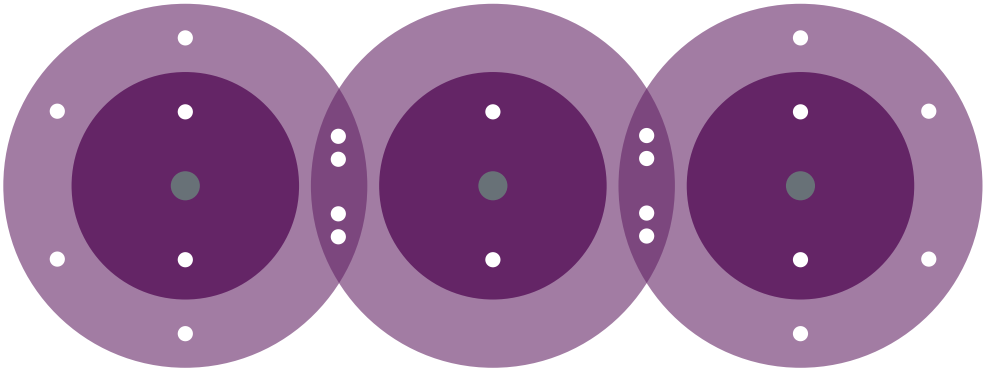
VEHICLE ELECTRIFICATION POLICY STUDY

TASK 5 REPORT

AUGUST 2012

Calculating Electric Drive Vehicle Greenhouse Gas Emissions

BY ED PIKE



icct
THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

The author appreciates the helpful review comments provided by:
Kate Blumberg, ICCT
Joshua Cunningham, Plug-in Electric Vehicle Collaborative
David Ganss, U.S. EPA
Pierre Gaudillat
John German, ICCT
Zoltan Jung, U.S. EPA
Li Lili, State Grid Energy Research Institute
Alan Lloyd, ICCT
Peter Mock, ICCT
Ed Nam, U.S. EPA
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Luke Tonachel, NRDC
Nic Lutsey
Michael Wang, Argonne National Laboratory

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1225 I Street NW, Suite 900, Washington DC 20005

EXECUTIVE SUMMARY

The object of this paper is to present a methodology for calculating the greenhouse gas (GHG) emissions attributable to the production of electricity and hydrogen used to power electric drive (edrive) vehicles such as battery electric (BEV), plug-in hybrid electric (PHEV), and fuel cell electric (FCEV) vehicles. Calculating these emissions is important for understanding the potential role of edrive vehicles in meeting GHG reduction goals, implementing passenger vehicle GHG standards, and providing consumer information about energy efficiency and emissions. This paper identifies methods to determine edrive vehicle efficiency, energy supply "well-to-tank" GHG intensity, edrive vehicle miles traveled, and mode split for plug-in hybrids, all of which can serve as a basis for calculating edrive upstream emissions. In addition, several areas of potential future refinement are identified.

First, test cycles used to determine edrive vehicle efficiency should reflect urbanization trends, aggressive driving, and cabin climate control. Relative to internal combustion engines (ICEs), batteries and fuel cells suffer less efficiency drop-off at low loads, such as when a vehicle is driven in congested traffic. On a similar note, cold and hot weather, which are covered only in certain test cycles, are expected to have differing effects, such as increased edrive electricity usage for cabin heating and cold-weather efficiency losses for ICE vehicles and potentially also BEVs. A representative test cycle is also important to determine the "blend" of ICE and stored grid electric energy supplied to the wheels of certain PHEVs. Thus, edrive vehicles should be evaluated on the basis of test conditions such as those used in the U.S. Environmental Protection Agency's five-cycle testing (with practical modifications as needed to address edrive vehicles). In addition, continuing evaluation of edrive vehicle energy consumption relative to ICE vehicles under these conditions should be performed.

Next, energy supply GHG intensity should be determined on a "well-to-tank" basis. The GHG intensity of energy production for transportation electricity should be determined on an average basis, including transmission and distribution losses, as an initial default. A more complex analysis of marginal electricity-generating resources and vehicle charging times can be considered on a country-by-country basis (or, in the case of the European Union, on a regional basis) as experience yields further data about charging behavior. Calculations based on marginal versus average electricity GHG intensity may yield substantially different final results. This point illustrates the importance of using real-world data to periodically update calculation methodology, although ICCT also recognizes the need for appropriate lead time in cases where these revisions are applied to passenger vehicle standard compliance calculations.

In the case of hydrogen-fueled (FCEV) transportation, calculating "well-to-tank" GHG emissions based on specific production pathways may be feasible immediately because the number of producers and end users is quite limited. In addition, California has a legislative requirement mandating a mix of low-GHG renewable hydrogen, and Germany has similar goals. "Well-to-tank" GHG emissions from gasoline production and refining should also be calculated and determined as an offset against edrive emissions.

Finally, another important element in determining total emissions is vehicle miles traveled (VMT) or kilometers traveled (VKT). The travel range of BEVs in daily use will have an effect on the total amount of ICE emissions that they displace, and hence on their net emissions impact. The electric-only travel range of PHEVs will affect the fraction of each trip that is powered by electricity rather than gasoline, which can be determined on the basis

of ”utility curves” for charge depletion range versus percent electric operation. Daily travel range should be used to determine annual electricity VMT/VKT, initially based on existing data sets such as National Household Travel Survey data for the United States, with further validation of this methodology and potential adjustment factors as additional real-world data are collected. Annual emission rates and emission reductions will fit well with emissions inventories and policy evaluations, and should be considered on a country-by-country (or regional) basis as a potential weighting factor when edrive vehicles are included in passenger vehicle standard GHG/CO_2 compliance calculations.

In conclusion, procedures to account for edrive vehicle–related GHG emissions can now be established with reasonable accuracy, based on real-world vehicle efficiency, energy supply carbon intensity, and vehicle usage data. As more data are gathered from increased EV operating experience, the methodology can be updated as needed over time. These GHG emission calculations will provide the best information to policymakers and give appropriate signals to guide automakers’ and consumers’ efforts to reduce GHG emissions.

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I. INTRODUCTION

The objective of this paper is to present an accurate and practical method to calculate greenhouse gas (GHG) emissions associated with electric drive (edrive) vehicles, including battery electric, plug-in hybrid, and fuel cell electric vehicles. This information will benefit policymakers, automakers, and consumers. A secondary purpose is to highlight areas where further data and research would be most beneficial for potential refinements.

