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A Microsimulation of Energy Demand and Greenhouse Gas Emissions from Plug-in Hybrid Electric Vehicle Use

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Abstract

A population of drivers was simulated using a microsimulation model. Consistent with the 2001 National Household Travel Survey (NHTS), a wide range of daily driving distance was observed. This heterogeneity implies that some drivers will realize greater fuel savings from driving a plug-in hybrid electric vehicle (PHEV) than others, therefore, consumers who choose to purchase PHEVs may tend to be those who drive farther than average.

The model was used to examine the effects of this difference in driving by estimating fuel use, electricity demand and GHG emissions by two populations, one assigned PHEVs at random to some fraction of drivers, and the other assigned PHEVs to drivers who realized operating cost savings at least as great as the amortized incremental cost of the PHEV relative to a comparable conventional vehicle. These two populations showed different distributions of daily driving distance, with the population of PHEV drivers selected on the basis of operating cost savings driving 40% farther per day on average than average drivers. This difference indicates the possible range of driving patterns of future PHEV drivers, which should be taken into account when estimating fuel savings and GHG reductions from PHEVs. For example, if 20% of U.S. vehicles were PHEVs, we find a potential reduction of fuel use of 0.17 gal per day per vehicle if PHEVs substitute randomly for conventional vehicles, whereas the fuel savings is as large as 0.26 gal per day per vehicle if PHEVs are substituted according to operating cost savings. Similar differences in GHG emissions were estimated as well.

The effects of electricity demand management on charging PHEVs was examined for these two populations. It was found for both that only a small fraction of PHEVs were impacted by interruptible electricity service (no charging permitted during peak hours). Most PHEV drivers were able to charge sufficiently during off-peak hours and saw little change in operating costs. This implies that interruptible electricity service may impact operating costs of only a small fraction of PHEV drivers.

Keywords: PHEV (plug in hybrid electric vehicle), energy consumption, emissions

1 Introduction

Plug-in hybrid electric vehicles (PHEVs) offer a means to reduce vehicular GHG emissions and petroleum use, but estimation of these reductions is made difficult by uncertainties and heterogeneity in behavior of driver populations. The fraction of distance driven under gasoline or electricity depends on the charge-depleting range of the vehicle as well as on how the vehicle is driven, in particular, the distance driven between charging. Most of estimates of potential reductions in gasoline use by PHEVs made by earlier studies [1 - 3] use estimates of the fraction of miles that PHEVs are driven electrically (or "utility factor") based on the distribution of trip distances from travel surveys and assumptions about the frequency of charging. Vyas et al. [1] and Samaras and Meisterling [2] estimated the utility factor from the trip distance distribution reported in the 2001 National Household Travel Survey (2001 NHTS) [4]. This requires assumptions about how many times per day and where vehicles are charged. In addition, the NHTS provides records on only one day's travel per household, making it necessary to make assumptions about how vehicles are driven from day to day.

A microsimulation model was developed to simulate a population of drivers and was used to track individual vehicles trip by trip, with realistic distributions of arrival time, speed, distance, interval between trips, and number of trips per day. Fuel and electricity use are tracked trip by trip, and GHG emissions are estimated. By assigning PHEVs to a fraction of drivers, the potential reduction in fuel use, electricity demand and GHG emissions can be estimated. These are estimated under different conditions such as with and without interruptible electricity and using different methods to assign PHEVs to drivers. From these results, we can gauge the sensitivity of estimated fuel and GHG reduction on assumptions about future PHEV driving patterns and potential impacts of interruptible electricity service on economical operation of PHEVs. Aggregate energy demand and emissions were estimated for a fleet of 7.3 million vehicles, representing the fleet of light-duty passenger vehicles in the state of Michigan.

Because PHEVs are more efficient, and because per mile, operating on electricity costs less than gasoline, PHEVs may be purchased preferentially by consumers who care more about operating cost savings. In addition, since total operating cost savings are proportional to vehicle-miles traveled, drivers who drive farther on average may be more inclined to purchase PHEVs. In reality, many factors influence vehicle purchasing behavior, not just cost savings. Actual purchase behavior is expected to be somewhere between two extremes of 1) vehicle choice based only on operating cost savings and 2) random choice of vehicle. These two extremes were used in simulations to bound the effect of vehicle choice on energy use and emissions by PHEVs. This approach is simpler than using a consumer choice model which would require much more data for consumer preferences and demographics and vehicle characteristics (see for example, Train [5]). The approach used here requires fewer assumptions and less data, but allows estimation of bounds on energy use and emissions and an assessment of the sensitivity of these to driving patterns.

