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Calculators for Estimating Greenhouse Gas Emissions from Public Transit Agency Vehicle Fleet Operations

ABSTRACT

This paper reviews calculation tools available for quantifying the greenhouse gas emissions associated with different types of public transit service, and their usefulness in helping a transit agency to reduce its “carbon footprint” through informed vehicle and fuel procurement decisions. Available calculators fall into two categories: registry/inventory based calculators most suitable for standardized voluntary reporting, carbon trading, and regulatory compliance; and life cycle analysis calculators that seek comprehensive coverage of all direct and indirect emissions. Despite significant progress in calculator development, no single calculator yet contains all of the information needed by transit agencies to develop a truly comprehensive, life cycle analysis-based accounting of the emissions produced by its vehicle fleet operations, and for a wide range of vehicle/fuel technology options.

INTRODUCTION

Public transportation systems offer unique and significant opportunities for mitigation of transportation sector greenhouse gas (GHG) emissions. Recent empirical studies show that the presence of mass transit systems in our larger cities has encouraged more resource efficient land use and personal activity patterns (*1*), and if public transit's mode share can be increased by a few percentage points, it can lead to considerable GHG reductions (*2*, *3*).

Effective management of GHG emissions associated with public transportation systems is important for several reasons. As major fleet operators and builders of extensive infrastructure systems, public transit agencies have an opportunity to demonstrate and highlight the benefits of a wide range of GHG emission reduction practices through both their day-to-day operations as well as their capital programs. Since the 1970 Clean Air Act the nation's transit agencies have served as test beds for emissions reducing vehicle technologies. With the addition of GHGs to the list of emissions to be controlled for, transit agencies can provide leadership in society's efforts to develop more environmentally benign transportation systems (*4*). And in addition to providing energy and emissions efficiency benefits to society at large, successful carbon management practices can bring some immediate rewards to the transit agency itself: by helping to market services to environmentally conscious riders, by reducing the costs of purchased energy, by making the agency more attractive to federal grant programs (*5*, *6*), and by preparing the agency for participation in climate change registries (*7*, *8*) and carbon trading schemes (*9*) that offer funding opportunities for GHG emissions reductions.

This paper examines publicly available GHG emissions calculators that can be used by transit agencies to evaluate vehicle and fuel alternatives. These calculators fall under two main categories, each one reflecting different emerging needs of transit agencies for GHG reporting:

1. Registry/inventory based calculators, most suitable for standardized voluntary reporting, carbon trading, and regulatory compliance.
2. Life cycle analysis (LCA) calculators, most suitable for pursuit of government funding and for demonstrating the benefits of transit over private automobile travel, or the advantages of one type of transit sub-mode or vehicle type over another.

Though reporting and analysis methods differ between these two categories of calculators, and while most transit agency decision-making contexts warrant an evaluation of GHG emissions (*10*), most attention is given to the GHG (and energy) savings resulting from the use of alterative vehicle/fuel combinations that have immediate relevance to vehicle fleet and fuel procurement decisions. Federal data collection and reporting requirements, notably through the National Transit Database (NTD), support the quantification of these actions by collecting fuel consumption, electricity use, and vehicle miles of travel data (*11*). Inventory-based calculators are found to be generally consistent in their approach to GHG emissions quantification; however, their more limited focus constrains their use for comprehensive GHG emissions estimation. LCA calculators, in contrast, represent a growing attention to the "upstream" and "downstream" GHG emissions associated with the complete vehicle and fuel supply chains.

The review begins with a juxtaposition of calculator outputs with agency reporting needs. The paper then discusses the analysis scopes of the calculators in terms of the types of GHG emissions reported, the life cycle analysis boundaries, the modal coverage, and the fuel/energy coverage. Next is a presentation and explanation of the calculation methods employed by the calculators, which includes a discussion of data needs and limitations. Based on the results presented, this paper concludes with a discussion of the need for a consistent accounting and calculation approach for transit agency GHG emissions management.

OVERVIEW OF AVAILABLE CALCULATORS

Tables 1 and 2 list the GHG emissions calculators found by a literature search of published sources. The literature search for calculators was conducted through three approaches: 1) a search for calculators referenced in public transportation research literature; 2) a search for calculators available on the Internet; and 3) a recall of calculators used by the authors in previous research. Only calculators either directly supporting or capable of relatively easy adaptation to transit vehicle applications in the U.S. are included. A calculator was considered if it incorporated vehicle and/or fuel systems used by transit agencies, and if it produced emissions estimates for any of the six Kyoto Protocol GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), or sulfur hexafluoride (SF_6). Some calculators requiring special memberships or user fees, such as the ISO 14064 Greenhouse Gases series of standards, or the International Council for Local Environmental Initiatives Clean Air & Climate Protection 2009 software, were not available for review. The term ‘calculators’ is used here in its broadest sense, inclusive of guidance reports, spreadsheets, online calculators and downloadable software tools. The guidance reports typically provide instructions on how to perform GHG emission calculations for various combinations of input data. These instructions normally include guidance on the preferred hierarchy of calculation methods; calculation formulae; default emissions factors by vehicle and fuel technology; and example calculations. Guidance specifically for transit agencies is available from the American Public Transportation Association’s (APTA) Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit (*12*), which references several of the guidance reports. Spreadsheet resources, such as the U.S. EPA’s Simplified GHG Emissions Calculators (*13*), generally enable calculations through built-in formulae and default or user-entered emission factors. Online calculators, for example The Climate Registry Information System (*14*), provide similar functionality through an internet web browser, while downloadable software programs typically provide a calculation capability based on a significantly larger number of user inputs, selections, or reference data sets.

