Lifecycle Analysis of Emissions of Greenhouse Gases from Transportation

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Recent LCAs of Fuels

- General Motors, Argonne National Lab, et al., *Well-toWheel Energy Use and Greenhouse Gas Emisions of Advanced Fuel/Vehicle Systems*, in three volumes, published by Argonne National Laboratory, June (2001). [GM-ANL U.S.]
- General Motors et al., *GM Well-to-Wheel Analysis of Energy use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study*, L-B-Systemtechnik GmbH, Ottobrunn, Germany, September 27 (2002). www.lbst.de/gm-wtw. [GM-LBST Europe]
- M.A. Weiss et al., *On the Road in 2020: A Lifecycle Analysis of New Automotive Technologies,* MIT Energy Laboratory Report EL 00-003, Massachusetts Institute of Technology, October (2000). [MIT 2020]
- P. Ahlvik and Ake Brandberg, *Well to Wheels Efficiency for Alternative Fuels from Natural Gas or Biomass*, Publication 2001: 85, Swedish National Road Administrattion, October (2001). [EcoTraffic]

Recent LCAs of Fuels (2)

- J. Hackney and R. de Neufville, “Life Cycle Model of Alternative Fuel Vehicles: Emissions, Energy, and Cost Trade-offs,” *Transportation Research Part A* **35:** 243-266 (2001). [ADL]
- H. L. Maclean, L. B. Lave, R. lankey, and S. Joshi, “A Lifecycle Comparison of Alternative Automobile Fuels,” *Journal of the Air and Waste Management Association* **50**: 1769-1779 (2000). [CMU]
- K. Tahara et l., “Comparison of CO2 Emissions from Alternative and Conventional Vehicles,” *World Resource Review* **13** (1): 52-60 (2001). [Japan]
- M. A. Delucchi, *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials*, UCD-ITS-RR-03-17, Institute of Transportation Studies, University of California, Davis,

Study aspects noted

Region	The countries or regions covered by the analysis.
Time frame	The target year of the analysis.
Transport mod	The types of passenger transport modes included. LDVs = duty vehicles, HDVs = heavy-duty vehicles; LRT = light-rail transit; HRT = heavy-rail transit
Vehicle drivetr type	ICEVs = internal combustion-engine vehicles, HEVs = hybric electric vehicles (vehicles with an electric and an ICE drive BPEVs = battery-powered electric vehicles (BPEVs), FCEVs fuel-cell powered electric vehicles.
Fuels	Fuels carried and used by motor vehicles. FTD = Fischer-Tr diesel, CNG = compressed natural gas, LNG = liquefied natu gas, CH2 = compressed hydrogen, LH2 = liquefied hydroger DME = dimethyl ether.
Feedstocks	The feedstocks from which the fuels are made.
Vehicle energy-use modeling	The models or assumptions used to estimate vehicular ene use (which is a key part of fuelcycle CO_2 emissions), and the dri cycle over which fuel usage is estimated (if applicable).
Fuel LCA	The models, assumptions, and data used to estimate emis from the lifecycle of fuels.

Study aspects noted (2)

Vehicle lifecycl The lifecycle of materials and vehicles, apart from vehicle The lifecycle includes raw material production and transpo manufacture of finished materials, assembly of parts and vehicles, maintenance and repair, and disposal.

GHGs and CEFs The pollutants (greenhouse gases, or GHGs) that are includ the analysis of CO_2-equivalent emissions, and the CO_2- equivalency factors (CEFs) used to convert non-CO_2 GHGs to equivalent amount of CO_2 (IPCC = factors approved by the Intergovernmental Panel on Climate Change [IPCC]; my CEF are those derived in Appendix D).

Infrastructure The lifecycle of energy and materials used to make and ma infrastructure, such as roads, buildings, equipment, rail lin so on. (In most cases, emissions and energy use associate the construction of infrastructure are smalled compared v emissions and energy use from the end use of transportat fuels.)