2 Methods and Data

The model represents a population of individual drivers, each having a vehicle and each driving trips to destinations they choose each day. During each day, there are times when drivers are routinely either at home or at work and not driving, and on workdays, there are times when drivers who drive to work (70% of the population in these simulations) routinely make commuting trips. Other trips are considered optional and are driven depending on each driver's schedule and sensitivity to travel cost. Drivers with PHEVs decide whether to recharge their vehicle batteries depending on the availability of electricity, the planned length of stay at their current location, and the relative costs of electric-powered travel and gasoline-powered travel. Details of the model can be found in Stephens [6].

These distributions are related to drivers' daily routines, travel needs and travel costs. The distributions of parameters governing trips were calibrated to match 2001 NHTS trip distances, speeds and arrival times. Drivers have decision rules for the number of trips to drive and whether to charge vehicle batteries when electricity is available, depending on their needs and preferences and on energy prices. The rule governing the number of trips was chosen to give drivers a short-term elasticity of travel demand close to that reported for U.S. drivers. Therefore, the number of trips and resulting vehicle-miles traveled (VMT) for each driver depends slightly on operating cost. The resulting population of drivers had a broad distribution of average daily driving distance, consistent with the 2001 NHTS. The rule governing PHEV charging was that a driver would plug in their PHEV when arriving at a location where electricity was available for charging if he planned to remain at that location for at least two hours. Locations for charging were either only at home or at both home and work. Figure 1 compares the distribution of arrival times at home, at work and at other locations given by the model and as estimated from the 2001 NHTS day trip data for arrivals of cars, vans, SUVs and pickups. Arrival times at home and work match very closely, and arrival times for other locations match well except for a slight over-prediction of arrivals in early morning hours. This slight discrepancy should have little effect on predicted energy use by PHEVs, since in the simulations, PHEV drivers charge their vehicles only at home or at work.

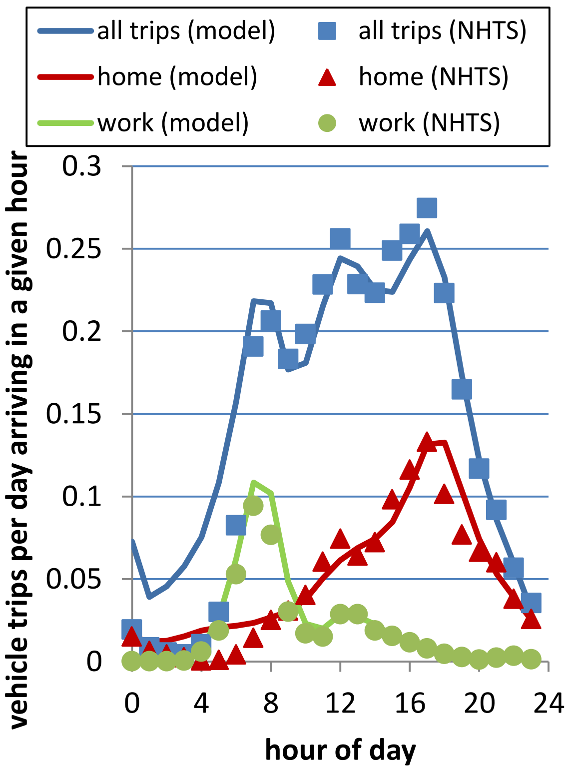

Figure 1. Arrival time distribution, vehicle-trips per vehicle per day, as estimated from the model (lines) and the 2001 NHTS (symbols).

The model tracks fuel and electricity use by trip for each driver, total electricity and fuel demand, and the resulting total fuel cycle greenhouse gas emissions from electricity and fuel consumption. Output also includes driver operating costs for each vehicle, and for PHEV owners, cost savings in comparison with a comparable conventional vehicle. Aggregate energy demand and emissions were estimated for a fleet of 7.3 million vehicles, representing the light-duty passenger vehicle fleet of the state of Michigan.

