ANL/ES/CP- 102928

Quantifying the Fuel Use and Greenhouse Gas Reduction Potential of Electric and Hybrid Electric Vehicles

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Abstract

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) have been promoted to help solve transportation's oil use and environmental problems. Quantifying the fuel use and greenhouse gas (GHG) emission reduction potential of EVs and HEVs is important in order to be able to evaluate these technologies relative to other technologies. While models exist that estimate the per vehicle potential of EVs and HEVs to reduce fuel use and GHG emissions, there is little on-the-road data to substantiate their findings. However, actual EV and HEV efficiencies were obtained from the 2000 American Tour de Sol (ATdS). The ATdS is a road rally for EVs and HEVs that is conducted annually. In it, a wide variety of EVs and HEVs travel several hundred miles under various driving conditions.

DISCLAIMER

The ATdS offers a unique opportunity to collect on-the-road energy efficiency data for EVs and HEVs as well as comparable gasoline vehicles driven under the same conditions. Using these data, electricity generation mix data, and a transportation fuel-cycle model (called GREET, Greenhouse gases, Regulated Emissions, and Energy use in Transportation), the full fuel-cycle energy use and GHG emissions of selected EVs, HEVs, and baseline gasoline vehicles were estimated. The oil use and GHG emission reduction potential of the individual EVs and HEVs competing in the ATdS were estimated and found to be substantial. These per-vehicle oil and carbon reductions were used to justify assumptions about EV and HEV efficiencies which were then combined with assumptions of market penetrations to estimate the possible future reductions in oil use and carbon emissions for the U.S.

Background

The U.S. transportation sector is almost entirely (95%) dependent on oil and it accounts for over two-thirds of the nation's oil use. Over the last twenty years, the sector's oil dependence declined from 97% to 95% as blends (mostly MTBE) were added to gasoline. While the use of MTBE in gasoline will be banned completely in the next few years, the use of alternative fuels could grow over the next twenty years (according to the reference case projections by the Energy Information Administration [EIA]) and the transportation sector's oil dependence could drop to 94% (1), still a significant level of oil dependence.

The oil security of the U.S. is uncertain today with about half of our oil use being supplied by imports (2). By 2020, EIA projects that the U.S. will rely on imports for nearly 70% of its needs (3). There is an additional concern about relying on a product which has its price and availability controlled by a cartel, the Organization of Petroleum Exporting Countries (OPEC). Because the cartel maintains the price of oil higher than a free market would dictate, the U.S. experiences a substantial drain of its wealth with the payments it makes each year for imported oil. Between 1970 and 1999, this "monopoly" or "cartel" payment has amounted to about $7 trillion, in present value 1998 dollars (4). To put this into perspective, the U.S. national GDP was about $7 trillion in 1995 (5).

Carbon (the most significant greenhouse gas) emissions from the U.S. transportation sector change from year to year pretty much in proportion to oil use. The light vehicle (cars and light trucks) carbon emissions grew about 30% from 1980 to 2000, to about 296 million metric tons per year (6). EIA projects carbon emissions from light vehicles will grow about 40% over the next twenty years (7). In comparison, the projected growths in carbon over the next 20 years are 33%, 29%, and 23% for residential, commercial, and industrial sectors, respectively (8).

Figure 1 shows the past and projected oil use by all of transportation and for light vehicles. Figure 2 shows the past and projected carbon emissions from all of transportation and from light vehicles.

