the introduction of alternative fuel vehicles may help ease the scale of the problem.

In this paper we explore the potential that Plug-in Hybrid Electric Vehicles (PHEVs) have to reduce gasoline consumption and CO_2 emissions, and the role that battery range and charging frequency, daily distances driven and energy sources have within the realm of possible results.

In contrast with Off-Grid Hybrid Electric Vehicles (OGHEVs), which convert the vehicle's kinetic energy into battery-replenishing electric energy, or use the internal combustion engine to generate electricity by spinning an electrical generator to either recharge their batteries or to directly power the electric drive motor, Plug-in Hybrid Electric Vehicles (PHEVs) get the electricity from the grid and store it in an on-board battery. If the electricity is generated in a low-carbon way the potential for carbon emission savings is important, relative not just to conventional internal combustion engine (ICE) vehicles but also relative to OGHEVs. On top of that, PHEVs contain a dual power-train system capable of both electric drive or ICE drive alone and combined, unlike OGHEVs, which can only work on a combination of both.

For the reasons outlined above PHEVs constitute an advantageous vehicle/fuel option. In China, these technical, environmental and financial advantages, combined with the clear infrastructure compatibility, have been recently identified by the government. Indeed, the State Council of China issued "The Energy Efficient and New Energy Vehicle Industry Development Master Plan 2012-2020" in April 2012. In that document the production of PHEVs is included in the key development strategy for the automobile industry in the near term, together with the production of Electric Vehicles (State Council of China, 2012). Within that framework there are a number of incentives in place. In 2010, for example, the central government introduced PHEV and EV purchase subsides in six pilot cities: Shanghai, Hangzhou, Changchun, Hefei, Shenzhen and Beijing (China Ministry of Finance, Ministry of Science and Technology, Ministry of Industry and Information Technology and National Development and Reform

Commission, 2010; China Ministry of Science and Technology, 2010a,b). The maximum subsidies are RMB 50,000 and RMB 60,000 for PHEVs and EVs respectively. Subsidies are linked to the capacity of on-board batteries, while the purchase of OGHEVs are subsidized by RMB 3,000 per vehicle.[1]

In addition, a number of local governments have also introduced local subsidies for new energy vehicles (Ministry of Science and Technology, 2010). In some cities, such as Beijing and Shenzhen, the total subsidy (central and local combined) for a PHEV or EV is more than RMB 110,000 per vehicle.

The current PHEV prototypes, such as the Toyota Hymotion Prius with an A123 battery system, can provide competitive performance when compared with mid-size conventional ICE vehicles. Also, in contrast with other alternative fuel/vehicle systems, such as hydrogen Fuel Cell Vehicles (FCVs), PHEVs may have an infrastructure advantage, as they use the electricity supplied by the already existent electric power grid. Having said that, flexible fuel vehicles, which have a combustion engine designed to run on more than one fuel and are capable of running on higher percentage biofuels, can use the existing refueling infrastructure.

[1] Just to put subsidies in context, that for a BYD E6 would be about 1/3 of the vehicle price, assuming a price of roughly 37,000 RMB per vehicle, as shown on the manufacturer's website (BYD, 2012).

PHEVs, however, may still constitute a good option. Production costs (and therefore the minimum price at which manufacturers will be willing to sell PHEVs) are not as large as those for pure Electric Vehicles (EVs) because of the reduced requirement for battery capacity (Weiss et al, 2000; EUCAR et. al, 2007). This would not be the case though if there were a breakthrough in battery technology which lowered pure EV production costs substantially relative to PHEV. However, this is unlikely in the time frame considered in the present study.[2]

Nevertheless, PHEVs also face many challenges. Although the batteries required are not as costly as those required by pure EVs, the capacity still needs to be high and that means higher production costs than conventional ICE cars. The battery capacity is one of the main problems that hybrid and pure electric vehicles face, as the electric driving range depends on the battery. Also, as mentioned above, the reduction in carbon emissions depends on how the electricity is generated. Bradley and Frank (2009) review the potential environmental benefits of PHEVs for the US and conclude that improvements to the electricity grid can yield environmental benefits in the PHEV fleet. Finally, people's travel behavior is an issue that is seldom mentioned but has an important role to play in carbon emission reduction, not just in the case of ICE vehicles but also in the case of PHEVs. By travel behavior in this study we are talking about refueling and battery charging frequency and daily distances driven, rather than mode, route or time of travel choice.

This paper investigates PHEVs' lifecycle energy consumption and carbon emissions for the case of 2020 China using the Greenhouse Gas, Regulated Emissions and Energy Use in Transport (GREET) Model.[3] The development of the GREET model started in 1995 and was funded by the US Department of Energy's Office of Transportation Technologies. GREET was originally released by the Argonne National Laboratory in 1996 and since then has been constantly updated. The model can be used to estimate fuel lifecycle energy use and emissions associated with conventional and alternative transport fuels and vehicles. It covers both the Well-to-Pump and Pump-to-Wheel stages. In the Well-to-Pump stage it models energy use and

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[2] As a side note, some PHEVs are actually more expensive than pure EVs because of larger batteries. A Volt is more expensive than a Leaf, for example.

[3] The version used here is GREET 1.8c and is downloadable for free from http://www.transportation.anl.gov/modeling_simulation/GREET/

emissions in the production, transport and storage of feedstock[4] and production, transport, distribution and storage of fuel. In the Pump-to-Wheel stage it models vehicle operation energy use and emissions, and covers refuelling, fuel combustion/conversion, fuel evaporation and tire/brake wear (Wang, 2001).

The answers to a questionnaire conducted in China are also used to make assumptions about travel behavior and energy consumption of PHEVs.

This study shows that PHEVs have great potential to reduce GHG emissions. We show that the extent of these reductions is not very sensitive to daily distances driven or battery ranges (or indirectly, to charging frequency), when compared to how sensitive it is to the electricity generation mix.

The results of this study offer clear guidance, at least to some extent,[5] to the Chinese government and auto manufacturers on what CO_2 emissions reductions can be achieved in road transport in China in 2020 by using PHEVs under different electricity generation mixes and different battery ranges. If concerned about the environment, potential car buyers in China could also use our findings to inform their decisions.

2. Methodology and Data

The specific energy consumption and carbon emissions of PHEVs are determined by two factors: energy source and the electricity/petroleum consumption split. The parameter values input into GREET correspond to China, and were sourced from Chinese data bases, as described below. As is already standard practice, lifecycle was divided in two stages: Well-to-

[4] Feedstock is defined as energy resources for fuel/electricity products.

[5] Our results are related to a small sample, which may not be necessarily representative of the Chinese population as a whole. Having said that, our 331 survey responses are extremely similar to the 1,163 responses of a survey carried out by Deloitte Touche, which we use for comparison purposes in Section 2.2.1. Both sets of findings are also in line with Wang et al. (2006, p.28).

Pump (WTP) and Pump-To-Wheel (PTW).

2.1 Well-to-Pump Stage

The energy recovery and refining data input onto GREET for WTP simulation were retrieved from the latest nationwide statistics and research reports. The exact source of each piece of information is further detailed below.

Because this study focuses on the energy consumption and emissions of PHEVs, both electricity generation and gasoline production are reviewed. Other vehicle fuels such as diesel, natural gas based fuels, hydrogen and biomass-based fuels are not included, although they can also be used by the dual-power-train systems of PHEVs.

2.1.1 Gasoline Pathway

The two key questions when modeling the gasoline pathway are how the gasoline is produced (energy feedstock types) and how it is processed and transported. Since GREET in default mode uses data for the US case, all the data regarding gasoline production, process and transport were replaced with numbers corresponding to the Chinese case. In this section a brief overview of the assumptions is presented.