The importance of accurately calculating these emissions is growing for several reasons:

- Edrive vehicle deployments, and hence the magnitude of their environmental effects, are expected to grow over time. Global edrive vehicle sales in major markets totaled approximately 42,000 vehicles in 2011 (ICCT, 2012a). With each of the largest automakers globally offering one or more models this year, edrive vehicles will represent an increasing percentage of the automobile fleet (OICA, 2010; Plug-in America, 2012). As shown in Figure 1, the projected GHG emissions of a Nissan Leaf battery electric vehicle (BEV) in all regions of the world in 2015 would be less than the GHG emissions of an internal combustion engine (ICE) compact car meeting the U.S. regulatory target for 2015. However, the Leaf's advantage relative to the best gasoline-fueled vehicle (i.e., the non–plug-in Toyota Prius), or relative to a compact car meeting E.U. emission standards for 2015, would vary according to the upstream emissions of the BEV and future improvements to ICE and edrive vehicles.
- Governments are investing substantial resources into research and development, battery manufacturing, consumer rebates, and regulatory incentives for the increased manufacturing and sales of advanced edrive vehicles (Shulock, 2011). These policies are driven by national goals for lower GHG emissions and petroleum consumption, increased industrial development, and in many cases improved air quality. These efforts highlight the need for an accurate GHG accounting method (which can be adapted for petroleum reduction and air quality as well).[1]

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[1] ICCT notes that addressing the public health impact of criteria air pollutants would also require assessment of the spatial impact of criteria air pollutants and chemical interactions of precursors to ozone and fine particulates. See for instance EPRI 2007.

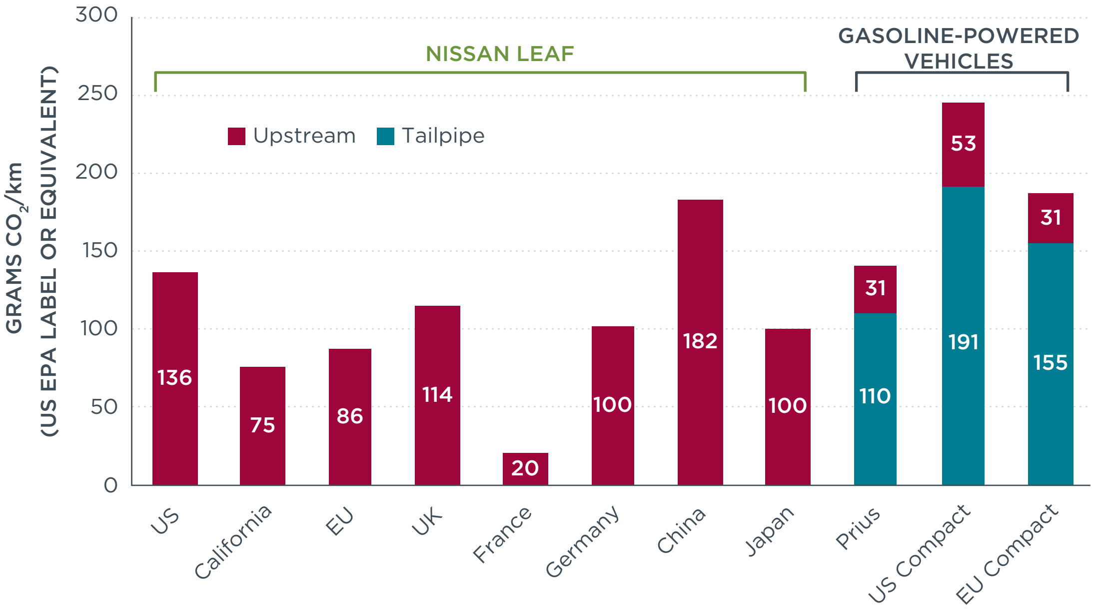

Figure 1. Projected GHG emissions for the Nissan Leaf in 2015 versus emissions of gasoline hybrid (2012 Toyota non–plug-in Prius) and ICE-powered compact cars meeting U.S. and E.U. standards for 2015. (Source: ICCT; data sources: ICCT Roadmap, International Energy Agency, and EPA)

» Accounting methods are also needed for regulatory purposes. For instance, the U.S. Environmental Protection Agency (EPA) has developed upstream accounting procedures for electric vehicles that would eventually be phased in, assuming that vehicle deployments reach certain levels (Federal Register, 2011, p. 75012). Final regulations for model years 2017 to 2025 are expected later this year. EPA is also calculating forgone GHG reductions from this exemption and other bonuses for edrive vehicles. In addition, the California Air Resources Board (CARB) has adopted upstream emission factors for edrive vehicles powered by grid electricity and/or hydrogen (CARB, 2011).[2] Regulators in the European Union face similar questions as they develop passenger vehicle carbon dioxide standards for 2020, and regulators in China also face related issues in implementing fuel consumption targets for 2015 and developing targets for 2020.

» Accurate emissions accounting will also benefit potential edrive vehicle purchasers. A recent survey found that nearly half of drivers in 13 countries (including seven EU countries) said that potential edrive purchasing decisions would be influenced by the availability of "green" electricity sources (Accenture, 2011, p. 17). This indicates a strong interest in "well-to-tank" environmental impact information, which can be provided by the internet and vehicle labeling. Moreover, 16 EU countries use CO_2-based vehicle taxation rates, creating a further incentive to understand edrive vehicle emissions (Creutzig et al., 2010, p. 23).

The following sections address the need for accurate GHG calculations with recommendations on three key issues: measuring vehicle efficiency with representative test cycles, calculating the GHG intensity of edrive vehicle energy supplies and the amount of avoided ICE fuel consumption, and converting g/km (or g/mile) estimates into tons per year. Each of these topics is addressed in detail below.

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[2] This paper does not address the advantages and disadvantages of accounting for upstream emissions in passenger vehicle standards. ICCT has addressed this issue separately (ICCT, 2012b).

II. DETERMINING ELECTRIC DRIVE VEHICLE EMISSIONS

A. VEHICLE EFFICIENCY

1. REPRESENTATIVE TEST CYCLES

Vehicle efficiency testing is a cornerstone of accounting for upstream emissions and depends on accurate test cycles reflecting real-world conditions. The test cycle used to measure vehicle efficiency will have a substantial effect on the resulting energy efficiency values, as shown in Figure 2.[3] This section describes existing test cycles such as EPA five-cycle testing and provides recommendations for capturing the influence of congestion, aggressive driving, and vehicle cabin climate control on plug-in hybrid electric vehicle (PHEV) and EV total energy usage; edrive-specific testing is also addressed.