Electricity emissions are estimated using a dispatch model of Kelly et al. [7] based on capacity factor. Capacity factor data, type of fuel used, and combustion emissions were obtained for Michigan power plants from the U.S. Environmental Protection Agency's (EPA) Emissions & Generation Resource Integrated Database [8] for year 2005. Upstream emission factors of fuels for nuclear, natural gas, biomass, residual fuel oil, bituminous coal and sub-bituminous coal or lignite power plants were obtained from the U.S. Life Cycle Inventory database [9]. Electricity demand in Michigan for year 2008 was obtained from the Federal Energy Regulatory Commission Forms 714 [10]. In the simulations reported here, the demand for these Michigan utilities during the first week in August of 2008 (the highest demand week of 2008) was used for the background (non-PHEV) electricity demand for all cases, including those with interruptible electricity service (which was assumed to apply only to PHEV charging). GHG emissions from gasoline consumption were calculated from a total fuel cycle emission factor of 11.185 kg CO2 eq/gal, based on the GREET model, version 1.8c [11].

The vehicles in the model were a mix of eight different market segments. For each segment, there was a conventional vehicle (CV) model with the on-road fuel economy values listed in Table 1, and a comparable PHEV having the fuel economy in charge-sustaining mode, electrical consumption rate in charge-depleting mode, and charge-depleting (CD) range shown. The useful battery capacity is the amount of energy available between recharges, i.e., the product of electrical consumption per mile and CD range. All PHEVs were assumed to have a series drive-train, and operated electrically in CD mode until the useful battery charge was depleted after which the vehicle would travel in charge-sustaining mode under gasoline power. The difference in purchase price between each PHEV and the comparable CV was estimated based on long-term price estimates for PHEV made by Simpson [12]. No tax credit or other purchase incentive was assumed for PHEVs.

PHEVs were assigned to a fraction of drivers either randomly or according to the operating cost savings over a comparable (CV). Random assignment was done by assigning PHEVs to a given fraction of drivers (20% in the simulations

Table 1. Fuel economy, electricity consumption per km and purchase price difference for conventional vehicles and PHEVs in the simulations.

	conventional		PHEV					
segment	fuel econ, city [mpg]	fuel econ, hwy [mpg]	fuel econ, city [mpg]	fuel econ, hwy [mpg]	electricity consumption [kWh/km]	charge-depleting range [mi]	useful battery capacity [kWh]	purchase price difference
1	32	40	48	48	0.162	10	2.61	$6,000
2	28	37.5	46	46	0.162	10	2.61	$6,000
3	26	34	42	42	0.186	20	5.99	$8,500
4	27	35	42	42	0.186	10	2.99	$6,000
5	23.5	33	40	40	0.186	20	4.18	$8,500
6	21	28	36	36	0.149	40	9.59	$12,000
8	21	28	34	34	0.286	10	4.60	$8,500
9	20	26	32	32	0.286	20	9.20	$12,000

reported here). Assignment by cost savings was done by initially assigning PHEVs to all drivers and simulating several weeks of driving while recording operating costs (cost of electricity and gasoline) for each driver and their estimated operating cost had they driven a comparable conventional vehicle for the same trips. The operating cost savings, the difference between the operating costs driving a CV and a PHEV was compared to the incremental monthly payment which was taken to be the difference in purchase price divided by 60 (a 5 year loan at 0% interest). Those drivers whose monthly average operating cost savings were at least as large as the incremental monthly payment were assigned PHEVs, the remainder were assigned CVs. This criterion was chosen to select those drivers whose driving pattern would result in a PHEV being economical to drive vs. the comparable CV. This was not intended to realistically represent consumer vehicle choice behaviour; rather this was to select a population that gave a bound on driving pattern and resulting energy use by PHEV drivers. The resulting fraction of drivers assigned PHEVs depended on the prices of gasoline and electricity. Although this assignment was not necessarily the PHEV that gave the maximum cost savings for each driver, it resulted in no PHEVs being assigned to drivers whose operating cost savings were less than the incremental cost of the vehicle. For the simulations reported here, an electricity rate of $0.10/kWh was assumed, and the gasoline price was adjusted to result in 20% of drivers being assigned PHEVs. Gasoline prices in these simulations were either $5.27/gal for cases in which PHEVs could be charged at home and at work or $5.92/gal for cases in which charging could be done only at home.

Once PHEVs were assigned, several weeks of driving were simulated to generate sufficient data to calculate average energy demand and emissions results. Interruptible electricity service was simulated by assigning the power for PHEV charging a value of zero for any PHEV plugged in during the time that power was interrupted. No change was made to the rule that drivers used to decide when to plug in their PHEVs in the simulations with interruptible service.