2.1.1.1 Crude oil

The oil recovery efficiency has improved for all the three major oil companies in China over the last 30 years (Zhang et al, 2007; China National Petroleum Corporation, 2011). However, given that many oil and gas fields in China are approaching their late-stage of extracting life, the efficiency improvement rate could decline gradually in the next few years (Zhang et al, 2007; China National Petroleum Corporation, 2011). The recovery efficiency assumptions for 2020 are therefore conservative. The crude oil recovery energy efficiency gap between China and the US in this study is assumed to remain at 5% or, in other words, the crude oil recovery energy efficiency, estimated as energy output (extracted oil) divided by energy input (residual oil, electricity, diesel and crude oil), in China in 2020 is assumed to be 93%, against 98% in the US (Zhang et al., 2007, p.37). All the efficiency parameters described here (and further below) input on to GREET, as well as their sources, are summarized on Table A1 in the Appendix.

2.1.1.2 Gasoline

Since 1999, Chinese domestic gasoline production has met domestic demand. Therefore, this study only considers the refining efficiency of Chinese refineries. The two main oil companies, China National Petroleum Corporation (CNPC) and China Petroleum and Chemical Corporation (Sinopec), jointly supply 90% of the gasoline in China. Domestic fuel production energy efficiency is assumed to be 87% (Zhang et al., 2007) for 2020 for both CNPC and Sinopec, in contrast with 92% for the US[6]. Since 2020 is less than ten years away from the year when this paper was written (2011) the assumption of China being able to supply all of its gasoline demand in the future seems reasonable.[7] Given the very rapid growth of China's gasoline demand, this assumption would be questionable further into the future. If gasoline were to be imported, emissions could potentially go up, although this would depend on the fuel production efficiency of overseas refineries and transport modes and distances.

2.1.1.3 Transport

Apart from the energy efficiency of oil recovery and gasoline production, the transport of both crude oil and gasoline also plays an important role in the lifecycle. In China the distances that the fuel needs to be transported are large and this causes relatively high energy consumption and emissions during the energy transport process.

Figure 1 summarizes the shares of oil sources for China, as well as the transport modes used and the average distances.

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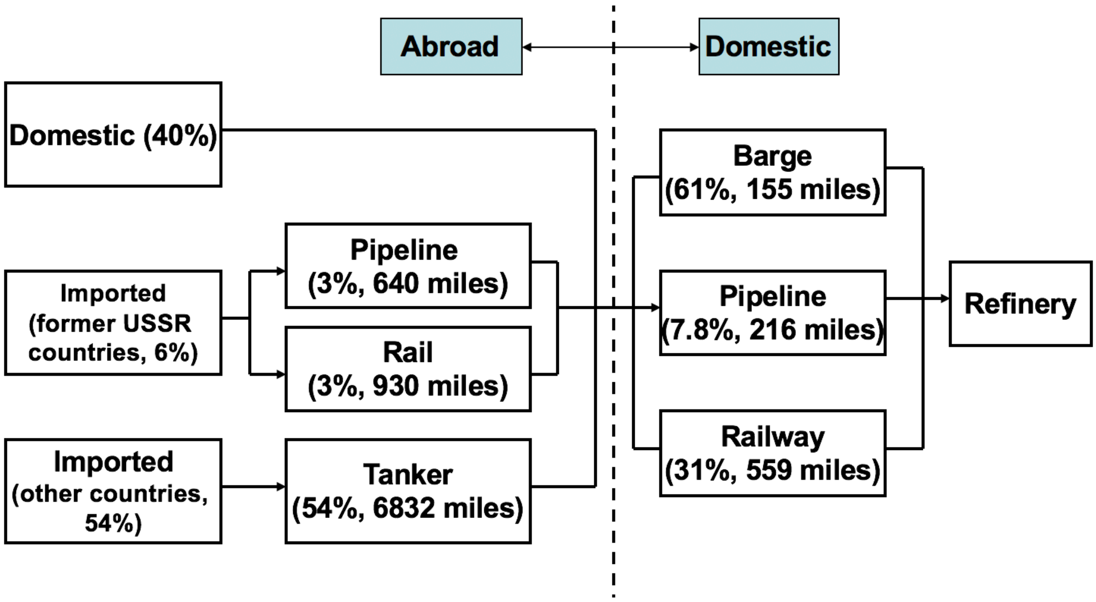
6 GREET 1.8c.0 assumes a fuel production energy efficiency in the US for 2020 of 92%.

7 On 25 May 2010 China Daily reported that China's annual crude-oil refining capacity may rise by 50% by 2015 (http://www.chinadaily.com.cn/bizchina/2010-05/25/content_9890521.htm).

Figure 1: Crude Oil Transport in China



Source: designed with data from Zhang et al (2007)

Currently, China's imported crude oil accounts for more than 55% of national demand (ChinaIRN, 2011) and this figure could reach 60% to 80% by 2020 (Zhang et al., 2007, p. 36, Table 3.1).

The imported crude oil is largely transported by tankers (90%), except for the crude oil from former USSR countries, which is usually delivered through pipelines and rail (China National Development and Reform Commission, 2006). There is also some oil imported from Southeast Asia and Russia, which is transported by railway. Taking into account transport routes and distances from the Middle East (38.5%), Asia-Pacific (17.4%), West Africa (19%), North Africa (1.9%), Southeast Africa (2.7%), Latin America (6.7%) and Europe (0.2%), the average transport distance by tankers can be assumed to be 11,000 km.

Domestic and imported crude oil *within* China is transported by three modes: pipeline (61%), barge (7.8%) and railway (31%). According to the China National Development and Reform Commission (2006), the average distance that crude oil was transported in China in 2005 was 390 km. The majority of barge-based crude oil transport in China takes place along the East China Sea and the Yangzi River, and the average transport distance is between 100 and 400 km (China Ministry of Communications and Transportation, 2005). The amount of oil transported by railway has increased relatively slowly compared to the increase in crude oil demand. The average transport distance by railway ranges from 860 km to 960 km. In 2020, it can be assumed that 60% of trains will run on electricity and 40% will run on diesel (China National Development and Reform Commission, 2008).

Since domestic gasoline meets and will continue to meet national demand in 2020, this analysis only considers the transport of gasoline within China. The main transport modes for fuel products currently are pipeline (15%), railway (50%), barge (25%) and highway (10%) (Jia, 2003). These shares are assumed to be the same in 2020. A considerable amount of gasoline has to be transported long distances by railway, from the north-east and north-west to the eastern provinces. The average transport distance by train is around 800 to 1,000 km (China Logistics Association, 2005).

Because the major Chinese oil refineries are located along the east coast and the Yangzi River, barge is also an important transport mode for fuel products. The China Ministry of Communications and Transportation (2005) and Jia (2003) estimate that 20% to 30% of oil products in China are transported by barge. Here an average of 25% is assumed, with an average distance of 1,200 km. Finally, gasoline and diesel from oil depots to service stations are transported by road and an average distance of 50 km is assumed. Although fuel transport via pipelines has increased in the period 2000 to 2010, its share among total transport remains minor. Assuming the share of pipeline transport continues to increase at 1.2% per year, this analysis assumes 30% of total fuel products will be transported by pipeline in China by 2020. Because pipelines currently are mainly applied for short distances, the average transport distance is assumed to be 160 km. However, with the progress of new “North-to-South” and “West-to-East” energy transport projects, the distance in 2020 is assumed to be 800 km (China National Development and Reform Commission, 2006).

2.1.2 Electricity Pathway

At present, China's national grid is operated by two state-owned companies: State Grid Corporation of China (SGCC) and China Southern Power Grid (CSPG). In both cases electricity is mainly generated in coal power stations. In fact 79% of all electricity in China is generated in coal power stations, as Table 1 shows. The new generation clean-coal technologies, such as Integrated Gas Combined Cycle, are currently only used to produce 1.25% of overall coal-based electricity. Following coal, hydropower ranks second, with a share of 17%. The shares of natural gas, residual oil and nuclear-based electricity generation are minor. Wind and biomass-based electricity generation are at their trial phase in some provinces only, including Inner Mongolia and Tibet (China National Statistics Bureau, 2006).