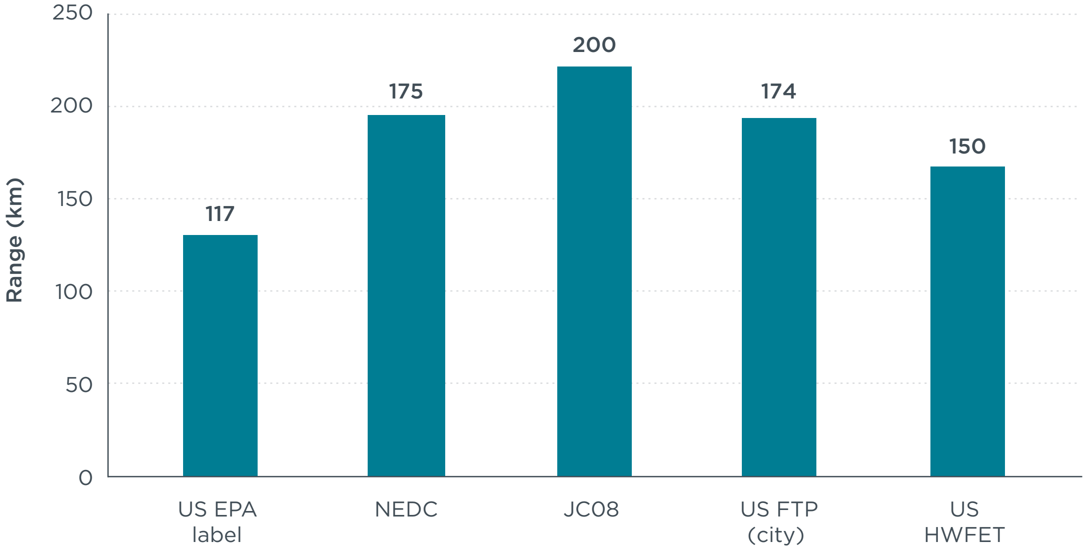

Figure 2. Nissan Leaf rated range from EPA consumer label; New European Driving Cycle (NEDC); Japanese JC08 test cycle; EPA Federal Test Procedure (FTP); EPA Highway Fuel Economy Test (HWFET) (Sources: Nissan, EPA)

Selecting test cycles that reflect global increases in urbanization and congestion (Sperling & Gordon, 2009, p. 5; United Nations, 2011, p. ES-1) is important for representative vehicle comparisons, and especially for comparing edrive vehicles to ICE vehicles. As shown in Table 1, BEVs and fuel cell electric vehicles (FCEVs) tested by EPA maintain fuel consumption levels or even achieve modest reductions in fuel consumption during EPA's city driving cycle. One reason is that, relative to ICEs, batteries and fuel cells suffer reduced efficiency drop-off at low output conditions that occur during slower-speed urban driving. In addition, "idle off" technology and regenerative braking technologies, seen in non-PHEVs as well, will further limit energy loss during start-stop traffic.[4] All vehicles will experience lower aerodynamic losses at lower speeds.

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[3] EPA five-cycle methodology test results yield consumer/label mpg values that are about 20 to 30% lower than CAFE two-cycle test values for gasoline vehicle technologies. EPA allows manufacturers to label EVs, in the absence of data analogous to five-cycle test results, using a proxy based on 30% lower range and 1/(1 – 0.30) or 42% higher electricity consumption than CAFE data. Real-world values can also vary from test values because of in-use conditions including hills, roadway roughness, and wind.

[4] In the future, start-stop technology may become widely deployed for ICE vehicles as well.

In addition, a testing system that includes aggressive on-road driving, such as US06, is necessary to represent real-world driving habits and to account for PHEVs that operate in "blended" electric/engine-on modes even before depleting stored grid electricity. For instance, the 2012 plug-in Prius operates in blended mode during strong acceleration, at sustained speeds of >100 kph, and/or while using climate control (Toyota, 2011). The Extra Urban Drive Cycle (EUDC) for Europe has a top speed of 72 mph/116 kph, which is an improvement over many test cycles (although not representative of top driving speeds in some countries). The US06 cycle is designed to capture the effects of aggressive driving and includes even higher speeds than the EUDC. The conditions leading to blended operation are not likely to be captured on other less severe test cycles.[5] Thus, test cycles that incorporate higher speeds and aggressive driving patterns should be used in addition to standard cycles such as U.S. corporate average fuel economy (CAFE) test cycles to estimate the share of stored grid electricity used to power PHEVs and overall efficiency. (Estimation of vehicle range on stored grid electricity is further discussed below.)

Table 1. Energy efficiency comparisons. (Sources: www.fueleconomy.gov, ICCT unit conversions)[6]

	Energy efficiency based on EPA label procedure			Energy efficiency based on EPA label procedure converted to MJ per 100 km	
	Energy source and units	City	Highway	City	Highway
2012 Honda Clarity	Hydrogen (kg/100 km)	1.0	1.0	138	138
2012 Nissan Leaf	Electricity (kwh/100 km)	19.9	23.0	72	83
2012 Chevy Volt	Electricity (kwh/100 km)	22.2	23.2	80	84
2012 Chevy Volt	Gasoline (liters/100 km)	6.7	5.9	214	187
2012 Toyota Prius	Gasoline (liters/100 km)	4.6	4.9	147	156
2012 Honda Civic hybrid	Gasoline (liters/100 km)	5.3	5.3	170	170
2012 Honda Civic non-hybrid	Gasoline (liters/100 km)	8.4	6.0	267	192
2012 Toyota Camry (typical U.S. car; 2.5-liter four-cylinder)	Gasoline (liters/100 km)	9.4	6.7	299	214
2012 VW Golf (typical E.U. car; 1.4-liter four-cylinder)	Gasoline (liters/100 km)	8.2 (E.U. urban cycle)	5.1 (E.U. extra-urban cycle)	261 (E.U. urban cycle)	213 (E.U. extra-urban cycle)

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[5] The ECE (United Nations Economic Commission for Europe) and Japanese JC08 test cycles have top speeds lower than 100 kph (DieselNet, 2011) and may not capture or fully capture real-world ICE engine engagement during charge depletion mode. Similarly, data collected for the World Harmonized Test Procedure (WHTP) reveal that speeds often exceed the maximum levels of CAFE and ECE 15 test procedures. ICE engagement is also a potential concern for conventional pollutant emissions, which are typically much higher if the engine is turned on before the catalyst is fully warmed up.

[6] Energy content assumptions: gasoline, 32 MJ/liter; H2, 143 MJ/kg.