TABLE 1: Inventory GHG Emissions Calculators for Revenue Transit Vehicles and Fuels

Calculator	Format	Output
World Resources Institute (WRI): The Greenhouse Gas Protocol (*15*), Calculating CO2 Emissions from Mobile Sources GHG Protocol Tool for Mobile Combustion, V2.0 Indirect CO2 Emissions from Purchased Electricity GHG Protocol Tool for Purchased Electricity, V4.0	guidance report and spreadsheets	Total metric tonnes of CO2e. For each mode: metric tonnes of CO2, kg of CH4, kg of N2O, metric tonnes of biofuel CO2e.
The Climate Registry (TCR): General Reporting Protocol V1.1 (*7*) The Climate Registry Information System (CRIS) (*14*), Mobile Combustion Emissions from Electricity Use Fugitive Emissions from the Use of Refrigeration and Air Conditioning Equipment	guidance report and online forms	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total metric tonnes of CO2e.
California Climate Action Registry (CCAR): General Reporting Protocol V3.1 (*16*), Direct Emissions from Mobile Combustion Indirect Emissions from Electricity Use Direct Fugitive Emissions from Refrigeration Systems	guidance report	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total metric tonnes of CO2e.
International Council for Local Environmental Initiatives (ICLEI): Local Government Operation (LGO) Protocol (*17*), Vehicle Fleet (Mobile Combustion) Vehicle Fleet (Fugitive Emissions from Motor Vehicle Air Conditioning) Electricity Use	guidance report	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total lbs or kg of CO2e.
Environmental Defense Fund (EDF) / NAFA Fleet Management Association Fleet Greenhouse Gas Emissions Calculator (*18*)	guidance report and online forms	Total metric tonnes of CO2, CH4, N2O, and HFCs.
U.S. EPA Climate Leaders: Cross Sector Guidance (*13*) Simplified GHG Emissions Calculator: Direct Emissions from Mobile Combustion Sources Indirect Emissions from Purchase of Electricity Direct Emissions from Refrigeration and Air Conditioning Equipment	guidance reports and spreadsheets	For each fuel, total kg of CO2. For each fuel and vehicle, g of CH4, g of N2O. Total metric tonnes of CO2e, biomass CO2e. For electricity, total lb of CO2, lb of CH4, lb of N2O, total metric tonnes of CO2e. For each refrigerant, total lbs or kg of CO2e.

TABLE 2: Life Cycle GHG Emissions Calculators for Revenue Transit Vehicles and Fuels

Calculator	Format	Output
Puget Sound Clean Air Agency & Puget Sound Clean Cities Coalition: Evergreen Fleets Emissions Calculator (*19*)*	online forms	For each vehicle, total tons of CO2
Transport Canada (TC) Urban Transportation Emissions Calculator (*20*)*	guidance report and online forms	For each vehicle type: Kg CO2e (upstream, operation, and total), Kg CAC's, veh-km of annual travel (road vehicles) pass-km of annual travel (non-road vehicles).
Travel Matters , Center for Neighborhood Technology (CNT): Transit Planning Calculator (*21*)*	online forms and spreadsheets	Total annual lbs CO2 by mode, lbs CO2/mile by vehicle type,
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fleet Footprint Calculator 1.0 (*22*)*	spreadsheet with user guide	Total short tons of CO2e and barrels of petroleum used
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fuel-Cycle Model 1.8c.0 (*23*)*	software and reference spreadsheets	For each fuel type: well-to-pump Btu/mmBtu of energy consumption, g/mmBtu of CO2e, CO2, CH4, and N2O, well-to-wheel Btu/mile of energy consumption, and g/mile of CO2e, CO2, CH4, and N2O.
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Vehicle-Cycle Model 2.7 (*24*)	spreadsheets	For each vehicle type: well-to-pump, vehicle cycle, vehicle operation, and total Btu/mile of energy consumption, and g/mile of CO2e, CO2, CH4, and N2O
Lifecycle Emissions Model (LEM) (*25*)	software	For each combination of vehicle type and fuel type process: well-to-pump g/GJ of CO2e, CO2, CH4, N2O, and HFC-134a, lifecycle g/mi of CO2e, CO2, CH4, and N2O, and HFC-134a
GHGenius 3.15 (*26*)	spreadsheets	For each combination of vehicle type and fuel type process: well-to-pump g/GJ of CO2e, CO2, CH4, N2O, HFC-134a, lifecycle g/km of CO2e, CO2, CH4, N2O, and HFC-134a
Economic Input-Output Life Cycle Analysis (EIO-LCA) (*27*)	online forms	Per $1M of economic activity and for each sector: total metric tonnes of CO2e and total CO2e of CO2, CH4, N20, and CFCs
U.S. EPA: Motor Vehicle Emission Simulator (MOVES) (*28*)*,**	software	CO2e and total energy consumption

* Partial life cycle: upstream fuel emissions
** MOVES is currently available in a draft version, but a complete version is scheduled to officially replace MOBILE 6.2 as the U.S. EPA’s on-road, mobile source, emission factor software.

SCOPES, METHODS, AND REPORTING PRACTICES

Emissions Reporting

The suitability and utility of a GHG emissions calculator depends upon the emissions reporting needs of the user. As noted earlier, in terms of emissions reporting, there are two main types of calculators: GHG emissions inventory calculators (see Table 1) and life cycle GHG emissions calculators (see Table 2). Inventory calculators are designed for a broad user-base of corporations and municipalities and support the quantification of total agency end-use GHG emissions, which may be reported to a voluntary data registry (U.S. EPA's Climate Leaders program) or a registry for carbon credit trading (such as the Chicago Climate Exchange). The inventory calculators that are based on a reporting protocol are designed to be consistent in their approach to GHG emissions estimation (*7, 15, 16, 17*). Life cycle calculators quantify not only end-use GHG emissions, but also upstream and/or downstream GHG emissions associated with the provision (and disposal) of fuels and vehicles. LCA calculators may enable the evaluation of government sponsored initiatives to reduce full life cycle emissions from transit agency operations. The LEM model is one of the first developed for life cycle emissions analysis and is the base model for the more recently created GHGenius. The GREET models listed in Table 2 provide emissions factor data that are used by many of the other life cycle calculators.

The inventory calculators that are based on a reporting protocol (*7, 13, 15, 17*) follow what has become a standard "three-scope" division of emissions: direct emissions controlled by the agency (Scope 1), indirect emissions that occur outside of the agency (Scope 2), and "optional" emissions (Scope 3). With respect to revenue transit vehicle emissions, vehicle fuel combustion and refrigerant leaks fall under Scope 1, purchased electrical energy falls under Scope 2, and upstream and downstream vehicle and fuel life cycle emissions fall under Scope 3. The assumption of Scopes 2 and 3 is that these emissions would be accounted for as Scope 1 emissions by the organizations or entities that directly control them.

In addition to serving the requirements of emissions reporting, the calculator outputs should support an internal evaluation of the emissions efficiency of fuel and vehicle procurement decisions. Evaluation of emissions efficiency may be accounted for in terms of energy inputs (GHG's per equivalent unit of fuel), operational activity (GHG's per unit of distance), or service output (GHG's per passenger-distance). A passenger-mile based metric provides a widely applicable normalization that allows for comparison of GHG emissions efficiencies across modes.