Price effects This refers to the relationships between prices and equilib final consumption of a commodity (e.g., crude oil) and an “ change in supply of or demand for the commodity or its substitutes, due to the hypothetical introduction of a new technology or fuel.

Structure of studies 1-4

Project	GM -ANL U. S.	GM –LBST Europ	MIT 2020	EcoTraffic
Region	North America	Europe	based on U. S. dat	weighted to Europe
Time frame	near term (about 2010)	2010	2020	between 2010 ar 2015
Transport mode	LDV (light-duty truck)	LDV (European mini-van)	LDV (mid-size family passenger car)	LDVs (generic sma passenger car)
Vehicle drivetra	ICEVs, HEVs, BPEVs, FCEVs	ICEVs, HEVs, FCEVs	ICEVs, HEVs, BPEVs, FCEVs	ICEVs, HEVs, FCEVs
Fuels	gasoline, diesel, naptha, FTD, CNG, methanol, ethanol CH2, LH2, electricity	gasoline, diesel, naptha, FTD, CNG, LNG, methanol, ethanol, CH2, LH2	gasoline, diesel, FTD, methanol, CNG, CH2, electricity	gasoline, diesel, FTD, CNG, LNG, methanol, DME, ethanol, CH2, LH2
Feedstocks	crude oil, NG, coal crops, ligno-cellulosic biomass renewable and nuclear power	crude oil, NG, coal crops, ligno-cellulosic biomass waste, renewable and nuclear powe	crude oil, NG, renewable and nuclear power	crude oil, NG, ligno-cellulosic biomass, waste

Structure of studies 1-4, cont.

Project	GM -ANL U. S.	GM –LBST Europ	MIT 2020	EcoTraffic
Vehicle energy-modeling, including drive cycle	GM simulator, U. S. combined city/ highway driving	GM simulator, European Drive Cycle (urban, extra urban driving)	MIT simulator, U. S. combined city/ highway driving	Advisor (NREL simulator), New European Drive Cycle
Fuel LCA	GREET model	LBST E^2 I/O model and data base	literature review	literature review
Vehicle lifecycle	not included	not included	detailed literature review and analys	not included
GHGs [CEFs]	CO_2, CH_4, N_2O [IPCC] (others as non-GHGs)	CO_2, CH_4, N_2O [IPCC]	CO_2, CH_4 [IPCC]	none (energy efficiency study only)
Infra-structure	not included	not included	not included	not included
Price effects	not included	not included	not included	not included

Structure of studies 5-8

Project	ADL AFV LCA	CMU I/O LCA	Japan CO2 from AFVs	LEM
Region	United States	United States	Japan	multi-country
Time frame	1996 baseline, future scenarios	near term	near term?	any year from 197 to 2050
Transport mode	subcompact cars	LDVs (midsize sedan)	LDVs (generic sma passenger car)	LDVs, HDVs, buses, LRT, HRT, minicars, scooters offroad vehicles
Vehicle drivetra	ICEVs, BPEVs, FCEVs	ICEVs	ICEVs, HEVs, BPEVs	ICEVs, BPEVs, FCEVs
Fuels	gasoline, diesel, LPG, CNG, LNG, methanol, ethanol CH2, LH2, electricity	gasoline, diesel, biodiesel, CNG, methanol, ethanol	gasoline, diesel, electricity	gasoline, diesel, LPG, FTD, CNG, LNG, methanol, ethanol, CH2, LH2, electricity
Feedstocks	crude oil, NG, coal corn, ligno-cellulos biomass, renewab and nuclear powe	crude oil, natural gas, crops, ligno-cellulosic biomas	crude oil, natural gas, coal, renewable and nuclear power	crude oil, NG, coal crops, lignocellulos biomass, renewab and nuclear powe

Structure of studies 5-8, cont.