3 Simulation Results

3.1 Cases Simulated

Driver populations in which 20% of vehicles were PHEVs were simulated with charging only at home or at both home and at work (70% of drivers drive to work). Energy and emissions were tracked for four weeks of simulated time with no electricity interruption. Following this, interruptible electricity service for PHEV charging was simulated in which no PHEV charging was permitted, either between noon to 10:00 pm or between 8:00 am to 10:00 pm. All PHEVs were assumed to be subject to interruption, and long interruption periods were chosen to represent severe cases of electric demand-side management in order to assess the maximum potential impact on PHEV drivers such interruption might have.

For all cases, PHEVs were assigned either at random or to drivers whose operating cost savings vs. a conventional vehicle were at least as large as the difference in monthly payment, as described above. This represents two extremes of potential vehicle choice: 1) based on operating cost savings and 2) purely random. This allowed us to examine the potential difference in driving patterns and the resulting energy demand and GHG emissions as well as sensitivity of operating costs to interruption of charging.

3.2 Driving Distance Distribution

The distribution of distance driven daily was determined for drivers of CVs and PHEVs for the two populations assigned at random and according to cost savings. Figure 2 shows the cumulative distribution of daily driving distance (the fraction of days in which a vehicle was driven at least a given distance). The distribution for CVs and PHEVs assigned at random were identical and this distribution was similar to that estimated from the 2001 National Household Travel Survey (NHTS).

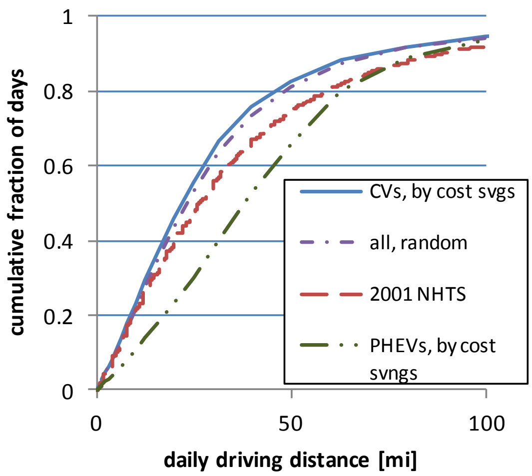

Figure 2. Cumulative distribution of daily driving distance for Conventional vehicles (CVs) assigned by operating cost savings, PHEVs assigned according to costs savings, vehicles assigned at random (both CVs and PHEVs) and the distribution estimated from the 2001 NHTS.

Figure 2 also shows the distribution for a population of drivers in which 20% of drivers were assigned PHEVs on the basis of cost savings and the distribution for the remaining 80% who were assigned CVs. The distribution shown for PHEVs assigned according to cost savings is for PHEVs that can be charged at home and at work. The corresponding case for PHEV that can be charged only at home showed a very similar distribution. The distribution for individual vehicle segments was more variable, but no consistent trend with charge-depleting range was seen. It is clear, however, that when PHEVs are assigned by cost savings, PHEV drivers tend to drive greater distance per day, and the remaining drivers tend to drive slightly less distance per day.

The utility factor (the fraction of miles that PHEVs were driven electrically) was also calculated. Averages for PHEVs of CD range 10, 20, and 40 miles are shown in Figure 3.

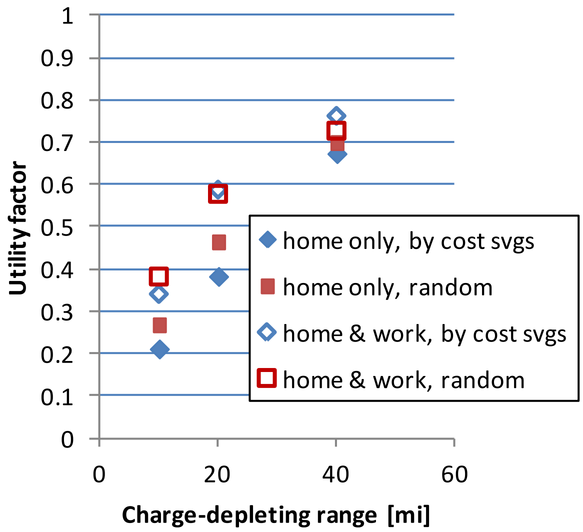

Figure 3. Utility factor (the fraction of miles that PHEVs were driven electrically), with PHEVs assigned to drivers either randomly or according to cost savings. Open symbols: charging at work and at home, solid symbols: charging at home.