Most GHG emissions calculators estimate only the total quantity of GHG emissions (see Tables 1 and 2). Among the calculators identified in Tables 1 and 2, the GREET Fuel-Cycle Model, LEM, and GHGenius normalize GHG emissions estimates by available energy (*23, 25, 26*). Many of the life cycle calculators provide distance normalized outputs of GHGs (*20, 21, 23, 24, 26*). Transport Canada's Urban Transportation Emissions Calculator estimates passenger-distance normalized GHG emissions, however, it does so only for non-road modes (*20*). While many of the calculators do not normalize GHG emissions, normalization may be possible through input data used to generate estimates of total GHG emissions. For example, in a mobile emissions calculator in which CH_4 and N_2O emissions are estimated from VMT data (either historical or forecasted), the same VMT data may be used to normalize the emissions. In the case of a purchased electricity calculator, GHG emissions calculations will not require VMT or PMT data, but normalization of the calculation results will require the collection of such data. For a more comprehensive outline of the motivation, analysis boundaries, reporting scopes, data requirements, and calculation outputs for GHG emissions reporting, transit agencies should refer to APTA's recommended practices (*12*).

Calculator Analysis Scopes

Types of GHG Emissions

With nearly 95% of transportation GHG emissions attributable to CO2 emissions (*29*), calculation tools have paid most attention to this pollutant. Other relevant GHGs are N_2O and CH_4, both of which are emitted in small amounts from highway vehicles. Using conversion factors to obtain the relative "Global Warming Potentials" (GWP) of each of these GHGs (*30*), it is now common practice to convert all GHGs into CO_2 equivalents, or CO2e, and to draw comparisons among different GHG emitters or different GHG mitigation strategies on the basis of the total mass of CO2e they produce. Most calculators use IPCC recommended GWPs. The 2007 IPCC Fourth Assessment Report now recommends CH_4 and N_2O GWPs of 25 and 298, respectively (*30*).

Other GHG emissions of concern to transit properties are PFCs and HFCs, which originate from transit vehicle air conditioning systems that use refrigerants for vapor-compression refrigeration. These are both very effective absorbers of infrared radiation, so that even the leakage of small amounts of these three gases is a concern. Fugitive refrigerant emission calculators include GWP data from the IPCC and the American Society of Heating Refrigerating & Air-conditioning Engineers (ASHRAE). While many existing transit vehicle air conditioning systems utilize R-22 as a refrigerant, none of the calculators contain R-22 GWP data. The rationale for omitting this information is that R-22 is not included in the Kyoto Protocol (*17, 31*), and that the Montreal Protocol prohibits the sale of new air-conditioning equipment with R-22 beyond January 1, 2010. Despite the impending ban from new equipment use, R-22 for equipment servicing is allowed by the Montreal Protocol until January 1, 2020, and recovered and recycled R-22 may be used beyond that date. Many existing R-22 units will continue to be in operation (and be serviced) on transit vehicle fleets, so transit agencies will need to obtain GWP data for R-22 and any other legacy refrigerants from ASHRAE Standard 34. Life cycle calculators do not contain R-22 data since they focus on passenger cars, which use either CFC-12 or HFC-134a (*26*). The EIO-LCA model allows users to approximate lifecycle PFC and HFC emissions (*27*). A number of the life cycle calculators (*23*, *24*, *26*) also account for sulfur hexafluoride (SF_6), which leaks from electrical insulating fluid in power distribution equipment involved in upstream processes. Like PFCs and HFCs, SF_6 emissions carry with them very high GWP multipliers.

Another important type of emission accounted for in some calculators (see Tables 1 and 2) is biomass GHG emissions. While direct combustion of biofuels does not contribute much to a net addition of CO_2 to the atmosphere, a number of the life cycle calculators (*23*, *24*, *26*) recognize that the manufacture of biofuels involves processes, such as industrial farming operations and fuel distribution, that do produce fossil fuel GHG emissions, and appropriately account for these fractional non-biomass emissions. In at least one calculator, these biomass and fossil fuel emissions are aggregated into a total mass of CO_2 equivalent (CO2e) emissions (*20*).

Life Cycle Analysis Boundaries

Propulsion of a transit vehicle involves not only emissions resulting from the combustion of fuel (or an alternative thermodynamic work-energy process), it also involves emissions released "upstream" of this activity due to the material extraction (mining or harvesting), manufacture, and also delivery of both the vehicles and fuels themselves (e.g. the fuel used to transport the fuel to its pumping station). In addition, transit vehicles and vehicle parts must ultimately be disposed of, leading to additional "downstream" emissions. Collectively, these often termed "indirect" upstream and downstream material and transport processes involve considerable GHG emissions, and the decisions that transit agencies make with respect to vehicle and fuel procurement can therefore have a significant impact on total emissions produced. The life cycle calculators presented in this paper are generally comprehensive in their coverage of upstream and downstream emissions, whereas the inventory calculators are more focused on direct combustion emissions and fugitive emissions of high GWP refrigerants. The focus away from upstream emissions in inventory calculators is due to the underlying reporting protocols that consider upstream emissions calculations to be optional.

Although inventory calculators account for plant efficiency losses in the production of purchased electricity, considerable upstream GHG emissions are neglected. For purchased electricity emissions, inventory calculators utilize data from the U.S. EPA's eGRID database of electrical power generation emission factors (*32*). The eGRID emission factors include neither upstream fuel extraction, refining, and transportation-related GHG emissions, nor GHG emissions associated with electrical energy transmission and distribution (T&D) losses. GHG emission registry protocols stipulate that that energy transmission and distribution losses are to be reported only if the reporting organization controls the transmission and distribution network (*7, 15, 17*). Electrical T&D networks experience line losses on the order of 10 percent of plant generated power (*33*) and the effect is a net increase in GHG emissions per MWh of electrical energy delivered to the agency. Transit agencies have little control over T&D losses on power grids. However, the emissions associated with such losses must be understood in order to evaluate properly mode and vehicle technology alternatives during the planning of fixed guideway services or to evaluate the development of onsite power generation alternatives.

Life cycle calculators can provide an explicit and detailed analysis of GHG emissions from upstream material and energy processes for both vehicles and fuels. Several life cycle calculators account for upstream fuel emissions, but neglect the upstream emissions related to the vehicles themselves (*19, 20, 21, 28*). The GREET Vehicle-Cycle Model includes upstream emissions, as well as downstream emissions from vehicle disposal processes (*24*). LEM and GHGenius uniquely account for disposal of nuclear and coal power plant waste products (*25, 26*). The recent report by Chester and Horvath employs the EIO-LCA model to provide one of the most detailed analyses to date on the life cycle emissions of on-road and rail transit vehicles (*34*).