ICCT also recommends selecting test cycles that capture differences in energy use due to ambient temperature. Cold temperatures lead to increased internal friction for ICEs and increased aerodynamic losses across all vehicle categories, and may also affect rolling resistance. For instance, at 20°F, EPA measured a fuel consumption increase of about 15% for several ICEs on a 7.5-mile urban test cycle relative to the same ICEs at 75°F (U.S. EPA, 2006, p. 79).[7] On the other hand, BEV electric-resistance cabin heating consumes energy, whereas the cabins of ICE vehicles are heated by circulation of engine waste heat (Consumer Reports, 2009; U.S. EPA, 2006, p. 117); battery discharge efficiency could be affected by cold temperature as well.[8] This extra energy draw could also be an issue for FCEVs when the stack is still warming up during initial operation. Cabin heating in PHEVs may use stored battery electricity (if available) or may require turning on the engine; these vehicles may also need to supply thermal energy to keep the emissions control catalyst warm. New technologies may reduce the cold-temperature penalty for both ICE and edrive vehicles in the future.[9] EPA cold-temperature urban drive-cycle testing is one way to determine both absolute EV efficiency values and values relative to ICE vehicles, with potential modifications as noted below.[10]

Furthermore, test cycles that account for air conditioning (A/C) efficiency, such as SC03 and the new AC17 standard under development by EPA and similar efforts in the European Union, are recommended to compare efficiency differences related to A/C usage. Technical studies in both the United States and the European Union estimate that A/C accounts for about 5% of energy usage in a conventional vehicle (Smokers et al., 2006, pp. 6, 102; U.S. EPA and NHTSA, 2011, pp. 5–24). This indicates that A/C usage is important, although less so than the effects of cold temperature noted earlier. Measurement of A/C system efficiency will help to determine improved system efficiency through A/C compressor motor electrification for edrive vehicles.[11]

2. PLUG-IN ELECTRIC HYBRID AND BATTERY ELECTRIC VEHICLE SPECIFIC TEST PROCEDURES

One important difference between PHEV/BEV testing procedures and traditional ICE test methods is the need to account for vehicle charging losses. EPA EV efficiency labels are based on measurements of electricity usage at the ac plug, which is similar to the J1711 procedures (SAE, 2006).[12] Charging efficiency can vary from 87% at 110 V and 20 A, to 83% at 220 V and 20 to 30 A (Elgowainy et al., 2010, p. 37). Standardizing charging rates at 240 V with an external charger of a given efficiency is recommended to provide comparable re-

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[7] EPA measured 4.03 gallons/100 miles (9.5 liters/100 km) fuel usage at 75°F (24°C) versus 4.70 gallons/100 miles (11.0 liters/100 km) fuel usage at 20°F (–7°C) for several ICEs on a 7.5-mile urban test cycle (FTP). EPA provides manufacturers with the option to determine 20°F (–7°C) road load or use a 10% adjustment to road load determined through coast-down testing [40 CFR section 86.229-94(b)]. Note that aerodynamic losses will increase with increased air density across all vehicle types. Tire rolling resistance losses will increase as a result of lower tire pressure at cold temperatures unless consumers adjust inflation levels to compensate.

[8] Using grid electricity to preheat a PHEV cabin would improve the electric travel range of the vehicle, although not necessarily its overall energy efficiency. Preheating the catalyst of a PHEV may also improve conventional pollutant emission rates during start-up.

[9] These technologies include accelerated warm-up for ICEs, and heat pumps and directed electrical heating for edrive vehicles.

[10] The cold test sequence is available at section 86.230-11 of the 2010 edition of the Code of Federal Regulations.

[11] ICCT notes that A/C testing would be conducted as a system, because individual components would be difficult to isolate through GHG emissions testing. ICCT also notes that switching to refrigerants with lower global warming potential may affect A/C energy usage for all vehicle types.

[12] Early et al. (2011, section 53) estimate charger losses of 12% and battery losses of 3 to 5% in China. The Interim Joint Technical Assessment Report of EPA, NHTSA, and CARB (2010, p. E-14) assumes charger losses of 10%. Better validation would help assess the impact of charger losses at both household and dc “fast charging” levels.

sults between tests (including any differences in internal battery losses). In the United States, 240 V service is representative of reported BEV charging experience thus far (U.S. Department of Energy (DOE), 2012b, p. 1). Electrical service at 240 V is also likely to represent a common charging rate in the European Union and China because of its widespread residential and commercial availability. Additional monitoring of dc "fast charging" and U.S. 120 V charging is also appropriate to determine potential future adjustments.

3. ADDITIONAL RESEARCH PRIORITIES

Additional data and experience will clarify whether other factors such as battery cycling and calendar aging can affect efficiency.[13] In addition, active battery cooling for parked BEVs or PHEVs may be used to preserve battery performance and could affect overall vehicle energy usage.

Another question is whether battery output efficiency varies according to a given battery's state of charge (SOC). Running cold testing until full battery depletion can be time-consuming because of the number of test runs that may be required and the need to return the vehicle to pre-test conditions between test runs. If battery output efficiency is consistent across SOC and different temperatures, and battery efficiency can be monitored, then a limited number of cold-cycle (and potentially also A/C) testing runs can be adjusted linearly on the basis of battery efficiency. If not, ICCT would recommend evaluating the feasibility of (1) mapping cold-temperature operation energy demand, including heater demand, and (2) determining battery output efficiency for the full range of SOC at cold temperatures.[14]

Although testing with available methods should yield reasonable accuracy in the near term, additional refinements should be considered as warranted, based on additional research and real-world data.

B. FUEL CARBON INTENSITY

1. ELECTRIC POWER PLANT EMISSIONS

Determining electricity GHG intensity is a critical input to calculating edrive vehicle upstream emissions. Electric power plant emission factors can vary along three dimensions that should be considered for both policy evaluation and regulatory accounting: (1) marginal versus average electricity production, (2) geographic resolution, and (3) the potential for the grid to become cleaner (or less clean) over time. General principles for taking into account these three dimensions are the availability of data, transparency, and the stability of the results, especially for regulatory purposes.

MARGINAL VERSUS AVERAGE ELECTRICITY SUPPLIES

ICCT recognizes the value of starting with average electricity GHG intensity scores as a regulatory default for the sake of simplicity, especially when vehicle deployments are relatively small. Determining electricity GHG intensity as an average value across all generation sources avoids the need to determine marginal power plant output at a given hour and to match marginal resources with the temporal distribution of plug-in charging. For instance,

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[13] ICE efficiency is assumed to be fairly stable with little deterioration, although conventional pollutant emissions controls are subject to deterioration. Battery capacity is expected to fade over time as a result of battery cycling and aging, but little information about whether this would also affect efficiency is available. Additional evaluation based on real-world experience would help to clarify whether a correction factor or adjustment to test procedures (such as cycling the battery prior to emissions testing) would be appropriate.

[14] Mapping cold temperature efficiency could potentially be developed using test cycles that do not require preconditioning of the vehicle.

in Figures 3 and 4 (based on scenarios from Kampman, 2010) for Germany and the United Kingdom, respectively, the total pool of resources for the year is represented by all resources under the demand curve (wind is assumed to run whenever available and is thus shown as an offset against demand) including a mix of natural gas, coal, and non-fossil resources.