The utility factor increases with CD range, and it is significantly higher when PHEV drivers who work can charge at work as well as at home, as expected. The utility factors reported here for PHEVs charged only at home are within the range of values estimated by others, e.g., [1 - 3], for series-drivetrain PHEVs charged once per day. The utility factor is higher when PHEV are charged at work and at home than when they are charged only at home, which is also expected. The increase with charging at work is less for PHEVs having a 40 mile CD range (PHEV40s). Since in these simulations, the average commute distance was 12.1 miles (consistent with the 2001 NHTS), a significant number of drivers of PHEV40s arrive at work with a partial charge and do not utilize as much electricity when they are charged at work.

The utility factor depends somewhat on how PHEVs are assigned to drivers, either by cost savings or at random. Since PHEVs in these simulations are more efficient than comparable

CVs even when operating on gasoline, operating costs are lower for PHEVs and drivers save more the more miles they drive. When PHEVs are assigned according to cost savings, they are driven significantly more miles than when assigned at random, and although they are driven more miles, a somewhat smaller fraction of their total miles is driven electrically. This is expected if PHEVs are driven farther than the CD range on average, since the more a PHEV driver's average daily distance exceeds the CD range of the PHEV, the greater fraction of miles driven will be powered by gasoline instead of electricity. This dependence is less for PHEVs with longer CD range, for which the amount of driving in excess of the CD range is less. This dependence is also less when PHEVs are charged at both work and at home, again, since the driving in excess of the CD range is less than if PHEVs are charged only at home. The difference in driving between those assigned PHEVs by cost savings from those assigned PHEVs randomly is significant and has implications for estimating energy consumption and emissions from PHEVs.

3.3 Energy Demand and GHG Emissions

Fuel use, electricity demand and total fuel cycle GHG emissions results for the case of charging only at home are shown in Table 2. The two methods for assigning PHEVs (random and by cost savings) give upper and lower bounds for miles driven, energy use and GHG emissions estimated from simulations in which 20% of vehicles were PHEVs. The vehicle-miles traveled (VMT) is sensitive to how PHEVs are assigned, and when PHEVs are assigned by cost savings, VMT per PHEV is much higher and VMT per CV is lower, as noted above.

In the case of random assignment of PHEVs, PHEVs are driven slightly more VMT per day than CVs on average, since the average number of trips drivers take per day depends somewhat on their operating cost, and since PHEVs cost less to operate per mile, the number of trips and average distance driven is slightly higher for PHEV drivers than CV drivers. The difference between average VMT per day by PHEV drivers and CV drivers is much larger when PHEVs are assigned by operating cost savings.

If PHEVs are charged at home and at work (70% drive to work), the range of utility factor is higher (consistent with Figure 3), but results are qualitatively similar to those for charging only at home. As shown Table 3, when PHEVs are assigned according to cost savings, VMT per PHEV is much higher and VMT per CV is lower, since drivers who drive farther on average tend to save more and are more likely to achieve monthly operating cost savings that are at least the difference in the monthly payment for PHEV vs. a comparable CV.

This has implications for estimating energy use and GHG emissions from PHEVs. If instead of random substitution, PHEVs are substituted for CVs that are driven farther than the average vehicle (as in the case where PHEVs are assigned by cost savings), reductions in fuel use and GHG emissions are greater. Table 4 shows daily fuel use and GHG emissions (total fuel cycle) per vehicle for three cases: a. no PHEVs, b. 20% PHEVs assigned randomly, and c. 20% PHEVs assigned by cost savings. In all three cases, PHEV drivers could recharge at work and at home at all hours of the day.