Table 1 also shows the predicted electricity generation mix in China 2020. The figures are taken from Zhang et al. (2007, pp. 94-95). Given the China National Development and Reform Commission's plans to implement a renewable energy program by 2020, the share of hydro, nuclear and wind power will increase, although coal will still remain the major resource in the medium term because China has a large amount of reserves (US Energy Information Administration, 2011). The electricity transmission loss is predicted to be around 7% by 2020, a slight improvement compared to the 2010 level of 7.1% (Zhang et al., 2007, pp. 94-95).

Two other mixes are also shown on Table 1: a 2020 slightly cleaner than predicted electricity mix and an all nuclear mix. These two electricity generation mixes in China 2020 are hypothetical cases, used in the study for comparison purposes and sensitivity analysis.

The 2009 electricity mix was used as a reference level. The 2020 electricity mix was used as the most probable one, with the reductions accruing under those assumptions to be taken as very likely to occur if PHEVs were to penetrate the market. The 'all nuclear' electricity mix was used to show that emissions reductions would be drastic if all electricity in China were produced at nuclear power stations. Having said that, as we discuss further down, nuclear electricity generation still causes some CO_2 emissions and so these would not completely disappear.

Table 1: National Grid Electricity Generation Share in China

	Coal	Oil	Natural Gas	Hydropower	Nuclear	Solar, Wind & Biomass
2009 mix[1]	79%	0.004%	1%	17%	2%	1%
2020 predicted mix[2]	63%	1%	6.8%	19%	6.7%	3.5%
2020 slightly cleaner mix[3]	40%	1%	10%	19%	20%	10%
All nuclear[4]	0%	0%	0%	0%	100%	0%

Sources: [1]International Energy Agency (2010); [2]Zhang et al. (2007, p.94)

Note: The electricity generation mixes '2020 slightly cleaner' and 'All nuclear' are unlikely and were used for sensitivity and comparison purposes only.

2.2 Pump-to-Wheel Stage

Two essential assumptions are needed for Pump-to-Wheel (PTW) simulation, which was also done with GREET: the selection of a reference plug-in vehicle for modeling and the share between electricity and gasoline consumption during vehicle operation.

The reference plug-in vehicle for modeling in this study was the Toyota Hymotion Prius with an A123 battery. The default parameters in GREET to model the PTW stage were replaced with those corresponding to the Toyota Hymotion Prius. The share between electricity and gasoline consumption during vehicle operation were also input onto GREET, based on the results from a survey we conducted in China, and which we describe below.

We chose the Toyota Hymotion Prius with an A123 battery because it was a promising prototype and the data we needed on fuel and electricity consumption was available at the time of writing this paper. We present the technical details on Table A2 in the Appendix. One drawback of this choice is that it essentially involves a conversion kit for a Prius (an OGHEV), and thus the costs, potential market, and consumer perceptions may be different.

The share between electricity and gasoline use is determined by kilometers traveled per charge, which further relates to the vehicle's electric operation range, and the required frequency of recharging. This in turn can be linked to driving behavior. A combination of a high-charging frequency rate and a low-driving distance per charge could offer nearly an all electric driving of PHEVs. This pattern would, for example, illustrate the driving behavior of workers commuting short distances by car and recharging the vehicle's battery at home every night.

To address the share of electricity and gasoline consumption, the concept of "Utility Factor" (UF) has been introduced in recent PHEV fuel economy studies (Elgowainy et al., 2009) to represent the percentage of a PHEV's electricity consumption over its entire energy consumption during vehicle operation. Normally, a daily charging basis is assumed and so a Daily Kilometers Traveled (DKT) becomes the key factor that needs to be identified. For this, daily travel behavior information is required. However, there is currently no such a nationwide level survey available for China. We therefore conducted a travel and attitudinal survey. The details and findings from the survey are described below.

2.2.1 The Survey

The survey was conducted on the 'Auto.Sohu' website[8] and the results reported in this paper correspond to responses posted in the period 24 February to 26 March 2010. Anyone visiting the website could see a link to the questionnaire. Participation was voluntary.

The survey was designed to elicit, among other things, daily distance traveled, expected battery range and acceptable lowest vehicle maximum speed. An abridged version of the questionnaire is included in the Appendix.

Three hundred and thirty one usable responses were collected and are used in this paper.

Figure 2 summarizes the DKT as reported by our survey respondents and also, for the purpose of comparison and validation, as reported by the respondents of another survey carried out by Deloitte Touche Tohmatsu's (DTTL) Global Manufacturing Industry group in April 2011.[9] Both groups of respondents reside mainly in urban and suburban areas in China. The three curves, which show the cumulative percentage of respondents and their typical DKT, follow

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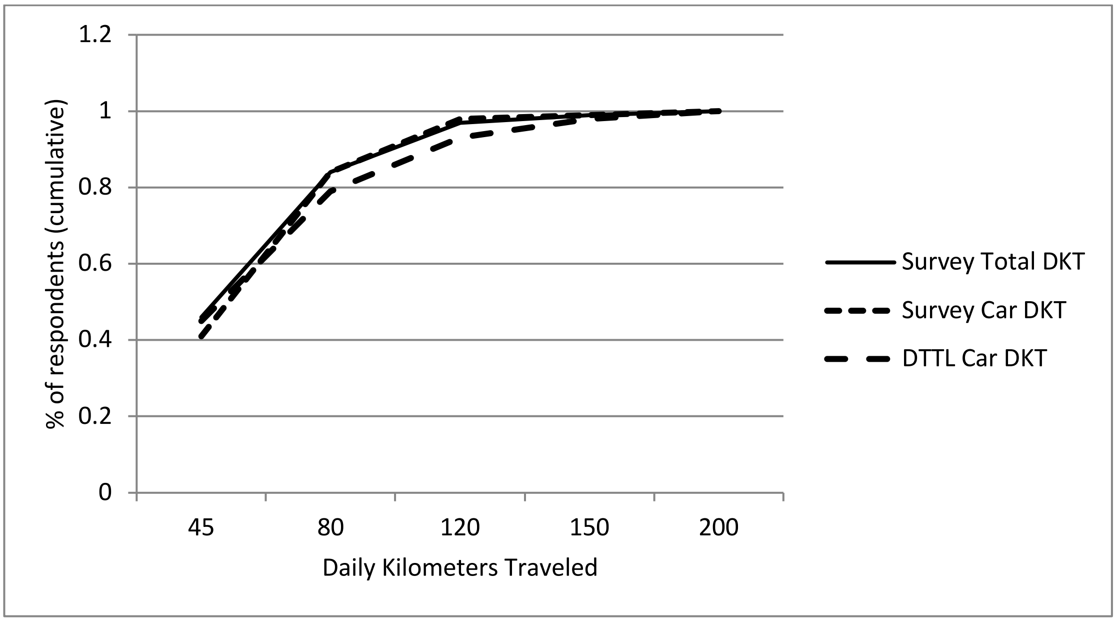
[8]The 'Auto.Sohu' website is a Chinese website owned by a private company that specializes on car reviews, car information, car news, car surveys and car data: http://auto.sohu.com/20100224/n270407525.shtml

[9] www. deloitte.com/view/en_GX/global/press/314e7162b8a5f210VgnVCM1000001a56f00aRCRD.htm

remarkably similar trajectories, regardless of whether all modes of transport or just the car is included and regardless of whether the values correspond to our survey or the DTTL survey. The results from both surveys are also in line with figures reported by Wang et al. (2006, p.28). All trip purposes were included: commuting, shopping, recreation, and also work-related trips, as well as all other trips (such as attending medical appointments, etc.).

