APPENDIX F

California Environmental Protection Agency
Air Resources Board
Stationary Source Division

Supplement to:

Stationary Source Division, Air Resources Board (February 28, 2009, v.2.1)

"Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California"

Release Date: October 28, 2011

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Need for a Supplement to the ULSD Pathway Document

The LCFS regulation considers 2010 as the baseline year against which a ten percent reduction in GHG emissions is mandated by 2020.[1] Because data for crude oil supplied to CA refineries in 2010 was not available during development of the original regulation, Lookup Table carbon intensity values for CARBOB and diesel were based on available crude supply data for the year 2006. At the time, an assumption was made that the carbon intensity for recovery of crude oil supplied to CA refineries would not change substantially between 2006 and the 2010 baseline year. This assumption turned out to be incorrect as the percentages of crude recovered using thermal methods, mining and upgrading have increased.[2,3] Therefore as part of 2011 Regulatory Amendments to the LCFS, ARB staff is proposing updates to the baseline carbon intensity values for CARBOB and diesel using the most recently available comprehensive set of crude oil supply data from the year 2009. Furthermore, it is ARB staff's intention to revise these values again in 2012 as part of a 15-day change to these Regulatory Amendments. In 2012, comprehensive crude oil supply data will be available for the year 2010. ARB staff will be recalculating the "California average" annually to reflect the most current crude slate. To assist in this effort, staff is working with Professor Adam Brandt at Stanford University to develop a lifecycle assessment tool for calculating carbon intensity values for crude oil recovery.[4,5]

Calculation Methodology for the Baseline Crude Average Carbon Intensity Value

We used a simple approach to calculate the Baseline Crude Average carbon intensity value (see Attachment 1 for details). For crude sources produced using thermally enhanced oil recovery (TEOR), bitumen mining and/or upgrading, a single carbon intensity value of 20 gCO2/MJ was assigned. All other crudes were assumed to be produced using conventional primary or secondary recovery methods. For these crude sources we assumed a common "base" carbon intensity value which accounts for extraction, venting, and fugitive emissions and added to this country specific values for flaring and transportation emissions. Crude oil produced in California, Canada, Venezuela, and Oman was recovered using a mixture of production methods. In California, approximately half of the crude was produced using TEOR.[6] For Canada we assumed that 89 percent was produced using TEOR, mining and/or upgrading while for Venezuela we assumed 51 percent was produced with upgrading and for Oman we

[1] Proposed Regulation to Implement the Low Carbon Fuels Standard, ISOR Volume 1, 2009, page V-7
[2] California Department of Conservation, 2010, Division of Oil, Gas, and Geothermal Resources, 2009 annual Report of the State Oil and Gas Supervisor, page 3.
[3] California Energy Commission, October 10, 2011, Email Correspondence: Data on Canadian and Venezuelan crude oil production.
[4] Brandt, A. and H. El-Houjeiri, September 15, 2011, Presentation to ARB Staff: Greenhouse Gas Emissions from Conventional and Unconventional Hydrocarbon Production.
[5] El-Houjeiri, H. and A. Brandt, October 3, 2011, Draft Model: Greenhouse Gas (GHG) Emissions from Upstream Petroleum Operations, Version 11.
[6] California Department of Conservation, 2010, Division of Oil, Gas, and Geothermal Resources, 2009 annual Report of the State Oil and Gas Supervisor, page 3.

assumed 18 percent was produced using TEOR.[7,8] The resulting carbon intensity values are shown in Table 1 based on state or country of origin. The Baseline Crude Average carbon intensity, 9.72 gCO_2/MJ, was calculated by weighting these values by the percentage contribution to total crude oil supplied to California refineries.

This value is greater than the value presented in the ULSD pathway document, 8.07 gCO_2/MJ, for two reasons. First, the calculation methodology is different and results in a slightly greater carbon intensity estimate. Applying the methodology described here to the 2006 crude data results in a carbon intensity for crude recovery and transport of 8.57 gCO_2/MJ. This increase is primarily the result of explicitly accounting for flaring emissions by state or country using satellite data. Crude produced in Alaska, Ecuador, Iraq, Angola, and Oman has flaring emissions that are much greater than assumed in the pathway document. Second, the percentages of TEOR, mining, and/or upgrading have increased from 2006 to 2009. For example, California TEOR has increased from 14.43 percent of total California crude in 2006 to 19.48 percent in 2009. Canadian, Venezuelan, and Omani crude imports have also increased.