Project	ADL AFV LCA	CMU I/O LCA	Japan CO_2 from AFVs	LEM
Vehicle energy-modeling, including drive cycle	Gasoline fuel economy assumed AFV efficiency estimated relative to this	Gasoline fuel economy assumed AFV efficiency estimated relative to this	none; fuel economy assumed	simple model, U. S combined city/highway driving
Fuel LCA	Arthur D. Little emissions model, revised	own calculations based on other models (LEM, GREET..)	values from another study	detailed own model
Vehicle lifecycle	not included	Economic Input-Output Life Cycle Analysis software	detailed part-by-part analysis	detailed literature review and analysis
GHGs [CEFs]	CO_2, CH_4, [partial GWP] (other pollutants included as non-GHGs)	CO_2, CH_4, N_2O? [IPCC] (others as non-GHGs)	CO_2	CO_2, CH_4, N_2O, NO_x, VOC, SO_x, PM, CO [IPCC and own CEFs]
Infra-structure	not included	not included	not included	very simple representation
Price effects	not included	not included (fixed-price I/O model)	not included	a few simple quasi elasticities

The Lifecycle Emissions Model (LEM)

- Lifecycle emissions of urban air pollutants and greenhouse-gases
  - -- VOCs, CO, NOx, SOx,PM (BC, OM, dust), CO2, CH4, N2O, H2, CFCs, HFCs, PFCs, individually and as CO2-equivalents
- Lifecycles for fuels, vehicles, materials, bus and rail transit
  - -- “well to wheel” lifecycle for fuels
  - -- “cradle to grave” lifecycle for materials and vehicles
  - -- upstream and infrastructure lifecycles in public transit
- Alternative transportation fuels and vehicles
  - -- LD ICEVs, HD ICEVs,LD battery EVs, LD and HD fuel-cell EVs
  - -- gasoline, diesel fuel, FTD, biodiesel (soy) methanol (NG, coal, biomass), ethanol (corn, grass, wood), CNG, LNG, CH2 and LH2 (water, NG)

Key features of the LEM

- Includes alternative transportation fuels, material and vehicle lifecycles, infrastructure, HDVs, LDVs, public transit, electricity, heating and cooking fuels, and more.
- Has international data for multri-country analysis.
- Includes representations of the global nitrogen cycle, changes in land use, and CO_2-equivalent impact of a wide range of gases.
- Extensive published documentation; 2003 version available at (www.its.ucdavis.edu/people/faculty/delucchi/).
- Can be used to model emissions impacts of complete passenger and freight transportation scenarios.
- Beginning to incorporate price/economic effects into traditional LCA.

Lifecycle stages in the LEM

<u>Fuels and electricity lifecycle</u>

- End use of fuel
- Dispensing of fuels
- Fuel distribution
- Fuel production
- Feedstock transport
- Feedstock production (including land use)

<u>Vehicles and infrastructure lifecycle</u>

- Materials production
- Vehicle assembly
- Maintenance and systems operation
- Lifecycle of transport modes (rail, water, truck, etc.)
- Infrastructure construction

Vehicle fuels and feedstocks in the LEM

Fuel --> ↓ Feedstock	*Gasoline*	*Diesel*	*Methanol*	*Ethanol*	*CNG, LNG*	*LPG*	*CH2, LH2*	*Electric*
Petroleum	ICEV, FCV	ICEV				ICEV		BPEV
Coal	ICEV	ICEV	ICEV, FCV					BPEV
Natural gas		ICEV	ICEV, FCV		ICEV	ICEV	ICEV, FCV	BPEV
Wood, grass			ICEV, FCV	ICEV, FCV	ICEV			BPEV
Soybeans		ICEV						
Corn				ICEV				
Solar							ICEV, FCV	BPEV
Nuclear							ICEV, FCV	BPEV

ICEV = internal combustion engine vehicle; BPEV = battery electric vehicle; FCV - fuel cell electric vehicle