Modal Coverage

The scope of vehicles covered by a GHG emissions calculator affects the accuracy of the emissions estimated from vehicle activity data (discussed in the calculation methods portion of this paper), and it also affects the degree to which emissions from alternative vehicle types may be evaluated and compared. Ideally, a calculator would include all possible modes and vehicle types operated by a transit agency, but no such calculator was found to exist. Tables 3 and 4 show the vehicle types included in each of the calculators identified in this paper (vehicle types considered to be non-applicable to transit agency fleet operations such as motorcycles, agricultural equipment, and aircraft were omitted). Most of the calculators are not designed exclusively for transit vehicle fleets and therefore include a diverse set of vehicles. Very few calculators (*15, 21, 22*) differentiate between types of bus or rail transit vehicles, and those that do generally classify transit vehicle types differently. Some of the calculators do not explicitly include transit vehicles (*18, 19, 23, 27*), yet contain vehicle types such as heavy duty vehicles, heavy vans, locomotives, ships, or boats which may approximate an agency's vehicle types. Transit agencies should be aware that the calculation spreadsheets are generally ambiguous in their definitions of (and emissions calculation methods for) the included transit vehicle types (*15*).

TABLE 3: Vehicle and Fuel Types Covered by GHG Emissions Calculators

Calculator	Vehicle Types	Fuel Types
WRI: The Greenhouse Gas Protocol (*15*) Calculating CO2 Emissions from Mobile Sources	local bus, coach, freight truck, light rail, tram, subway (gasoline, diesel, CNG, ethanol) bus. (gasoline, diesel) passenger car, light goods vehicle. (diesel) locomotive. (gasoline, diesel, CNG, LNG, LPG, ethanol) heavy duty vehicle.	gasoline, diesel, residual fuel oil, LPG, CNG, LNG, ethanol, B100, jet fuel, aviation gasoline, E85 (both with biofuel or fossil fuel), B20 (both with biofuel or fossil fuel).
TCR: General Reporting Protocol Version 1.1, CRIS, (*7*, *14*) Mobile Combustion *	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
CCAR: General Reporting Protocol V3.1 (*16*), Direct Emissions from Mobile Combustion*	(gasoline, diesel) passenger cars, light trucks, ships, boats. (diesel) locomotives, heavy-duty vehicles. (biodiesel) heavy duty vehicles. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
ICLEI LGO Protocol (*17*): Vehicle Fleet (Mobile Combustion)*	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
EDF Fleet Greenhouse Gas Emissions Calculator (*18*)**	(gasoline, diesel, LPG, ethanol, biodiesel, LNG, CNG, electricity) passenger cars, light duty trucks, vans, SUVs, medium and heavy duty vehicles, (gasoline, diesel) ships, boats, other. (diesel) locomotives.	gasoline, diesel, LPG, ethanol, biodiesel, LNG, CNG, electricity.
EPA Climate Leaders: Simplified GHG Emissions Calculator (*13*): Direct Emissions from Mobile Combustion Sources*,***	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (*methanol*, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles. (residual fuel oil) ships, boats.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel, residual fuel oil (#5 and 6), crude oil, *B100*, ethanol, *E100*, *methanol*, LNG, LPG, *propane, ethane, isobutane, n-butane*, CNG.
Puget Sound Clean Air Agency & Puget Sound Clean Cities Coalition: Evergreen Fleets Emissions Calculator (*19*)**	(gasoline, ethanol) small cars, midsize cars, large cars, light vans, heavy vans, pick-up trucks, full size SUV trucks, large >10,000 lbs trucks. (diesel, biodiesel) small trucks, large >10,000 lbs. (hybrid) Prius, Civic, Camry, Escape.	gasoline, E85 (corn), E85 (cellulosic), diesel, B99, B75, B50, B20, B5.

*CH4 and N2O calculations are limited to combinations of vehicles and fuels shown in vehicle type field, where fuels are shown in parentheses, followed by the vehicles available for the fuel type. CO2 calculations are performed for any vehicle shown
** Calculations are limited to combinations of vehicles and fuels shown in vehicle type field, where fuels are shown in parentheses, followed by the vehicles available for the fuel type.
***Fuels shown in italics are not available in the spreadsheet calculator, but are available in calculation guide.

TABLE 4: Vehicle and Fuel Types Covered by GHG Emissions Calculators (continued)