Table 2. Bounds on average vehicle miles traveled (VMT), energy, total fuel cycle GHG emissions, and operating costs for conventional vehicle (CV) and PHEV drivers, with PHEVs charging at home.

	no electric charging interruption	with electric charging interruption for 10 hr	with electric charging interruption for 14 hr
VMT per day per CV	29.4* – 32.9	no change	no change
VMT per day per PHEV	34.2 – 47.2*	34.4 – 48.0*	33.9 – 48.3*
Utility factor	0.37* – 0.38	0.35* – 0.37	0.34* – 0.36
Daily charging demand per PHEV, kWh	4.05 – 5.19*	3.94 – 4.94*	3.82 – 4.79*
Daily CV fuel use, gal	1.16 – 1.32	no change	no change
Daily PHEV fuel use, gal	0.52 – 0.75*	0.53 – 0.78*	0.53 – 0.80*
Fuel cost, CV, $/day	$6.88* – 7.79	no change	no change
Fuel + elec cost, PHEV, $/day	$3.51 – 4.95*	$3.56 – 5.13*	$3.53 – 5.23*

*Estimates for population with PHEVs assigned according to cost savings.

Table 3. Bounds on average vehicle miles traveled (VMT), energy, total fuel cycle GHG emissions, and operating costs for conventional vehicle (CV) and PHEV drivers, with PHEVs charging at home and at work.

	no electric charging interruption	with electric charging interruption for 10 hr	with electric charging interruption for 14 hr
VMT per day per CV	29.6* – 33.0	no change	no change
VMT per day per PHEV	33.7 – 46.9*	34.1 – 48.0*	33.8 – 47.6
Utility factor	0.49 – 0.50*	0.44* – 0.45	0.36* – 0.39
Daily charging demand per PHEV, kWh	5.21 – 7.28*	4.77 – 6.32*	4.11 – 4.98*
Daily CV fuel use, gal	1.18* – 1.32	no change	no change
Daily PHEV fuel use, gal	0.43 – 0.58*	0.47 – 0.66*	0.51 – 0.76*
Fuel cost, CV, $/day	$6.21* – 6.97	no change	no change
Fuel + elec cost, PHEV, $/day	$2.81 –3.78*	$2.94 – 4.10*	$3.11 – 4.50*

*Estimates for population with PHEVs assigned according to cost savings.

As shown in Table 4, reductions in average fuel use and GHG emissions per vehicle are larger when PHEVs were assigned by cost savings rather than at random. A significant part of these reductions is from substituting more efficient PHEVs for CVs that are driven more miles than average. This means the remaining CVs are driven less on average, which explains the reduction in fuel per CV (0.14 gal/day) with 20% PHEVs assigned by cost savings.

Table 4. Average Fuel Use and GHG Emissions per Vehicle per Day for Three Cases. PHEVs could be charged at home and at work.

	zero PHEVs	20% PHEVs assigned randomly	20% PHEVs assigned by cost savings
fuel used per CV gal/day	1.32	1.32	1.18
fuel use reduction per CV, gal/day	-	0.0	0.14
fuel used per PHEV, gal/day	-	0.43	0.58
fuel used per vehicle, gal/day	1.32	1.15	1.06
fuel use reduction per CV, gal/day	-	0.17	0.26
GHG emitted per vehicle, kg/day	14.8	13.9	13.3
GHG reduction per vehicle, kg/day	-	0.9	1.5

GHG emission reductions are also higher when PHEVs are assigned according to cost savings (1.5 vs. 0.9 kg per vehicle per day). These are bounds, so actual reductions are expected to lie between these. However, the difference between the upper and lower bounds of potential reductions show how important it is to take into consideration how PHEVs will be driven, since PHEV drivers may tend to drive farther on average. This means that the fuel savings and GHG reduction from adoption of PHEVs may be significantly larger than estimates based on the average driving distance distribution.

3.4 Electricity Demand Management (Interruptible Service)

The effects of electricity demand management were examined by simulating scenarios of interruptible electrical service. On average, PHEV drivers travel only slightly fewer miles on electricity when charging is not allowed during peak hours (noon to 10:00 pm), so energy use, GHG emissions, and operating costs for PHEVs are only very slightly impacted by electricity interruption. On the other hand, the microsimulation allowed us to examine which drivers in the population would be affected, and it was found that a small fraction of PHEV drivers experience interruption of charging fairly often. Nonetheless, this is important as such circumstances might incentivize some PHEV owners to switch back to conventional vehicles, or to opt out of interruptible service. Figures 4 and 5 show the fraction of PHEV drivers who experience interruption of charging a given number of times per month, when charging is not permitted between noon and 10:00 pm. In figure 4, PHEVs were charged only at home, and very few drivers experience interruption more than a few times per month. In figure 5, PHEVs

