PRELIMINARY COMPARATIVE LIFECYCLE ANALYSIS OF LOW SULFUR DIESEL, COMPRESSED NATURAL GAS, AND ELECTRIC BAGGAGE TRACTORS FOR UNITED AIRLINES

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Abstract

The purpose of this study was to perform a comparative lifecycle analysis of low sulfur diesel, compressed natural gas, and electric baggage tractors for United Airlines' seven domestic hubs (SFO, LAX, DEN, IAH, ORD, EWR, and IAD). Both baggage tractor manufacturing burdens as well as fuel and electricity consumption burdens were modeled for the three different technologies. Due to a lack of baggage tractor specific fuel consumption and production data, this study relied heavily on information and assumptions in the GREET lifecycle model; MHDVs were used as proxies for determining CNG and LS diesel baggage tractor fuel consumption and emissions and an electric and ICEV pickup truck were used as proxies to model the production burdens of baggage tractors. Electricity generation mixes were approximated using NERC subregion mixes and eGrid data. The model shows that electric baggage tractors at each hub emit more vehicle lifecycle PM10 emissions compared to CNG and LS diesel baggage tractors. Electric baggage tractors at most hub airports emit lower lifecycle GHG emissions compared to CNG and LS diesel baggage tractors, with the exception of electric baggage tractors at DEN and ORD airports emitting higher lifecycle CO_2 emissions compared to CNG tractors. Electric baggage tractors at DEN and ORD also emit higher SO_x emissions as compared to the fossil fuel baggage tractors, and electric baggage tractors at EWR and IAH emit more SO_x as compared to LS diesel. It is recommended that electric baggage tractors be used at SFO, LAX, IAH, EWR, and IAD airports, and CNG baggage tractors be used at ORD and DEN airports.

ACKNOWLEGMENTS

I would like to thank my company sponsor, United Airlines, for providing monetary support for this project. I would also like to thank my contacts at United Airlines, Greg Kozak and Aaron Robinson, for answering my questions and providing me with relevant information when accessible. Additionally, I would like to thank my contact at Charlatte America, Joe Hart, for fielding my questions on baggage tractor manufacturing. Finally, I would like to thank my project advisor, Gregory Keoleian, for all his help and support throughout this project.

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List of Nomenclature

BEV – battery electric vehicle

BT – baggage tractor

CAMX – NERC subregion for LAX and SFO airports

CH_4 – methane

CNG – compressed natural gas

CNGV – compressed natural gas vehicle

CO_2 – carbon dioxide

DEN – Denver International Airport

eGrid – Emissions and Generation Resource Integrated Database

ERCT– NERC subregion for IAH airport

EV – electric vehicle

EWR – Newark Liberty International Airport

GHG – greenhouse gas

GHG-100 – greenhouse gas emissions global warming potentials over a 100-year time horizon

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation model

GSE – ground support equipment

GWP – global warming potential

HC – hydrocarbon

IAD – Dulles International Airport (Dulles, VA)

IAH – George Bush Intercontinental Airport (Houston, TX)

ICEV – internal combustion engine vehicle

LAX – Los Angeles International Airport

LCA – lifecycle analysis

LHV – Lower heating value

LS diesel – low sulfur diesel

MHDV – medium and heavy duty vehicles

NERC – North American Energy Reliability Council

NG – natural gas

NGCC – natural gas combined cycle

NO_x – nitrous oxides

ORD – Chicago O'Hare International Airport

PM10 and PM2.5 – particulate matter that is less than 10 microns in diameter and less than 2.5 microns in diameter

RFCE – NERC subregion for EWR airport

RFCW – NERC subregion for ORD airport

RMPA – NERC subregion for DEN airport

SFO – San Francisco International Airport

SO_x – sulfur oxides

SRVC – NERC subregion for IAD airport

VMT – vehicle miles traveled

WTP – well to pump

WTW – well to wheel

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Executive Summary

Background

The purpose of this study was to analyze the environmental impacts of LS diesel, compressed natural gas, and electric baggage tractors for United Airlines' seven domestic hubs (SFO, LAX, DEN, IAH, ORD, IAD, and EWR). Through its Eco Skies program, United is seeking to deploy more sustainably fueled baggage tractors. Even without more stringent EPA standards, emissions-cutting initiatives for ground support equipment (GSE) are being instituted by airlines and airports.

Methods

Both the vehicle production burdens and fuel cycle and electricity lifecycle emission were modeled for electric, CNG, and LS diesel baggage tractors. Baggage tractor end of life was not considered in this analysis. The following emissions were considered in this analysis: CO_2, CH_4, NO_x, PM10, PM2.5, SO_x, and GHG-100. "GHG-100" emissions are greenhouse gas emissions measured based on a 100-year global warming potential.

The benefits of electric baggage tractors over LS diesel- and CNG-powered baggage tractors depends on the electricity grid fuel mix. Since it is difficult to identify the specific grid mixes for individual airports, airport electricity grid mixes were approximated based on the NERC subregions in which the airports are located (CAMX, ERCT, RFCE, RFCW, RMPA, and SRVC). eGrid 2014 provided the grid mix percent breakdowns for each NERC subregion studied. Battery information provided by United was then used to model the electricity consumption for an electric baggage tractor.

The greenhouse gas emissions of a CNG vehicle are highly dependent on the leakage levels of natural gas in the natural gas upstream fuel cycle. Due to a lack of baggage tractor-specific fuel consumption data from United Airlines and incomplete baggage tractor manufacturing information from tractor vendor Charlatte America, the GREET lifecycle model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation model) was relied on for vehicle data and assumptions. Charlatte American provided fuel consumption information for a gasoline baggage tractor. Energy ratios from GREET for a gasoline and CNG and gasoline and LS diesel medium to heavy duty vehicle (MHDV) were used to calculate estimated fuel consumption rates for a CNG and LS Diesel baggage tractor. This conversion was based on the assumption that MHDV fuel consumption is similar to that of baggage tractors. For baggage tractor production burdens, an

ICEV and EV pickup truck were used as proxies for baggage tractors. An ICEV baggage tractor was used to model both diesel and CNG baggage tractors because studies have shown that vehicle production emissions are similar for these two vehicle types.

Preliminary Results and Recommendations

The results for this analysis are preliminary due to using MHDVs as proxies for CNG and LS diesel baggage tractor fuel consumption and pickup trucks to model the manufacturing burdens for both ICEV and EV baggage tractors. Based on the results of this study, electric baggage tractors at SFO, LAX, IAH, EWR, and IAD airports emit higher PM10 lifecycle emissions compared to CNG and LS diesel baggage tractors, and electric baggage tractors at IAH and EWR airports emit higher SO_x lifecycle emissions compared to LS diesel baggage tractors and higher PM2.5 emissions compared to CNG baggage tractors. As a result, it is recommended that electric baggage tractors be deployed at these airports. At ORD and DEN airports, electric baggage tractors emit higher PM10 and SO_x emissions compared to both CNG and LS diesel baggage tractors, and as well as higher PM2.5 and CO_2 emissions compared to CNG baggage tractors. Based on these results, it is recommended that CNG baggage tractors be operated at DEN and ORD airports.

It is recommended that a more thorough study be conducted to further investigate the environmental benefits and implications of different baggage tractor technologies. It is important to note that this study relies heavily on assumptions and GREET data due to the lack of information available from United on the fuel use, duty cycles, and maintenance of baggage tractors. To conduct a more thorough analysis and one more specific to United’s use of baggage tractors, it is recommended that United track and compile of the following information:

- Fuel use for baggage tractors (per mile or per hour)
- Charging data (How frequently are EV baggage tractors charged, and for how long? For how long can an EV baggage tractor operate on a full charge? What time of day are the baggage tractors charge?)
- Fleet duty cycle information (How many tractors are used throughout the day? How long is a single baggage tractor used? How long do fossil fuel baggage tractors idle?)

1. Introduction and Background

Ground support equipment vehicles (GSE) are ubiquitous at airports. Depending on the capacity needs and location, an airport can have as many as 24 different types of GSE.[1] Of these types, baggage tractors are the most numerous. The Airport Cooperative Research Program (ACRP) performed a survey on GSE at different airports across the country, and found that baggage tractors are approximately 26% of an airport's GSE fleet.[2] This adds up to roughly 25,360 baggage tractors deployed at airports across the country.[3] The majority of these baggage tractors are fueled by gasoline or diesel. At a single hub like San Francisco International, United Airlines alone deploys roughly 300 baggage tractors.[4] This means that just at United's seven domestic hubs, the airline operates approximately 2,100 baggage tractors on a daily basis.

1.1 United Airlines

United Airlines, the third largest airline in the world, has focused on cutting operation-sourced emissions for over two decades.[5] Since 1994, United has increased its aviation fuel efficiency by 34% and reduced carbon dioxide emissions by 1 million metric tons.[6] In 2011, United launched its Eco-Skies program that focuses on increasing aviation fuel efficiency, utilizing alternative jet fuel sources, improving product sustainability, managing company-generated waste, and partnering with other sustainably-minded organizations.[7] As a result of the company's sustainability efforts, United Airlines was awarded the Sustainability Outstanding Achievement Award by the Global Business Travel Association in 2014.[8] As of 2012, United Airlines owned more than 3,600 electrified or alternative fueled (GSE) vehicles.[9] In 2015, the company set a goal for 2016 to "Continue to expand conversion from fossil fuel to electric ground service equipment (eGSE)."[10] United added 100 electric GSE units to the company's fleet in 2015.[11]

1.2 Environmental Policy

Since baggage tractors are considered off-road vehicles, they are not held to as rigorous emissions standards as commercial on-road vehicles. In light of less stringent standards, individual airports, cities, and regions have established their own standards.

In 2000, for example, San Francisco International Airport (SFO) adopted a voluntary Clean Vehicle policy that, "strongly encourages the replacement of gasoline and diesel vehicles with clean air vehicles powered by alternative fuels like compressed natural gas (CNG) and electricity." This policy includes GSE.[12] Two years later, a Memorandum of Understanding (MOU) for GSE was enacted in Southern California.[13] Since, at that time, the Clean Air Act prohibited states from setting their own emission standards for vehicles and airplanes, this MOU for GSE provided only voluntary guidelines for cutting hydrocarbons (HC) and NO_x emissions in Southern California.[14]

In 2004, the United States Congress passed the "Vision 100 – Century of Aviation Reauthorization Act," which gives the Federal Aviation Administration (FAA) the power to provide funding to airports or state agencies in the interest of reducing airport emissions.[15] This program, called the Voluntary Airport Low Emissions program (VALE), provides funding for implementing emissions reductions in exchange for carbon credits from state governments to help airports comply to the Clean Air Act.[16,17] The city of Philadelphia, in partnership with United Airlines and US Airways, was awarded funds in FY 2008 and 2009 to install charging stations for electrified GSE at Philadelphia International Airport (PHL).[18] United Airlines and US Airways have replaced in total 288 GSE vehicles with electric GSE at Philadelphia.[19] In 2008, George Bush Intercontinental Airport was awarded $25,000 under the VALE program to purchase two electric GSE units.[20] With the construction of the Denver International Airport, Denver implemented an "Alternative-Fuel Vehicle" program, under which the airport was awarded money to invested in 40 CNG baggage tractors.[21] More recently, in April 2015, the Los Angeles International Airport enacted a policy to cut HCs and NO_x emissions from ground service equipment (GSE) by 2021.[22]

2. Purpose

The purpose of this study is to evaluate air pollutant emissions from compressed natural gas (CNG) and battery electric-powered baggage tractors to help inform United Airlines' decision-making regarding future baggage tractor purchases at the company's seven domestic hubs. United's domestic hubs are: San Francisco International (SFO), Los Angeles International (LAX), George Bush Intercontinental Airport (IAH; Houston, Texas), Newark Liberty International Airport (EWR), Denver International Airport (DEN), Dulles

International Airport (IAD; Dulles, Virginia) and Chicago O'Hare International Airport (ORD).

3. Previous Studies

There have been no published studies to date comparing the environmental impacts of fuel use for different baggage tractor technology. However, there are studies that examined the emissions differences among diesel, CNG and electricity use for other types of vehicles. Additionally, there are studies that analyze the natural gas fuel cycle and electricity lifecycle.

Based on baggage tractor curb weight (roughly 7,800 lbs), baggage tractors fall into class 2a trucks (which have a curb weight range from 6,001 to 8,500 lbs), which are defined as light duty vehicles (LDVs). Due to the lack of data from United Airlines and suppliers to model baggage tractor emissions, the GREET lifecycle model from ANL was used to estimate life cycle emissions. Medium-heavy duty vehicles (MHDVs) are used to model the baggage tractor fuel consumption and emissions instead of LDVs. Pickup trucks, transit buses, and garbage trucks are considered MHDVs. Due to a lack of data on MHDV manufacturing emissions in GREET, Pickup trucks (PUTs) were used to model the material manufacturing emissions of the baggage tractors.

3.1 University of Michigan Class Study

In the Industrial Ecology (NRE 557) course during the winter of 2016, my class group (Nick Machinski, Bhuvan Neema, Kayva Vayyasi, and myself) performed a preliminary lifecycle analysis of electric and compressed natural gas baggage tractors for SFO and LAX airports. Due to the limitations of data and time, we relied heavily on industry-wide information and assumptions built into the Argonne GREET Vehicle Cycle Model. Our preliminary analysis indicated that, due to the California grid fuel mix, electric baggage tractors emit lower lifecycle emissions compared to compressed natural gas or diesel baggage tractors.

3.2 Electricity and Battery Electric Vehicles

The environmental benefits of using battery electric vehicles (BEVs; also referred to as electric vehicles, EVs) is dependent on the grid fuel mix from which the electricity is generated. A study conducted in China evaluating the environmental impacts of electric vehicles (EVs) compared to conventional gasoline vehicles and CNGVs, showed that the advantages of EVs over gasoline and CNGVs depended greatly on the electricity feedstock grid fuel mix.[23] In provinces with a large reliance on coal-generated electricity (ranging from 98% to 74% grid reliance on coal), EV GHG emissions were found to be higher than those of CNGVs and conventional gasoline vehicles.[24] Additionally, in coal-dependent areas, electricity generation "…can increase criteria pollutants (PM2.5 and PM10) 3-5 times compared to ICEVs and CNGVs."[25] A study by Tong et al. (2015)[26] looking at transit buses found that "BEVs with natural gas electricity emit the lowest GHG emissions, achieving 31% reductions compared to diesel buses."[27] BEVs powered with the average grid mix provide less of a reduction. For box trucks, the same trend is seen where BEVs powered by NGCC offers the lowest lifecycle GHG emissions, followed by BEVs powered by the average grid mix. For box trucks, CNGVs emit lower emissions compared to conventional diesel vehicles.[28] In contrast, for pickup trucks, while BEVs powered by NGCC still offer the lowest GHG emissions, conventional diesel emits lower emissions compared to BEVs powered by the grid average fuel mix, and CNGVs emit higher emissions compared to conventional diesel.[29]

It is predicted that an influx of electric vehicle use, and the associated daily charging cycles, will require a larger reliance of peaking electric power plants. These plants are generally fueled by natural gas, and do not reflect the grid average emission profiles.[30] Tong et al. (2015)[31] argues that increased demand for electricity driven by BEVs will be met by predominantly natural gas combined cycle (NGCC) plants.[32]

3.3 Natural Gas and Compressed Natural Gas Vehicles.

Natural gas (NG) is primarily composed of methane (CH_4), which has 87 times more potent global warming potential (GWP) over 20 years, and 25 times more potent global warming potential (GWP) over 100-year time horizon, compared to carbon dioxide (CO_2).[33] CO_2 and CH_4 are the main gases emitted in the natural gas fuel cycle. There is considerable controversy over the emissions associated with NG recovery and transportation, specifically with leakages ('fugitive emissions'), gas venting, and incomplete combustion ('methane slips') of NG. In a breakdown of CH_4 and CO_2 (non-combustion) emissions in each stage of the upstream fuel cycle, 64% of the lifecycle CH_4 emissions come from the production of the fuel, while 56% of non-combustion CO_2 emissions result from processing.[34] Production includes extraction of gas from the well, well-site processing, and transportation of gas to transmission pipelines or processing facilities (depending on the quality of the gas extracted).[35] Processing is the stage in which the gas is refined to produce pipeline-quality gas.[36] In a comparative lifecycle analysis of emissions from conventional natural gas, shale gas, coal, and petroleum for both transportation and electricity generation, Burnham et al. (2011)[37] found that the largest source of emissions of CH_4 in the natural gas upstream fuel cycle is the venting and leaking of gas during the extraction and recovery of the gas.[38] The authors concluded that, for electricity generation on a lifecycle basis, "…upstream CH_4 leakage and venting is a key contributor to the total upstream emissions of NG pathways, and can significantly reduce the life-cycle benefits of NG compared to coal or petroleum."[39] As a result, the benefits of using CNGVs depends greatly on the tightness, or lack of leakage, of the upstream fuel cycle.

Burnham et al. (2011)[40] found that, when comparing 100-year global warming potentials of upstream greenhouse gas emissions for transit buses, "there is no statistically significant difference in well-to-wheel (WTW) GHG emissions evident among [diesel, conventional natural gas, and shale gas] on a vehicle kilometer traveled basis."[41] On the other hand, Tong et al. (2015)[42] found that CNG transit buses and garbage trucks emit higher GHG emissions compared to conventional diesel. In yet another study, that compared lifecycles of CNG and diesel garbage trucks, Rose et al. (2013)[43] found that CNG garbage trucks emit 24% less lifecycle GHG emissions compared to diesel alternatives. These three sources do not indicate definitively whether CNG MHDVs are better on a lifecycle basis compared to diesel. The discrepancies across these studies are due largely to the fact that the calculation for use phase emissions for MHDV vehicles rely heavily on the duty cycle of the vehicles.[44]

3.4 Vehicle Production

Vehicle production emissions, although important to consider in a lifecycle analysis of a vehicle, is less impactful compared to the fuel cycle emissions of the vehicle. Rose et al. (2013)[45] found that, when comparing the fuel cycle (including feedstock transport and fuel production) and vehicle cycle (including material production and vehicle assembly) of CNG and diesel garbage trucks, the vehicle operation (combustion) CO_2 equivalent emissions are by far the highest as compared to all other lifecycle stages (both fuel and vehicle cycle stages). Ma et al. (2012)[46], in a comparison of ICEV and BEV vehicles, found similar results, where fuel cycle emissions dominate over vehicle manufacturing and assembly. Despite the differences in combustion emissions, CNG and diesel vehicle production burdens are similar. Rose et al (2013)[47] also found that vehicle assembly and vehicle production emissions (CO_2 eq, NO_x, SO_x, PM, CO and VOC) are similar between CNG and diesel garbage trucks.

4. Methodology

Preliminary, comparative lifecycle assessments were carried out on electric, LS diesel, and CNG baggage tractors, with diesel serving as the comparative base case. Diesel was chosen instead of gasoline because the majority of United's baggage tractors are diesel-powered.[48] This analysis includes the upstream, production, and combustion emissions for LS diesel, CNG, and electricity, as well as the vehicle production emissions for each type of vehicle. A diagram of the scope of this analysis can be seen in Figure 1. ISO 14040 series LCA guidelines were followed wherever possible (Figure 2). Argonne National Labs publishes a transportation model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation model) in both an Excel format (GREET_2016 and GREET2_2016) and a software format (GREET.net). Both the GREET.net model and the Excel models were used for determining emission rates for the different fuels and materials used in this analysis. eGrid 2014 was used to determine electricity grid fuel mixes for the regions containing the seven domestic hubs.

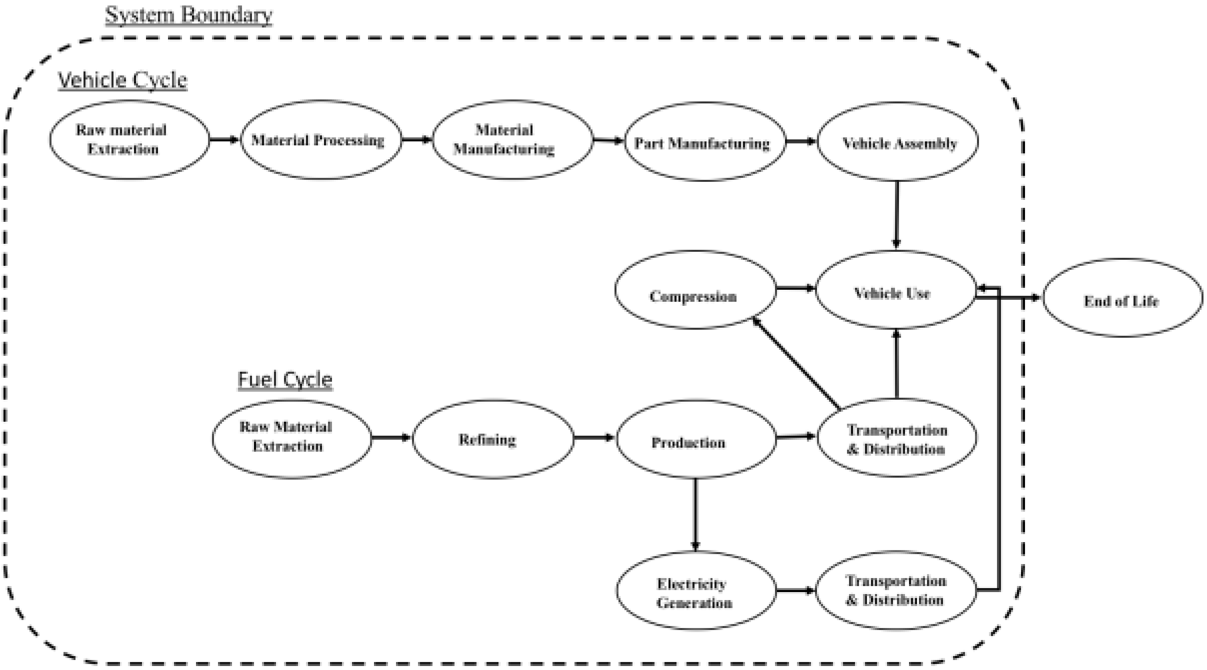


Figure 1: System boundary and scope for study

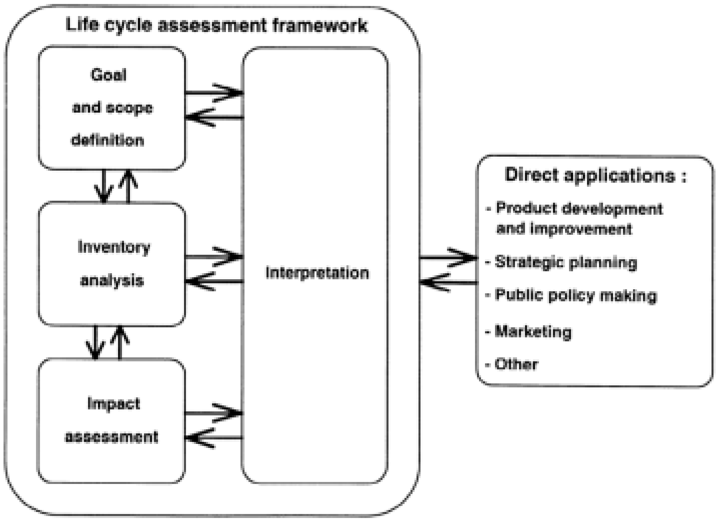


Figure 2: ISO 14040 series framework for LCA analysis[49]

The following emissions reported in GREET were considered when evaluating vehicle production, CNG and LS diesel fuel cycles, and electricity lifecycles: CO_2, CH_4, NO_x, SO_x, PM10, PM2.5, along with global warming potentials (GWPs) over 100-year time horizon of greenhouse gases (GHG-100). Greenhouse gases are gases that contribute to the greenhouse effect, a phenomenon in which heat radiating from the earth is trapped in the atmosphere. This causes the atmospheric temperature to increase, which in turn increases temperatures on land and in the ocean. Global warming potential (GWP) measures the ability of a gas to absorb energy, and therefore contribute to the warming of the atmosphere. GWP is used to compare GHGs and their impacts on climate change. All GWPs are compared to CO_2, making CO_2's GWP equal to 1. "GHG-100" refers to the GWPs of greenhouse gases over a 100-year time horizon.

Table 1 lists the air pollutants included in this study and their impacts along with GWPs where applicable:

Table 1: List of emissions this study examines and their significance.

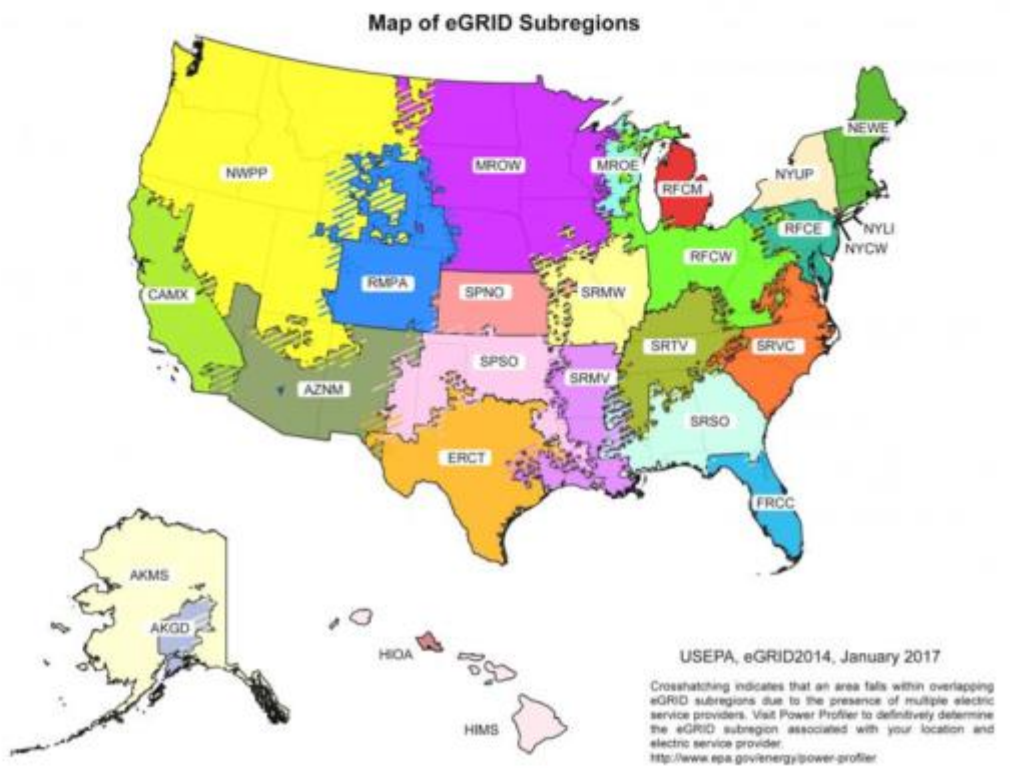
Emissions	Chemical abbreviation	Significance
Carbon dioxide	CO_2	Anthropogenic CO_2 is formed through the burning of fossil fuels and solid waste.[50] CO_2 has a GWP of 1, since it is the comparative base case and CO_2 can remain in the atmosphere for 1,000's of years.[51]
Methane	CH_4	CH_4, although less prominent than CO_2 in the atmosphere, is 25 times more potent than CO_2 in terms of its global warming potential (GWP) over 100 years. CH_4 remains in the atmosphere for around a decade. It is emitted into the atmosphere during the production and transportation of coal, natural gas, and oil.[52]
Nitrous oxides	NO_x	NO_x refers to a group of seven nitrous oxides, the most prominent in our atmosphere being the greenhouse gas N_2O. Nitrous oxides are formed when fossil fuels are burned, and can react with volatile organic compounds (VOCs) to form ground level ozone (O_3) and acid rain. N_2O has a GWP of 298 over a 100-year time horizon, and remains in the atmosphere for about 100 years.[53]
Sulfur oxides	SO_x	SO_x represents a group of sulfur oxides, in which SO_2 is the most prominent in the atmosphere. Sulfur oxides can react with the atmosphere to form particulate matter (PM). Inhaling SO_2 can harm the body's respiratory system.[54]
Particulate matter	PM10 and PM2.5	Particulate matter (PM) refers to small solid and liquid particles in the atmosphere. PM10 includes particulate matter with diameters less than 10 microns, whereas PM2.5 includes particulate matter with a diameter of less than 2.5 microns. The smaller the particle, the longer it stays in the atmosphere. When inhaled, particulate matter can harm the human respiratory system.[55]

In addition to secondary research sources, the following individuals have provided information on baggage tractors for this study: Gregory Kozak (Former Senior Manager of Environmental Strategy and Sustainability and currently the Regional Manager of Airport Affairs), Aaron Robinson (Senior Manager of Environmental Strategy and Sustainability at United Airlines), and Joe Hart (Engineering Manager at Charlatte America (a baggage tractor vendor). In this analysis, the following assumptions have been applied to all baggage tractors: 1) fleet sizes are estimated to be 300 vehicles per hub airport; 2) based on an industry standard, baggage tractor use is measured at an average assumed speed of 25 mph; 3) the average shift of a baggage tractor is 10.5 hours/day (an assumption based on shifts ranging from 9 to 12 hours/day); 4) it is assumed that baggage tractors are on duty for 360 days/year to account for periodic maintenance; and 5) the useful life of a baggage tractor is estimated to be 15 years. Assumptions provided in GREET were relied on heavily due to the lack of baggage tractor-specific information provided by United Airlines.

4.1. Electric Baggage tractor

4.1.1 Electricity Generation

North American Energy Reliability Council (NERC) divides the United States into regions and subregions for the purpose of instituting and maintaining grid reliability standards. A map depicting the geographic organization of subregions is presented in Figure 3. NERC subregions in which the seven United domestic hubs are located were used to approximate the grid fuel mix for electricity generation. eGrid 2014 data, released in early 2017, were used to determine grid fuel mixes for each relevant subregion. The NERC regions and subregions associated with each airport are listed in Table 2. In addition to the NERC subregion mixes, a pure coal grid and a pure natural gas grid were also analyzed to indicate the range of emissions from fossil fuel plants.



Map of eGRID Subregions

USEPA, eGRID2014, January 2017

Crosshatching indicates that an area falls within overlapping eGRID subregions due to the presence of multiple electric service providers. Visit Power Profiler to definitively determine the eGRID subregion associated with your location and electric service provider.
http://www.epa.gov/energy/power-profiler

Figure 3: NERC and eGrid subregions[56]

Table 2: NERC region and subregion association for each of United's domestic hubs.

Airport	NERC Region	NERC region abbreviation	NERC Subregion	NERC Subregion abbreviation
San Francisco International (CA; SFO)	Western Electricity Coordinating Council	WECC	WECC California	CAMX
Los Angeles International (CA; LAX)	Western Electricity Coordinating Council	WECC	WECC California	CAMX
George Bush Intercontinental Airport (Houston, TX; IAH)	Texas Regional Entity	TRE	ERCOT All	ERCT
Newark Liberty International Airport (NJ; EWR)	Reliability First Corporation	RFC	RFC East	RFCE
O'Hare (Chicago, IL; ORD)	Reliability First Corporation	RFC	RFC West	RFCW
Denver International Airport (CO; DEN)	Western Electricity Coordinating Council	WECC	WECC Rockies	RMPA
Washington Dulles (D.C.; IAD)	Southeastern Electric Reliability Council	SERC	SERC Virginia-Carolina	SRVC

Using the eGrid 2014 mixes, a subregion grid fuel mix for each airport was used to create a "New Pathway Mix" in the GREET.net model. These pathway mixes provided emission factors for upstream and electricity generation. The grid fuel mixes contained ten energy sources, which are: coal, oil, natural gas, nuclear, hydroelectric, biomass, wind, solar, geothermal, and other. The names in the GREET.net model of the energy sources used to build the electricity pathways are listed in Table 3. The fuel mix for each relevant NERC subregion can be found in Figure 4.

Table 3: Names of energy sources used in GREET.net model

Feedstock Type	**Name of Feedstock in GREET.net model**
Coal	Non-distributed – Coal-fired power generation
Oil	Non-distributed oil-fired power generation
Natural Gas	Non-distributed natural gas fired power generation
Nuclear	Non-distributed nuclear power generation
Hydroelectric	Non-distributed hydroelectric power generation
Biomass	Non-distributed biomass power generation
Wind	Non-distributed wind power generation
Solar	Other purpose solar power plant
Geothermal	Non-distributed geothermal electricity production
Other	Non distributed other power generation plants

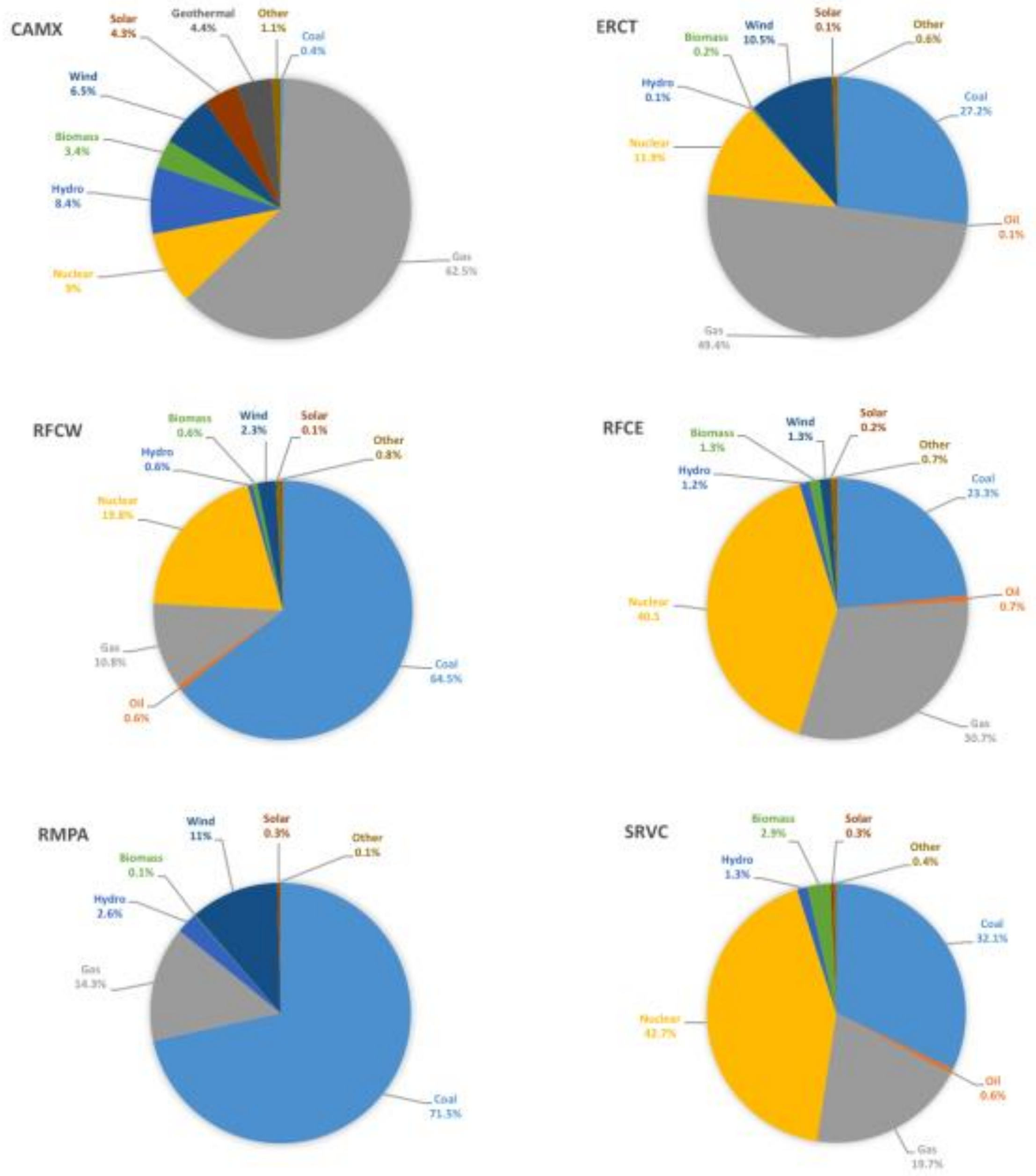


Figure 4: NERC subregion grid fuel mix breakdown

4.1.2 Electric Tractor Use

An Excel model was built to calculate the electricity use of an electric baggage tractor. Table 4 below shows the assumptions for the electricity usage calculations.

Table 4: Information and assumptions used in calculating electric baggage tractor electricity use

GIVEN/ASSUMPTIONS			
		Units	**Source/Reasoning**
Motor Rating @80V	30	kW	EV Baggage Tractor Charlatte Quote from Greg Kozak[57]
	40	Hp	EV Baggage Tractor Charlatte Quote from Greg Kozak[58]
Battery Rating	80	V	Deka (40-D125-11)[59]
Ampere Hour (@ 6 hours)	625	AH	Deka Battery Breakdown PDF[60]
Amps Finish Rate	30	A	Deka Battery Breakdown PDF[61]
Charging	4	hrs/shift	Email from Greg Kozak[62]
	1	charges/day	ASSUMPTION
Charger Efficiency	0.925		Average of 0.9 and 0.95, numbers from Posi sheet[63] from Greg Kozak. ASSUMPTION = average
Power factor	0.96		Posi info sheet[64] from Greg Kozak
Fleet size	486	Baggage Tractors/airport	Email from Greg Kozak[65]
Usage	25	mph	From Greg Kozak email[66], industry average
Shift	10.5	hrs/day	Average of 9 and 12 hours. Range from Greg Kozak Email[67]. ASSUMPTION = average of range
Days of operation	360	d/year	ASSUMPTION
Useful Life	15	years	Email from Greg Kozak[68]

To calculate the electricity usage per day, in kilowatt hours, the product of the voltage of the battery, ampere hour @ 6 hours of the battery, and number of charges per day were divided by the product of the charger efficiency and the charger's power factor. See equation 1 for the calculation.

$$\frac{80v\ x\ 625\ AH\ x\ 1\ charge}{(0.925\ charger\ eff.\ x\ 0.96\ pf)} = 56{,}306.31\frac{Wh}{day} \quad or\ 56.31\frac{kWh}{day} \tag{1}$$

To determine the miles traveled per day, the number of hours of charging per shift was subtracted from the tractor's daily shift length. This was then multiplied by the industry standard 25 miles per hour. See equation 2 for the calculation.

$$\left(10.5\ hrs - \frac{4\ charging\ hrs}{shift}\right) x\ 25\ mph = 162.5\frac{mi}{day} \tag{2}$$

To determine fleet usage, both the electricity use and the miles traveled were scaled up by multiplying by the number of baggage tractors. Because it was assumed that the electric baggage tractors are recharged 4 hours per shift, and the shift for the electric and fossil fuel baggage tractors is the same length, this means that an electric baggage tractor does not travel as far as a fossil fuel baggage tractor. Since it is assumed that if a fleet is all CNG or all electric, the fleet must perform the same level of work per shift, the number of electric baggage tractors was increased to account for this discrepancy. Instead of a fleet comprised of 300 baggage tractors, the number United estimates having in a typical hub fleet, the electric baggage tractor fleet was scaled up to 486 baggage tractors to accommodate the charging assumption. This was determined by multiplying 300 by the ratio of daily miles traveled between the electric a fossil fuel baggage tractors (1.62). Appendix A provides the calculated electricity usage and miles traveled of the baggage tractors.

The calculated kilowatt hours per day and per lifetime of a full airport fleet was used to calculate electricity emissions for each NERC subregion used. Tables 5 provides the greenhouse gas and criteria pollutant emission factors for each subregion.

Table 5: Upstream electricity emissions for each NERC subregion (g/MJ)

	CAMX	**ERCT**	**RFCE**	**RFCW**	**RMPA**	**SRVC**
CO_2	86.11	133.33	105.56	208.33	188.89	119.44
CH_4	0.3000	0.3389	0.2444	0.3500	0.3111	0.2306
NO_x	0.0833	0.0944	0.0806	0.1139	0.1111	0.0833
PM10	0.0223	0.0153	0.0197	0.0333	0.0333	0.0333
PM2.5	0.0082	0.0069	0.0077	0.0129	0.0127	0.0115
SO_x	0.0257	0.1944	0.1750	0.4833	0.4417	0.2333
GHG-100	97.22	144.44	113.89	200.00	219.44	127.78

4.2 Fossil Fuel Baggage Tractors

A low sulfur diesel, CNG, and gasoline (E-10) Medium and Heavy Duty (MHD) Vocational Vehicle were used to determine the emission factors in the GREET.net model for the LS diesel and CNG baggage tractors. Due to the controversy surrounding upstream natural gas emissions, the assumptions and levels in GREET were used instead of building a new upstream model. The emission factors for the upstream and use phase for a CNG and LS diesel baggage tractor can be found in Tables 6 and 7. A model was also built in Excel to calculate the fuel use of the vehicles. Table 8 provides the information given and assumptions made for the LS diesel and CNG baggage tractor usage calculations.

Table 6: LS diesel fuel cycle upstream and combustion emission factors (g/MJ)

	Upstream	**Combustion**
CO_2	13.51	74.84
CH_4	0.17	0.0447
NO_x	0.03124	0.04995
PM10	0.00204	0.00082
PM2.5	0.00167	0.00076
SO_x	0.02012	0.0
GHG-100	18.61	75.12

Table 7: CNG fuel cycle upstream and combustion emission factors (g/MJ)

	Upstream	**Combustion**
CO_2	9.75	54.93
CH_4	0.37	0.26
NO_x	0.04279	0.02123
PM10	0.0009	0.0007
PM2.5	0.00061	0.00064
SO_x	0.01687	0.0
GHG-100	21.25	63.73

Table 8: Information and assumptions used in calculating CNG and LS diesel baggage tractor use

GIVEN/ASSUMPTIONS			
		Units	**Source/Reasoning**
General			
Fleet size	300	BTs	Greg Kozak E-mail[69]
Usage	25	mph	Greg Kozak E-mail[70], industry average
Shift	10.5	h/day	Average of 9 and 12 hours, from Greg Kozak email[71]
Days of operation	360	d/year	ASSUMPTION
Useful Life	15	years	Greg Kozak Email[72]
Conversion (BTU-->MJ)	1	0.001055	Given
Gasoline			
Low rpm	1.8	gal gasoline/hr	Charlatte America[73]
	50%	of shift	ASSUMPTION
High rpm	3	gal gasoline/hr	Charlatte America[74]
	50%	of Shift	ASSUMPTION
Energy content of Gasoline	112,194	BTU (LHV)/gallon	Greet1_2016 "Fuel Specs" Sheet[75]
Total Energy Use Gasoline (Use Phase)	13	MJ/mi	Greet.net model, MHD Vocational Vehicle[76]
Total Energy Use Gasoline (WTW)	17	MJ/mi	Greet.net model, MHD Vocational Vehicle[77]
Total Energy Ratio - Gasoline	1.307692308		Calculated
CNG			
Total Energy Use CNG (Use phase)	19	MJ/mi	Greet.net model, MHD Vocational Vehicle[78]
Total Energy Use CNG (WTW)	23	MJ/mi	Greet.net model, MHD Vocational Vehicle[79]
Total Energy Ratio - CNG	1.210526316		Calculated
Gas:CNG efficiency ratio	0.684210526		Calculated
Diesel			

Total Energy Use Diesel (Use)	16	MJ/mi	Greet.net model, MHD Vocational Vehicle[80]
Total Energy Use Diesel (WTW)	20	MJ/mi	Greet.net model, MHD Vocational Vehicle[81]
Gas:Diesel efficiency ratio	0.8125		Calculated
Total Energy Ratio - Diesel	1.25		Calculated

Since the fuel use for CNG and LS diesel baggage tractors was not provided by United, the fuel use of a gasoline baggage tractor was used as a proxy. Gasoline baggage tractor fuel use (in gallons gasoline/hour) was provided by Charlatte America (a baggage tractor vendor). Fuel use was provided at a high rpm (3 gallons gasoline/hour) and a low rpm (1.8 gallons gasoline/hour). Per information provided by Charlatte America, it was assumed that the high rpm was equivalent to driving around the airport and the low rpm was similar to idling. An assumption was made that a fossil fuel baggage tractor is performing at a low rpm 50% of the time due to idling at gates during unloading and loading. Using these assumptions, the gallons of gasoline consumed per day was calculated to be 25.2 gallons gasoline/day. Multiplying this by the miles traveled per day (262.5 mi/day), the gasoline baggage tractors have a mileage of 0.1 gal/mi or 10.4 mi/gal.

To convert from a gasoline baggage tractor to a LS diesel and CNG baggage tractor, the Btu (LHV) per mile of the gasoline baggage tractor was calculated, and then multiplied by energy ratios of both gasoline to CNG MHDV and gasoline to LD diesel MHDV. These ratios were used based on the assumption that MHDV fuel use is similar to baggage tractor fuel use. Numbers for the energy ratios were found in the GREET.net model. This resulted in Btu (LHV)/mi of the other fuel (CNG or LS diesel). From there, the energy usage per mile was converted into MJ (1 Btu = 0.001055 MJ) and multiplied by the miles traveled per day. Finally, this was then multiplied by emission factors in g/MJ to get the emissions of the vehicle at each stage.

An example of the calculation for the use phase of a CNG baggage tractor follows below in equations 3 through 6.:

$$\frac{25.2\ gal\ gasoline}{day} x \frac{1\ day}{262.5\ mi} x \frac{112{,}194\ Btu\ (LHV)}{gal\ gasoline} x \frac{19\frac{MJ}{mi}\ (CNG)}{13\frac{MJ}{mi}(gasoline)} = 15{,}741.68\ \frac{Btu\ (LHV)\ CNG}{mi} \tag{3}$$

$$\frac{15{,}741.68\ Btu\ (LHV)\ CNG}{mi} x \frac{0.001055\ MJ}{Btu} x \frac{262.5\ mi}{day} = 4359.46\ \frac{MJ}{day} \tag{4}$$

$$\frac{4359.46\ MJ}{day} x \frac{54.93\ g\ CO_2}{MJ} = 239{,}465.14 \frac{g\ CO_2}{day} \tag{5}$$

$$\frac{239{,}465.14g\ CO_2}{day} x \frac{1\ metric\ ton}{10^6 grams} = 0.24\ \frac{metric\ tons\ CO_2}{day} \tag{6}$$

LS diesel emissions were calculated with the same method. These use phase emissions were scaled up by fleet size and per a baggage tractor’s useful life to get a full emissions picture. For determining total fuel cycle emissions, the calculated Btu/mi of CNG and diesel was multiplied by a total energy ratio for the respective fuels before converting into MJ. Appendix B lists all the calculations made for gasoline, diesel, and CNG baggage tractors.

4.3 Vehicle Production

Vehicle production looks at the material and parts produced as well as vehicle assembly. Due to the limitations in the GREET2_2016, a pickup truck (PUT), instead of a MHDV vocational vehicle, was used to compare the emissions associated with the production of the components of an ICEV PUT vs. an EV PUT. Both lead-acid and Li-ion batteries were considered when modeling the EVs because United currently uses lead acid and may switch to Li-ion. The emissions for vehicle components provided by the GREET vehicle cycle model were summed and then compared. The sums of component emissions can be found in Table 9. All of the assumptions in the GREET model were used as-is for this model except the number of battery replacements per lifetime of the vehicle. The GREET vehicle cycle model assumes that lifetime vehicle miles traveled is 180,000 mi. Based on the number of miles an EV baggage tractor travels per day, lifetime vehicle miles traveled is 877,500 miles, which is 4.88 times farther than what is assumed by GREET. Therefore, the battery replacements assumption in GREET was multiplied by four to get the estimated battery replacements for the electric baggage tractor. The number was rounded down to the closest whole number (four) because 0.88 of a battery cannot be changed. This ends up being eight replacements for a lead-acid battery and two replacements for a Li-ion battery.

Table 9: Pickup truck production burdens for an EV with a lead acid battery, an EV with a Li-ion battery, and an ICEV. Emissions are in grams per vehicle lifetime

EV: Conventional Material (lead acid battery)	Vehicle Production	Lead Acid Battery	Total Emissions
CO_2	2,263,563.94	22,686.72	2,286,250.66
CH_4	5,823.13	133.99	5,957.11
NO_x	2,615.33	32.76	2,648.09
PM10	1,102.01	31.92	1,133.94
PM2.5	526.39	15.62	542.01
SO_x	15,364.27	372.83	15,737.09
GHG-100	2,489,004.57	26,915.49	2,515,920.06

EV: Conventional Material (Li-ion battery)	Vehicle Production	Li-ion Battery	Total Emissions
CO_2	2,263,563.94	912,713.01	3,176,276.95
CH_4	5,823.13	2,418.85	8,241.98
NO_x	2,615.33	1,393.55	4,008.88
PM10	1,102.01	663.98	1,765.99
PM2.5	526.39	387.77	914.16
SO_x	15,364.27	7,763.13	23,127.40
GHG-100	2,489,004.57	1,014,224.60	3,503,229.17

ICEV Conventional Material	Vehicle Production
CO_2	2,650,164.90
CH_4	7,106.42
NO_x	2,949.83
PM10	1,418.94
PM2.5	673.80
SO_x	11,591.06
GHG-100	2,926,540.52

5. Preliminary Results and Discussion

5.1 Fuel Cycles

In terms of GHGs, EVs in most NERC subregions are better than CNG and LS diesel baggage tractors, but in terms of particulate matter and SO_X, the benefits of EV baggage tractors over CNG baggage tractors depends on what fuels make up the NERC region electricity grid. A more detailed analysis follows.

5.1.1 Electric Baggage Tractor Electricity Lifecycle Emission Comparison to LS Diesel and CNG MHDV Fuel Cycle Emissions: GHGs (CO_2, CH_4, NO_x, and GHG-100)

Figure 5 depicts the fuel cycle (upstream and combustion) and lifecycle electricity (upstream and generation) emissions for an airport's baggage tractor fleet (in metric tons) over the useful life of the tractors for EVs for each of the six NERC subregion (CAMX, ERCT, RFCE, RFCW, RMPA, SRVC) as well as coal- and natural gas-generated electricity; additionally, Figure 5 shows the fuel cycle (upstream and combustion) emissions for LS diesel-powered and CN G-powered baggage tractor fleets. Fleet emissions, rather than individual baggage tractor emissions, were analyzed because of the differences in fleet sizes between electric and fossil fuel baggage tractors.[1] Appendix C provides the fleet lifetime fuel and electricity emissions calculated (in metric tons).

Regardless of NERC subregion, natural gas or coal electric power generation, electric baggage tractor lifecycle electricity emissions of CH_4 and NO_x are lower than those of LS diesel or CNG MHDV fuel cycle emissions. For the six NERC subregions, CH_4 lifecycle electricity emissions from electric baggage tractors are 64% (RFCW) to 76% (SRVC) lower than those of LS diesel fuel cycle emissions, and 94% (CAMX, ERCT, RFCW) to 96% (RFCE, SRVC) lower than CNG MHDV fuel cycle emissions; and NO_x emissions from electric baggage tractors are 83% (RMPA) to 88% (RFCE) lower as compared to LS diesel MHDV fuel cycle emissions and 83% (ERCT, RFCW) to 88% (CAMX, RFCE, SRVC) lower than

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[1] Since EV baggage tractors are charged for 4 hours out of the 10.5 hour shift, and CNG and LS diesel baggage tractors run for the full 10.5 hours, the number of EV baggage tractors was scaled up from 300 to 486 to be able to compare emissions between EV, CNG, and LS Diesel baggage tractors.

CNG MHDV fuel cycle emissions. Table 10 lists what percent lower/higher the NERC subregion electricity lifecycle emissions are as compared to LS diesel and CNG.

For CO_2, the electric baggage tractor electricity lifecycle emissions in NERC regions modeled are between 76% (RFCW) to 90% (CAMX) lower than LS diesel, and 31% higher (RFCW) to 46% lower (CAMX) as compared to the CNG MHDVs. For GHG-100, the EV lifecycle electricity emissions are 75% (RMPA) to 89% (CAMX) as compared to LS diesel and 36% (RMPA) to 72% (CAMX) lower as compared to CNGVs. Overall, the EVs in all subregions emit lower greenhouse gas emissions compared to LS diesel. When compared to CNG, EVs emit lower greenhouse gas emissions with the exception of CO_2 emissions in the RMPA and SRVC subregions.

5.1.2 Electric Baggage Tractor Electricity Lifecycle Emissions Comparison to LS Diesel and CNG MHDV Fuel Cycle Emissions: SO_x

With regards to SO_x electricity lifecycle emissions and fuel cycle emissions, CAMX and natural gas-based electricity emit the lowest levels, followed by LS diesel. Because of the highly-varied electricity generation fuel mix, electric baggage tractors in the six NERC subregions emit between 760% higher (RFCW) to 54% lower SO_x lifecycle emissions (CAMX) compared to CNG baggage tractors. As compared to LS diesel, electric baggage tractors emit 79% higher (RFCW) to 91% lower (CAMX) lifecycle SO_x emissions.

5.1.3 Electric Baggage Tractor Electricity Lifecycle Emission Comparison to LS Diesel and CNG MHDV Fuel Cycle Emissions: PM10 and PM2.5

Electric baggage tractors powered by natural gas-generated electricity emit the lowest electricity lifecycle PM10 and PM2.5 emissions. For PM10, electric baggage tractors emit 3% (ERCT) to 124% (RFCW, RMPA, SRVC) higher lifecycle electricity emissions as compared to LS diesel MHDVs and between 6% (ERCT) to 131% (RFCW, RMPA, SRVC) higher PM10 lifecycle electricity emissions as compared to CNG MHDV fuel cycle emissions. For PM2.5, electric baggage tractors emit between 2% (RFCW) to 48% (ERCT) lower lifecycle emissions compared to LS diesel MHDV fuel cycle emissions, while emitting 32% higher (RFCW) to 30% lower (ERCT) PM2.5 electricity lifecycle emissions compared to CNG MHDV fuel cycle emissions vehicles.

5.1.4 CNG MHDV Fuel Cycle Emission Comparison to LS Diesel MHDVs

CNG MHDVs emit lower fuel cycle GHG emissions compared to LS diesel except for CH_4, where CNG MHDVs emits 509% more CH_4 as compared to LS diesel MHDVs. CNGVs also emit higher SO_x (by 381%) and higher NO_x (by 6%) compared to the LS diesel. Table 11 lists the percent lower/higher CNG emissions compared to LS diesel emissions.

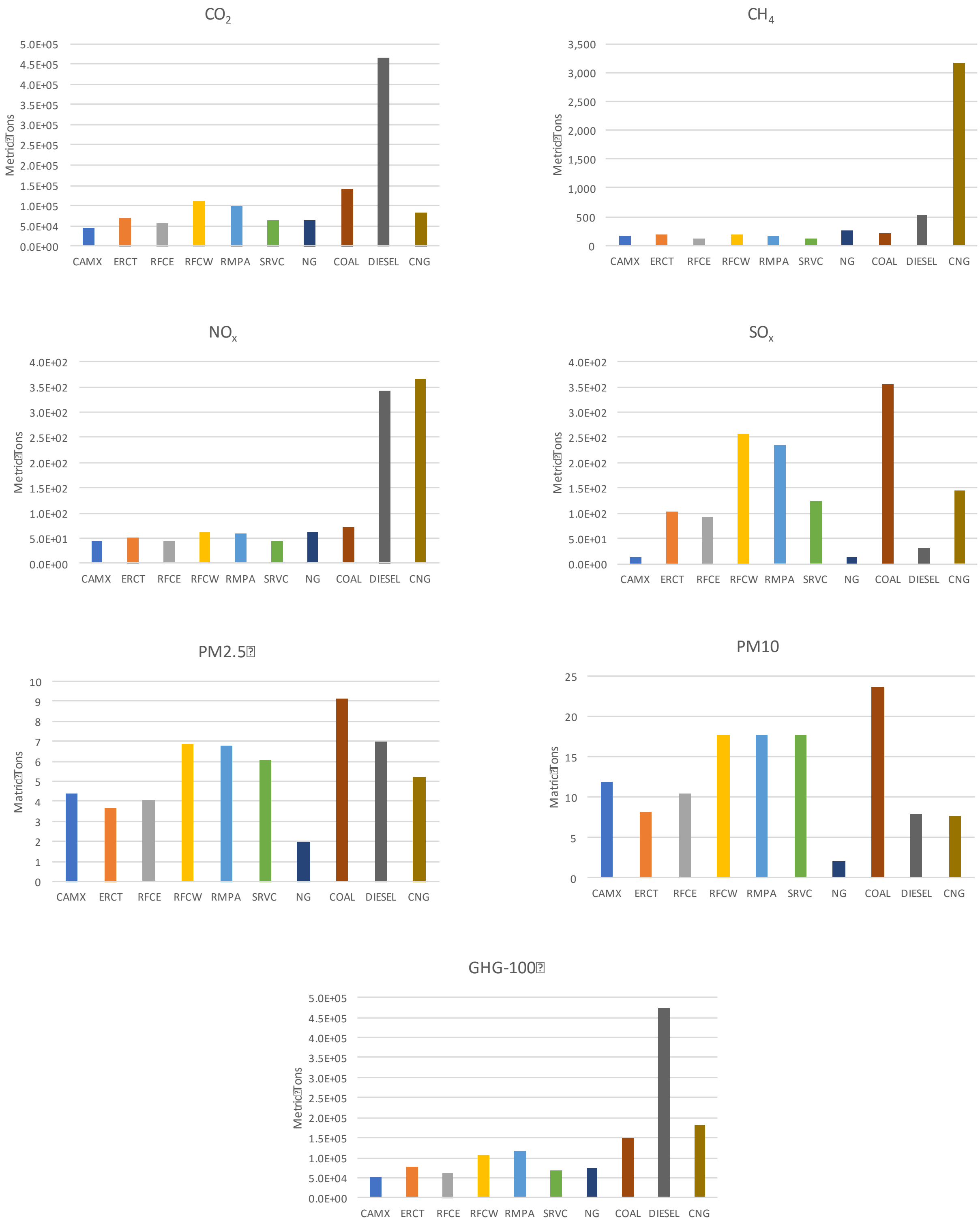

Figure 5: Lifetime electricity lifecycle emissions for electric baggage tractors and fuel cycle emissions (upstream and combustion) emissions LS diesel and CNG baggage tractors.

Table 10: Comparison of percent higher (negative, red) and percent lower (positive) lifecycle electricity emissions for NERC subregions as compared to LS Diesel and CNG MHDV fuel cycle emissions. The corresponding airport short codes are in parentheses. Positive percentages represent electricity emissions that are lower than those of LS diesel and/or CNG, while negative emissions represent electricity that emissions are higher than LS diesel and/or CNG.

CAMX (SFO & LAX)		
	Diesel	**CNG**
CO_2	90%	46%
CH_4	69%	94%
NO_x	87%	88%
PM10	-50%	-54%
PM2.5	38%	16%
SO_x	54%	91%
GHG-100	89%	72%

ERCT (IAH)		
	Diesel	**CNG**
CO_2	85%	16%
CH_4	65%	94%
NO_x	85%	83%
PM10	-3%	-6%
PM2.5	48%	30%
SO_x	-246%	28%
GHG-100	84%	58%

RFCE (EWR)		
	Diesel	**CNG**
CO_2	88%	34%
CH_4	75%	96%
NO_x	88%	88%
PM10	-32%	-36%
PM2.5	42%	22%
SO_x	-211%	35%
GHG-100	87%	67%

RFCW (ORD)		
	Diesel	**CNG**
CO_2	76%	-31%
CH_4	64%	94%
NO_x	82%	83%
PM10	-124%	-131%
PM2.5	2%	-32%
SO_x	-760%	-79%
GHG-100	78%	42%

RMPA (DEN)		
	Diesel	**CNG**
CO_2	78%	-19%
CH_4	68%	95%
NO_x	83%	84%
PM10	-124%	-131%
PM2.5	3%	-30%
SO_x	-685%	-63%
GHG-100	75%	36%

SRVC (IAD)		
	Diesel	**CNG**
CO_2	86%	25%
CH_4	76%	96%
NO_x	87%	88%
PM10	-124%	-131%
PM2.5	13%	-17%
SO_x	-315%	14%
GHG-100	86%	63%

Table 11: Comparison of percent higher (negative, red) and percent lower (positive) fuel cycle emissions for CNG as they compares to LS diesel. Positive percentages represent CNG fuel cycle emissions that are lower than those of LS Diesel, while negative emissions represent CNG fuel cycle emissions that are higher than LS diesel.

CNG	
	Diesel
CO_2	82%
CH_4	-509%
NO_x	-6%
PM10	3%
PM2.5	26%
SO_x	-381%
GHG-100	61%

5.1.5 Comparison of Upstream and Combustion CNG and LS Diesel Emissions

Figures 6 and 7 depict the fuel cycle upstream versus combustion emissions for CNG and LS diesel baggage tractor on a daily basis. As seen in Figure 6, combustion emissions are higher for CO_2 and GHG-100 CH_4, NO_x, PM10, and PM2.5 for the CNG baggage tractor. The upstream fuel cycle of the CNG baggage tractor emits more SO_x compared to combustion. As for LS diesel, Figure 7 shows that the combustion stage emits more CO_2, GHG-100, PM10, PM2.5, and NO_x, whereas more CH_4 and SO_x are emitted during the upstream fuel cycle. For both CNG and LS diesel, combustion emissions dominate in terms of gases emitted because the emission factors (Tables 6 and 7) are in g/MJ and more energy is used during vehicle use than during the upstream fuel cycle.

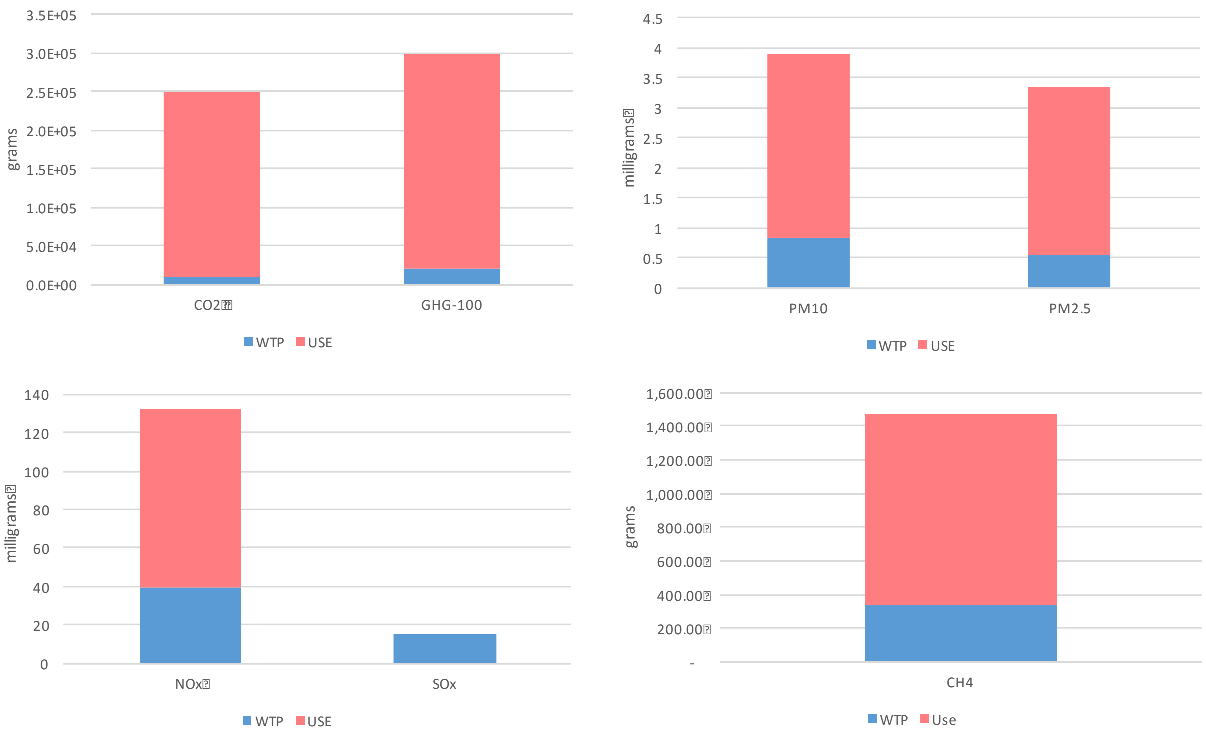

Figure 6: Comparison of upstream (blue) and combustion (pink) emissions for CNG MHDVs

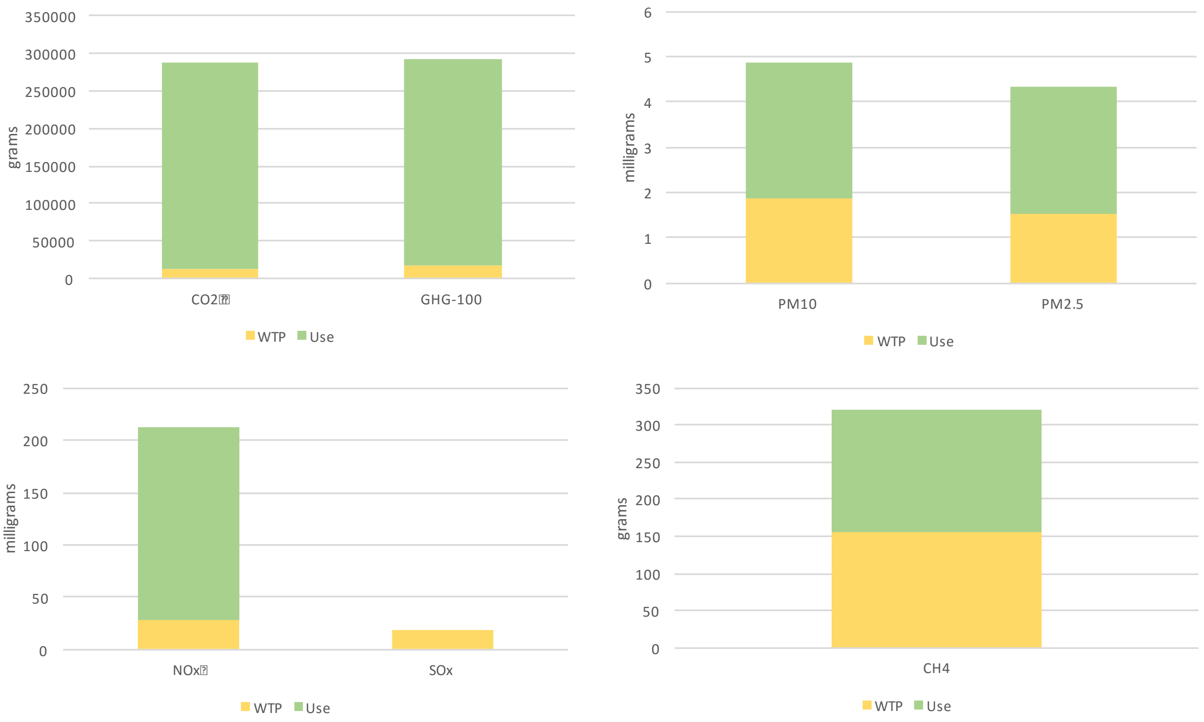

Figure 7: Comparison of upstream (yellow) and combustion (green) emissions for LS diesel MHDVs

5.2 Baggage Tractor Production Emissions

As seen in Table 12, despite having to use four times more lead acid batteries compared to Li-ion batteries per the lifetime of the vehicle, the eight lead acid batteries combined have lower lifecycle emissions compared to the two Li-ion batteries. As a result, the EV pickup truck with a Li-ion battery has higher manufacturing emissions compared to the ICEV pickup truck. The EV pickup truck with a lead acid battery has lower manufacturing emissions compared to the ICEV except for SO$_x$ emissions. These results can be seen in Figure 8.

Table 12: Comparison of lead acid and Li-ion battery manufacturing emissions

Lead Acid and Li-ion Battery Lifecycle Emissions (metric tons)		
	Lead Acid	Li-ion
CO_2	0.18	0.91
CH_4	1.07E-03	2.42E-03
NO_x	2.62E-04	1.39E-03
PM10	2.55E-04	6.64E-04
PM2.5	1.25E-04	3.88E-04
SO_x	2.98E-03	7.76E-03
GHG-100	0.22	1.01

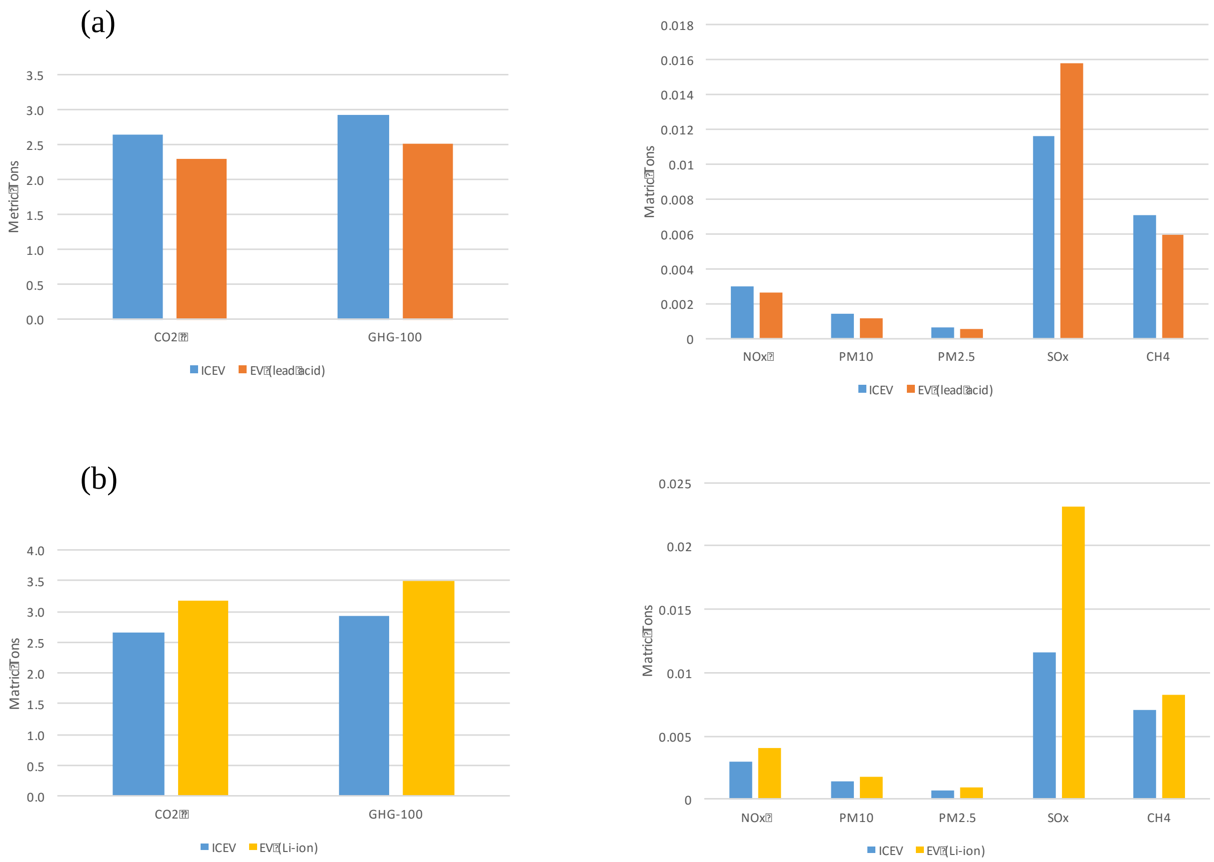

Figure 8: Comparison of ICEV (blue) and EV PUT production emissions with lead acid battery (orange) (a) and Li-ion battery (yellow) (b).

5.3 Total Baggage Tractor Lifecycle Emissions

Similar to the findings of Rose et al. (2013)[82] and Ma et al. (2012)[83], baggage tractor manufacturing and assembly emissions are minimal as compared to upstream and combustion emissions for electricity, CNG, and LS diesel. Figure 9 shows a breakdown of vehicle cycle, fuel cycle emissions, and combined lifecycle emissions for baggage tractors. As compared to the fuel cycle emissions in Figure 5, combining the fuel cycle and vehicle cycle emissions does not change the comparative emissions between EV baggage tractors powered by NERC subregions, natural gas and coal powered electricity, and baggage tractors powered by LS diesel and CNG. Appendix D provides tables of the breakdown between vehicle cycle emissions, the fuel cycle emissions as well as the total lifecycle emissions for electric, CNG, and LS diesel baggage tractors.

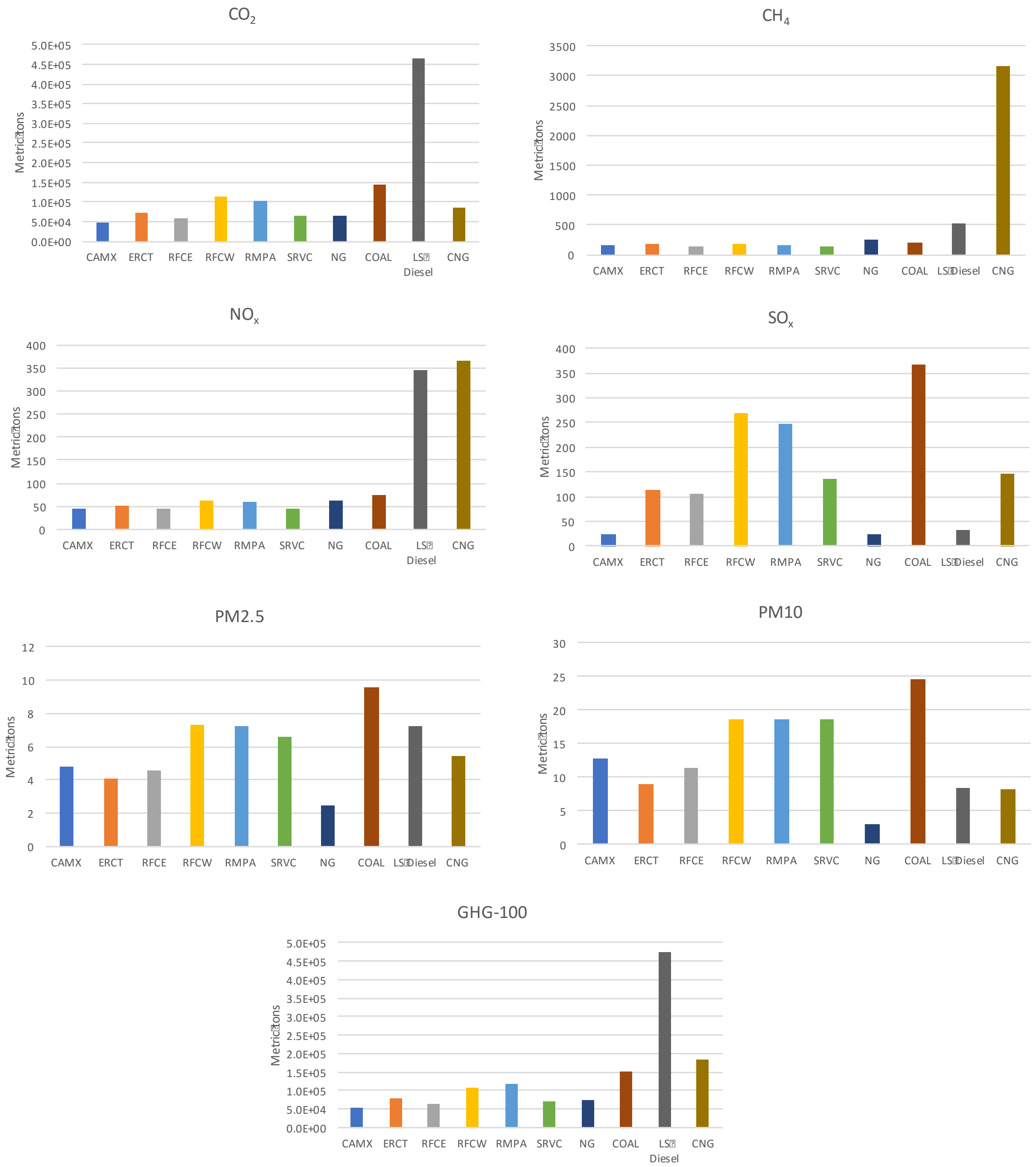

Figure 9: Total fleet lifetime vehicle lifecycle emissions (vehicle cycle and fuel cycle/electricity upstream and combustion) for electric, CNG, and LS diesel baggage tractors. Emissions are in metric tons.

6. Conclusions and Recommendations

This is a preliminary lifecycle analysis of electric, CNG, and LS diesel baggage tractors. Due to the lack of baggage tractor-specific fuel consumption data available from United, and incomplete baggage tractor production information from Charlatte America, a number of assumptions were made and information in the GREET model was relied on heavily. MHD vocational vehicles were used to model the CNG and LS diesel baggage tractor fuel consumption and emissions, and battery information from one of United's electric baggage tractors was used to model the electricity consumption of an electric baggage tractor. Build-in information and assumptions in the GREET model were used to model the CNG and LS diesel fuel emissions, whereas electricity grid fuel mixes from six NERC subregions were used to model the electric baggage tractor emissions at each of United's seven domestic hubs. An EV and ICEV pickup truck were used to model the electric, CNG, and LS diesel baggage tractor production burdens.

Due to the differences in electricity grid fuel mixes for each of the NERC subregions (see Figure 4), the benefits of electric baggage tractors over CNG and LS diesel baggage tractors depends on where the airport is located. Electric baggage tractors at San Francisco and Los Angeles International airports, located in the CAMX NERC subregion, are modeled to emit lower emissions compared to LS diesel and CNG baggage tractors for all the emissions analyzed except for PM10. Based on these emissions, it is recommended that electric baggage tractors be deployed at SFO and LAX airports. Electric baggage tractors at George Bush Intercontinental and Newark Liberty airports, located in the ERTC and RFCE NERC subregions, are modeled to emit higher PM10 emissions as compared to CNG and LS diesel baggage tractors and higher SO_x emissions as compared to LS diesel. Denver International and Chicago O'Hare airports, in the RMPA and RFCW NERC subregions, have grid fuel mixes that are dominated by coal (see Figure 4). Consequently, electric baggage tractors at these airports emit higher SO_x and PM10 lifecycle electricity emissions compared to both CNG and LS Diesel baggage tractors, as well as higher PM2.5 and CO_2 compared to CNG baggage tractors. Based on these comparative emissions, it is recommended that CNG baggage tractors be operated at the Denver and Chicago airports. Finally, electric baggage tractors at Washington Dulles airport, which is in the SRVC NERC subregion, are modeled to emit higher PM10 and SO_x emissions compared to CNG and LS diesel and higher PM2.5 emissions compared to CNG baggage tractors. Therefore, it is recommended that electric baggage tractors be operated out of Washington Dulles airport. A summary of the baggage tractor technology recommendations for each airport is summarized in Table 13.

Table 13: Summary of baggage tractor technology recommendations for each of United's domestic hubs.

Airport	**Recommended Baggage Tractor Technology**
San Francisco International	Electric
Los Angeles International	Electric
Denver International	CNG
George Bush Intercontinental	Electric
Chicago O'Hare	CNG
Washington Dulles	Electric
Newark Liberty	Electric

It is recommended that a more thorough study be conducted to further investigate the environmental benefits and implications of different baggage tractor technologies. It is important to note that this study relies heavily on assumptions and GREET data due to the lack of information available from United on the fuel use, duty cycles, and maintenance of baggage tractors. To conduct a more thorough analysis and one more specific to United's use of baggage tractors, it is recommended that United track and compile of the following information:

- Fuel use for baggage tractors (per mile or per hour)
- Charging data (How frequently are EV baggage tractors charged, and for how long? For how long can an EV baggage tractor operate on a full charge? What time of day are the baggage tractors charge?)
- Fleet duty cycle information (How many tractors are used throughout the day? How long is a single baggage tractor used? How long does the baggage tractor idle?)

APPENDIXES

Appendix A: EV Baggage Tractor Electricity Use and VMT calculations

CALCULATIONS		
		Units
Single BT Energy Use	56.31	kWh/day
	20,270.27	kWh/yr
	304,054.05	kWh/useful life
	1,094,594.59	MJ/useful life
	69,162,162.16	BTU/useful life
Fleet Energy Use	27,364.86	kWh/day
	9,851,351.35	kWh/yr
	147,770,270.27	kWh/lifetime
	531,972,972.97	MJ/lifetime
	33,612,810,810.81	BTU/lifetime
Energy rate	0.346500347	kWh/mi
	1.247401247	MJ/mi
	1182.259182	BTU/mi
Single BT VMT/d	162.5	miles/day
Single BT: VMT/yr	58,500.00	mi/year
Single BT: Lifetime VMT	877,500.00	mi/lifetime
Fleet: VMT/d	78,975.00	VMT/d
Fleet: VMT/yr	28,431,000.00	VMT/yr
Fleet: Lifetime VMT	426,465,000.00	VMT/lifetime

Appendix B: Gasoline, CNG, and LS Diesel Baggage Tractor Fuel use and VMT

CALCULATIONS		
		Units
Single BT: VMT/d	262.5	miles/day
Single BT: VMT/yr	94,500.00	mi/year
Single BT: Lifetime VMT	1,417,500.00	mi/lifetime
Fleet: VMT/d	78,750.00	VMT/d
Fleet: VMT/yr	28,350,000.00	VMT/yr
Fleet: Lifetime VMT	425,250,000.00	VMT/lifetime
GASOLINE		
Single BT Fuel Use: Low rpm	9.45	gal gasoline/day
Single BT Fuel Use: High rpm	15.75	gal gasoline/day
Single BT Fuel Use: Total	25.2	gal gasoline/day
Fleet Fuel Use: Total	7560	gal gasoline/day
Mileage	0.10	gal gasoline/mile
	10.41666667	miles/gal gasoline
BT: Energy Content	10770.624	BTU (LHV)/mi

CNG		
		Units
BT: **USE** PHASE Energy Use	15741.68	BTU(LHV)/mi
	16.61	MJ/mi
	4359.46	MJ/day
	5978.69	MJ/year
	89680.36	MJ/lifetime
FLEET: **USE** PHASE Energy Use	4722504.37	BTU (LHV)/mi
	4982.24	MJ/mi
	1307838.55	MJ/day
	1793607.16	MJ/Year
	26904107.39	MJ/lifetime
BT: **WTW** Energy Use	19055.72	BTU(LHV)/mi
	20.10	MJ/mi
	5277.24	MJ/day
	1899807.58	MJ/year
	28497113.75	MJ/lifetime
FLEET: **WTW** Energy Use	5716715.82	BTU (LHV)/mi
	6031.14	MJ/mi
	1583172.99	MJ/day
	569942275.00	MJ/Year
	8549134125.06	MJ/lifetime
BT: **WTP** Energy Use	3314.04	BTU(LHV)/mi
	3.50	MJ/mi
	917.78	MJ/day
	1893828.89	MJ/year
	28407433.39	MJ/lifetime
FLEET: **WTP** Energy Use	994211.45	BTU (LHV)/mi
	1048.89	MJ/mi
	275334.43	MJ/day
	568148667.84	MJ/Year
	8522230017.67	MJ/lifetime

Diesel		
		Units
Single BT: **USE** PHASE Energy Use	8751.1	BTU(LHV)/mi
	9.2	MJ/mi
	2,423.52	MJ/day
	872466.0	MJ/year
	13086989.7	MJ/lifetime
Fleet: **USE** PHASE Energy Use	2625339.6	BTU (LHV)/mi
	2769.7	MJ/mi
	727055.0	MJ/day
	261739794.8	MJ/Year
	3926096921.6	MJ/lifetime
Single BT: **WTW** Energy Use	10938.92	BTU(LHV)/mi
	11.54	MJ/mi
	3029.40	MJ/day
	1090582.48	MJ/year
	16358737.17	MJ/lifetime
Fleet: **WTW** Energy Use	3281674.50	BTU (LHV)/mi
	3462.17	MJ/mi
	908818.73	MJ/day
	327174743.46	MJ/Year
	4907621151.96	MJ/lifetime
Single BT: **WTP** Energy Use	2187.78	BTU(LHV)/mi
	2.31	MJ/mi
	605.88	MJ/day
	218116.50	MJ/year
	16358737.17	MJ/lifetime
Fleet: **WTP** Energy Use	656334.90	BTU (LHV)/mi
	692.43	MJ/mi
	181763.75	MJ/day
	65434948.69	MJ/Year
	981524230.39	MJ/lifetime

APPENDIX C: Fleet lifetime fuel cycle and electricity lifecycle emissions in metric tons.

	CO_2	CH_4	NO_x	PM10	PM2.5	SO_x	GHG-100
CAMX	45808.78	159.59	44.33	11.84	4.36	13.65	51719.59
ERCT	70929.73	180.28	50.24	8.13	3.65	103.44	76840.54
RFCE	56152.70	130.04	42.85	10.45	4.09	93.10	60585.81
RFCW	110827.70	186.19	60.59	17.73	6.88	257.12	106394.59
RMPA	100483.78	165.50	59.11	17.73	6.76	234.95	116738.51
SRVC	63541.22	122.65	44.33	17.73	6.10	124.13	67974.32
NG	65018.92	248.25	60.59	2.04	1.99	13.93	73885.14
COAL	141859.46	209.83	72.41	23.64	9.10	356.13	149247.97
LS Diesel	465176.97	518.60	343.51	7.91	7.00	29.91	474424.91
CNG	84569.59	3160.22	365.24	7.69	5.22	143.77	182811.99

APPENDIX D:

Total fleet lifecycle emissions (metric tons) for EV (with Li-ion battery) baggage tractors and CNG and LS Diesel baggage tractors. “EV” and “ICEV” represents the manufacturing emissions for the fleet of tractors (300 ICEV baggage tractors, 486 EV baggage tractors) and the NERC subregion, “Coal”, “Natural Gas Electricity”, “LS Diesel”, and “CNG” represents fuel cycle emissions over the lifetime of the fleet.

	EV	**CAMX**	**Total**
CO_2	1,543.67	45,808.78	47,352.45
CH_4	4.01	159.59	163.60
NO_x	1.95	44.33	46.28
PM10	0.86	159.59	160.45
PM2.5	0.44	4.36	4.80
SO_x	11.24	13.65	24.89
GHG-100	2,366.43	51,719.59	54,086.03

	EV	**ERCT**	**Total**
CO_2	1,543.67	70,929.73	72,473.40
CH_4	4.01	180.28	184.29
NO_x	1.95	50.24	52.19
PM10	0.86	8.13	8.98
PM2.5	0.44	3.65	4.10
SO_x	11.24	103.44	114.68
GHG-100	2,366.43	76,840.54	79,206.97

	EV	**RFCE**	**Total**
CO_2	1,543.67	56,152.70	57,696.37
CH_4	4.01	130.04	134.04
NO_x	1.95	42.85	44.80
PM10	0.86	10.45	11.31
PM2.5	0.44	4.09	4.53
SO_x	11.24	93.10	104.34
GHG-100	2,366.43	60,585.81	62,952.24

	EV	**RFCW**	**Total**
CO_2	1,543.67	110,827.70	112,371.37
CH_4	4.01	186.19	190.20
NO_x	1.95	60.59	62.53
PM10	0.86	17.73	18.59
PM2.5	0.44	6.88	7.32
SO_x	11.24	257.12	268.36
GHG-100	2,366.43	106,394.59	108,761.03

	EV	**RMPA**	**Total**
CO_2	1,543.67	100,483.78	102,027.45
CH_4	4.01	165.50	169.51
NO_x	1.95	59.11	61.06
PM10	0.86	17.73	18.59
PM2.5	0.44	6.76	7.21
SO_x	11.24	234.95	246.19
GHG-100	2,366.43	116,738.51	119,104.95

	EV	**SRVC**	**Total**
CO_2	1,543.67	63,541.22	65,084.89
CH_4	4.01	122.65	126.65
NO_x	1.95	44.33	46.28
PM10	0.86	17.73	18.59
PM2.5	0.44	6.10	6.55
SO_x	11.24	124.13	135.37
GHG-100	2,366.43	67,974.32	70,340.76

	EV	Natural Gas Electricity	Total
CO_2	1,543.67	65,018.92	66,562.59
CH_4	4.01	248.25	252.26
NO_x	1.95	60.59	62.53
PM10	0.86	2.04	2.90
PM2.5	0.44	1.99	2.43
SO_x	11.24	13.93	25.17
GHG-100	2,366.43	73,885.14	76,251.57

	EV	Coal	Total
CO_2	1,543.67	141,859.46	143,403.13
CH_4	4.01	209.83	213.84
NO_x	1.95	72.41	74.36
PM10	0.86	23.64	24.50
PM2.5	0.44	9.10	9.54
SO_x	11.24	356.13	367.37
GHG-100	2,366.43	149,247.97	151,614.41

	ICEV	LS Diesel	Total
CO_2	795.05	307,089.49	307,884.54
CH_4	2.13	342.36	344.49
NO_x	0.88	226.77	227.66
PM10	0.43	5.22	5.65
PM2.5	0.20	4.62	4.83
SO_x	3.48	19.75	23.23
GHG-100	877.96	313,194.57	314,072.53

	ICEV	CNG	Total
CO_2	795.05	39,590.75	40,385.80
CH_4	2.13	1479.44	1,481.57
NO_x	0.88	170.98	171.87
PM10	0.43	3.60	4.03
PM2.5	0.20	2.44	2.64
SO_x	3.48	67.31	70.78
GHG-100	877.96	85,582.34	86,460.30

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