Calculator	**Vehicle Types**	**Fuel Types**
TC Urban Transportation Emissions Calculator (*20*)	light-duty passenger vehicles, light-duty commercial vehicles, medium-duty commercial vehicles, heavy-duty commercial vehicles, public transit buses, public transit trolley buses, light rail, subway/metro, heavy rail (diesel-fuelled) commuter rail.	gasoline, diesel, propane, CNG, LNG, E10, E85, M85, ED10, B100, hybrid, plug-in hybrid, electric vehicle, fuel cell.
LEM (*25*)	Light-duty passenger cars, battery-powered electric vehicles, fuel-cell vehicles, full-size buses, mini-buses, mini-cars, heavy-rail transit, light-rail transit, medium and heavy-duty trucks, diesel trains.	gasoline, methanol, ethanol, diesel, biodiesels, CNG, LNG. Electricity: coal, petroleum, NG, nuclear, solar, biomass, hydro.
GHGenius 3.15 (*26*)	For fuel calculations: light duty vehicle, heavy duty vehicle, bus, truck. For vehicle calculations: passenger cars, light trucks, other.	gasoline, methanol, ethanol, butanol, petrol diesel, FT diesel, biodiesels, H2, CNG, LNG. Electricity: coal, fuel oil, NG, nuclear, wind, biomass, hydro, other.
EIO-LCA (*27*)	automobile, light truck, heavy duty truck, railroad rolling stock, ships, boats.	petroleum (oil and gas), electricity.
GREET Fuel-Cycle Model 1.8c.0 (*23*)	passenger cars, light duty vehicles 1, light duty vehicles 2.	gasoline, diesel, CARFG, LPG, Crude Naptha, CNG, LNG, Methanol, DME, FTD, Naptha, LPG, E5-10, E50-90, E100, gaseous hydrogen, liquid hydrogen, biodiesel. Electricity: residual oil, natural gas, coal, nuclear power, biomass, other. Ethanol: corn, woody biomass, herbaceous biomass, corn stover, forest residue, sugar cane.
GREET Fleet Footprint Calculator 1.0 (*22*)	school bus, transit bus, shuttle/paratransit bus, transport/freight truck, medium/heavy duty pickup truck, other.	gasoline, diesel, biodiesel (B100), corn ethanol (E100), cellulosic ethanol (E100), CNG, LNG, LPG, liquid hydrogen, gaseous hydrogen. Electricity: residual oil, natural gas, coal, nuclear power, biomass, wind/solar/hydro.
GREET Vehicle-Cycle Model 2.7 (*24*)	For both passenger car and SUV (conventional or lightweight materials): internal combustion engine vehicle, hybrid electric vehicle, fuel-cell vehicle.	Process fuels: residual oil, diesel, natural gas, coal, electricity.
Travel Matters, Center for Neighborhood Technology: Transit Planning Calculator (*21*)	Online form: Vehicles reported by transit agency on Form 408 (Revenue Vehicle Inventory Form) for NTD 2002 data report. Spreadsheet: Bus, commuter rail, heavy rail, light rail/trolleybus.	Online form: (bus and van): diesel, B20, biodiesel, CNG, Electro-diesel, ethanol, fuel-cell/natural gas, fuel-cell/electrolysis. (rail electricity): biomass, coal, gas, geothermal, hydro, nuclear, oil, solar, wind, other. Spreadsheet: (bus) diesel, B20, CNG/LNG, Electricity, fuel-cell/electrolysis. (rail) electricity.
U.S. EPA: MOVES (*28*)	intercity bus, light commercial truck, motor home, passenger car, passenger truck, school bus, transit bus. Alternative Vehicle and Fuel Technologies: conventional internal combustion (IC), advanced IC, moderate hybrid - conventional IC, full hybrid - conventional IC, hybrid - advanced IC, moderate hybrid - advanced IC, full hybrid - advanced IC, electric, fuel cell, hybrid - fuel cell.	CNG, diesel fuel, electricity, E85, gasoline, LPG.

The GREET Fuel-Cycle Model software does not include transit vehicle types; however, the reference spreadsheet can be used to model transit modes by modifying fuel economy values and tracing the calculation steps across the various worksheets (*23*). Similar modification is necessary for use of the GHGenius spreadsheet for transit vehicles (*26*). Furthermore, the GREET Vehicle-Cycle Model spreadsheet does not include transit vehicles, but can be used to model transit modes by entering appropriate vehicle composition and weight data (*24*). The GREET Fleet Footprint Calculator explicitly includes transit vehicles, but the calculator contains limited functionality for modeling upstream emissions (*22*). In many of the calculators, CH_4 and N_2O emissions calculations are limited to subsets of the vehicle types covered (see notes for Table 3).

Fuel/energy Coverage

In addition to vehicle scopes, Tables 3 and 4 show the various fuels for each of the calculators. The calculators vary considerably with respect to the included alternative fuels. Some calculators accommodate additional fuel types by allowing the user to customize fuel emission factors (*15, 27*), but for the most part, the fuels included are tied to particular default emissions factors and compatible vehicle technologies. The GREET and GHGenius calculators provide users with the most detailed capability for modeling various combinations of energy feedstocks, provided that the user is able to obtain feedstock data. The level of detail and accuracy of GHG emissions calculations depends upon the transit agency's records of fuel consumption data. APTA provides data collection and utilization hierarchies for maximizing the accuracy of GHG emissions calculations (*12*).

Calculation Methods

Although different methodologies are used to estimate GHG emissions from different processes, the calculators are generally consistent in the calculation methodologies within processes. In cases where emissions may be calculated by one or more possible methods, such as mobile direct emissions, inventory calculators define a calculation method hierarchy according to the increasing or decreasing accuracy of the GHG emissions estimation method, thus showing a tradeoff between accuracy and data availability.

Estimating Mobile Direct Emissions

Two main approaches are used by the calculators to estimate mobile combustion GHG emissions, one based on the amount of fuel used and the other based on the amount of vehicle-miles travelled.

Fuel Use For estimating CO_2 emissions from mobile combustion, the most accurate method is to estimate by the volume of fuel used, the measured carbon content of the fuel per unit of energy (or per unit of volume or mass), and the measured heat content (or density) of the fuel used, represented as:

$$E_{CO2} = F \text{ x } R \text{ x } K \text{ x } (44/12) \tag{1}$$

where E_{CO2} = emissions of CO_2 [kg]
F = fuel use [gal]
R = heat content [Btu/gal] (or fuel density [kg/gal])
K = carbon content [kg C/Btu] (or [kg C/kg fuel])

According to the U.S. EPA, "carbon content factors based on energy units are less variable than carbon content factors per mass or volume units because the heat content or energy value of a fuel is more closely related to the amount of carbon in the fuel than to the total physical quantity of fuel" (*13*). Transit agencies report fuel consumption data to the National Transit Database (NTD) and thus should have this data available for CO_2 emissions calculation (*35*). Some of the calculators facilitate the estimation of fuel consumption from fuel cost data (*17, 19*). Fuel consumption data as well as fuel heat content and fuel density data may be obtained from fuel suppliers. Fuel density varies inversely with temperature, so fuel density and thus CO_2 emissions will vary seasonally for a given volume of fuel combustion. In the absence of measured heat content or fuel density data from the fuel supplier, default data may be used from the U.S. EPA or IPCC, and many calculators include some form of this data.

The estimation of the CO_2 emissions for a bus fleet merely requires fuel consumption and fuel emission factor data for the fleet as a whole. However, the evaluation of the CO_2 emissions of various bus propulsion technologies within a transit fleet requires either segmented fuel consumption data for each vehicle type, or both vehicle-specific fuel economy and VMT data for estimating each vehicle type's fuel consumption.

CH_4 and N_2O emissions may also be estimated by multiplying the amount of fuel used by the vehicle fuel economy, and a distance-based emission factor, represented as;

$$E_{CH4} = F \ x \ M \ x \ G \quad (2)$$

where E_{CH4} = emissions of CH_4 [g]
F = fuel use [gal]
M = vehicle fuel economy [miles/gal]
G = emission factor [g CH_4/mile]

CH_4 and N_2O emissions factors are distance-based since these emissions are highly dependent on vehicle-specific engine and fuel technologies. Several calculators contain various portions or derivations of vehicle-specific fuel efficiency and emissions factors data from the U.S. EPA (*7, 13, 15, 17*).