Pollutants and climate effects in the LEM

Pollutant → effects related to global clima	CEF (U.S. 19	CEF (U.S. 20
CO_2 → +R	1	1
CH_4 → +R, −OH, +O_3 (t), +CH_4, +H_2O (s), +CO_2	19	16
N_2O → +R	380	320
CFC-12 → +R, -O_3 (s)	17,300	15,500
HFC-134a → +R	1,780	1,600
O_3 → +R, +CO_2 (plants, soil)	6.0	6.0
PM (black carbon) → +R, clouds	3,490	3,150
PM (organic matter) → -R, clouds	-300	-270
PM (dust) → -R, clouds	-60	-50
CO → −OH, +O_3 (t), +CH_4, +CO_2	9.3	9.1
H_2 → −OH, +O_3 (t), +CH_4	37	36
NMOCs → −OH, ±O_3 (t), +CH_4, +CO_2	3.4 + C	3.1 + C
NO_2 → −CO_2 (plants, soil), +N_2O, +O_3 (t), −CH_4, +PM nitrate → -R	-0.6	4.3
SO_2 → +PM sulfate → -R	-60	-54
H_2O → +R (s), +OH, −CH_4, clouds	n.e.	n.e.

LEM/LCA references

- M. A. Delucchi, *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials*, UCD-ITS-RR-03-17, Institute of Transportation Studies, University of California, Davis, Decembr (2003). With appendices. www.its.ucdavis.edu/people/faculty/delucchi/.

- M. A. Delucchi, “A Lifecycle Emissions Analysis: Urban Air Pollutants and Greenhouse-Gases from Petroleum, Natural Gas, LPG, and Other Fuels for Highway Vehicles, Forklifts, and Household Heating in The U. S.,”*World Resources Review* **13** (1): 25-51 (2001).

- M. A. Delucchi, “Transportation and Global Climate,” *Journal of Urban Technology* **6** (1): 25-46 (1999).

- M. A. DeLuchi, “Emissions from the Production, Storage, and Transport of Crude Oil and Gasoline,” *Journal of the Air and Waste Management Association* **43**: 1486-1495 (1993).

The importance of the upstream fuelcycle: upstream emissions as a percentage of end-use emissions

	RFG *oil*	diesel *oil*	LPG *oil,NG*	CNG *NG*	EtOH *corn*	EtOH *cellul.*	BD *soy*	FTD *NG*	CH2 *water*	CH2 *NG*	MeOH *NG*
CO_2	31	22	14	21	101	-14	65	34	1674	7834	42
NMOC	33	22	39	56	225	31	589	19	10	99	30
CH_4	2356	5050	1537	247	1295	491	15562	5378	3059	8727	3856
CO	4.7	8.4	3.9	3.8	20	19	248	11.6	2.8	21.2	5.1
N_2O	1.9	27.8	1.0	1.5	169	64	7736	34.4	n.a.	n.a.	3.4
NO_x	57	9	33	41	252	154	-38	11	24	80	75
SO_x	716	898	572	503	1346	108	677	175	592	904	317
PM	311	55	565	315	4444	1708	317	13	364	736	192
CO2eq	32	28	16	29	117	3	164	39	852	3801	40

Source: my runs of LEM. Based on 26 mpg LDGV, 6 mpg HDDV, year 2010 parameters. NG = natural gas, BD = biodiesel, cellul. = wood & grass.

The importance of the vehicle lifecycle: LEM estimates of emissions from materials & assembly

Pollutant	Emissions	(g/lb)	Emissions	(g/mi)	Emissions	(% of end use)
	LDGVs	*HDDVs*	*LDGV*	*HDDV*	*LDGVs*	*HDDVs*
CO_2	2,694	2,548	59.7	95.3	18.2%	5.5%
NMOCs	1.80	1.79	0.04	0.07	4.6%	4.1%
CH_4	5.98	5.49	0.13	0.21	292%	196%
CO	7.29	8.22	0.16	0.31	2.2%	1.7%
N_2O	0.08	0.08	0.00	0.00	1.3%	4.1%
NO_x	6.53	6.40	0.14	0.24	17.6%	1.1%
SO_x	6.42	6.78	0.14	0.25	147%	163.6%
PM	3.74	3.95	0.08	0.15	293%	17.5%
CO2eq	2,970	2,926	65.7	105.4	16.0%	5.5%

Source: my runs of LEM. Based on 26 mpg LDGV, 6 mpg HDDV, year 2010 parameters.