Figure 1
Transportation Energy Use

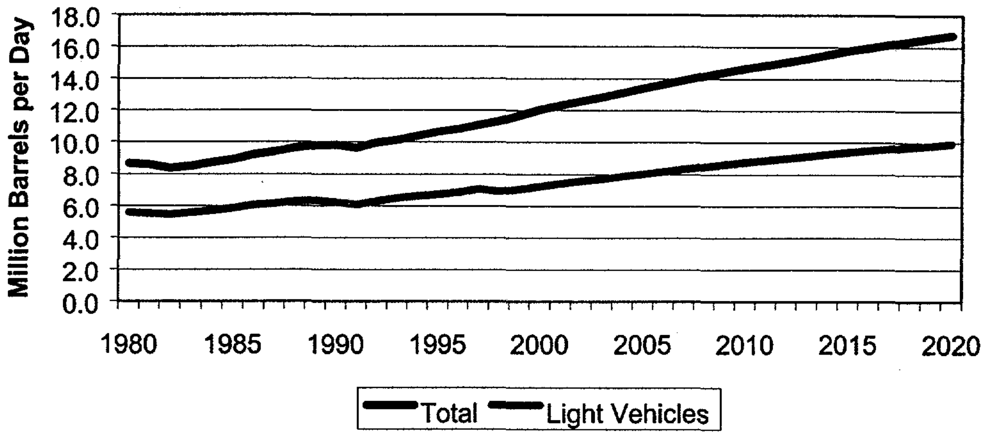
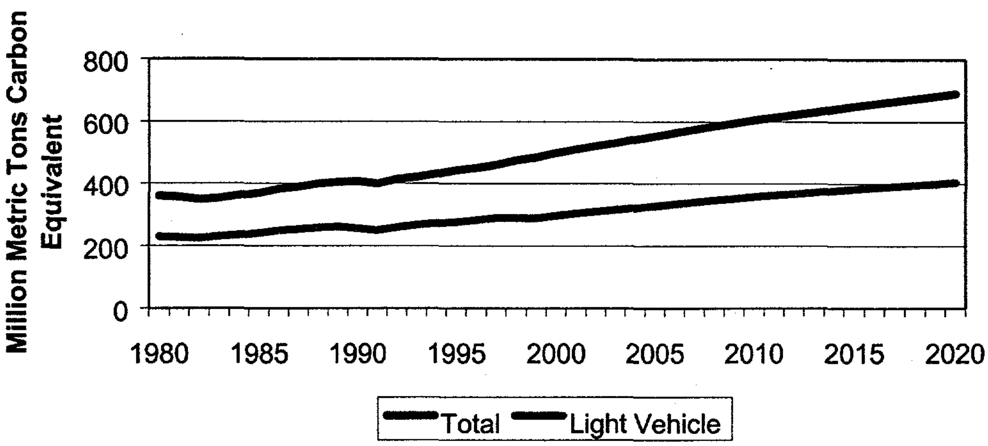


Figure 2
Transportation Carbon Emissions



Since oil use and carbon emissions are projected to grow to what may be unacceptable levels under a business-as-usual scenario, it is important to look for light vehicle technologies that can reduce the nation's demand for oil and generation of carbon emissions. Two potential technologies that can help accomplish this are electric vehicles (EVs) and hybrid electric vehicles (HEVs). EVs have no direct oil use or carbon emissions. However, oil is used to generate about three percent of the electricity in the U.S. and carbon is emitted by all the fossil fuels used in electric power generation. Similarly, some types of HEVs may be recharged with electricity generated from power plants and all HEVs under development for the U.S. market will use some gasoline or diesel fuel. Therefore, it is necessary to take a fuel cycle analysis approach to estimate the total oil and carbon impacts of replacing conventional vehicles with EVs and/or HEVs.

GREET 1.5a

The GREET model (9) provides a means to conduct such a fuel cycle analysis. In 1995, with funding from the Office of Transportation Technologies of the U.S. Department of Energy, the Center for Transportation Research at the Argonne National Laboratory (ANL) began to develop the GREET (*G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation) model. The model has been expanded and evolved considerably over the last four years. The GREET model is in the public domain. The current version of the model – GREET 1.5a - and its documentation are available at the ANL website (http://www.transportation.anl.gov/ttrdc/greet/). GREET has been used by various organizations (both in the U.S. and elsewhere) to evaluate the energy, air pollutant emissions, and greenhouse gas implications of alternative vehicle and fuel technologies. GREET users include government agencies, auto companies, energy companies, public interest groups, and research institutes.