Table 1: Baseline Crude Average Carbon Intensity

Crude Source	Percentage of Total CA Crude	Conventional Crude CI (g/MJ)	Percentage TEOR, Mining, Upgraded	Total CI (g/MJ)
California	39.5	4.38	49.3	12.08
Alaska	15.06	7.28	0	7.28
Saudi Arabia	11.32	6.37	0	6.37
Iraq	8.49	10.39	0	10.39
Ecuador	7.81	8.29	0	8.29
Brazil	4.2	6.40	0	6.40
Columbia	2.61	5.74	0	5.74
Canada	2.31	5.75	89	18.43
Angola	2.28	7.86	0	7.86
Oman	1.58	8.87	18	10.87
Peru	0.95	5.52	0	5.52
Venezuela	0.9	6.54	51	13.41
Others	2.98	7.73	0	7.73
Weighted Average				**9.72**

[7] California Energy Commission, October 10, 2011, Email Correspondence: Data on Canadian and Venezuelan crude oil production.
[8] Schremp, G., California Energy Commission, 2011, Presentation for Crude Screening Workgroup: Results of Initial Screening Process to Identify Potential HCICOs, revised March 3, 2011.

Baseline Average Carbon Intensity Value for ULSD

The Baseline Average carbon intensity value for ULSD, 96.36 gCO_2/MJ, was determined by substituting the Baseline Crude Average carbon intensity value discussed above for the crude recovery (6.93 gCO_2/MJ) and crude transport (1.14 gCO_2/MJ) values reported in the ULSD pathway document.[9]

[9] California Air Resources Board, February 28, 2009, Detailed CA-GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California, Version 2.1

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ATTACHMENT 1

Calculation of Baseline Crude Average Carbon Intensity Value

Composition of Average Crude Oil Refined in California

Table 1 shows the sources of crude oil refined in California for the calendar year 2009. Total volumes of crude oil for California, Alaska, and foreign sources and percentages of crude for each foreign country were obtained from the California Energy Commission.[10] The volume of crude oil produced using thermally enhanced oil recovery (TEOR) in California was obtained from the California Department of Conservation.[11] We assumed that all oil produced using TEOR in California was refined in California.

Table 1: Sources of Crude Oil Refined in California in 2009

Crude Oil Source	Volume (1000 bbl)	Percent of Total CA
California	239,058	
• TEOR	• 117,900	19.48%
• Non-thermal	• 121,158	20.02%
Alaska	91,147	15.06%
Foreign	274,884	
• Saudi Arabia	• 24.92%	11.32%
• Iraq	• 18.68%	8.49%
• Ecuador	• 17.18%	7.80%
• Brazil	• 9.25%	4.20%
• Columbia	• 5.75%	2.61%
• Canada	• 5.08%	2.31%
• Angola	• 5.01%	2.28%
• Oman	• 3.48%	1.58%
• Peru	• 2.10%	0.95%
• Venezuela	• 1.99%	0.90%
• Others	• 6.55%	2.98%

Of the crude oil imported from Canada, we assumed 89 percent was produced using TEOR, bitumen mining and/or upgrading and the remaining crude was produced using conventional recovery methods. Of the crude oil imported from Venezuela, we

[10] California Energy Commission, Energy Almanac Webpage, Oil Sources to California Refineries, viewed on October 6, 2011 at http://energyalmanac.ca.gov/petroleum/statistics/crude_oil_receipts.html.
[11] California Department of Conservation, 2010, Division of Oil, Gas, and Geothermal Resources, 2009 annual Report of the State Oil and Gas Supervisor, page 3.

assumed 51 percent was upgraded prior to transport to California.[12] Of the crude imported from Oman, we assumed 18 percent was recovered using TEOR.[13]

Estimated Carbon Intensity Values for Crude Oil Sources

All crude oil produced using primary or secondary recovery was assigned a "base" carbon intensity value, 4.0 gCO_2/MJ.[14] This value was determined using the GREET model and accounts for crude extraction, venting, and fugitive emissions. Jacobs Consultancy reports similar crude recovery emissions for nine crude sources using primary and secondary recovery methods.[15] Crude recovery estimates obtained using the GHGenius model are also similar and range from 2.2 to 6.3 g/MJ, not including venting or fugitive emissions.[16] Additional emissions from flaring and transport were calculated using state or country-specific data as described below.

Table 2 presents state or country-specific data and calculations for flaring. Data presented for California are continental U.S. values while Alaska data is state specific. Annual flaring volumes are from satellite data published by the National Oceanic and Atmospheric Administration.[17] Crude production values for Alaska, the continental U.S., and foreign countries were obtained from the Energy Information Administration.[18,19] The normalized flaring values are obtained by dividing the annual flaring volumes by the annual crude production volumes. The normalized flaring value is converted to a carbon intensity using a conversion factor of 1.0 scm/bbl being equivalent to 0.49 gCO_2/MJ. The following assumptions were made in deriving the conversion factor:

- The LHV of average crude is 129, 670 BTU/gal.[20] This converts to 5740 MJ/bbl.
- The composition of flared gas is approximately 75 percent methane, 15 percent ethane, 5 percent propane, and 5 percent carbon dioxide.[21]