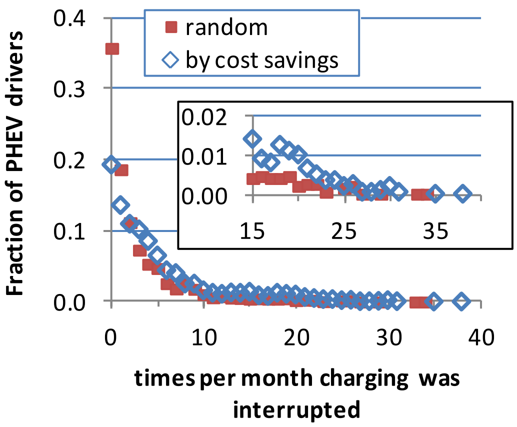

Figure 4. Fraction of PHEV drivers who experience interruption of charging, with interruptible electricity service (no charging permitted between noon and 10:00 pm) and charging only at home. The inset in the left plot shows the same data on an expanded vertical scale.

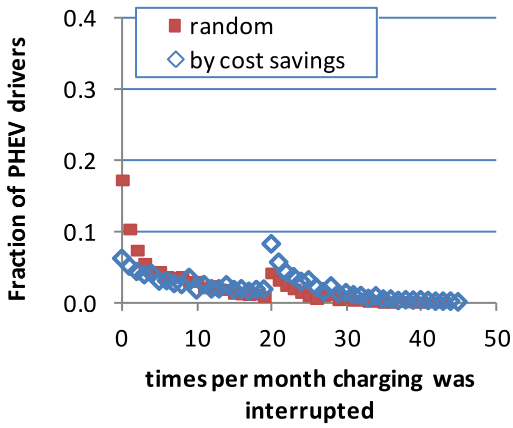

Figure 5. Fraction of PHEV drivers who experience interruption of charging, with interruptible electricity service with charging at work and home.

were charged at work and at home. In this case, more drivers experience interruption of charging more frequently. The peak near 20 times per month is due to PHEV drivers who charge at work and who regularly experience interruption. This is expected, since they are more likely to be plugged in during the peak hours.

In all cases, interruption of electricity decreases the fraction of miles driven electrically and increases operating costs per day for PHEVs, but only slightly on average, as seen in Table 3. Interruptible electricity between noon and 10:00 pm was accompanied by an increase in the operating cost of only a small fraction of drivers by much more than \$0.01 per mile. Figure 6 shows the distribution of this increase by the frequency of charging interruption for the case of PHEVs assigned according to cost savings (under no charging interruption), with PHEVs charged at home (solid diamonds) and both at home and at work (open diamonds). The errors bars show ± one standard deviation and show the wide range of change in operating cost per mile. The wide range is due to the variability in driving, from driver-to-driver and from month-to-month for each driver. Of the PHEV drivers who charged only at home, about 10% saw an increase of more than \$0.015/mi, and of those who could charge at both home and work, about 20% saw an increase of more than \$0.015/mi. When PHEVs were charged at work, charging was more frequently interrupted, however, operating costs were not increased much by this greater frequency. Charging times at work are shorter than charging times at home, so interruption of charging at work appears to have a smaller impact Very similar results for operating costs were seen for the same case with PHEVs assigned at random.

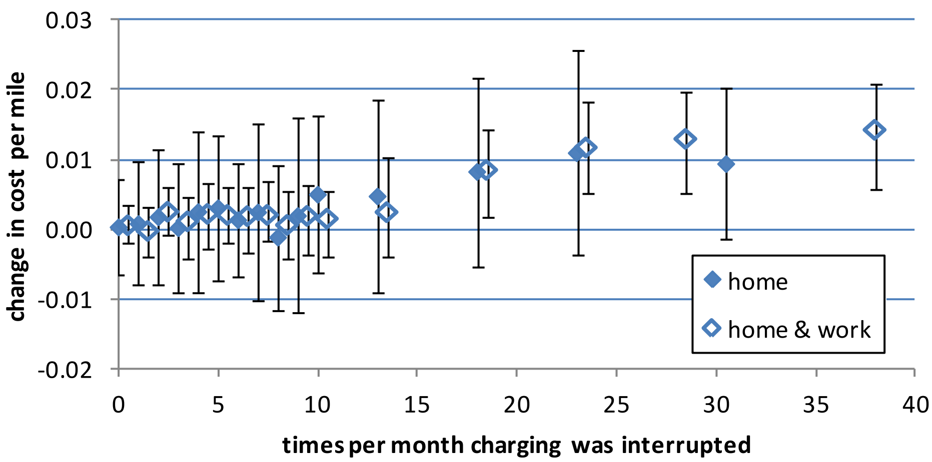

Figure 6. Increase in operating cost per mile for PHEVs as a function of the number of times per month that charging is interrupted by interruptible electricity service (no charging between noon and 10:00 pm), for PHEVs charged only at home (solid diamonds), and both at home and at work (open diamonds). Error bars show ± one standard deviation. Open diamonds are displaced 0.5 unit to the right for visibility.