Figure 2: Typical Daily Kilometers Travelled (DKT) per weekday by all modes and by car only



Source: Responses to the survey conducted by the authors and responses to the survey conducted by DTTL

Note: Total DKT refers to DKT by all modes, whereas Car DKT refers to DKT by car only

The geographical distribution of the respondents in our sample is uneven. For example, 22% of the responses came from Beijing province, where only 1.09% of the Chinese population lives; and almost 17% of the responses came from Shanxi province, where only 2.85% of the population lives. Having said that, it is worth highlighting that the findings are not very different from those of the DTTL survey, which was also conducted online, between 28 January and 8 March 2011, and to which 1,163 Chinese drivers responded.

Interestingly, as it can be seen on Figure 2, drivers from urban areas in China do not seem to travel longer distances than non-drivers. Eighty-four per cent of drivers in our sample travel 80 km or less per day. When all modes of transport are included, 84% of respondents still report they travel 80 km or less per day. When all modes of transport are included except the car, 84% of respondents travel 80 km or less per day. According to the DTTL survey, 79% of drivers in urban areas in China travel 80 km or less per day. It is slightly surprising and somewhat difficult to explain why drivers do not travel longer distances than non-drivers. Reasons for this may be linked to congestion in Chinese cities (note that virtually all respondents live in urban areas), or even with habits. Travel habits may be well-established and it may take some time before car owners start to exploit the advantages and freedom that a car brings.

It should be born in mind that car ownership in China is still very low, with only 36% and 2.2% of households owning a car in Beijing and the whole of China, respectively (China National Statistics Bureau, 2009, Table 15-27: Private Car Ownership 2009), in contrast with the UK, where 76% of all households have regular access to at least one car (UK Department for Transport, 2009, Table 9.15, p.166). It should be noted, however, that car ownership in China is likely to double by 2020. The mean of the long-run income elasticity of demand for car ownership is 0.74 (Graham and Glaister, 2004, p.264). With this in mind, if income in China between 2010 and 2020 were to increase by 134.7%, as some forecasts predict (Rosen, 2012), car ownership would increase by 99.7%.

3. Data Analysis

If and when a consumer decides to buy a PHEV rather than a conventional ICE vehicle, he/she will typically consider a number of issues in addition to the cost of the vehicle itself and the cost of operating it,[10] including battery capacity (i.e., for how long the car can be driven without re-charging the battery) and possible speeds.[11]

[10] Axsen and Kurani (2009) conducted an Internet-based survey of 2,373 new car-buying households in the US and found that fuel economy appears to be the most important characteristic for potential buyers of PHEVs in their sample. Similarly, 52% of our respondents thought that lower operating costs were an important advantage of HEVs and EVs.

[11] Thirty-eight per cent of our respondents stated that the minimum distance per charge they would find acceptable would be 200 km, and 33% stated that it would over 200 km. Thirty-one per cent of our respondents stated that the lowest vehicle maximum speed they would find acceptable would be 100

In this paper it is assumed that drivers recharge the vehicle battery once a day.[12] As already explained above, if drivers had the necessary facilities to fully recharge the vehicle battery twice or three times a day, they would be able to drive longer distances on electricity.

3.1 Utility Factor

PHEVs can run on conventional oil-based fuels and electricity from the grid. Since their storage capacity is limited, PHEV batteries can only supply electricity to drive the vehicle for a limited number of kilometers. As a result, PHEVs operate in two modes: a charge-depleting mode, where the energy used by the car comes entirely or at least mainly from the battery, and a charge-sustaining mode, where the energy used by the car does not come from the battery (Bradley and Quinn, 2010, pp. 5399).

The daily distance utility factor (UF) of a PHEV can be defined as the ratio of the number of kilometers driven under charge-depleting mode to the total number of kilometers driven:

$$UF_{distance}(R_{CD}) = \frac{\min(d, R_{CD})}{d}$$

where d is the distance driven and R_{CD} is the charge depleting range. As Bradley and Quinn (2010, p.5400) put it, the daily distance UF of a PHEV is equal to the ratio of the charge-depleting range to the distance traveled: R_{CD}/d if $d < R_{CD}$, and 1 if $d > R_{CD}$.

Following Elgowainy et al. (2009), in order to identify the UF for various PHEV models (or battery energy storage capacities), the survey observations are categorized into 12 groups in

km/h and 57% stated it would be 150 km/h.

[12] This assumption is common in the literature. Even the documents produced by the Society of Automotive Engineers (SAE) in the US assume that batteries are only recharged once a day (Bradley and Quinn, 2010). Axsen and Kurani (2010) evaluate different re-charging patterns and, not surprisingly, conclude that PHEV electricity use could be increased through policies supporting non-home recharging opportunities, although this increase would occur during daytime hours and would therefore potentially increase peak electricity demand.

terms of DKT, as shown in Table 2. Only the responses from car drivers are taken into account for these calculations, as DKT by other modes would not be a good estimate of driver behavior.

Table 2 can be read as follows. The first two columns indicate the limits of the range of DKT. For example, the first range corresponds to respondents who travel between 0 and 10 km per day. The ‘Frequency’ column is the number of respondents who gave that answer. The ‘Share’ column is the percentage of respondents with a DKT falling in that range. The rest of the columns give the daily distance UF for different R_{CD}. Paraphrasing Bradley and Quinn (2010, p.5400), the daily distance UF is the fraction of km traveled by the sample fleet in charge depleting mode.

For example, when the R_{CD} is 10 km, drivers with DKT between 0 and 10 km will be able to drive all those km on charge depleting mode. As long as the R_{CD} is higher than the DKT the PHEV will be able to drive on charge depleting mode alone. When the R_{CD} is 50 km but the DKT is between 80 and 90, drivers will be able to drive the first 50 km on charge depleting mode but they will drive the remaining 30 to 40 km on conventional fuel. The PHEV Utility Factor on the last row indicates the proportion of total DKT by survey respondents that can be driven on electricity. If the R_{CD} is 10 km only 32.28% of DKT by all respondents can be driven on charge depleting mode, whereas if the R_{CD} is 70 km then 94.63% of DKT by all survey respondents can be done on charge depleting mode.

Table 2 shows that the UF increases when R_{CD} increases, provided DKT remains constant, and the UF decreases when DKT increases, provided R_{CD} remains constant. In addition to that, it should be borne in mind that if drivers were able to fully recharge the vehicle battery more than once a day, all UF estimates on Table 2 would be higher, for every combination of DKT and R_{CD}.

Table 2: Utility Factors (UF) for PHEV with different charge depleting ranges (R_{CD})

DKT (km, min - max)		Frequency	Share	10 km	20 km	30 km	40 km	50 km	60 km	70 km	80 km	90 km	100 km	110 km	120 km
0	10	12	5.15%	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515	0.0515
10	20	33	14.16%	0.0944	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416	0.1416
20	30	32	13.73%	0.0549	0.1099	0.1373	0.1373	0.1373	0.1373	0.1373	0.1373	0.1373	0.1373	0.1373	0.1373
30	40	17	7.30%	0.0208	0.0417	0.0625	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730
40	50	59	25.32%	0.0563	0.1125	0.1688	0.2251	0.2532	0.2532	0.2532	0.2532	0.2532	0.2532	0.2532	0.2532
50	60	20	8.58%	0.0156	0.0312	0.0468	0.0624	0.0780	0.0858	0.0858	0.0858	0.0858	0.0858	0.0858	0.0858
60	70	2	0.86%	0.0013	0.0026	0.0040	0.0053	0.0066	0.0079	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086
70	80	21	9.01%	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0043	0.0043	0.0043	0.0043
80	90	1	0.43%	0.0136	0.0271	0.0407	0.0542	0.0678	0.0813	0.0949	0.1084	0.1220	0.1288	0.1288	0.1288
90	100	30	12.88%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100	110	0	0.00%	0.0007	0.0015	0.0022	0.0030	0.0037	0.0045	0.0052	0.0060	0.0067	0.0075	0.0082	0.0086
110	120	2	0.86%	0.0011	0.0021	0.0032	0.0043	0.0054	0.0064	0.0075	0.0086	0.0097	0.0107	0.0118	0.0129
120	Max	4	1.72%	**0.3228**	**0.5469**	**0.6963**	**0.8078**	**0.8808**	**0.9178**	**0.9463**	**0.9682**	**0.9838**	**0.9924**	**0.9943**	**0.9957**
PHEV Utility Factor		233	100%	**0.3228**	**0.5469**	**0.6963**	**0.8078**	**0.8808**	**0.9178**	**0.9463**	**0.9682**	**0.9838**	**0.9924**	**0.9943**	**0.9957**

Source: Calculations by the authors using survey responses

Figure 3 shows the daily distance UF curve for various PHEVs with R_{CD} of 10 km to 120 km for average daily distances of 53.14 km, 79.71 km and 106.28 km, which are the average, 1.5 times and twice the average distance traveled by the drivers in the sample, respectively, on the assumption that they would not change their DKT as a result of driving a PHEV rather than a conventional ICE vehicle. As can be seen on the figure, the UF decreases when average distance traveled increases. In other words, the share of kilometers driven on battery declines the longer the distance driven.