Vehicle Miles Traveled (VMT) Both inventory and life cycle GHG emission calculators for estimating CH_4 and N_2O emissions prefer to use VMT data, since these emissions are considerably dependent upon vehicle type and vehicle activity. Unlike CO_2 emissions which are simply the result of the degree of combustion and the carbon content of fuels, CH_4 and N_2O emissions are a complex function of combustion dynamics that vary between vehicle and fuel-types. Fleet managers should be aware that CH_4 and N_2O emissions can be significantly higher for alternatively fuelled vehicles. For example, biofuels produced from nitrogen-rich, fossil fuel-based fertilizers can produce higher emissions of N_2O, which have a much higher GWP than CO_2. CH_4 and N_2O emissions may be estimated by multiplying VMT by vehicle/fuel technology-specific, distance-based emission factors, represented as:

$$E_{CH4} = V \ x \ G \quad (3)$$

where E_{CH4} = emissions of CH_4 [g]
V = VMT [miles]
G = emission factor [g CH_4/mile]

The emission factors are produced by the U.S. EPA (*36*) and are published in emission calculation resources at various levels of vehicle and fuel-type detail. If fuel usage data is unavailable for a particular vehicle type, CO_2 emissions may be estimated by dividing VMT data for each vehicle type by the corresponding fuel economy data from the U.S. EPA, which is typically included within the calculators. From this fuel usage estimate, CO_2 emissions may be calculated using Equation 1. One should be aware that the fuel economy data provided by the U.S. EPA may deviate substantially from the fuel economy rates experienced in actual duty cycles (*37*).

Estimating Purchased Electricity Direct Emissions

Much of the electricity used to propel transit vehicles is purchased from electric power utilities. Calculators for purchased electricity GHG emissions use metered electrical power usage data and power generation emission factors. In some calculators, electrical power generation emissions are estimated from VMT inputs and imbedded values for vehicle energy efficiency (*15, 20*). Nearly all U.S. GHG emissions inventory calculators for purchased electricity utilize regional electrical power generation emission factors (lbs GHGs/MWh) from the EPA's eGRID database (*32*). Regional electric power generation emission factors are average emission factors of electrical power plants within a defined statewide or multi-state region. It should be noted that an averaged regional emission factor may deviate substantially from the actual emission factor associated with an end user at a particular point within the region, and calculator users may enter generator-specific emission factors if available. In a recent unpublished study of emissions from the Metropolitan Atlanta Rapid Transit Authority's (MARTA) heavy rail operations, for example, emission factors for each of the nine power plants supplying electricity to MARTA heavy rail operations were weighted in proportion to the amount of power supplied from each. The emission factor data was collected from the Georgia Environmental Facilities Authority and the U.S. EPA. The averaged CO_2 emissions factor from the local power plants was 2,040 lbs CO_2/MWh, whereas the eGRID subregion emission factor for SERC South, which includes Atlanta, GA, is 1,490 lbs CO_2/MWH – a relative difference of over 30 percent.

In measuring the GHGs produced by electricity powered transit services, the mix of fuel feedstocks used to produce the electricity is the key variable (i.e. the mix of high carbon content coal or petroleum versus very low carbon emitting nuclear or hydro power systems). Since this mix of electricity feedstocks varies a good deal by region of the country, so too does the carbon intensity of the electricity used to power grid-connected transit vehicles. The carbon intensity of electrical power production may also vary between peak and off-peak production periods. Between peak and off-peak power demand periods, changes in the carbon intensity of electrical power may occur in two ways: 1) Baseload power plants may be ramped-up to a more efficient level of operation, thereby decreasing GHG emission factors; and 2) Additional power plants with different energy feedstocks may be brought on-line, thereby increasing or decreasing GHG emission factors. Although transit agency fleet operations typically span both peak and off-peak power periods, GHG emission calculators currently do not enable quantification of peak and off-peak variations in electrical power emissions.

An additional source of CO2 emissions factors from electricity generation for the nation's largest 100 metropolitan areas was recently developed by Brown et al (*38*) using proprietary data supplied by Platt Analytics. These data were subsequently used by Southworth and Sonnenberg (*39*), along with electricity consumption data from the NTD, to estimate transit agency carbon emissions associated with rail transit operations within these metropolitan areas.

Estimating Fugitive Refrigerant Emissions

Many transit vehicles have air conditioning systems that use refrigerants for vapor-compression refrigeration, usually CFCs, HFCs, or PFCs. Two methods are usually followed for estimating these emissions: a mass balance of refrigerant use or equipment-based usage (*7, 13, 14, 15, 16, 17*).

Mass Balance The mass balance method accounts for the changes in refrigerant inventory within a defined time period. This approach is the most accurate, but it requires data on stored refrigerant inventory, purchases, sales, returns, recycling, and disposal, both for stand-alone reserves and for charged equipment. Transit agencies may not have sufficient data to perform a complete mass balance; therefore, the equipment-based estimation method may be the method of choice.

Equipment-Based This method utilizes default emission factors for mobile air conditioning equipment from the IPCC (*7*). The emission factors allow agencies to estimate emissions associated with the size, installation, operation, disposal (and refrigerant recovery) of mobile air conditioning equipment. Under the equipment-based estimation method, an agency would need data on the amount of refrigerant charged into new equipment, the proportion of operating time during the year, and the quantity of refrigerant of disposed equipment.

Estimating Upstream/Downstream Emissions

The supply chains of transit vehicles and fuels involve a complex array of upstream material and energy activities that produce GHG emissions. To estimate these emissions most of the life cycle calculators employ a process-based approach, in which input data for each individual activity is used to generate emission outputs that are then aggregated for the given product's life cycle (*23, 24, 25, 26*). The calculations rely upon known quantities of product components, such as the weight of various materials in a vehicle or the proportion of various feedstocks in alternative fuels. The details of each process calculation are too numerous to cover in this paper, and this fact is an indication that the complexity of process-based life cycle calculators may be too onerous for transit agency evaluations of vehicle and fuel procurement alternatives. Nevertheless, these calculators may help transit agencies explore the impact of various energy feedstocks and supply paths on life cycle GHG emissions. To simply examine the significance of upstream processes on GHG emissions, several calculators that use emission factors from process-based models to calculate upstream emissions are available (*19, 20, 21, 28*), although few calculators delineate the upstream emissions from the direct emissions. Transport Canada's Urban Transportation Emissions Calculator uses GHGenius to calculate upstream fuel costs and these are reported separately in the calculator output.