More frequent interruption of charging and larger impacts on operating costs were seen for 14 hour electricity interruption. For this case, about 11 to 14% of PHEV drivers who charged only at home saw an operating cost increase of more than $0.015/mi with interruptible electricity service. For the case where PHEVs charged at work and at home, the cost impact depended somewhat on how PHEVs were assigned. With random assignment, 35% of PHEV drivers saw an increase of more than $0.015.mi, while with assignment by cost savings, 48% of PHEV drivers saw such an increase. Fourteen hours is longer than would be reasonable for interrupting electricity service in order to manage electricity demand, however even for this "worst case", the majority of PHEV drivers do not see a large increase in operating costs.

These estimates of the fraction of PHEV drivers impacted by interruptible service are probably upper bounds, since interruption was assumed to apply to all PHEV drivers every day. If demand management by were applied for fewer hour per day and not every day of the week, PHEV drivers would be impacted less. Other forms of demand management, such as dynamic pricing, might offer even more flexibility and allow consumers to choose the option that least impacts their operating cost.

4 Discussion and Conclusions

Implications of heterogeneity in driving patterns of U.S. drivers on the potential fuel use reduction and GHG emissions reduction from PHEVs were examined using a microsimulation of a population of drivers. In estimating energy use and GHG emissions, the distribution of driving distance must be taken into account. Estimates based on the assumption that PHEVs will be driven the same distance distribution as U.S. drivers may be biased, since the distribution of driving distance for PHEV drivers may differ from that of average drivers. This could be expected if consumers who drive more tend to have a greater preference for fuel-efficient vehicles, in which case consumers who purchase PHEVs may tend to be those who drive farther on average. To examine the potential effects of this difference in driving, a microsimulation was used with PHEVs assigned to drivers either randomly or to those drivers whose operating cost savings from a PHEV were at least as large as the incremental monthly payment of the PHEV over that of a comparable conventional vehicle. In the simulations, PHEVs assigned according to cost savings were driven about 40% farther per month on average, and the estimated reductions in fuel use and GHG emissions reduction were much larger than for the population of PHEVs assigned randomly. This is due not only to the fact that PHEVs driven farther can save more fuel and emissions, but these PHEVs substitute for CVs that are driven farther than average, and the remaining CVs are driven less than average. The effect on estimated fuel and emissions reductions may be as large as 50%.

The microsimulation model was also used to simulate the effects of interruptible electricity service on the operating costs of PHEVs. Results imply that demand management by electric utilities may significantly impact operating costs of only a small fraction of PHEV drivers. In the simulations with 10 hours of interruption, no more than 20% of PHEV drivers saw an increase of more than $0.015/mi in their operating cost. Interruptible service was applied to all PHEV drivers every day in these simulations. In reality, more flexible electricity demand management schemes would be implemented, such as interruption or critical peak pricing only during critical peaks (not every day) or dynamic pricing (consumer could still charge during peak periods, but pay a higher electricity rate). Consumers with PHEVs could determine which option impacts their operating costs least. These options would allow demand management with even lower cost impacts to PHEV drivers. So the fraction of PHEV drivers significantly impacted by electricity demand management would probably be less than the 20% estimated from the simulations. Even if this fraction of PHEV drivers were to opt out of demand management, if the remainder were under a demand management scheme, this would offer management of the vast majority of the electricity demand for PHEVs.

The microsimulations allow us to examine distributions of effects and to bound possible reductions in fuel use and GHG emissions by taking into account heterogeneity in driving patterns in the U.S. population, which increases the robustness of such estimates. The microsimulation demonstrated in this study is expected to provide further insights in the deployment of PHEV's in the vehicle fleet as travel survey data for these vehicles becomes available in the near future.

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