Lifecycle GHG emissions from LDVs (g/mi CO_2-equivalent and % changes)

	fuelcycle only	fuel + materials+assembly
Baseline gasoline ICEV	*507 g/mi*	*576 g/mi*
ICEV, diesel (low-sulfur)	+4%	+2%
ICEV, natural gas (CNG)	-28%	-24%
ICEV, LPG (P95/BU5)	-26%	-23%
ICEV, ethanol from corn	+13%	+11%
ICEV, ethanol from cellul.	-57%	-50%
Battery EV, coal plants	-22%	-19%
Battery EV, NG plants	-64%	-55%
FCEV, methanol from NG	-54%	-49%
FCEV, H2 from water	-90%	-80%
FCEV, H2 from NG	-60%	-53%

Source: my runs of LEM. Based on 26 mpg gasoline baseline, U. S. year 2020 parameters.

Lifecycle GHG emissions from HDVs (g/mi CO_2-equivalent and % changes)

	fuelcycle only	fuel + materials+assembly
Baseline diesel ICEV	*4,572 g/mi*	*4,4742 g/mi*
ICEV, natural gas (CNG)	-20%	-19%
ICEV, LPG (P95/BU5)	-19%	-19%
ICEV, methanol from NG	-6%	- 6%
ICEV, FTD from NG	-2%	- 2%
ICEV, biodiesel from soy	+221%	+213%
ICEV, ethanol from corn	+27%	+26%
ICEV, ethanol from cellul.	-60%	-58%
FCEV, methanol from NG	-43%	-42%
FCEV, H2 from water	-87%	-84%
FCEV, H2 from NG	-50%	-49%

Source: my runs of LEM. Based on 3 mpg diesel baseline, U. S. year 2020 parameters.

Contribution of individual pollutants to lifecycle CO_2-equivalent emissions

Heavy-duty diesel buses, US and China

	US 1980 0.330% S	US 2000 0.032% S	US 2020 0.001% S	China 1980 0.450% S	China 2000 0.160% S	China 2020 0.003% S
End use CO_2	25%	37%	72%	18%	18%	55%
Lifecycle CO_2	33%	47%	90%	34%	33%	89%
CH_4	2%	2%	3%	3%	2%	4%
N_2O	0%	1%	3%	0%	0%	3%
CO	7%	7%	4%	7%	7%	4%
NMOC	0%	0%	0%	0%	0%	0%
NO_2	0%	1%	0%	0%	1%	1%
SO_2	-7%	-3%	-4%	-18%	-8%	-6%
PM (BC+OM)	64%	46%	4%	74%	65%	7%
HFC-134	0%	0%	0%	0%	0%	1%

Effect of switching from IPCC GWPs to LEM CEFs

	Δ g/mi (LEM vs. IPCC)	% ch. vs base (IPCC)	% ch. vs base (LEM)
Baseline gasoline vehicle	2.1%	n.a.	n.a.
ICEV, diesel (low-sulfur)	47.5%	-28%	+4%
ICEV, natural gas (CNG)	1.0%	-28%	-28%
ICEV, LPG (P95/BU5)	1.8%	-26%	-26%
ICEV, ethanol from corn	3.7%	+11%	+13%
ICEV, ethanol from cellul.	17.2%	-62%	-57%
Battery EV, coal plants	-8.4%	-12%	-22%
Battery EV, NG plants	-1.8%	-62%	-64%
FCEV, methanol from NG	-1.5%	-52%	-54%
FCEV, H2 from water	15.0%	-91%	-90%
FCEV, H2 from NG	-0.9%	-58%	-60%

Source: my runs of LEM. IPCC GWPs are N2O 310, CH4 21. U. S. year 2020.