[12] California Energy Commission, October 10, 2011, Email Correspondence: Data on Canadian and Venezuelan crude oil production.
[13] Schremp, G., California Energy Commission, 2011, Presentation for Crude Screening Workgroup: Results of Initial Screening Process to Identify Potential HCICOs, revised March 3, 2011.
[14] Wang, M., J. Han, Z. Haq, W. Tyner, M. Wu, and A. Elgowainy, 2011, Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes, Biomass and Bioenergy, 35, 1885-1896.
[15] Jacobs Consultancy, 2011, Presentation: EU Pathway Study – Lifecycle Assessment of Crude Oils in a European Context, September 13, 2011.
[16] O'Connor, Don, October 7, 2011, Email Correspondence: Conventional crude carbon intensity values from GHGenius.
[17] National Oceanic and Atmospheric Administration, 2011, National Geophysical Data Center, Global Gas Flaring Estimates, downloaded from http://www.ngdc.noaa.gov/dmsp/interest/gas_flares.html
[18] U.S. Energy Information Administration, 2011, International Energy Statistics, downloaded from http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=57&aid=1&cid=regions,&syid=2006&eyid=2010&unit=TBPD
[19] U.S. Energy Information Administration, 2011, U.S. Crude Oil Production, downloaded from http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm
[20] California Air Resources Board, February 27, 2009, Detailed CA-GREET Pathway for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) from Average Crude Refined in California, Version 2.1
[21] Jacobs Consultancy and Life Cycle Associates, 2009, Life Cycle Assessment Comparison of North American and Imported Crudes, prepared for Alberta Energy Research Institute.

- The flared gas is undergoes complete combustion to carbon dioxide producing 2455 gCO_2/scm.
- 1.15 MJ crude feed will result in 1.0 MJ of fuel products.[22]

Table 2: Flaring Data and Calculations for 2009

Crude Source	Flaring (billion scm/yr)	Crude Production (billion bbl/yr)	Normalized Flaring (scm/bbl)	Carbon Intensity (gCO_2/MJ)
California	0.64	1.7	0.38	0.18
Alaska	1.39	0.259	5.37	2.63
Saudi Arabia	3.39	3.01	1.13	0.55
Iraq	8.08	0.873	9.26	4.54
Ecuador	1.28	0.177	7.23	3.54
Brazil	1.59	0.712	2.23	1.09
Columbia	0.48	0.245	1.96	0.96
Canada	1.85	0.942	1.96	0.96
Angola	3.4	0.696	4.89	2.39
Oman	1.89	0.297	6.36	3.12
Peru	0.04	0.026	1.54	0.75
Venezuela	2.79	0.817	3.41	1.67
Others	147.13	26.41	5.57	2.73

Table 3 presents carbon intensity values for transport of crude oil to California. These estimates were determined using the GREET model.

Table 3: Crude Oil Transport

Crude Source	Transport Carbon Intensity (gCO_2/MJ)
California	0.2
Alaska	0.65
Saudi Arabia	1.82
Iraq	1.85
Ecuador	0.75
Brazil	1.31
Columbia	0.78
Canada	0.79
Angola	1.47
Oman	1.75
Peru	0.77
Venezuela	0.87
Others	1.0

[22] Brandt, A. and S. Unnasch, 2010, Energy Intensity and Greenhouse Gas emissions from Thermal Enhanced Oil Recovery, Energy and Fuels, 24, 4581-4589.

All crude oil produced using TEOR, bitumen mining, and/or upgrading was assigned a carbon intensity value for production and transport of 20 gCO_2/MJ. This estimate is based on the following analysis.

- Table 4 shows some literature and model default values for in situ TEOR with upgrading, in situ TEOR without upgrading, and bitumen mining with upgrading.[23,24,25] These values are for Canadian oil sands production. The in situ thermal recovery values assume a steam-to-oil ratio of 3 to 3.4. In 2009, slightly more than half of oil sands production was mined and upgraded with the remainder being in situ production. Approximately 10 percent of in situ production was upgraded. Applying these rough percentages to the default values shown in Table 4 results in an average CI value of 19 g/MJ for Canadian oil sands production and transport. NETL reports similar average carbon intensity for Canadian oil sands of 21 g/MJ.[26]
- Venezuelan extra-heavy crude oil is primarily produced using in situ recovery (thermal and non-thermal) with upgrading. The steam-to-oil ratio for thermal recovery in Venezuela is lower than that for Canada because of higher reservoir temperatures and lower viscosity oil. NETL has estimated an average carbon intensity of 19 g/MJ for production and transport of upgraded Venezuelan extra-heavy crude oil.
- For California TEOR without upgrading, Jacobs provides an estimate of approximately 21 g/MJ which includes an estimated allocation of 2 g/MJ for upstream natural gas emissions. TIAX reports a value of 12.2 g/MJ while Brandt and Unnasch report a value of 27.5 g/MJ.[27]