An alternative calculation approach to detailed bottom-up process-based quantification of GHG emissions is offered by the Green Design Institute at Carnegie Mellon University, whose economic input-output life cycle analysis (EIO-LCA) estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy (*27*). The method uses information about the purchase of materials by one industry from other industries, and combines this with information about the direct environmental emissions of industries, to estimate the total emissions produced throughout a supply chain. Since transactions and emissions across all industry sectors are included in the input-output matrix, even small emissions that occur during processing are included. While complex to develop, applying this calculation method is straight-forward for the user, who can use the on-line tool to generate an emissions table (of C02,CH_4,$N_2$0,CFC, and total GWP in CO2e units) for a specific industrial activity. For example, the broad sector “transit and ground passenger transportation” generates over 100 industrial connections with GHG emissions contributions of their own. This inclusivity comes at a price, however, that of accepting the average levels of inter-industry interactions represented by national I-O tables, with a 2002 table the latest available.

A full life cycle analysis of vehicle operating GHG emissions should include the downstream emissions associated with material disposal. The GREET Vehicle-Cycle Model’s downstream analysis, limited to vehicle dismantling, determines the associated emissions from the total vehicle weight and a dismantling energy rate (1.4 million Btu/3,000 lbs), which is derived from Stodolsky et. al. (*40*). Recycling processes are deliberately not included in the downstream analysis since emissions associated with material recycling are accounted for in the vehicle production analyses. LEM and GHGenius calculate the downstream emissions associated with the disposal of waste products from nuclear and coal power plants by estimating the material transportation emissions. As with upstream emissions, the EIO-LCA Models estimates material disposal emissions on the basis of associated industry reported emissions per $ of economic activity.

CONCLUSIONS

A number of tools are available to transit agencies for either developing a carbon emissions inventory that is consistent with the accounting standards of several carbon emissions registries, or for analyzing relevant vehicle and fuel life cycle GHG emissions. Quantifying GHG emissions that occur upstream or outside of the operations controlled by the agency is generally much more complex, and much more data intensive, than doing the same for direct emissions based only upon in-service vehicle energy consumption. To estimate upstream/downstream emissions transit agencies would need to obtain additional data on fleet vehicle technologies/components and fuel/energy feedstocks, or use national and regional defaults, which may not be representative of a particular agency’s operation. Nevertheless, estimating GHG emissions from external processes like electrical power generation is vital for characterizing the emissions implications of transit agency decisions. The emissions produced by these external processes are often referred to as “indirect” emissions, but it should be understood that these emissions are in fact the direct result of transit agency activities – the boundaries of responsibility should not be confused with the boundaries of consequence.

Recommendations for an Improved Calculator

Though many existing calculators may be drawn upon to develop vehicle and fuel GHG emissions, a fully specified transit LCA calculator that can be adapted easily to handle the wide range of transit vehicles and modes does not currently exist. An improved calculator should model and compile manufacturing, maintenance, and disposal emissions for each of the types of vehicles reported to the NTD. Existing LCA calculators have made some progress, but much more capability is needed, especially for maintenance emissions and for the life cycle of non-road vehicles. A similar compilation or simplification of upstream fuel/energy feedstock data would help to distill existing process-based upstream fuel emissions calculators down to a level of complexity that is more compatible with the level of detail of fuel/energy feedstock data available to fuel procurement personnel. Compilation of life cycle emissions would reduce the data gathering burden on transit fleet managers and would develop consistency in vehicle LCA GHG emissions estimates.

Existing calculators are generally consistent in their approach to estimating emissions from purchased electricity, but the accuracy of the calculators would be much improved if they accounted for T&D losses, utilized either local or statewide (as opposed to multi-state) plant emission factors, where such factors are more representative of the fuel feedstock mix, and accounted for temporal variations in peak and off-peak emission rates. Improvements in the geographic and temporal accuracy of electrical power emissions calculations would benefit the GHG emissions estimation efforts of many organizations beyond the public transportation sector. Unfortunately, such improvements are currently limited by the aggregation of reported power generation emissions data.

One of the important considerations for transit officials is the cost of achieving GHG emissions reductions, which are often measured by cost effectiveness in units of $’s/tonne of CO_2e reduced. Only one of the calculators identified in this review contained an analysis or estimation of emission reduction cost effectiveness (*26*). To be more useful to agency decision makers, an improved calculator should support such considerations of cost effectiveness by either estimating cost or allowing users to input estimates of the component costs of alternative fleet management decisions.

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REFERENCES

1. Bailey L., P. L. Mokhtarian, et. al. *The Broader Connection Between Public Transportation, Energy Conservation, and Greenhouse Gas Reduction.* ICF International, Fairfax, VA, 2008.

2. Bailey, L. *Public Transportation and Petroleum Savings in the U.S.: Reducing Dependence on Oil*. Prepared for American Public Transportation Association by ICF International, Fairfax, VA, 2007. http://www.apta.com/research/info/online/documents/apta_public_transportation_fuel_savings_final_010807.pdf

3. Hodges, T. *Public Transportation's Role in Responding to Climate Change*. Federal Transit Administration, Washington D.C., 2009. http://www.fta.dot.gov/documents/PublicTransportationsRoleInRespondingToClimateChange.pdf

4. *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*. NREL/TP-560-42781-1, U.S. Department of Energy, Washington, D.C., 2008. http://www.fta.dot.gov/documents/HydrogenandFuelCellTransitBusEvaluations42781-1.pdf

5. FTA Grant Programs. *Clean Fuels Grant Program (5308)*. Federal Transit Administration. http://www.fta.dot.gov/funding/grants/grants_financing_3560.html. Accessed July 7, 2009.

6. TIGGER. *Solicitation of Comments and Notice of Availability of Fiscal Year 2009 Funding for Transit Investments for Greenhouse Gas and Energy Reduction Grants*. Federal Transit Administration. http://edocket.access.gpo.gov/2009/pdf/E9-6420.pdf. Accessed July 7, 2009.

7. The Climate Registry. *General Reporting Protocol.* Version 1.1. http://www.theclimateregistry.org/downloads/GRP.pdf. Accessed July 7, 2009.