In the longer term, hourly vehicle charging profiles can be used to create more precise upstream plug-in GHG emission estimates, but such profiles hinge on an accurate understanding of the marginal electric generating resources in use when charging occurs. In Figures 3 and 4, for instance, the marginal resources needed to charge BEVs and PHEVs are represented by the edge of the demand curve, at least while PEV deployment levels are small. In the scenario shown below (Kampman, 2010), in Germany by 2020 coal is projected to make up a substantial fraction of aggregate electricity generation but to fuel marginal generation only at low load conditions. The marginal electricity fuel in the United Kingdom is projected to be natural gas during almost all hours of the year by 2020.[15]

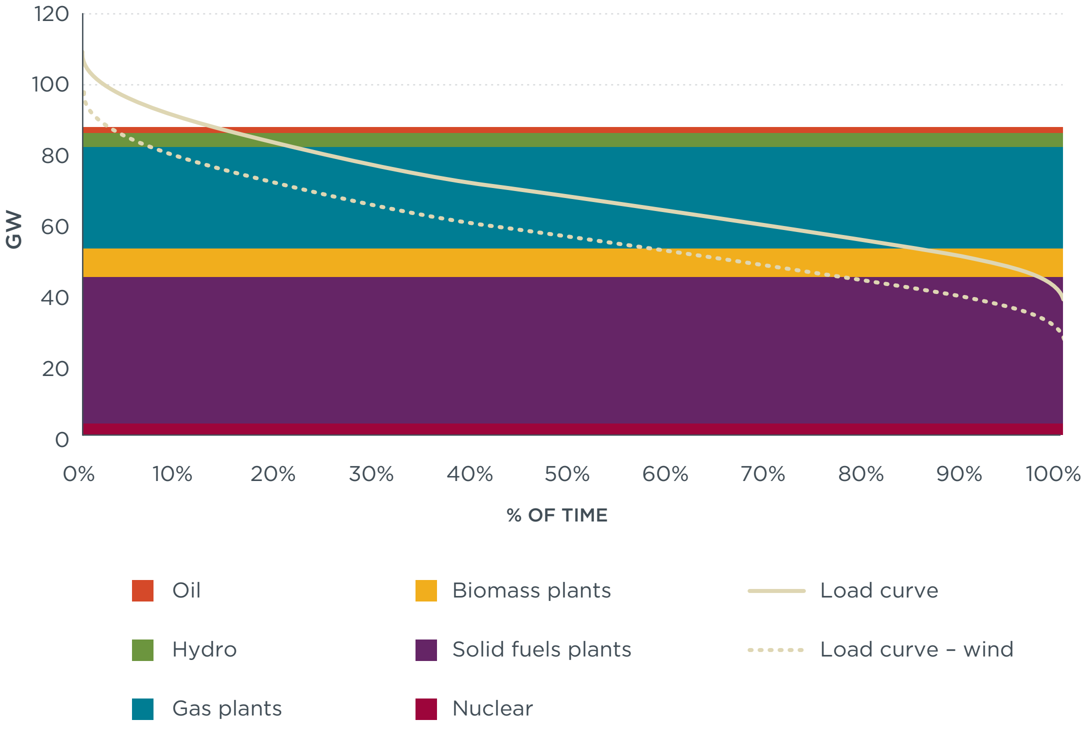

Figure 3. Projected 2020 load curve for Germany. (Source: Kampman, 2010)

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[15] Natural gas stack GHG emissions typically vary between 400 and 700 g/kwh, and coal power plant GHG emissions typically vary between 900 and 1000 g/kwh (U.S. EIA, 2012; U.S. EPA, 2007; author's estimates). Source-specific emission rate can vary according to plant design, operational efficiency, and feedstock production energy intensity and methane emissions.

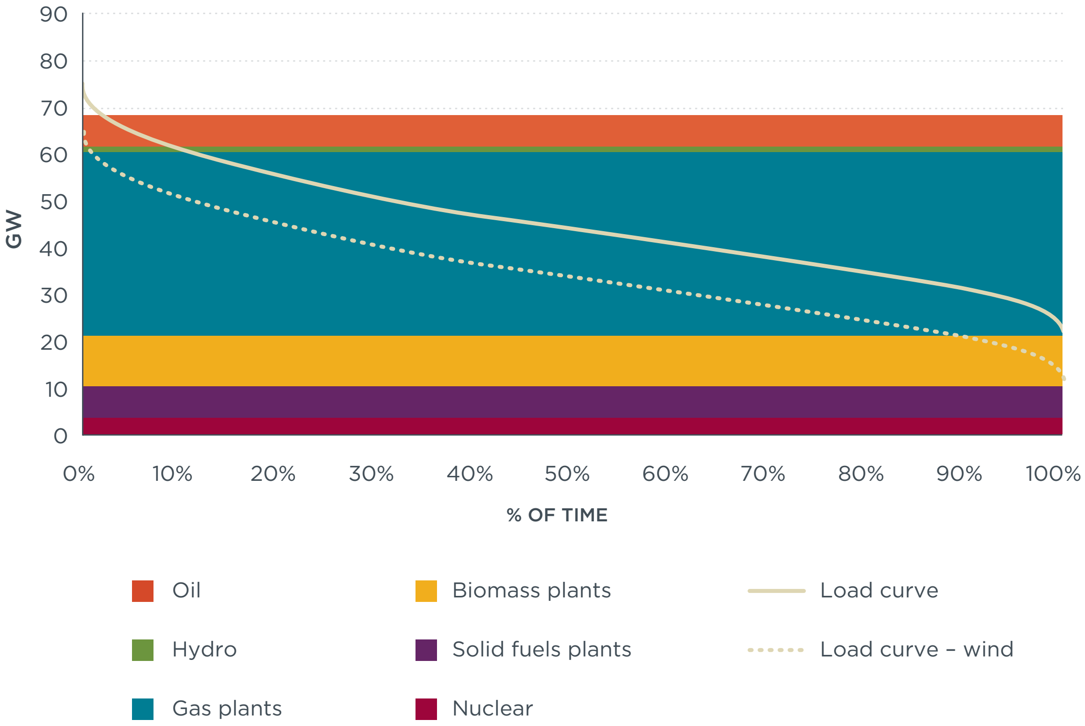

Figure 4. Projected 2020 load curve for the United Kingdom. (Source: Kampman, 2010)

In the United States, EPA has used power plant modeling to project an average national electricity GHG intensity score of 613 g GHG/kwh in 2025, including distribution losses (Federal Register, 2011, p. 75014). (EPA is calculating the effect of exempting edrive vehicle upstream emissions from GHG standards up to certain caps as well as the effect of other bonuses, and would also use these calculations for regulatory purposes for edrive vehicles produced above the cap.) EPA is also considering additional modeling to account for time distribution of electric vehicle charging. In the longer term, analysis of the marginal effect of PEV charging should be an increasing priority once PEV deployments scale up to the early commercial market because of the potential for significant variations between average and marginal electricity carbon intensity as noted in Table 2 for the United Kingdom.