This is not trivial and may reflect a challenging obstacle to the mass penetration of PHEVs in China.

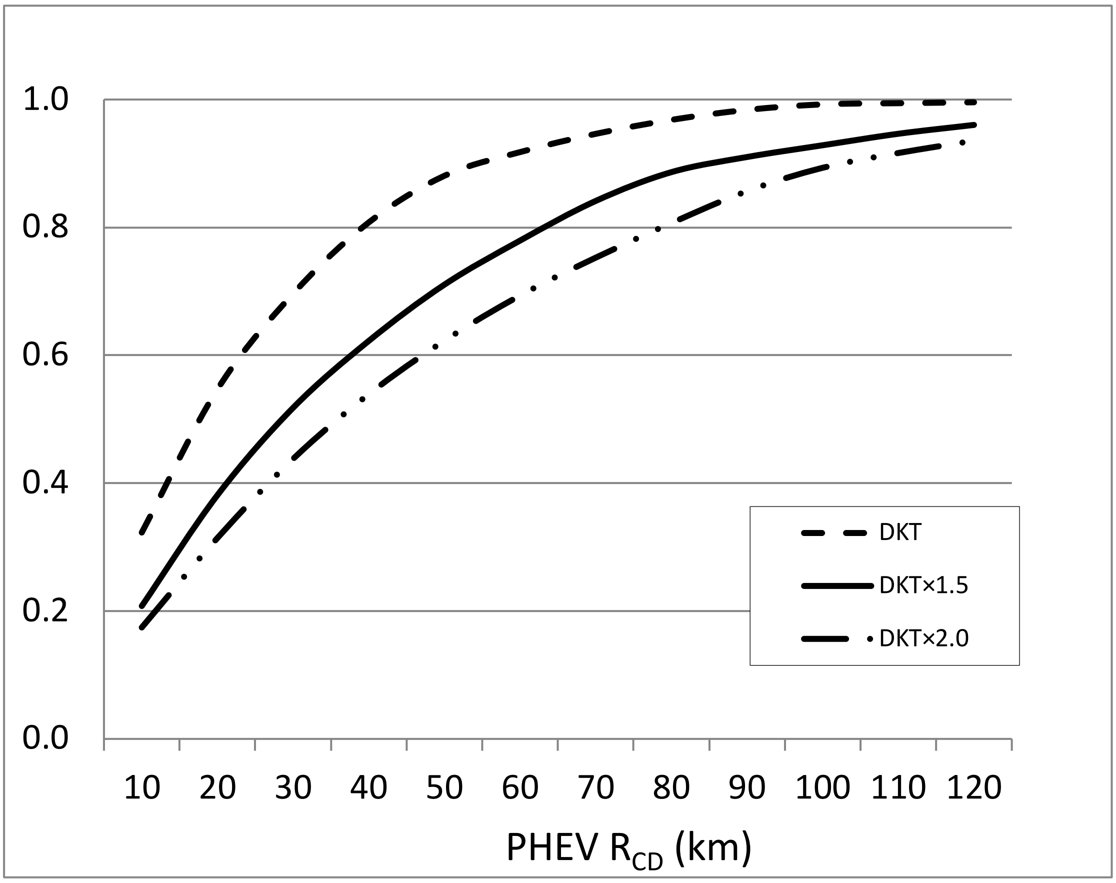
Travel distances in China are likely to increase with increases in car ownership (already discussed above), reductions in lower vehicle operating costs, and increases in income.

Lower vehicle operating costs cause a 'rebound effect', as is well-documented in the transport studies literature (Greening et al., 2000; Gorham, 2002, Portney et al., 2003; De Haan et al., 2007; Evans, 2008). In short, as costs decrease (be it fuel costs, time costs, etc.) quantity and/or length of trips increase.

The mean of the long-run elasticity of demand for car-km with respect to income is 0.73 (Graham and Glaister, 2004, pp. 263).[13] Assuming this elasticity and the forecast real income growth used in Section 2 above (134.7%), car-km would increase by 98.4%. If this translated straight into average daily distance driven, the distance driven in 2020 would be twice as high as that reported by respondents in 2010. The UF curve relevant to the present study can therefore be assumed to be the one corresponding to DKTx2.

[13] Graham and Glasiter (2004) review a number of studies conducted for different countries.

Figure 3: Daily Distance Utility Factor (UF) Curves for DKT, 1.5 DKT and 2 DKT



Source: calculations produced by the authors

A PHEV with a R_{CD} of 60 km offers a UF of 0.92 for the 2010 DKT or 0.69 for the 2020 DKT. In other words, 69% of all DKT by all survey respondents could be driven in charge depletion mode in 2020, provided they all drove PHEVs. It would be interesting to conduct a nationwide travel survey and be able to compare the Chinese UF with the one computed by Elgowainy et al. (2009, p.22) for the US, which they estimate at 64% for 2001, or the one computed by Vyas et al. (2009, p.56), also for the US, which they estimate at 74.9% for 2001 as well (as both studies use the 2001 US National House Travel Survey).

As we show in Section 4, different UF (which are affected by travel distances, battery ranges and charging frequencies) do not have a substantial impact on absolute emissions or emissions reductions.

4. Lifecycle Assessment Results

Figure 4 summarizes the lifecycle energy consumption and emissions for PHEVs with R_{CD} of 60 km relative to ICE vehicles, assuming the DKT in 2020 are twice as high as those in 2010 and the corresponding UF is 0.69, as shown on Figure 3 and highlighted above. GHG emissions are 34% lower and total energy consumption is 38% lower.[14] These results are not substantially different from those reported in Samaras and Meisterling (2008), who argue that PHEVs could reduce emissions in the US by 32%, compared to ICE vehicles.[15]

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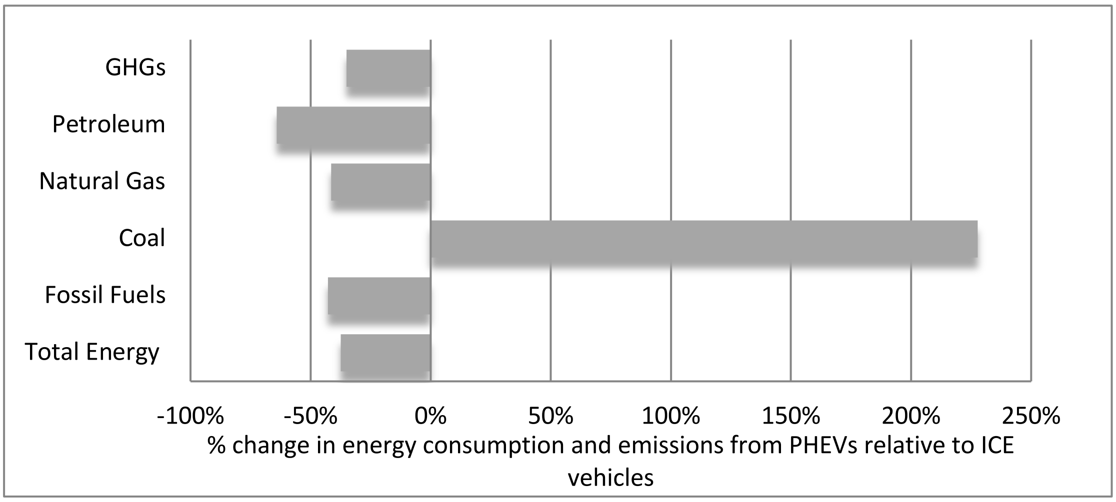
[14] For the fuel cycle of baseline ICEs, the electricity is consumed in both processes of crude oil recovery and gasoline production. For instance, in the crude oil recovery process, the electricity consumption is 3872Btu for every million Btu of petroleum, which accounts for 19% of total energy consumption in this process. As the electricity is largely generated from the combustion of coal, the crude oil recovery and fuel production involve coal consumption. Tables A3 and A4 provide absolute values of fuel cycle energy consumption and emissions of IVE vehicles and PHEVs, as well as changes of PHEV values relative to ICE values for the 2020 predicted electricity mix and for the all nuclear mix, respectively.