8. The European Climate Registry. http://www.europeanclimateregistry.eu/. Accessed July 7, 2009.

9. Climate Exchange Plc. http://www.climateexchangeplc.com/. Accessed July 7, 2009.

10. *Transit Greenhouse Gas Emissions Management Compendium*. D2008-GHG-TRI, Federal Transit Administration, Washington, D.C., 2008. http://www.fta.dot.gov/documents/TransitGreenhouseGasEmissionsCompendium-D2008-GHG-TRI.pdf

11. *FTA National Fuel Cell Bus Program Projects*. Federal Transit Administration. http://www.fta.dot.gov/documents/FTA_National_Fuel_Cell_Bus_Program_Projects.doc. Accessed July 1, 2009.

12. *Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit*. APTA CC-RP-001-09, American Public Transportation Association, Washington, D.C., 2009. http://www.apta.com/resources/hottopics/Documents/apta_climate_change_recommended_practice_final_august_14.pdf

13. Climate Leaders. *Cross-Sector Guidance*. U.S. Environmental Protection Agency. http://www.epa.gov/stateply/resources/cross-sector.html. Accessed July 7, 2009.

14. CRIS. *Climate Registry Information System*. The Climate Registry. http://cris.theclimateregistry.org/eats/tcr/. Accessed July 7, 2009.

15. The Greenhouse Gas Protocol. *Corporate Accounting and Reporting Standard*. World Resources Institute. http://www.ghgprotocol.org/standards/corporate-standard. Accessed July 7, 2009.

16. The California Climate Action Registry. *The General Reporting Protocol*. Version 3.1. http://www.climateregistry.org/. Accessed July 7, 2009.

17. ICLEI. *Local Governments Operations Protocol*. Version 1.0. http://www.icleiusa.org/programs/climate/ghg-protocol. Accessed July 7, 2009.

18. Environmental Defense Fund. *Fleet Greenhouse Gas Emissions Calculator*. http://innovation.edf.org/page.cfm?tagID=37020. Accessed July 7, 2009.

19. Evergreen Fleets. *Evergreen Fleets Emissions Calculator*. Puget Sound Clean Air Agency & Puget Sound Clean Cities Coalition. http://psgreenfleets.org/calculate-emissions. Accessed July 7, 2009.

20. *Urban Transportation Emissions Calculator*. Transport Canada. http://wwwapps.tc.gc.ca/prog/2/UTEC-CETU/Calculator.aspx?lang=eng. Accessed July 7, 2009.

21. Travel Matters. *Transit Planning Emissions Calculator*. The Center for Neighborhood Technology. http://www.travelmatters.org/calculator/transit/?sid=f2290aedb949de6206fea832124affc4. Accessed July 7, 2009.

22. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fleet Footprint Calculator V1.0*. U.S. Department of Energy, Argonne National Laboratory.

http://www.transportation.anl.gov/modeling_simulation/GREET/index.html. Accessed June 18, 2009.

23. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) V1.8c.0 Fuel-Cycle Model*. U.S. Department of Energy, Argonne National Laboratory. http://www.transportation.anl.gov/modeling_simulation/GREET/index.html. Accessed June 18, 2009.

24. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) V2.7 Vehicle-Cycle Model*. U.S. Department of Energy, Argonne National Laboratory. http://www.transportation.anl.gov/modeling_simulation/GREET/index.html. Accessed June 18, 2009.

25. Delucchi, M. *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, eScholarship Repository, University of California, Berkeley, CA, 2003. http://repositories.cdlib.org/itsdavis/UCD-ITS-RR-03-17

26. *GHGenius*. Natural Resources Canada. http://www.ghgenius.ca/. Accessed July 7, 2009.

27. Green Design Institute. *Economic Input-Output Life Cycle Assessment (EIO-LCA) US Dept of Commerce 1997 Industry Benchmark (491) model*. Carnegie Mellon University. http://www.eiolca/net/. Accessed July 7, 2009.

28. *MOVES (Motor Vehicle Emission Simulator)*. U.S. Environmental Protection Agency. http://www.epa.gov/otaq/models/moves/index.htm. Accessed July 7, 2009.

29. *Greenhouse Gas Emissions from the U.S. Transportation Sector 1990-2003*. EPA 420 R 06 003, U.S. Environmental Protection Agency, Washington, D.C., 2006.

30. *IPCC Fourth Assessment Report*. Intergovernmental Panel on Climate Change, 2007.

31. Ozone Layer Depletion - Regulatory Programs. *What You Should Know about Refrigerants When Purchasing or Repairing a Residential A/C System or Heat Pump*. U.S. Environmental Protection Agency. http://www.epa.gov/Ozone/title6/phaseout/22phaseout.html. Accessed July 7, 2009.

32. eGRID2007. *The Emissions & Generation Resource Integrated Database*. U.S. Environmental Protection Agency. http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html. Accessed July 7, 2009.

33. Deru, M. and P. Torcellini. *Source Energy and Emission Factors for Energy Use in Buildings*. NREL/TP-550-38617, U.S. Department of Energy, National Renewable Energy Laboratory, Washington, D.C., 2007.

34. Chester, M. and A. Horvath. *Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2*. eScholarship Repository, University of California, Berkeley, CA, 2008. http://repositories.cdlib.org/its/future_urban_transport/vwp-2008-2

35. National Transit Database. Federal Transit Administration. http://www.fta.dot.gov/documents/PublicTransportationsRoleInRespondingToClimateChange.pdf. Accessed July 7, 2009.

36. *Inventory of U.S. Greenhouse Gas Emissioins and Sinks: 1990-2007*. EPA 430-R-09-004, U.S. Environmental Protection Agency, Washington, D.C., 2009. http://epa.gov/climatechange/emissions/usinventoryreport.html

37. *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation*. FTA-WV-26-7004.2007.1, U.S. Department of Transportation, Federal Transit Administration, Washington, D.C., 2007.

38. Brown, M. A. and C. E. Logan. *The Residential Energy and Carbon Footprints of the 100 Largest Metropolitan Areas. Working Paper 39*. Georgia Institute of Technology, School of Public Policy, Atlanta, GA, 2008.

39. Southworth, F. and A. Sonnenberg. *Estimation of the Energy and Carbon Footprints for Public Transit Systems in the Nation's 100 Largest U.S. Metropolitan Areas (Draft).* Prepared for the Metropolitan Program, Brookings Institution, Washington, D.C., 2008.

40. Stodolsky, F., et al. "Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles". *Proceedings of the 1995 Total Life Cycle Conference & Exposition*, Vienna, Austria. 1995.