Table 2. Estimated CO_2 emissions associated with electricity generation in the United Kingdom. (Source: UK DECC, 2011)

Year	kg CO_2 per Mwh	
	Average	Marginal
2015	460	394
2020	372	394
2030	209	275
2050	23	23

GEOGRAPHIC RESOLUTION

ICCT recommends applying regional emission factors when supported by sufficient data on vehicle placements and the GHG impacts of any major power transfers between regions. In the United States, California and other West Coast and New England states that have adopted California's Zero Emission Vehicle program have both strong incentives for edrive deployments and relatively low-carbon grids. For instance, CARB has projected 270 g GHG/kwh at the outlet for 2020, including imports (CARB, 2011, p. 136), compared to EPA's national score of 613 g GHG/kwh in 2025 as noted above. EPA is considering additional modeling to address regional variations.

In China, substantial regional variation will also occur as a result of coal generation, ranging from 65% in the Southern Region to 98% in the Northern Region (Huo et al., 2010). In the European Union, national-level scores can vary markedly as seen in Figure 1, although using regional scores for E.U. regulatory compliance purposes may be barred by Lisbon "harmonization" principles.[16]

CHANGES IN ELECTRICITY GHG INTENSITY OVER TIME

ICCT recommends setting initial GHG intensity scores based on the best available data and then reevaluating circumstances periodically to determine whether updates are needed. These initial estimates can reflect decarbonization requirements in the European Union, China, the United States, and other countries that will take effect during the lifetime of an EV deployed in the near future. CARB has adopted an initial electricity score based on compliance with 33% renewable electricity standards by 2025. Table 2 projects significant differences in marginal versus average U.K. electricity GHG through at least 2030 with effective electricity decarbonization policies in place.[17]

Future updates can adjust for actual levels of renewable resource deployment, natural progression in power plant efficiency and stock turnover, and economic or other trends. EPA and CARB will conduct a midterm review of 2022–2025 standards by 2018, for instance, and can make any appropriate updates to the electricity GHG intensity values at that time. We note that policymakers will likely wish to use the most recent GHG emission data available. On the other hand, automakers will benefit from a certain number of years of regulatory stability before any changes to compliance requirements (due to changes in electricity GHG intensity or other types of updates to regulatory compliance systems) become effective.

2. HYDROGEN PRIMARY PRODUCTION

The carbon intensity of hydrogen production should be calculated specifically for transportation fuels if data on production methods can be tracked and correlated to transportation end uses.

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[16] For instance, see Article 107 of the Treaty of the Functioning of the European Union.

[17] These scores include power flows into and out of the United Kingdom. They do not include fuel production emissions (Mathew Behull, UK DECC, personal communication, March 13, 2012).

The U.S. Energy Independence and Security Act of 2007, section 202, defines lifecycle accounting principles for liquid transportation fuels and offers a useful precedent for edrive vehicles:

> "LIFECYCLE GREENHOUSE GAS EMISSIONS: The term 'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential."

Figure 5 shows that the amount of environmental benefit for a 2020 FCEV is strongly dependent on the hydrogen production pathway. This example is based on the 2010 EPA fuel economy rating for the midsized Honda Clarity FCX, adjusted for the New European Driving Cycle (NEDC) and an assumed 2.5% annual improvement in FCEV efficiency to 2020. The 2020 proposed passenger vehicle tailpipe standards of 95 g/km (E.U.) and 111 g/km (U.S.) in Figure 5 are adjusted to account for upstream emissions (which could instead be counted as a credit to lower the FCEV emissions score).[18]

These scores can be used for both policy evaluation and regulatory compliance purposes. For instance, the California Low Carbon Fuel Standard establishes different carbon intensity scores for different production pathways. CARB has also adopted a carbon intensity value to be used in passenger vehicle GHG compliance scores, based on a statewide 33% renewable hydrogen requirement combined with natural gas production for the balance (CARB, 2011, p. 137). Germany has adopted a 50% renewable hydrogen policy goal (GermanHy, 2008). Unlike electricity, tracking hydrogen carbon intensity is less complicated because hydrogen production and end uses tend to be concentrated at a relatively small number of refineries, as well as some industrial processes and other discrete points including distributed generation. In addition, policies such as California's Low Carbon Fuel Standard will result in tracking data about production pathways.

Alternatively, if data on production pathways are not available, then a score based on the typical production methods for industrial hydrogen can be applied initially. For example, steam methane reforming is the commonly used method in the United States.

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[18] E.U. values from announced 95 g/km tailpipe standard (EUCAR/CONCAWE/JRC/IES, 2006, p. 60); g/MJ values and MJ/liter gasoline energy content from Thomas (2000); and 8788 g CO_2 per gallon. U.S. values from U.S. proposed passenger vehicle tailpipe standards at 120 g/km and 24 g/km upstream petroleum (Federal Register, 2011, p. 75014). ICCT notes that vehicle-specific comparisons may vary from this example because regulatory targets will likely scale up or down as a result of vehicle mass or footprint, and because "off-cycle" credits are proposed by EPA for 2017–2025 standards and are included in current E.U. standards and could be extended.

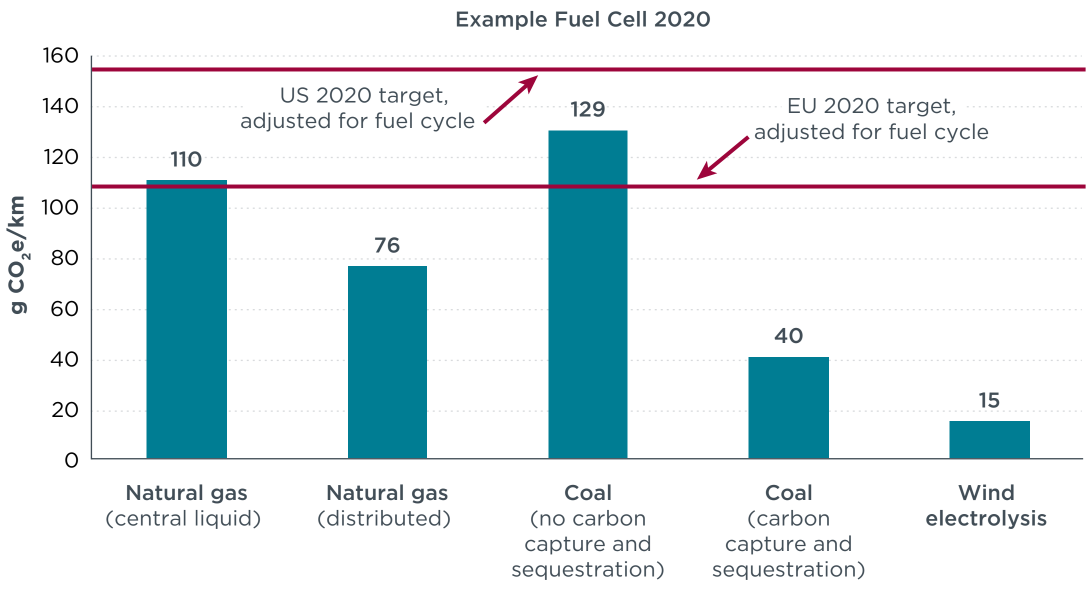

Figure 5. Example upstream GHG emissions for the Honda Clarity FCEV, adjusted to the NEDC test cycle. (Sources: CARB, EPA, DOE)