[15] Duvall et al. (2007) estimate GHG reductions in the whole of the US for the year 2050 as a result of low, medium and high market penetration of PHEVs. Although they report results under a number of different assumptions, they report them in billion metric tons of CO_2e rather than percentage changes. Also their analysis concerns marginal emission reductions rather than total emission reductions. The model they use is the National Electric System Simulation Integrated Evaluator (NESSIE), developed at the Electric Power Research Institute. The NESSIE models the US electricity sector from 2010 to 2050. For all those reasons comparisons with the Chinese case in the present study are not straightforward.

Figure 4: Lifecycle Energy Consumption in BTUs and GHG Emissions in CO2e for PHEVs with RCD of 60 km relative to 2009 ICE vehicles for the travel survey sample in China under the predicted 2020 electricity generation mix



Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted

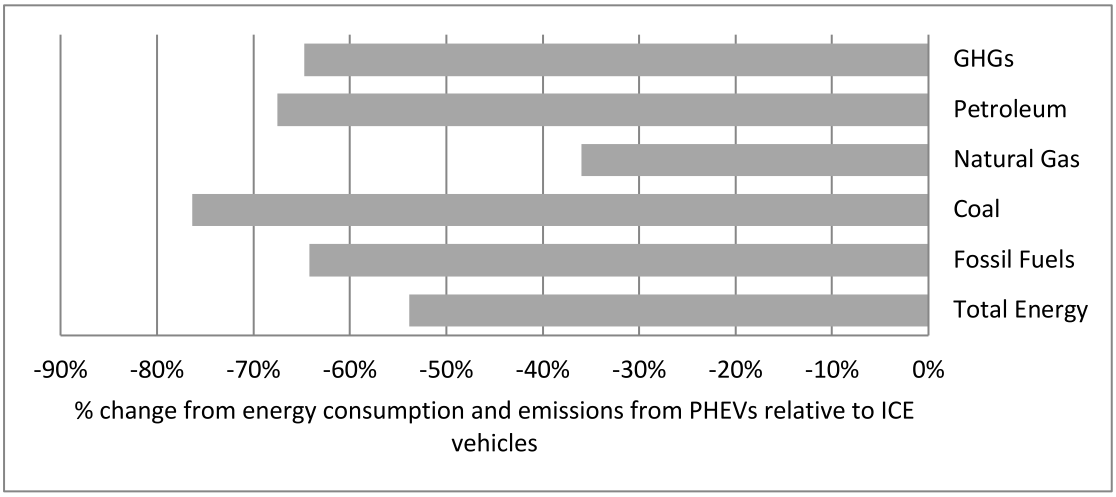
Note: The 2020 UF of 0.69 corresponds to twice the DKT from the 2010 survey, as explained in the text

Note: The changes reported in this figure are from PHEVs relative to 2009 ICE vehicles (current gasoline vehicles) assuming the predicted 2020 electricity generation mix in China from Table 1

Assuming that grid electricity in China continues to be mainly generated in coal power stations, coal consumption increases. It can be seen from Figure 4 that for PHEVs to be truly 'environmentally friendly' and make significant improvements on energy consumption and GHG emissions, the electricity to power them needs to be generated using clean technologies. Even though energy consumption from coal (measured in BTUs) increases, energy from all fossil fuels (coal, oil and natural gas) decreases because energy consumption from oil and natural gas (measured in BTUs) decreases. Energy consumption from oil, unsurprisingly, declines. Energy consumption from gas also declines because the upstream process to produce gasoline involves a significant amount of natural gas and in the predicted 2020 electricity generation mix gas only accounts for 6.8%. This would be different if China had a higher share of natural gas for electricity generation, as other countries do.

Although GHG emissions and energy consumption would both be reduced, it is interesting to see what the changes would be if all electricity in China were produced in nuclear power stations, rather than by coal. Figure 5 shows the results of this exercise, which represents a hypothetical ‘maximum reduction’ in emissions. In any case, power plants are long lived investments, which also take time to be built, and ten years would not be a long enough period of time to substantially change the shares of electricity production from different sources. Furthermore, as the figure shows, emissions would not be completely eliminated. This is because nuclear power stations are associated with large amounts of indirect GHG emissions. These are caused during the facility construction and supply of materials, as well as during the operational processes, which include uranium mining, milling, conversion, fuel rod fabrication, transportation, facility operation and maintenance, and reprocessing, and activities that take place after the power station ceases to operate, such as decommissioning, nonradioactive waste disposal/recycling, and radioactive waste storage (Warner and Heath, 2012, p.S74). Having said that, there is consensus in the lifecycle analysis literature that ‘life cycle GHG emissions from nuclear power are only a fraction of traditional fossil sources’ (Warner and Heath, 2012, p.S90).

Figure 5: Lifecycle Energy Consumption in BTUs relative to 2009 ICE vehicles for the travel survey sample in China under the hypothetical assumption that all electricity in 2020 is generated in nuclear power stations



Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted

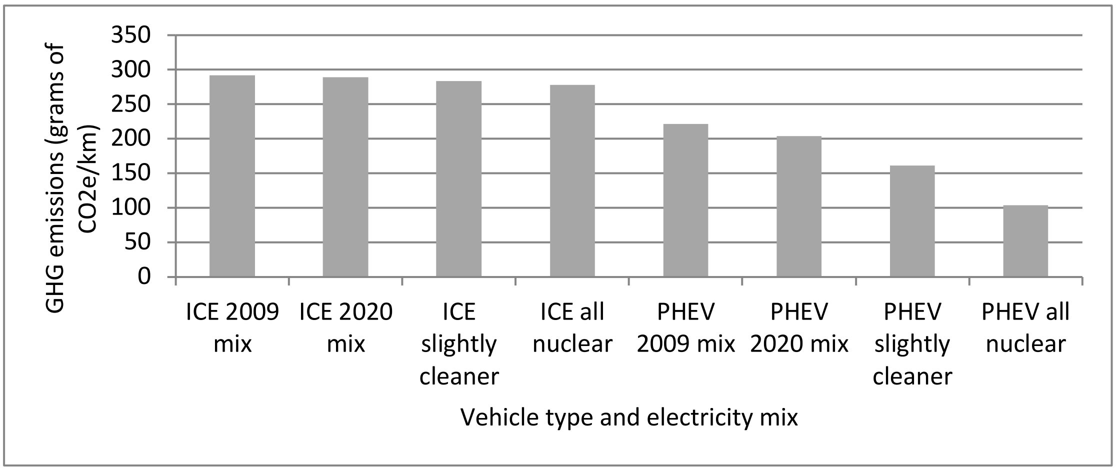
Note: The 2020 UF of 0.69 corresponds to twice the DKT from the 2010 survey, as explained in the text

Note: The changes reported in this figure are from PHEVs relative to 2009 ICE vehicles (current gasoline vehicles) assuming that all electricity in China in 2020 is generated in nuclear power stations

As can be seen in Figure 5, if electricity were generated in a clean way the reduction in energy consumption and GHG emissions resulting from using PHEVs rather than ICE ones would be drastic. Although China could not convert to all nuclear by 2020 the exercise serves as a warning of the forgone benefits from feeding PHEVs electricity produced in coal power stations.