Indirect or “upstream” emissions for transit modes

- U. S. studies indicate that station and maintenance energy is ~40% of traction energy for heavy rail, and 25% for light rail. Percentage may be higher in some other countries.
- Some studies suggest that infrastructure energy is 35% of traction energy for heavy rail, and 15% for light rail.

Lifecycle GHG emissions from transport modes (*gpm*, % ch.)

Mode	Fuel (feedstock)	U. S.	Mexico	Chile	China	India	S. Africa
LDV	*gasoline (crude oil)*	*469*	*453*	*342*	*252*	*223*	*685*
LDV	diesel (crude oil)	2%	5%	4%	14%	19%	35%
LDV	ethanol (wood & grass)	-47%	-44%	-37%	-42%	-45%	-47%
LDV	electricity (national mix)	-26%	-47%	-65%	-44%	-23%	-35%
LDV	comp. H2 (NG)	-50%	-54%	-60%	-54%	-50%	-58%
bus	diesel (crude oil)	-24%	-72%	-59%	-52%	-61%	-84%
bus	F-T diesel (NG)	-26%	-74%	-60%	-55%	-63%	-85%
bus	CNG (NG)	-37%	-81%	-70%	-65%	-71%	-90%
bus	biodiesel (soy)	120%	-31%	+16%	+21%	+6%	-60%
rail transit	heavy rail (electricity)	-66%	-86%	-80%	-55%	-22%	-87%
rail transit	light rail (electricity)	-64%	-88%	-89%	-84%	-64%	-89%
mini-bus	diesel (crude oil)	-67%	-67%	-60%	-58%	-52%	-83%
mini-bus	LPG (oil and NG)	-77%	-82%	-78%	-76%	-71%	-91%
mini-car	RFG (crude oil)	-62%	-58%	-48%	-56%	-48%	-66%
mini-car	electricity (national mix)	-80%	-79%	-82%	-75%	-59%	-78%
scooter 2-str.	gasoline (crude oil)	-67%	-59%	-46%	-30%	-49%	-74%
scooter 4-str.	RFG (crude oil)	-80%	-77%	-68%	-58%	-69%	-85%
scooter	electricity (national mix)	-81%	-80%	-81%	-59%	-56%	-83%
nonmotorized	bicycles	-95%	-95%	-93%	-88%	-89%	-96%
nonmotorized	walking	-100%	-100%	-100%	-100%	-100%	-100%

Findings

- The energy use of new fuel-production processes and the relative energy use of advanced vehicles remain the main determinant of lifecycle emissions in most cases.
- The materials lifecycle may differ significantly from one mode to another, and for BPEVs compared with ICEVs, but probably not among advanced HEVs and ICEVs.
- The climatic effects of PM, SOx, and NOx may be important in some cases. (PM may have large positive CEF, but SOx may have countervailing large negative CEF.)
- Land-use impacts and N-cycle impacts can be important in some biofuel lifecycles.
- Failure to consider price/economic effects may not matter much when comparing fossil-fuel-based alternatives with limited co-products, but may matter significantly in most other cases.

Overall conclusion

- Conventional LCAs of energy use and emissions may reasonably well represent differences between similar alternatives, but needs further development to adequately represent differences between transport modes or between dissimilar fuel production pathways (such as biofuels vs. fossil fuels).

Lifecycle research areas

- Incorporation of price-dynamic economic effects of transportation policies on use of (and hence emissions from) vehicles and fuels (exploratory project with USDOE completed).
- More detailed treatment of byproducts and coproducts (related to above).
- More detailed and better documented treatment of biomass and land use in fuelcycles (partly finished; USDOE funding).
- Better estimates of CO_2-equivalency factors for PM, SOx, and NOx.
- Incorporation of more formal treatment of uncertainty.
- Routine updating of emissions and input/output parameters.
- Better treatment of energy use and emissions associated with infrastructure.
- New vehicle/energy pathways (e.g., HEVs, bio-derived hydrogen, carbon sequestration).