3. LIFECYCLE ACCOUNTING FOR FOSSIL FUEL PRODUCTION AND DISTRIBUTION

Upstream fossil fuel production and distribution emissions for both edrive and ICE vehicles can be addressed in one of two ways. One possibility, as proposed by EPA and CARB, is to adjust the edrive upstream scores used to calculate passenger vehicle GHG regulatory credits; a given score could be adjusted upward (for power plant or hydrogen fossil fuel feedstock) or downward (for avoided petroleum upstream emissions).[19] Alternatively, instead of the present system of vehicle-only accounting with an upstream adjustment, the entire vehicle regulation framework could shift to a well-to-wheels basis covering both the vehicle and the associated upstream fuel cycle emissions. The latter provides a more complete view of total emissions, but the former more closely parallels the tailpipe-only approach currently used for passenger vehicle regulatory standards and labels. Both provide accurate relative comparisons between vehicle technology types that use fuels with different upstream emission impacts.

The Nissan Leaf would be assigned an emission value of about 9 to 13 g/mile (6–8 g/km) for upstream electric power plant fossil fuel production under California and EPA regulatory accounting methods.[20] By comparison, EPA estimated that an example EV would benefit from avoided upstream GHG emissions of 39 g/mile (24g/km) (Federal Register, 2011, p. 75014) in 2025 relative to a midsized gasoline vehicle; E.U. upstream petroleum GHG values will be lower.[21] (Upstream petroleum GHG emissions are due primarily to production and refining of crude oil; such emissions vary according to the energy intensity of extracting and refining crudes, as well as the venting or flaring of associated hydrocarbon gases.)

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[19] The EPA proposal does not address upstream vehicle manufacturing emissions. ICCT recognizes that upstream vehicle manufacturing emissions represent an emerging area of research for future consideration.

[20] EPA estimates a 6% increase in the GHG intensity of U.S. electricity generation due to upstream fossil fuel-related power plant emissions (U.S. EPA, 2011, pp. 4–43). CARB has estimated a 10% increase in GHG intensity of electricity consumed in California due to upstream emissions, which would be slightly lower than the EPA value in absolute terms (CARB, 2010, p. 26). ICCT's calculation is based on 0.34 kwh/mile and 37 g/kwh EPA and 27 g/kwh California upstream electricity fossil fuel production adders.

[21] E.U. values of 12 g/MJ from EUCAR (EUCAR/CONCAWE/JRC/IES, 2006, p. 60) are substantially less than U.S. values of 2478 g per gallon (Federal Register, 2011, p. 75014) using a conversion of 31.1 MJ/liter (Thomas, 2000).

Edrive vehicles can thus be compared to ICE tailpipe emissions on a g/km basis as follows:

edrive GHG emissions (g/km) = [edrive efficiency (MJ/km) x edrive upstream fuel cycle emissions (g GHG/MJ)] – ICE upstream fuel emissions (g CO_2e/km)

C. VEHICLE MILES/KILOMETERS TRAVELED

Vehicle miles traveled (VMT)/vehicle kilometers traveled (VKT) are important for several reasons. First, electric VMT/VKT determines total electricity GHG emissions.[22] Range also has an effect on the PHEV share of electric versus petroleum-powered miles, as recognized in CARB and EPA regulations. The VMT/VKT of a BEV with limited range will vary from that of an ICE, and thus may displace only part of the typical mileage of an ICE.

BEV VMT/VKT

ICCT proposes estimating U.S. annual mileage on the basis of annual mileage corresponding to a vehicle with daily trips within the daily travel range of a BEV (see Table 3). ICCT also proposes adjusting this score to reflect the additional range allowed by additional daily charges, as well as a “range anxiety” factor:

BEV daily travel range (km) = BEV range (km) x (1 – range anxiety factor) x average charges per day when driven

Annual activity levels can then be determined by multiplying average annual conventional vehicle activity levels by scaling factors linked to the data shown in Table 3:

BEV annual activity (km) = average vehicle activity (km) x BEV scaling factor

Initial U.S. Nissan Leaf data (U.S. DOE, 2012b) show that the average Leaf VMT is slightly more than half that of a typical new car, corresponding to a daily travel range factor of slightly more than 60 miles (97 km) per day based on Table 3. This annual VMT factor corresponds fairly well with the annual VMT for a vehicle with the Leaf’s rated range of 72 miles (116 km). Additional adjustments may result in an even closer match, such as a 10% increase due to opportunity charging during the day (1.1 charges per day when driven) and an assumed downward adjustment of, for instance, 20% for range anxiety, which results in 66 miles (106 km) per day.[23] The total estimated US mileage in this case would be approximately 7,000 miles per year. Real-world monitoring and data collection should focus on (1) additional validation of the daily travel range correlation with annual VMT for the United States and additional countries, and (2) validation of the proposed adjustment downward for perceived range anxiety as well as an upward adjustment for opportunity charging and potentially additional adjustments as well.[24]

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[22] Travel distances do not appear to be an important issue for FCEVs, assuming that infrastructure needed to allow market introduction is provided. For instance, the Honda Clarity is rated with a 230-mile EPA label range, and 98% of U.S. drivers have a daily commute of 50 miles or less. In addition, FCEVs can be refueled rapidly to accomplish extended trips. See the 2009 NHTS Average Annual Vehicle Miles of Travel Per Driver by Distance to Work, http://nhts.ornl.gov/tables09/ae/AnalysisVariable2009.aspx, http://nhts.ornl.gov/tables09/ae/OutputArea.aspx.

[23] Reported 2011 Q4 VMT are 4,878,735 miles for 2645 Leaf BEVs. Some vehicles may have been added during the quarter; there were 2394 participants at the end of Q3, and the Q4 data may be influenced by holidays. EPA estimates new car annual VMT at 14,231 (U.S. EPA and NHTSA, 2011).

[24] Additional factors could also be considered, such as displacement of additional ICE trips in multi-vehicle families; conversely, opportunity charging may occur for shorter periods that do not fully recharge the battery in some cases. In addition, some trips may cover multiple days where one or more days, but not all, exceed the vehicle’s range.