Figure 6 shows absolute CO_2e emissions in grams per km for ICE vehicles and PHEVs under the four different electricity generation mixes introduced in Table 1. ICE vehicles run on gasoline and emissions PTW do not vary with how the electricity is generated. Emissions WTP, however, are lower for cleaner electricity generation mixes, as the upstream oil recovery, refinery and fuel transport consume electricity. The figure also shows that lifecycle PHEV emissions decline when electricity is generated using cleaner technologies. In an all nuclear mix emissions are much lower but they are not zero, for the reasons explained above, i.e., when electricity is generated from nuclear power, the upstream stage still involves fossil fuel consumption for uranium recovery, transport, and refinery for reactor use.

Figure 6: Lifecycle GHG emissions (in grams of CO2e per km) for ICE vehicles and PHEVs with a UF of 0.69 under different electricity generation mixes in China 2020



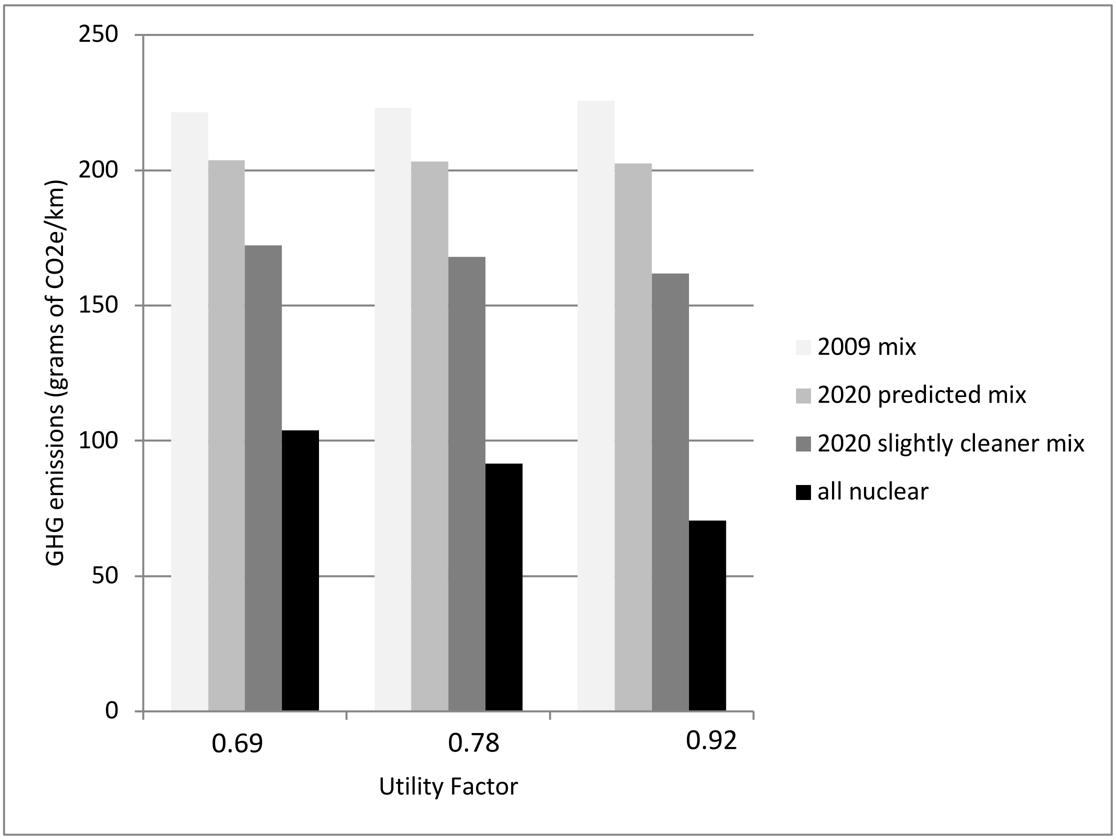
Source: estimates produced by the authors using GREET 1.8c

Note: the electricity mixes correspond to those in Table 1

Note: The ICE vehicle emissions on this figure correspond to 2020 ICE vehicles, with a higher fuel efficiency than 2009 (current) ICE vehicles

Figure 7 shows lifecycle GHG emissions from PHEVs in grams of CO_2e per km under the four electricity mixes depicted in Table 1 and three different utility factors (0.69, 0.78 and 0.92). These utility factors correspond to a R_{CD} of 60 km on the three curves on Figure 3 (with the DKT, 1.5 times the DKT and twice the DKT by our survey respondents). It should be noted that the results on Figure 7 can also be taken as representative of a range of battery ranges and even different charging frequencies as well. For example, with an R_{CD} of 100 km and twice the DKT (which is the estimated DKT for 2020), the UF is 0.89, which falls in-between 0.78 and 0.92. If the PHEV battery were charged twice a day, the UF would reach 1, which would be just over the 0.92 depicted on the figure.

Figure 7: Lifecycle GHG emissions (in grams of CO2e per km) for PHEVs with different utility factors under different electricity generation mixes in China 2020



Source: estimates produced by the authors using GREET 1.8c

Note: the electricity mixes correspond to those in Table 1

Importantly, emissions decline according to how clean the electricity mix is. The reductions can be substantial, as shown on Figure 7. Interestingly, emissions can increase with the UF, as is the case for the 2009 mix and at the margin, the predicted 2020 mix. The reason for this is that these electricity generation mixes are fairly dirty in terms of GHG emissions. A higher UF, which implies a higher percentage of km driven on charge depleting mode, entails higher electricity use. When the carbon intensity of the grid is high PHEVs using more electricity cause higher CO_2 emissions than gasoline combustion. These findings are in line with those from Huo et al (2010), who conclude that electric vehicles would generate more GHGs than ICE vehicles under the North and North East power grids, which are coal intensive. They also conclude that electric vehicles would cause lower GHG emissions than hybrid electric vehicles under the South power grid only. Similarly, Ou et al (2010) find that electric vehicles would save GHG emissions substantially only if state-of-art power generation technologies were used.

Figure 7 also shows that emission reductions due to a higher UF (which might be the result of lower DKT, higher R_{CD}, or even higher charging frequency) are not significant, when compared to those that can be achieved from cleaner electricity generation mixes.

Table 3 summarizes absolute energy consumption and emissions for the most important combinations (it only excludes the 2009 electricity mix, as this has already been shown graphically and is used in the study for comparison purposes only). The numbers in parenthesis represent the changes relative to 2009 ICE vehicles under the relevant electricity generation mix.

Table 3: Lifecycle Energy Consumption (in BTUs per km) and GHG Emissions (in grams of CO_2e per km) for ICE vehicles and PHEVs with a charge depleting range (R_{CD}) of 60 km and different electricity mixes in China 2020

Items	PHEV 2020 mix	PHEV slightly cleaner mix	PHEV all nuclear
Petroleum	1175	1159	1059
	(-64.1%)	(-64.5%)	(-67.5%)
Natural Gas	256	304	264
	(-41.4%)	(-32.1%)	(-36.0%)
Coal	834	533	19
	(227.7%)	(181.5%)	(-76.3%)
Fossil Fuels	2265	1995	1341
	(-42.8%)	(-48.9%)	(-64.2%)
Total Energy	2496	2290	1772
	(-37.5%)	(-42.0%)	(-53.9%)
GHGs	204	172	104
	(-35.0%)	(-44.0%)	(-64.7%)

Source: estimates produced by the authors using GREET 1.8c, with UF = 0.69

Note: Numbers in parenthesis correspond to % changes relative to 2009 ICE vehicles (current gasoline vehicles) under the relevant electricity mix

PHEVs under the predicted 2020 mix provide a 64.1% reduction in petroleum consumption and 41.4% reduction in natural gas consumption, when compared to current ICE vehicles under the same mix. Coal consumption increases by 227.7% due to the higher demand for electricity, 63% of which is generated in coal power stations under the 2020 electricity mix. Notwithstanding that, overall fossil fuel and energy consumption and GHG emissions decline. The story for PHEVs under a slightly cleaner electricity generation mix is similar.