The GREET model employed in this paper is a fuel-cycle model. The *fuel cycle* for a given transportation fuel includes the following processes: energy feedstock (or primary energy) production; feedstock transportation and storage (T&S); fuel production; fuel transportation, storage, and distribution (T&S&D); and vehicle operations that involve fuel combustion or other chemical conversions (Figure 3). The processes that precede vehicle operations are often referred to as upstream activities; vehicle operations are referred to as downstream activities.

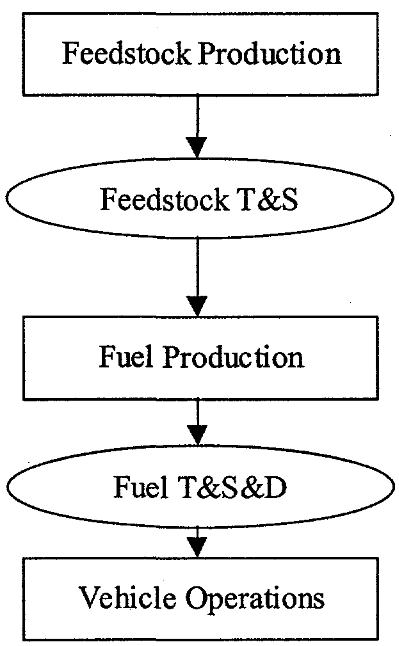


Figure 3
Stages of a Fuel Cycle

GREET calculates Btu-per-mile (Btu/mi) energy use and grams-per-mile (g/mi) emissions by taking into account energy use and emissions of fuel combustion and non-combustion sources such as fuel leaks and evaporation. The model calculates total energy use (all energy sources), fossil energy use (petroleum, natural gas, and coal), and petroleum use. It includes emissions of three major GHGs (CO_2, CH_4, and N_2O) and five criteria pollutants (VOCs, CO, NO_x, PM_{10}, and sulfur oxide [SO_x]). Table 1 lists output items from the GREET model.

The three GHGs (CO_2, CH_4, and N_2O) represent the largest percentage of total GHG emissions, and are the ones most likely to be affected by the use of alternative transportation fuels. In this study, we combine emissions of the three GHGs with their GWPs in order to calculate CO_2-equivalent GHG emissions. GREET1.5a adopts IPCC-recommended GWPs for the 100-year time horizon, which are 1, 21, and 310 for CO2, CH4, and N2O, respectively.

Table 1
Output Items from the GREET Model

Category	Output Item	Remarks
Energy (Btu/mi)	All energy sources Fossil energy (petroleum, NG, and coal) Petroleum	
Greenhouse gases (g/mi)	CO_2 CH_4 N_2O VOC (optional) CO (optional) NO_x (optional)	GHGs are converted into CO_2-equivalent emissions with their global warming potentials (GWPs).
Criteria pollutants (g/mi)	VOC CO NO_x PM_{10} SO_x	These emissions are separated into total and urban emissions.

Vehicle Technologies in GREET

The GREET model deals with two time periods: near-term (applied to model year 2000 vehicles) and long-term (applied to model year 2010 vehicles). There are three light vehicle classes: cars, LTD1 (light duty truck with gross vehicle weight up to 6,000 pounds), and LDT2 (LTD1 (light duty truck) with gross vehicle weight from 6,000 to 8,500 pounds). There is one type of EV and three types of HEVs in the near term database. The number of HEV types grows to 20 for 2010 (varying by fuel type, engine type, and grid-connection), while a single EV type remains.

HEVs are grid-connected if they are intended to be plugged into the grid to obtain much of their needed energy. These are often called charge-depleting or EV-range HEVs. All of the HEVs currently available in and planned for the U.S. market are non-grid. They are called charge-sustaining, and include HEVs that are called mild HEVs.

The GREET model is very flexible in that most assumptions with respect to vehicle and fuel characteristics can be easily changed. But the model does have default values that represent judgment based on literature reviews. For example, the efficiencies of an EV or a non-grid HEV compared to a conventional vehicle are 3X and 2X, respectfully, in the near-term and 4X for EVs and 1.7X to 2.3X (depending on fuel and engine type) in the long-term. If actual measured EV and HEV fuel economies are available, as is the case for this paper, a user can readily input actual data into GREET to generate fuel-cycle results.

Electric Power Generation

The fuel or energy source used to produce electricity, the so-called electric generation mix, is very important in determining the oil and carbon impacts of EV and HEV use. GREET incorporates the various ways to produce electricity. In particular, it calculates the energy use and emissions associated with electricity generation from oil, natural gas, coal, nuclear, and renewable power plants. The actual generation mix of a given utility company's service area can be input to GREET to simulate energy and emission impacts of the utility company's electricity generation. The default electricity generation mix in GREET is the U.S. generation mix.

The oil used by and the carbon emissions from the generation of electricity using the U.S. electric generation mix are well-known for today's power generation. The fuel-cycle grams of CO2 per KWh for the five major fuels are shown in Table 2. The first row shows the CO2 per KWh when 100% of the electricity is produced using each fuel separately. The 1999 share shows the contribution that each fuel made that year to the national average and the weighted total of 709.9 grams per KWh. The EIA base case projection for the year 2020 shows a big decline in the nuclear share, and this results in a higher CO2 emission value (757.3 grams per KWh).

If the DOE programs to shift to lower GHG electricity are successful, the carbon per KWh could be reduced substantially. The Clean Energy Futures (CEF) (10) advanced scenario for electric power generation has a fuel mix as shown in the next row. This mix results in 520.8 grams of CO2 per KWh, a 31% reduction compared to the EIA 2020 base case value.

The near-term and long-term values for CO2 emissions per KWh employed by the GREET model are also shown for comparison purposes. Note that the GREET near-term value is very close to the 1999 actual value and that the GREET long-term value is a lot closer to the EIA 2020 value than to the CEF value. This paper uses the near-term numbers.

Electric utilities in many states have gone through deregulation in the past six or seven years. As a result, a new phenomenon is the so-called distributed generation, by which companies, or even households, can purchase or lease small-size electric generation units to produce electricity for their own consumption. Although distributed generation does not appear to have a large share of total electric generation now, it could have an increased share in the future, if economics begins to favor such practice.

Distributed generation units are likely to use natural gas, oil, solar panels, and other renewable sources to generate electricity. If natural gas or oil is used, distributed generation will certainly have energy and emissions impacts. Because distributed generation units are usually smaller than centralized electric power plants, they could generate more emissions per KWh of electricity than centralized plants do. If EVs are to be recharged with distributed generation electricity, their energy and emissions impacts will certainly be different from what we present here.

The GREET model does not have an option to simulate distributed generation. However, if one has sufficient data on efficiency and emissions of distributed generation units, one can input this data into the GREET model, and then simulate EV energy and emissions impacts with distributed generation.

Table 2
CO_2 Emissions from Electric Power Plants

(Grams per KWh)

	Fuel-Specific Power Plants:					
	Oil	**NG**	**Coal**	**Nuclear**	**Renew**	**Total**
	991.9	627.7	1078.7	104.9	0	
1999 U.S. Electric Generation Mix						
Share	0.027	0.092	0.558	0.224	0.099	1
CO_2	26.8	57.7	601.9	23.5	0.0	709.9
EIA 2020 Electric Generation Mix						
Share	0.009	0.219	0.556	0.106	0.110	1
CO2	8.9	137.5	599.8	11.1	0.0	757.3
CEF 2020 Electric Generation Mix						
Share	0.003	0.223	0.331	0.198	0.245	1
CO2	3.0	140.0	357.0	20.8	0.0	520.8
GREET-Near Term Emissions						
Share	0.010	0.149	0.538	0.180	0.123	1
CO2	9.9	93.5	580.3	18.9	0.0	702.7
GREET-Long Term Emissions						
Share	0.008	0.211	0.540	0.124	0.117	1
CO2	7.9	132.4	582.5	13.0	0.0	735.9

Sources: EIA's Monthly Energy Review and Annual Energy Outlook, Clean Energy Future draft, and GREET documentation.

The American Tour de Sol (ATdS)

This over-the-road alternative vehicle competition has been conducted in the Northeast states annually since 1988. It is organized and run by the Northeast Sustainable Energy Association (NESEA) with sponsorship by DOE, auto companies, power companies, and others. Over the years, the number of entries and their quality has grown impressively. For example, the longest range achieved by an EV grew from 78 miles in 1991, to 180 miles in 1993, to 235 miles in 1995, and to 373 miles in 1996. This was accomplished with better vehicles, more efficient motors and a new type of battery (a shift from lead-acid to nickel-metal hydride [NiMH]).

The ATdS route in 2000 started in New York (on May 14) and concluded four days and 287 miles later in Washington, DC. The event included EVs from companies such as Daimler/Chrysler, Solectria, Blue Bird, and Nissan and from schools such as Lawrence Tech, Boston University, the New Hampshire Technical Institute, the University of Maine, and about a dozen high schools. The HEVs in the 2000 ATdS were provided by Honda, Lawrence Tech, Team New Jersey, Swarthmore, and the University of Tulsa.

Most of the HEVs in the ATdS are grid-HEVs. This is because many of the HEVs built by schools and small companies are designed to travel part of their miles as zero emission vehicles (ZEVs). They tend to have ZEV ranges of 20 to 50 miles. HEVs with higher ZEV ranges will earn higher ZEV credits toward meeting the 10% ZEV mandate in California and several other states. In the 2000 ATdS, the HEVs used a variety of alternative fuels: propane, compressed natural gas, methanol, and biodiesel.

Energy Use

Data on vehicle energy use, range, reliability, and acceleration are collected during the tour. The data of greatest interest for estimating fuel use and greenhouse gases is the energy use data. Also of interest is the comparative data: how EVs and HEVs compare with the conventional vehicles they might replace. Thus, the tour also collected data on several control vehicles (CVs). Measuring the energy used to travel a rally leg was measured differently for EVs, HEVs, and CVs. The method of data collection for each are described below.

EV Energy Data. All EVs recharged every night by hooking up to the NESEA charging trailer after completion of a rally leg. The charging trailer took power either from a utility line drop or a large diesel generator and divided it into a number of output plugs through circuit breaker panels. Each vehicle was assigned an output plug based on their charger voltage and current requirements. The charging trailer preceded the rally vehicles along the route and was set up and ready to provide charging when the vehicles arrived each day. Each vehicle remained hooked up to the charging trailer all night to ensure full "state-of-charge".

NESEA required every team to purchase a General Electric model kV electronic AC kilowatt hour (kWh) meter to be installed in their charging circuit between the charging trailer and their battery charger. These meters read to 1 watt hour (0.001 kWh), are quoted as having ±0.2% accuracy at standard test points, record power factor and other parameters as well as energy, and have an optical link for downloading data to a laptop computer. The kV meters assure precision and comparability of energy data as well as eliminating meter reading and data transcription errors. The meters were read before the beginning of charging the first night to obtain a baseline reading, then recharge data were downloaded every morning immediately before the vehicles were disconnected from the charging trailer. These recharge data were paired with distances from the previous day's rally leg to compute energy efficiency (kWh/mile).

Gasoline Control Vehicle Energy Data. Collecting energy use data from the gasoline-powered conventional vehicles that were used as control vehicles was a fairly straightforward process. Each control vehicle was assigned to follow the same route as an EV counterpart. Control vehicle drivers filled out the same daily data collection cards as the other vehicles, though they included slightly different data. Control vehicle drivers recorded odometer readings at the start and end of every leg driven, as well as recording extra distances driven to refuel. Drivers refueled every day and recorded refueling amounts on the data collection card. Tour scoring staff were able to use the data on these cards to determine energy efficiency (mpg) for the ATdS leg distances driven.

The accuracy of this data collection process assumes that the different gas pumps used are equally well calibrated and that they stop fuel delivery at the same point in the refueling process (where the handle first "clicks off"). The first assumption is good because gas pumps are measured and certified by state agencies. The second assumption is not as good. However, it seems safe to assume that differences in refueling due to "click off" thresholds are in the several fluid ounce area, certainly less than 0.1 gallon.

HEV Energy Data. The energy used by the HEVs was collected in the same manner as both the EVs and the CVs. For grid-connected HEVs, both electricity and gasoline data were collected. For non-grid HEVs, only gasoline use was measured.

Vehicle Comparisons

While data was collected for all vehicles participating in the ATdS, this paper deals only with the data for the three EVs and one HEV for which there is comparable CV data. Three gasoline control conventional vehicles (a GM Saturn, a Suzuki Swift, and a Dodge Caravan) were matched with the following three EVs and one HEV.

* **EV1**: a GM purpose-built electric two-passenger car operated by Dempsy World Record Associates. This vehicle had GM Ovonic NiMH batteries.
* Solectria NiCad **Force**: a Solectria Force operated by the Connecticut Partnership and using NiCad batteries.
* **EPIC** Minivans, #51 and #52: Chrysler electric minivans operated by Daimler/Chrysler and using Saft NiMH batteries.
* Honda **Insight** HEVs, the average of five vehicles: Two-passenger HEVs operated by persons who purchased the vehicles. The vehicles use NiMH batteries.

EV1 and Insight were matched with the Saturn, Force was matched with the Suzuki, and EPIC was matched with the Caravan.

Results

The three EVs, the HEV, and the three control vehicles were driven on four days. Each day's route covered a different number of miles and terrain. The following analysis is based on the total four days combined. Converting the gallons of gasoline and the kilowatts of electricity to BTUs (British Thermal Units) and using the GREET model for estimating the total fuel cycle ramifications, yielded the results in Table 3. Estimates of gasoline mpg equivalents are made using the conversions factors of 114,000 BTUs per gallon of reformulated gasoline and 3412 BTUs per kilowatt-hour.

Table 3
Fuel Economy of EVs, HEVs and Control Vehicles
Participating in
American Tour de Sol 2000

	EVs			HEVs	Control Vehicles		
	GM EV1	Solectria Force	EPIC Minivan	Honda Insight	GM Saturn	Suzuki Swift	Dodge Caravan
Mileage on Tour (miles)	224	131	269	420	324	254	230
KWh/ Mile	.195	.250	.398	-	-	-	-
Gasoline MPGe	171.3	133.6	84.0	74.1	32.6	40.0	18.5

Table 4
Fuel-Cycle Energy Use and GHG Emissions
of EVs, HEVs and Control Vehicles
Participating in
American Tour de Sol 2000

		Solectria Force			**EPIC Minivan**			**Suzuki Swift**	**Caravan**
		US Mix	**CA Mix**	**NE US Mix**	**US Mix**	**CA Mix**	**NE US Mix**		
Total Energy	(BTU/Mi)	2,812	2,701	2,795	4,486	4,308	4,459	3,639	7,854
Fossil fuels	(BTU/Mi)	1,962	1,006	1,731	3,130	1,605	2,761	3,601	7,772
Petroleum	(BTU/Mi)	50	13	88	80	21	141	2,825	6,098
CO2	(G/Mi)	177	72	140	283	115	224	271	585
GHGs	(G/Mi)	183	76	146	292	121	233	290	618

	EV1			**Insight**	**GM Saturn**
	US Mix	**CA Mix**	**NE US Mix**		
Total Energy	2,204	2,116	2,190	1,963	4,462
Fossil fuels	1,537	789	1,356	1,942	4,415
Petroleum	40	11	69	1,524	3,464
CO2	139	56	110	146	332
GHGs	144	59	114	161	353

Table 5
Petroleum and GHG Benefits EVs and HEVs
Participating in American Tour de Sol 2000
Relative to the Control Vehicles

	EV1 vs. Saturn	Insight vs. Saturn	Force vs. Swift	EPIC vs. Caravan
MPGe	+ 425%	+127%	+234%	+354%
Total Petroleum	-98.8%	-56.0%	-98.2%	-98.7%
Total CO2	-58.1%	-56.0%	-34.7%	-51.6%
Total GHG	-59.2%	-54.4%	-36.9%	-52.8%

As seen in Table 3, EV1 and Force had weighted average energy efficiencies of 0.195 and 0.250 kWh/mile, respectively. This is quite a bit better than the GREET default value of 0.34 kWh/mile. EPIC had a weighted average energy efficiency 0.398 KWh/mile which is much better than the GREET default value of 1.00 KWh/mile for light trucks.

One does not often think of the fuel economy of EVs in terms of miles per gallon, but this is the way it needs to be estimated for giving EVs credits in the calculation of manufacturer's Corporate Average Fuel Economy (CAFÉ) values. Formulas are used to give CAFÉ credits to several different alternative fuels. EVs earn credits by being assigned a value between 200 and 300 miles per gallon.

EV1 averaged 0.195 KWh/mile over the 224 miles it traveled in the ATdS. This equates to 171 miles per gallon equivalent. Force got slightly lower miles per gallon, 134 for the four days.

The GREET model assumes that EVs are more efficient than conventional gasoline vehicles. For the near term, the model has EVs (both cars and light trucks) being three times as efficient as conventional vehicles at the plug (that is, they are 3X vehicles). The ATdS car EVs were quite a bit better than this, obtaining 5.2X for EV1 and 3.4X for Force over the four days. The light truck EV in ATdS was a lot more efficient obtaining a fuel economy of 4.5X.

Since there are strong incentives in the ATdS for EVs to be very efficient, the vehicles are designed and driven to achieve high efficiency. It is not known how much the results presented here are influenced by this. Furthermore, the EVs are operated without air conditioning (most do not have it to begin with), but all vehicles must have a passenger in addition to the driver. These conditions tend to offset one another. In sum, the EVs in the ATdS might achieve somewhat higher fuel efficiency than they would in normal driving.

As shown in Table 4, the California mix results in about 49% less fossil fuel use, a little less oil use, and 60% less carbon emissions than the U.S. mix. The New England mix results in about 12% less fossil fuel use, a little more oil use, and 21% less carbon emissions. The fact that the total energy required is different for the three mixes implies that they have different efficiencies. The California mix is about 4% more efficient than the national average, and the New England mix is about 1% more efficient.

As seen in Table 5, EV1 reduced its oil use by 98.8% compared to the control vehicle and it generated 58.1% less carbon. Insight did not reduce oil as much, since it reduced oil entirely via efficiency improvements and had no substitution of fuel. Its oil reduction was 56% and its carbon emission reduction was 56% (almost equal to that for the EV1). Force and EPIC performed almost the same as EV1 in reducing oil use. But Force did not perform quite as well with respect to carbon emission reductions, even though it did reduce them 34.7% relative to its control vehicle. EPIC had a carbon emission reduction of 51.6%, very close to that for EV1.

Possible Oil and Carbon Benefits of EVs and HEVs

The market potential for EVs and HEVs is anything but clear. There have been projections of EVs over the last 25 years that have ranged from practically zero (11) to close to 6 percent of the car market by the year 2000 (12). Regulations exist that mandate about 4 percent EV sales in California (and possibly several other states) within the next several years. Whether these mandates will actually be carried out is unknown. But for purposes of illustration, it will be assumed that EV technology improves to the point that 5 percent of the 2020 light vehicle fleet is comprised of EVs.

There are fewer projections of HEV market potential since viable HEVs are a fairly recent consideration. The Clean Energy Future study estimated a market potential for HEVs of about 15 percent in 2020. Two manufacturers are now selling HEVs in the U.S. and practically all vehicle makers have said that they will be selling HEVs within the next few years. The potential for HEVs in the U.S. is probably even greater than past projections have estimated. For illustrative purposes, this paper assumes an HEV stock in 2020 of 25%.

A survey performed for DOE in 1999 found that 29% of the respondents would choose a non-grid HEV if it had a 10% incremental cost and got 50% better fuel economy. The same survey found that 12% would choose a grid HEV that also got a 50% gain in fuel economy and had a 40-mile ZEV range, but had an incremental cost of 15% (13). If this sales ratio was realized in the future, about 4 grid HEVs would be bought for every 10 non-grid HEVs, or 29% of all HEV sales.

The question is, what average efficiency for light vehicle EVs and HEVs should be used to calculate the benefits? The ATdS results show higher EV efficiency for cars than the GREET default value (3.4 to 5.2 times the conventional vs. the GREET value of 3 times), and light truck EVs are even more efficient than the GREET truck EV default vales. The efficiency results from the ATdS for the HEV are 4.5 times that of the control vehicle. For the illustrative purposes of this paper, it is assumed that in 2020 EVs are 4X the efficiency of the conventional vehicle and grid and non-grid HEVs are 2X the efficiency.

It is appropriate to use the U.S. average fuel mix for estimating future impacts because electricity de-regulation will probably bring about a situation where a plug anywhere in the U.S. will have a chance of being powered by the average mix. Therefore, EIA's 2020 electricity mix is used for the calculations that follow. Their projection of a decline in the renewable share is not consistent with what DOE is attempting to change with new initiatives for wind, solar, and biomass generation of electricity. Therefore, one could argue that with a higher renewable contribution to electric generation the carbon reduction benefits would be even greater.

The sales assumptions and oil and carbon reduction benefits of substantial market penetration of EVs and HEVs are presented in Table 6.

Table 6
Sales and Benefits of EVs and HEVs

	2005	2010	2015	2020
Hybrid Vehicles				
Percent of Stock	0.9%	7.0%	16.9%	25.0%
Oil Reduction (mbpd)	0.0	0.4	1.0	1.4
Carbon Reduction(mmtc)	0.0	14.0	38.3	58.7
Electric Vehicles				
Percent of Stock	0.1%	1.1%	2.8%	5.0%
Oil Reduction (mbpd)	0.01	0.12	0.31	0.55
Electricity Use (mbpde)	0.01	0.03	0.08	0.16

The American Tour de Sol did not measure the criteria pollutants of the participating vehicles. However, EVs are generally expected to reduce these pollutants, potentially significantly (14). Sulfur oxide and total particulates may increase on a total fuel cycle basis depending on the fuel mix used to generate electricity.

Conclusions

EVs and HEVs (both grid and non-grid) have great potential to reduce oil use and carbon emissions on a vehicle per mile basis. This is especially so for travel that is similar to the city driving cycle or any other driving cycle that has a lot of stop and go driving. The actual driving of the most recent ATdS was a combination of rural and urban driving that one might experience in many part of the U.S. Vehicle efficiencies for EVs, HEVs, and control vehicles from the ATdS were used in conjunction with the GREET total fuel cycle model to obtain "well to wheels" oil use and carbon emission reductions for these advanced vehicle technologies. Compared to conventional gasoline vehicles, EVs in the ATdS are estimated to be able to reduce full cycle oil use over 98% and reduce carbon emissions from 37% to 58%. The ATdS non-grid HEVs'potential reductions are 56% for oil and 56% for carbon emissions.

The overall impact that EVs and HEVs can make on lowering future U.S. oil use and carbon emissions will depend on the market penetration of these advanced vehicles. Using some market penetration assumptions, the oil and carbon emission reductions for light vehicles could be in the range of 17% to 14%, respectively. This would imply that EVs and HEVs have an important role to play, in concert with other programs, in addressing two important national concerns.

Acknowledgements

The authors would like to thank the many volunteers and participants who make the annual American Tour de Sol the challenging event that it is. Our thanks also go to John Maples who ran the vehicle stock model that estimated the EV and HEV market impacts.

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