Table 4: Some Literature CI Values for Crude Produced using TEOR and Mining

Source	In situ TEOR[1] with upgrading to SCO (gCO2e/MJ)	In situ TEOR[1] w/o upgrading to SCO (gCO2e/MJ)	Bitumen mining[2] with upgrading to SCO (gCO2e/MJ)
GHGenius	28.6	13.3	19.7
GREET[3]	18.7	13.6	15.4
Jacobs report[4]	~26	~16	~17
TIAX report	26.7	16.6	12.8
Average value[5]	**25 + 1 = 26**	**15 + 1 = 16**	**16 + 4 + 1 = 21**

Notes for Table 4:

1. In situ TEOR
    a. GHGenius: SAGD with steam-to-oil ratio (SOR) of 3.2
    b. Jacobs: SAGD with SOR of 3.0

[23] O'Connor, Don, September 27, 2010, Email Correspondence (2 messages): GHGenius carbon intensity values for oil sands crude.
[24] Jacobs Consultancy and Life Cycle Associates, 2009, Life Cycle Assessment Comparison of North American and Imported Crudes, prepared for Alberta Energy Research Institute.
[25] TIAX, 2009, Comparison of North American and Imported Crude Oil Lifecycle GHG Emissions, prepared for Alberta Energy Research Institute.
[26] NETL, 2009, An Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on Life Cycle Greenhouse Gas Emissions (Appendix A), DOE/NETL-2009/1362.
[27] Brandt, A. and S. Unnasch, 2010, Energy Intensity and Greenhouse Gas Emissions from Thermal Enhanced Oil Recovery, Energy and Fuels, 24, 4581-4589.

c. TIAX:
    i. With upgrading: SAGD with SOR of 3,
    ii. w/o upgrading: CSS with SOR of 3.4
d. GREET: Process method and SOR unknown.

2. Mining carbon intensity values obtained from the literature do not include land use change/tailings pond emissions.
3. GREET values were taken from Table 6-3 in the TIAX report.
4. Jacobs values from Table 8-7 in Jacobs report. These values do not appear to include venting and flaring emissions. Also, there is some uncertainty about allocation of upstream natural gas emissions between recovery and refining in the Jacobs values. Values in Table 4 (above) include upstream natural gas emissions estimates of 2 g/MJ for in situ recovery with upgrading, 1.5 g/MJ for in situ recovery without upgrading, and 1 g/MJ for mining recovery.
5. Average values include emissions associated with transport of crude oil to the refinery. These are dependent on location but typically are about 1 g/MJ. Bitumen mining value also includes 4 g/MJ to account for land use change/tailings pond emissions. Yeh et al. have estimated these emissions at approximately 4 g/MJ (range 0.8 to 10.2 g/MJ).[28]

Calculation of Baseline Crude Average Carbon Intensity Value

Table 5 shows carbon intensity estimates for conventional crude production by state or country as well as the percentage of crude from that state or country produced using TEOR, bitumen mining, and/or upgrading. The "Total CI" for each state or country is a weighted average of the carbon intensity value for conventional production and the assumed value of 20 gCO_2/MJ for crude produced using TEOR, mining, and upgrading. The Baseline Crude Average carbon intensity of 9.72 gCO_2/MJ is obtained by calculating a weighted average of the state and country "Total CI" values.

Table 5: Baseline Crude Average Carbon Intensity

Crude Source	Percentage of Total CA Crude	Conventional Crude CI (g/MJ)	Percentage TEOR, Mining, Upgraded	Total CI (g/MJ)
California	39.5	4.38	49.3	12.08
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Saudi Arabia	11.32	6.37	0	6.37
Iraq	8.49	10.39	0	10.39
Ecuador	7.81	8.29	0	8.29
Brazil	4.2	6.40	0	6.40
Columbia	2.61	5.74	0	5.74
Canada	2.31	5.75	89	18.43
Angola	2.28	7.86	0	7.86
Oman	1.58	8.87	18	10.87
Peru	0.95	5.52	0	5.52
Venezuela	0.9	6.54	51	13.41
Others	2.98	7.73	0	7.73
Weighted Average				**9.72**

[28] Yeh, S., S. Jordaan, A. Brandt, M. Turetsky, S. Spatari, D. Keith, Land Use Greenhouse Gas Emissions from Conventional Oil Production and Oil Sands, *Environ. Sci. Technol.*, 2010, *44* (22), pp 8766–8772.

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21. Brandt, A. and S. Unnasch, 2010, Energy Intensity and Greenhouse Gas emissions from Thermal Enhanced Oil Recovery, Energy and Fuels, 24, 4581-4589.

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