Table 3. Share of daily vehicle miles covered by a given distance range. (Source: Elgowainy, 2010, p. 42, from 2001 NHTS data)

Daily travel range of vehicle		Percentage of total VMT for daily travel	Cumulative mileage for all daily travel of this distance range or less
Miles	Kilometers		
Up to 10	Up to 16.1	3.3%	3.3%
10 to 20	16.1 to 32.2	8.1%	11.4%
20 to 30	32.2 to 48.2	10.0%	21.4%
30 to 40	48 to 64.4	10.0%	31.4%
40 to 60	64.4 to 96.6	16.8%	48.2%
Over 60	Over 96.6	51.8%	100%

Annual estimates of BEV GHG emissions (and ICE mileage and emissions avoided) based on expected VMT/VKT will be helpful for planning and evaluating incentives. Weighing BEV compliance scores for regulatory compliance purposes based on expected VMT/VKT should be considered on a country-by-country basis (or, in the case of the European Union, on a regional basis). Regulatory compliance scores for BEVs that are expressed in terms of g CO_2e/km could be weighted according to expected VMT/VKT for edrive vehicles with limited range to provide credits more closely corresponding to expected annual emission reductions. However, some regulations such as current E.U. CO_2 standards are indexed according to vehicle mass. Although ICCT has recommended moving away from mass-based standards, mass-based standards could increase the amount of credit available for some vehicles with increased range due to increased battery mass (increased battery energy density and vehicle efficiency would also increase vehicle range).[25] In addition, some countries or regions may seek to use standards to promote technology development, not just emission reductions. Accordingly, future regulatory decisions should address on a case-by-case basis the appropriateness of VMT/VKT weighting of BEV GHG standard compliance credits and, as noted earlier, provide appropriate lead time for any adjustments.

The following calculation is an example of determining weighted GHG reductions:

$$\begin{gathered}\text{edrive emissions displacement (g } CO_2\text{e/km)} = [\text{ICE tailpipe emissions (g } CO_2\text{e/km)} \\ + \text{ ICE upstream fuel cycle emissions (g } CO_2\text{e/km)} \\ - \text{ edrive fuel cycle emissions (g } CO_2\text{e/km)}] \times \text{annual edrive distance factor}\end{gathered}$$

PHEV CHARGE DEPLETION RANGE

PHEVs are a special case because they can be powered by either gasoline or stored grid electricity until the stored charge is depleted. The share of VMT/VKT attributed to gasoline versus electricity use can vary according to trip length and how often a given vehicle is recharged. SAE J2841 provides an example utility curve to estimate electric miles driven

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[25] Some regulations provide less strict targets for vehicles with higher mass, although ICCT recommends alternative approaches (Mock, 2011). We note that added battery mass leads to increased rolling resistance and inertial losses, with effects on energy consumption rates that will be captured during regulatory test cycles. Shiau et al. (2009) estimate that the increased mass of a 60-mile PHEV relative to a 20-mile PHEV could increase energy consumption by 7% in one scenario that assumes that battery mass increase is doubled by additional structural mass.

based on mileage that falls within the charge depletion range of the PHEV (i.e., before stored grid electricity is depleted) using the same NHTS data as Table 3 above. SAE J1711 estimates PHEV mileage by combining the SAE J2841 utility curve with the approximation that drivers will start each day at 100% charge and that no other charging will occur until the driver returns home. For instance, the Chevy Volt "utility factor" is between 55% and 60%.[26] [A study of 135 plug-in Chevy Volt hybrids in the United States shows that 84% of trips started with a full battery (U.S. DOE, 2012a).]

For PHEVs that are operated with a blended combination of stored grid electricity (until depletion) and ICE power, the utility factor based on real-world charge depletion range should be multiplied by the real-world share of electricity during charge depletion. For instance, a PHEV with a range of 28 miles (45 km) until charge depletion, including blended ICE power, would be given a 50% unadjusted utility factor under SAE J1711 and J2841. If this vehicle operates on 80% stored grid electricity until the charge is depleted (as discussed above), the overall stored electricity usage factor, calculated as follows, would be 40%.[27]

$$\text{PHEV electricity usage factor} = \text{charge-depleting utility factor} \\ \times \text{charge-depleting electricity share}$$

III. CONCLUSION

Edrive vehicles offer the potential for substantial environmental benefits, which can and should be accurately calculated to inform policy decisions such as emission reduction strategies, incorporation of edrive vehicles into passenger vehicle CO_2/GHG standards, and consumer labeling. GHG emissions can be calculated by coupling vehicle energy efficiency with calculations for energy supply GHG intensity, PHEV stored grid electricity usage, and edrive VMT/VKT.

Vehicle efficiency measurement priority recommendations include:

- Use EPA five-cycle or similar test cycles to capture the effects of urbanization, aggressive driving, ambient temperature, and cabin climate control (including any potential practical modifications needed for edrive vehicles).
- Evaluate edrive vehicle performance in the real world and the potential need for additional adjustment(s) to the above measurements.
- Test with 240 V charging while monitoring use of "fast charging" (and in the United States, 120 V charging).

Upstream energy supply carbon intensity determination priority recommendations include:

- Use average electricity GHG intensity as a default; evaluate, as vehicle deployments grow over time, the feasibility of determining marginal GHG intensity based on modeling and further experience with charging behavior (such as time of day) and/or other updates. Changes from average to marginal electricity generation and updates to regulatory compliance practices will likely require sufficient lead time to provide manufacturers with regulatory certainty.

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[26] GM reports that early Volt users operate on electric power for about 70% of their mileage. See www.motortrend.com/features/auto_news/1201_chevrolet_volt_by_the_numbers.

[27] www.fueleconomy.gov provides a Toyota Prius fuel economy rating with both electricity and gasoline used during the first 11 miles of operation.

- Apply regional factors if accurate data on vehicle placements and regional assessments of electricity GHG intensity are available, including power flows between regions, in areas that do not face constraints such as the E.U. harmonization requirements.
- Adjust hydrogen GHG intensity factors for specific production processes when sufficient data are available, especially where renewable or low-carbon hydrogen requirements are in place.
- Compare edrive fuel emissions against the combined vehicle and fuel cycle emissions of ICE vehicles.

Vehicle activity level determination priority recommendations include:

- Adjust PHEV utility curves to account for PHEV blended operation that would extend charge depletion range due to partial ICE usage.
- Calculate edrive vehicle total emissions, and emissions displaced, using annual VMT/VKT correlated with daily travel range. Additional real-world data should be used to further validate daily travel range correlation with VMT/VKT and to validate proposed adjustment factors for range anxiety and opportunity charging.
- Use total emission calculations for policy evaluation and inventory purposes. Policymakers should consider weighting BEV regulatory compliance scores based on VMT/VKT on a case-by-case basis.

These calculations will assist policymakers, automakers, and consumers in assessing the level of GHG benefits provided by edrive vehicles while also providing a foundation for related energy efficiency and air quality data.

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