When all electricity is assumed to be generated in nuclear power stations the results are different. PHEVs under an all nuclear mix do not increase but rather, decrease, coal consumption. Consequently, fossil fuel and total energy consumption reductions as well as GHG emissions reductions are greater in absolute terms.

5. Conclusions

In this paper we estimated the potential that PHEVs have for reducing energy consumption and GHG emissions relative to current gasoline vehicles in China 2020 under different electricity generation mixes and utility factors (in turn covering different combinations of average distances driven per day and battery ranges as well as, implicitly, charging frequencies).

The main findings are: (a) the way in which electricity is generated has a substantial impact on energy consumption and lifecycle GHG emissions; and (b) the utility factor (in turn determined by battery range, average daily distance driven and charging frequency) does not have much of an impact on energy consumption and lifecycle GHG emissions, in comparison with the impact that the electricity generation mix has.

Unsurprisingly, we find that the cleaner the technology used to produce electricity, the lower the absolute energy consumption and GHG emissions from PHEVs are. We also find that in a coal intensive electricity generation mix, lifecycle GHG emissions from PHEVs increase slightly with the utility factor. The reason for this is that the higher the share of total distance driven on electricity, the higher the electricity consumption will be and, if this electricity comes from coal power stations, the higher the lifecycle GHG emissions will be.

The reductions that can be achieved by PHEVs in China 2020 relative to current gasoline vehicles are therefore very sensitive to the electricity generation mix but not very sensitive to the utility factor, or in other words, to the average distance driven per day, the battery range, or the charging frequency. The reductions in energy consumption and GHG emissions are 37.5% and 35% under the predicted 2020 electricity generation mix, which assumes a share of coal of 63%, but increase to 53.9% and 64.7% respectively under an all nuclear electricity generation mix.

The conclusion from these findings, which can be generalised to other countries, is that increasing the battery range or charging frequency of PHEVs and/or decreasing daily distances traveled by car when the electricity generation mix is not clean will not enhance reductions in energy consumption or GHG emissions substantially, and could, when the share of coal is important, slightly increase both. Increasing the share of clean technologies used to generate electricity, on the other hand, will enhance reductions in energy consumption or GHG emissions that PHEVs can achieve relative to gasoline vehicles.

Acknowledgements

The authors are indebted to four anonymous reviewers of the International Journal of Sustainable Transportation for comments and suggestions that greatly improved this paper. Thanks are also due to anonymous reviewers and attendees of the 12^{th} Meeting of the World Conference on Transport Research Society, Lisbon, July 11-15, 2010 and the Transportation Research Board 90th Annual Meeting, Washington DC, January 23-27, 2011. The usual disclaimer applies.

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Appendix

Abridged version of the online survey conducted on the Auto.Sohu website in China

1. Would you consider Hybrid Electric Vehicles (HEVs) or Electric Vehicles (EVs) when choosing a car to buy?

A. Yes

B. No

C. Not sure

2. Compared with conventional gasoline vehicles, what do you think is the biggest strength of HEVs and EVs?

A. Lower operation costs

B. Environmentally friendly

C. Other (please specify)

3. What are your concerns about HEVs and EVs? (You may tick more than one choice)

A. Expensive

B. Lower performance, quality or reliability when compared to standard gasoline cars

C. Repair and after-sales services insufficient

D. Limited models for selection

E. Other (Please specify)

…

5. Under what payback period would you be prepared to buy a HEV or EV?

A. Less than 6 months

B. 6 months to 1 year

C. 1 to 1.5 years

D. 1.5 to 2 years

E. 2 to 3 years

F. 3 to 5 years

G. More than 5 years

…

8. What would be your minimum acceptable distance per charge is?

A. 100 km

B. 150 km

C. 200 km

D. More than 200 km

9. What is your acceptable lowest vehicle maximum speed?

A. 100 km/h

B. 150 km/h

C. 200 km/h

D. More than 200 km/h

…

11. Please specify your average travel distance per day in km.

…

Table A1: Energy efficiency parameters input onto GREET

Parameter	**Value**	**Source**
Barges	10,119BTU/hphr (horsepower hour)	GREET
Lorries	25,690 BTU/mile	GREET
Coal power plants (conversion efficiency of coal to electricity)	29.8%	Zhang et al. (2007)
Natural gas power plants (conversion efficiency of natural gas to electricity)	24.8%	Zhang et al. (2007)
Refineries	82.7%	Zhang et al. (2007)
Gasoline ICE vehicles	23.4 MPG	GREET
PHEVs Charge Sustaining mode	32.8 MPG	GREET
PHEVs Charge Depleting mode (fuel) PHEVs Charge Depleting mode (electricity)	601 BTU/km 134 wh/km	Prius Hymotion

Table A2: Parameters input on to GREET for the Toyota Hymotion Prius with an A123 battery with a charge depleting range (R_{CD}) of 60km

Simulation options	
Fuel consumption in charge depleting mode (BTU-fuel/km)	601
Electricity consumption in charge depleting mode (Wh/km)	134
Miles per gallon change in charge sustaining mode relative to ICE vehicles (%)	140
Operational charge sustaining range (km)	60
Share of km travelled for charge depleting mode (%)	69
Share of km travelled for charge sustaining mode (%)	31
Electric charger efficiency (%)	85
Toyota Hymotion Prius with an A123 battery	
Vehicle configuration	Pre-transmission parallel
Vehicle class	Mid-size
Vehicle test class	1661 kg
Front area	2.2 m^2
Drag coefficient	0.29
Transmission	5-speed manual
Accessory load electrical	200 watt average
Electric machine	75 kw peak at base speed of 3000 rpm
Battery model	SAFT-JCS VL41M
Battery capacity	41 Ah at 3/c
Battery operating voltage	194-288 V
Battery continuous current	150A for 30 sec at 30°C
Battery discharge power	65 kw for 30 sec at 50% state of charge* at 30°C

*The state of charge is the percentage of available electricity capacity to the battery's total storage capacity. It is the equivalent of a fuel gauge for the battery pack (0% = empty; 100% = full). Source: Rousseau et al. (2007)

Table A3: ICE vehicle and PHEV fuel cycle energy consumption and emissions (R_{CD}=60km) under the predicted 2020 mix

(Btu/km or g/km)	ICE vehicle	Relative Change	PHEV
Total Energy	3853.24	-37.90%	2392.87
Fossil Fuels	3826.17	-41.42%	2241.54
Coal	186.95	224.43%	606.51
Natural Gas	734.39	-13.87%	632.52
Petroleum	2904.83	-65.80%	993.46
CO2	283.65	-34.74%	185.10
CH4	0.39	-35.87%	0.25
N2O	0.01	6.22%	0.01
GHGs	295.92	-34.43%	194.04

Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted

Table A4: ICE vehicle and PHEV fuel cycle energy consumption and emissions (R_{CD}=60km) under an all nuclear mix

(Btu/km or g/km)	ICE vehicle	Relative Change	PHEV
Total Energy	3733.99	-53.87%	1722.63
Fossil Fuels	3661.53	-64.21%	1310.43
Coal	51.15	-76.34%	12.10
Natural Gas	715.55	-35.99%	458.03
Petroleum	2894.83	-67.49%	941.17
CO2	267.90	-65.31%	92.94
CH4	0.38	-62.09%	0.14
N2O	0.01	-9.15%	0.01
GHGs	279.97	-64.72%	98.78

Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted