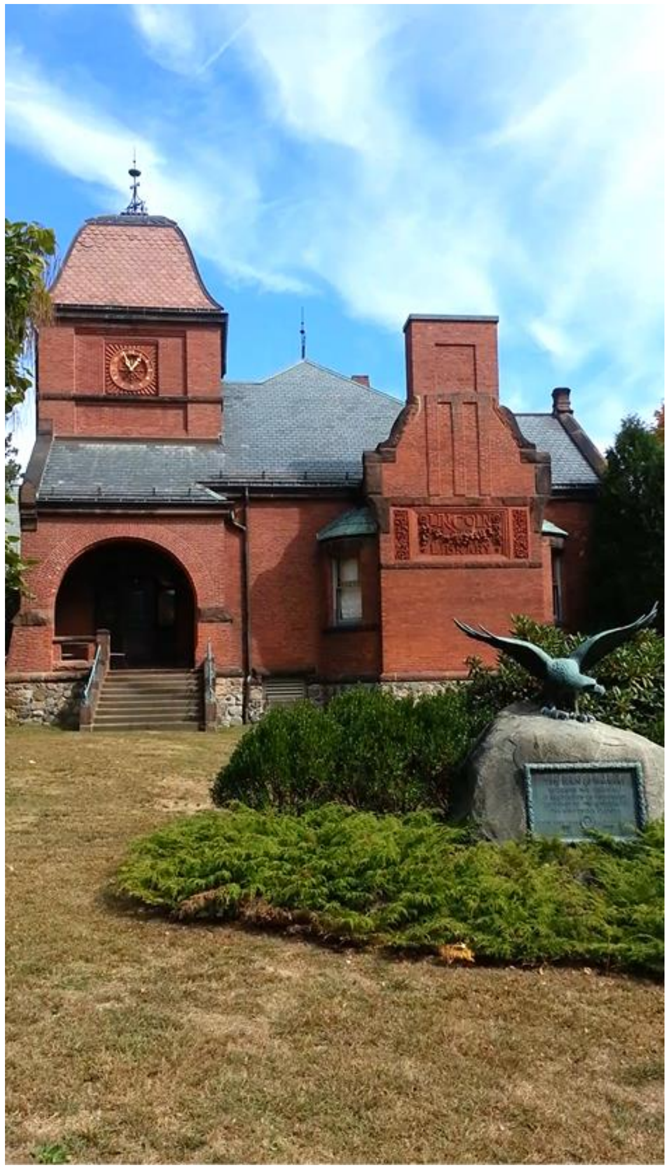
Town of Lincoln

Community greenhouse gas emissions report



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January 2020

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1. Executive Summary

This inventory provides an assessment of greenhouse gas emissions for the town of Lincoln for the year 2017. Three sectors are considered: transportation (46% of total emissions), stationary energy (52%) and waste (2%). Total emissions for 2017 were estimated to be approximately 61,000 metric tons of CO_2 equivalent (CO_2e) (Table 1 and Figure 1).

Transportation:

Vehicles: Use of vehicles accounted for about 34% of total emissions. The number of vehicles in Lincoln has stayed constant in recent years while the average emissions per vehicle have declined slightly due to a decrease in miles driven per vehicle and an improvement in vehicle fuel efficiency.

Air travel: Based on the income distribution of Lincoln households, it was estimated that on average adults in Lincoln take 2.7 personal trips by air per year, leading to an estimate for emissions of ~7000 tons CO_2e (11% of total emissions).

Commuter rail: Emissions associated with operation of the MBTA Fitchburg commuter rail line represent 2% of emissions.

Stationary Energy:

Natural Gas: Emissions from combustion of natural gas in Lincoln accounted for 20% of emissions. Release of unburned methane from the distribution system through gas leaks was estimated to account for an additional 6% of total CO_2e emissions, based on an estimated leakage rate for the greater Boston area and using a 100-year global warming potential (GWP) for methane.

Fuel Oil and Propane: Use of fuel oil and propane account for 7% and 1% of total emissions, respectively; oil use has declined in recent years as households have switched to gas or electric heating systems.

Electricity: Electricity use accounted for 18% of emissions, based on the current carbon intensity of the New England electric grid. An additional 1% of emissions results from electricity system losses.

Waste:

Incineration of Lincoln's trash accounted for 0.6% of CO_2e emissions, while wastewater treatment in septic systems accounted for 1% of CO_2e emissions.

Opportunities for emissions reductions:

Electrification coupled with a transition to carbon-free electricity is a key strategy to enable deep emissions reductions. The largest opportunities for reductions lie in the choices made when residents replace vehicles and heating systems; adoption of electric vehicles and heat pumps offers the potential for large immediate reductions in emissions and provides a pathway to zero emissions. Community Choice Aggregation would allow Lincoln to choose carbon-free electricity, reducing emissions from current sources of electricity use and those arising from further electrification of transportation and heating. Opportunities for emissions reductions are discussed in more detail in Section 4 of the report.

Summary of emissions:

Sector	Sub-Category	Scope 1	Scope 2	Scope 3	Total emissions (MT CO2e)
Transportation	Vehicles	•		•	20700
	Air Travel			•	7000
	Commuter Rail	•			1010
Stationary Energy	Natural Gas	•			11900
	Natural Gas, fugitive emissions	•			3300
	Fuel Oil	•			4200
	Propane	•			420
	Electricity		•		10700
	Electricity distribution losses			•	580
Waste	Solid waste incineration			•	360
	Wastewater treatment	•			810
Total emissions					**61000**

Table 1 – Emissions Summary (2017)[1]

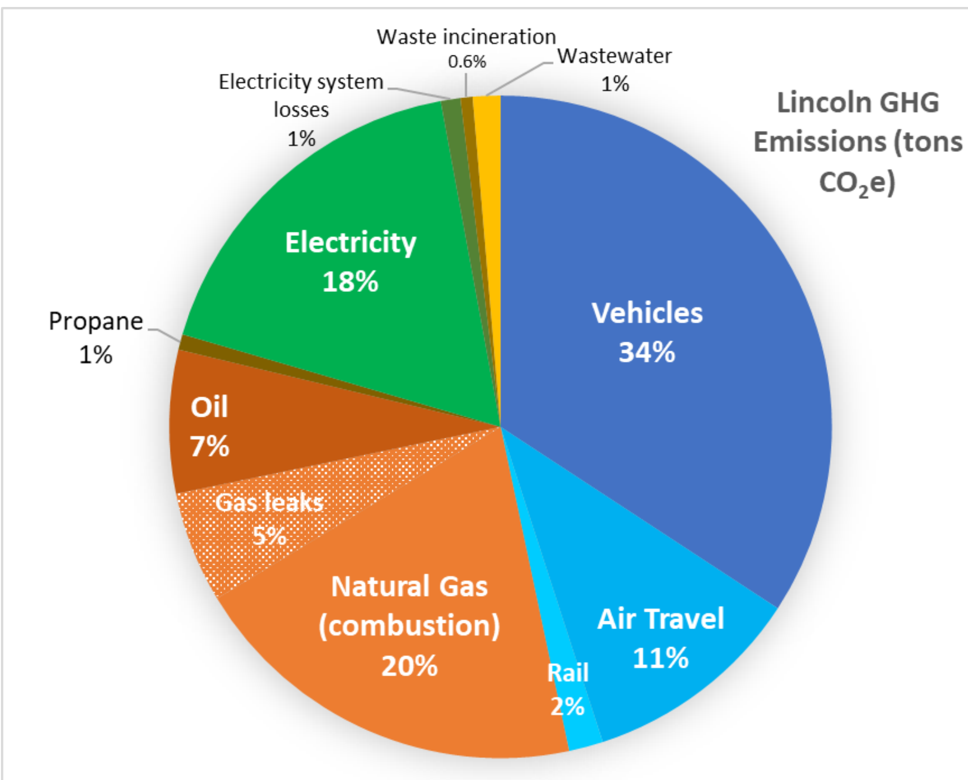


Figure 1 – Emissions Summary (2017)

[1] Values are rounded to reflect uncertainties in underlying estimates.

2. Introduction

Greenhouse gases drive global warming by trapping heat in the atmosphere. This inventory of greenhouse gases was prepared for the Green Energy Committee of the Town of Lincoln to help identify the major sources of greenhouse gas emissions in Lincoln and to inform actions in the town to reduce these emissions. It includes emissions from the community as a whole, with a separate discussion of emissions from municipal sources.

The principal heat-trapping gas is carbon dioxide (CO_2), which is produced primarily by the burning of fossil fuels. Other heat-trapping gases include methane, nitrous oxide, and a variety of fluorinated gases, which are quantified in terms of tons of CO_2 equivalent (CO_2e; see section 3.2.1.1 for more discussion of this concept).

This inventory follows the general approach described in the Global Protocol for Community-Scale Greenhouse Gas Inventories (GPC) developed by the World Resources Institute, the C40 Cities, and ICLEI[2]. This protocol was developed to provide a framework to guide the creation of community inventories that satisfy the core principles of *relevance, completeness, consistency, transparency, and accuracy*.

Following the GPC, emissions can be classified into three Scopes:

Scope 1: Emissions occurring within the geographical boundaries of the town.
Scope 2: Emissions resulting from grid-supplied energy.
Scope 3: Emissions influenced by activities in the town, but occurring outside of the town's boundaries.

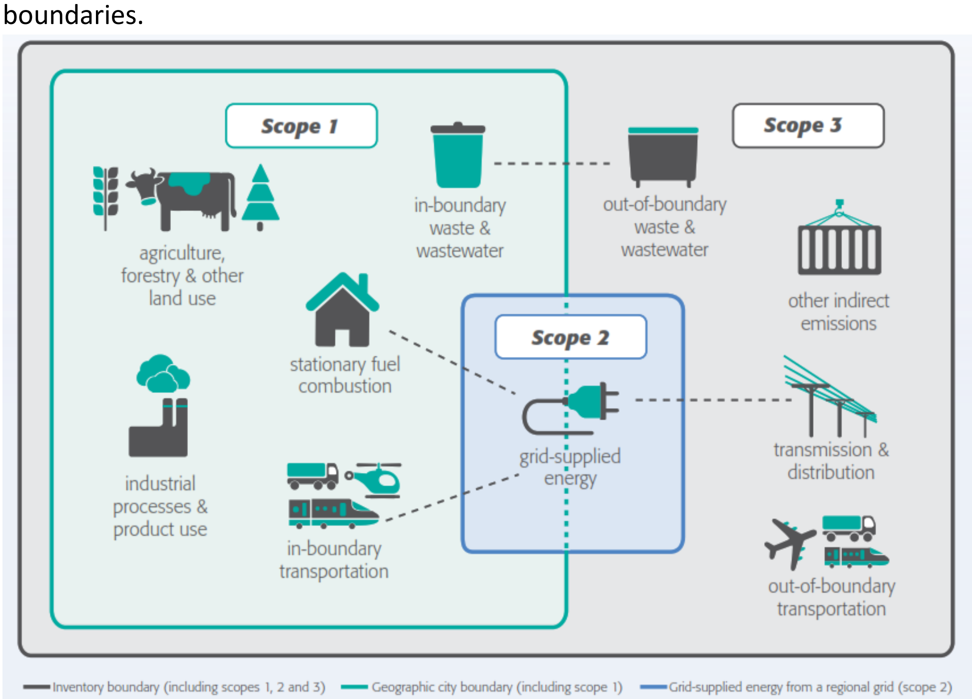


Figure 2. Definition of Scopes. Source: https://ghgprotocol.org/sites/default/files/standards/GHGP_GPC_0.pdf

[2] https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities

This inventory includes the categories covered by the GCP "city-induced" framework at the BASIC accounting level, which are primarily Scope 1 and Scope 2 emissions. Three sectors are considered:

- Transportation
- Stationary Sources (fuel and electricity use in buildings)
- Waste

The GCP offers particular flexibility concerning methods used to quantify emissions from transportation, so as to allow tailoring of inventories as appropriate for the characteristics and needs of different communities. Of specific note, this inventory for Lincoln includes an estimate of emissions from air travel, something not included in GCP BASIC level reporting; the rationale for this inclusion is outlined in section 3.1.2.

This inventory does <u>not</u> include:

- Emissions from industrial processes
- Emissions from agriculture and other land use

These were excluded because of lack of relevant data and in recognition of the fact that Lincoln is a largely residential town, such that emissions from industrial or agricultural sources are likely to be small.

This inventory also does <u>not</u> include most indirect Scope 3 emissions that ultimately result elsewhere in the economy as a consequence of the activities of Lincoln residents such as their purchasing of food, goods and services. There is a discussion of how such activities may be considered via consumption-based accounting in section 5.

The base year for this inventory is 2017. The means by which emissions are estimated and sources of uncertainty in those estimates are outlined in the Results; further details regarding the data sources and calculations of CO_2e emissions for different activities are provided in the Appendix.

3. Results

<u>Summary of Results</u>

The following table and figure summarize the estimates of emissions from all included sources for the town.

Sector	Sub-Category	Scope 1	Scope 2	Scope 3	Total emissions (MT CO2e)
Transportation	Vehicles	•		•	20700
	Air Travel			•	7000
	Commuter Rail	•			1010
Stationary Energy	Natural Gas	•			11900
	Natural Gas, fugitive emissions	•			3300
	Fuel Oil	•			4200
	Propane	•			420
	Electricity		•		10700
	Electricity distribution losses			•	580
Waste	Solid waste incineration			•	360
	Wastewater treatment	•			810
Total emissions					**61000**

Table 2 – Emissions Summary for 2017[3]

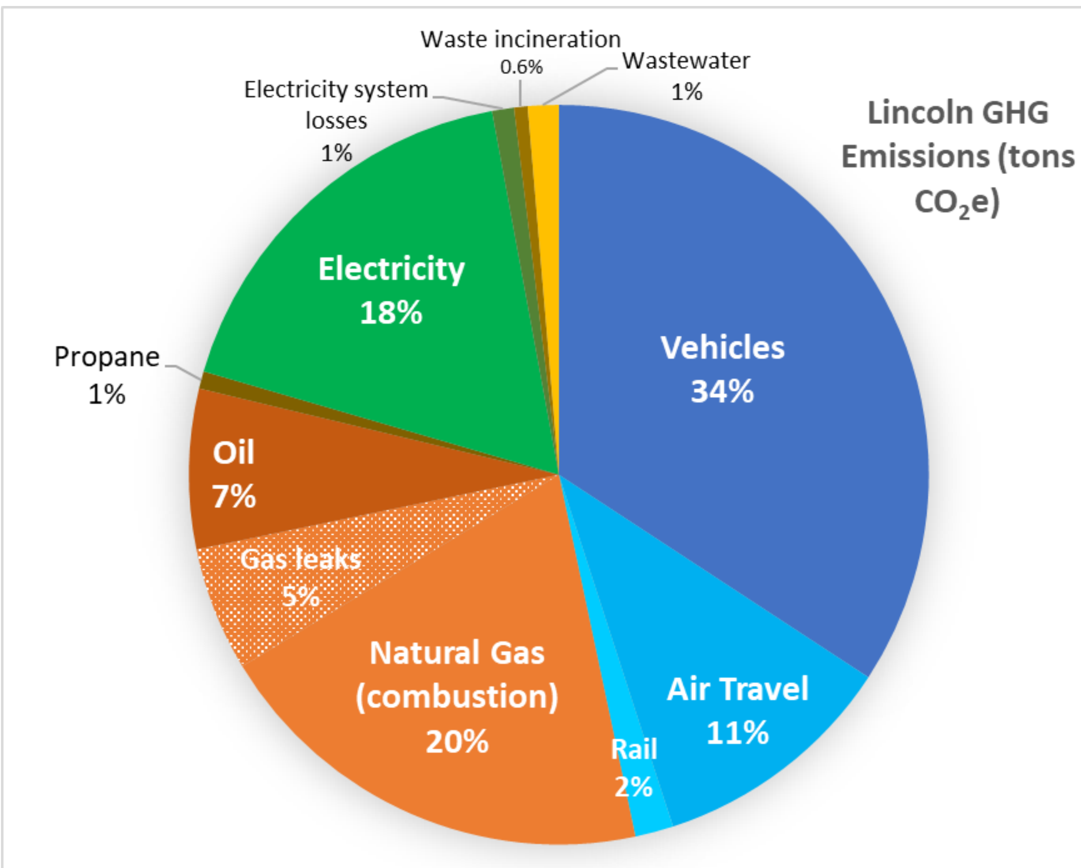


Figure 3 – Emissions Summary for 2017

[3] Values are rounded to reflect uncertainties in underlying estimates.

3.1. Transportation

3.1.1. Vehicles

On-road vehicles are a major source of emissions in many communities. Such emissions can be accounted for in a variety of ways. The method selected for this inventory was the *resident activity* method: all emissions resulting from driving vehicles garaged in Lincoln are included, whether the travel occurs inside or outside the boundaries of the town of Lincoln.

There are several advantages of the resident activity method that led to it being selected for this inventory:

- **Data availability/accuracy**. The detailed data about Lincoln vehicles in the Massachusetts Vehicle Census (see below) is freely available and will continue to be so as it is updated in the future. An alternative approach to the resident activity method is an origin-destination approach wherein emissions from cross-boundary trips are allocated to multiple jurisdictions (e.g. the emissions resulting from a Lincoln resident commuting by car from Lincoln to Boston would be divided between both communities); however, this would require detailed and expensive modeling.
- **Relevance and agency**. The emissions resulting from the use of personal vehicles by residents of Lincoln are under the direct control of those residents through their choices about type of vehicle and driving activity. While policies adopted in destination communities (e.g. regarding availability of parking or alternative transit options) can influence decisions about vehicle use, these decisions ultimately fall to the vehicle users.
- **Simplicity**. The resident activity method is conceptually simple to explain to stakeholders.
- **Lincoln as an "origin" town**. A disadvantage of the resident activity method is that it does not capture emissions resulting from visitors to the town, a category of emissions over which policies and decisions made in Lincoln could have some influence. However, while Lincoln does boast a number of sites that draw visitors from outside of town (e.g. Drumlin Farm), it seems likely that as a community it is more of an "origin" than a "destination"; that is, the number of roundtrips that originate in Lincoln by Lincoln residents likely significantly exceeds the number of roundtrips by visitors who are coming to Lincoln as a destination.

The source of information about vehicle use is the Massachusetts Vehicle Census (MAVC), a resource assembled by the Metropolitan Area Planning Council (MAPC, 2015[4]). This resource draws on Registry of Motor Vehicle records for every vehicle registered in Massachusetts, incorporating data from odometer readings and information on vehicle characteristics, which allows a detailed picture of the use of vehicles by Lincoln residents to be obtained. The MAVC currently covers vehicles registered in the years 2009-2014, but updates to the database are being worked on.

Three factors determine emissions from vehicles: the number of vehicles, the miles driven by each vehicle, and the emissions resulting per mile driven based on the efficiency of the vehicle.

The total number of vehicles in Lincoln recorded in the MAVC remained quite constant during the years 2011-2014 (Figure 4A) at around 4950 vehicles. This is very close to the number of vehicles for which

[4] https://www.mapc.org/learn/data/#vehiclecensus

tax excise bills were issued in Lincoln during the first commitment period of each of the years 2017 through 2019, which also stayed constant at about 4980 vehicles[5]. Over 95% of the vehicles in Lincoln were classified in the MAVC as non-commercial in 2014. The number of vehicles with different model years is shown in Figure 4B; the distribution of model years suggests a typical lifespan for new vehicles of 10-15 years.

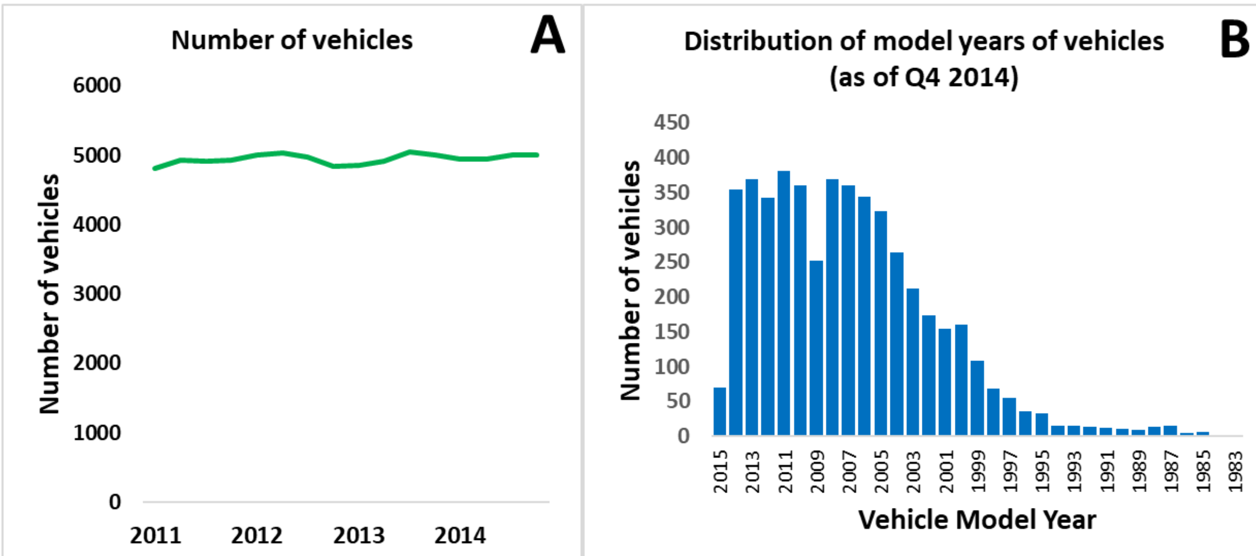


Figure 4. Vehicle number and distribution of model years. A) Number of vehicles garaged in Lincoln. Total vehicles by quarter, 2011-2014 from MAVC. B) Distribution of vehicle model years as of the fourth quarter of 2014.

Vehicles are categorized in the MAVC into different vehicle types. The most common type of vehicle in Lincoln is non-hybrid cars (Figure 5A). The percentage of vehicles that were hybrid cars increased during the time period covered by the MAVC, as did the percentage that were non-hybrid SUVs (Figure 5B).

[5] Auto excise bill data received from the town Treasurer.

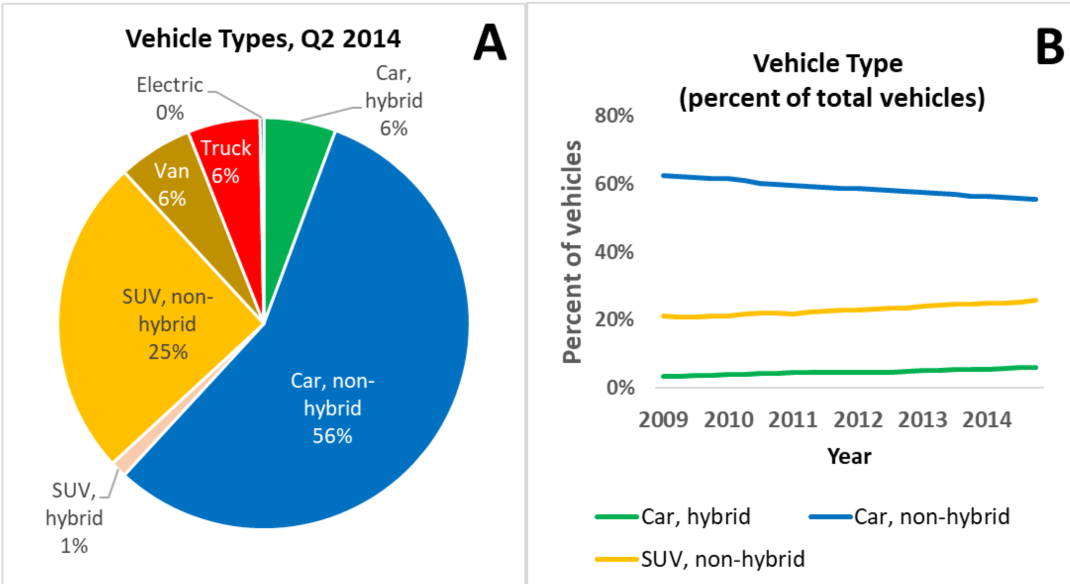


Figure 5. Vehicle types in Lincoln, 2009-2014[6].

There was a wide distribution in the average number of miles driven per day among the Lincoln vehicles (Figure 6A). During the time period currently covered by the MAVC, the average miles per vehicle declined slightly (Figure 6B). (Note that this is a per-vehicle analysis, not per-household).

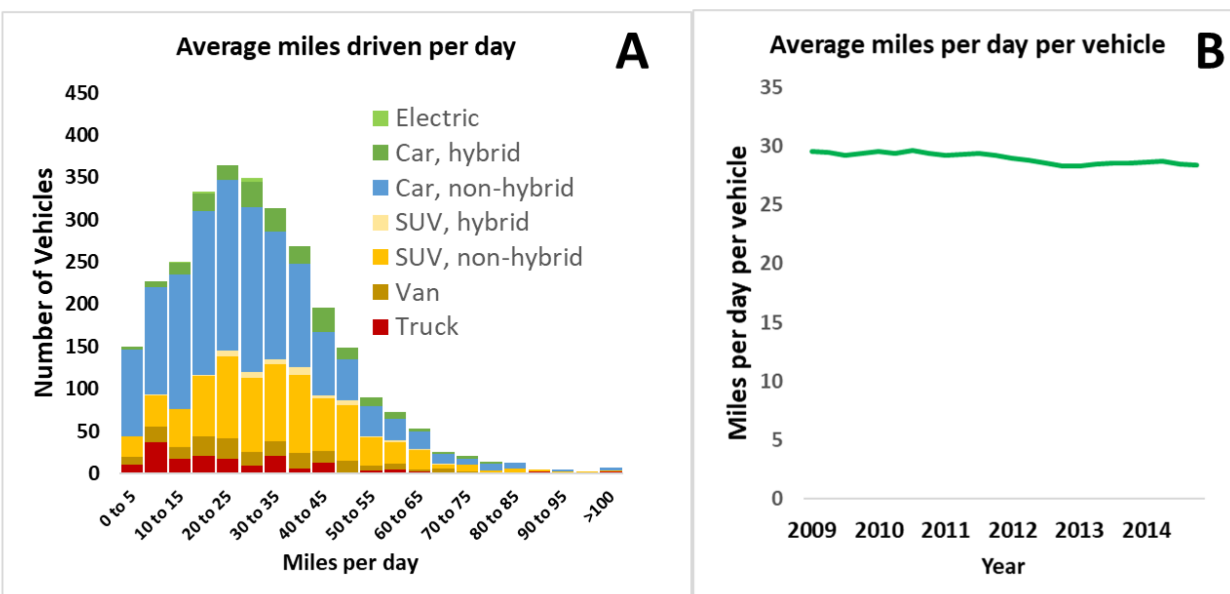


Figure 6. A) Average miles driven by day by type of vehicle (Q2 of 2014). B) Average miles driven per day per vehicle, 2009-2014.

[6] Electric vehicles are not classified as a separate vehicle type in the MAPC, but can be identified based on their fuel type. Only 14 electric vehicles were in the database for Lincoln as of 2014.

Both the number of vehicles per household and the average distance driven per day per vehicle are comparable to those seen in neighboring towns (Table 3). As would be expected, the distances driven in these towns are higher than those for communities closer to downtown Boston, but less than those in more rural areas of the state[7]. The estimated average number of passenger vehicles per household also closely corresponds to that reported for Lincoln for 2017 in census data from the American Community Survey (about 1.8)[8].

	Miles per day	Vehicles per household
Lincoln	28.3	1.83
Bedford	28.1	2.04
Concord	29.5	1.70
Lexington	25.9	1.84
Sudbury	30.7	2.19
Waltham	27.1	1.51
Wayland	28.3	2.06
Weston	27.2	2.09

Table 3. Comparison of average miles per day for all vehicles and number of passenger vehicles per household for Lincoln and surrounding towns. Source: MAVC municipality summaries for Q2 2014 (MAPC, 2015).

Fuel efficiency also varied widely among vehicles, with the least efficient vehicles (mainly SUVs and trucks) using over four times as much fuel per mile as more efficient hybrid cars (Figure 7A)[9]. Average fuel efficiency improved slightly during the period 2009-2014 (Figure 7B); this was influenced by multiple concurrent underlying trends:

- An increase in the percentage of vehicles that are higher efficiency hybrids (Figure 5B)
- Conversely, a simultaneous increase in the percentage of vehicles that are SUVs (which *reduces* overall fuel efficiency since SUVs have a lower average fuel efficiency than cars) (Figure 5B)
- A small overall increase in fuel efficiency of non-hybrid vehicles (Figure 7B)

7 "Vehicle Miles Traveled in Massachusetts: Who is Driving and Where are they Going?" Presentation by Timothy Reardon, Metropolitan Area Planning Council. Available at http://willbrownsberger.com/wp-content/uploads/2010/04/MAPC_Reardon_Climate-Change-Committee-4_13_10.pdf

8 American Community Survey (ACS). Unless otherwise indicated, all numbers from the ACS in this inventory are from the 2013-2017 five-year estimates. https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml

9 Note that fuel efficiency is adjusted for the age of vehicle in the MAVC and so is lower than manufacturer's specifications.

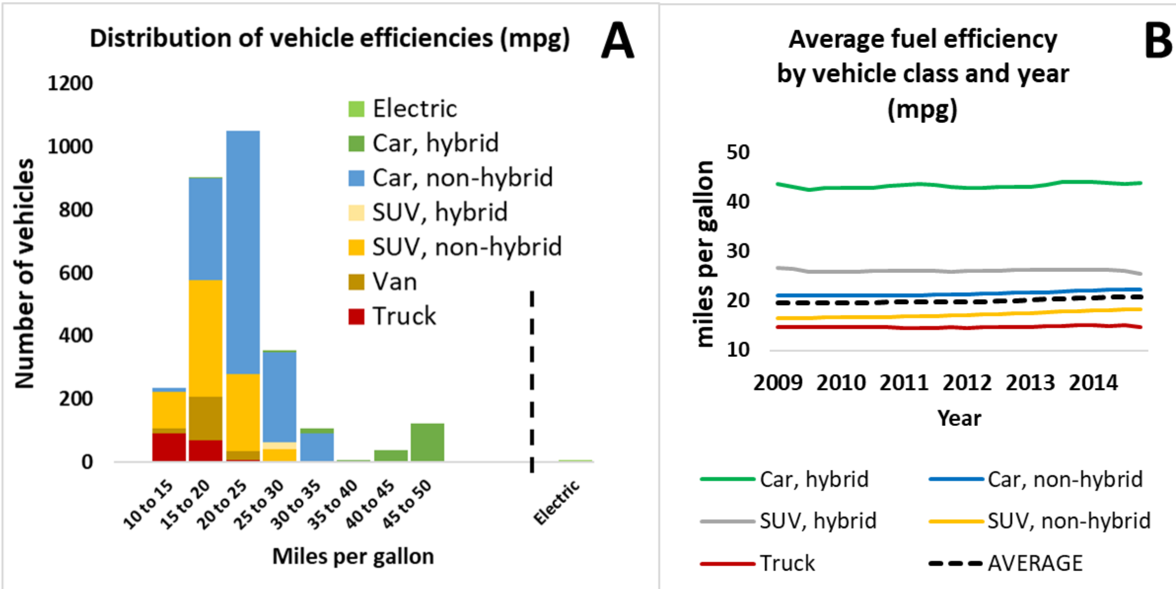


Figure 7. A) Distribution of vehicle efficiencies by class of vehicle (Q2 of 2014) B) Change in average fuel efficiencies within each class of vehicle in Lincoln, 2009-2014. Dotted line shows overall average for all vehicles.

The MAVC computes the average CO_2 emissions per day for each individual vehicle based on its combination of fuel efficiency and miles per day driven (Figure 8A). Overall, the average CO_2 emissions per day per vehicle declined from 2009-2014 (Figure 8B), due to the combined effects of reduced miles driven and higher vehicle efficiency.

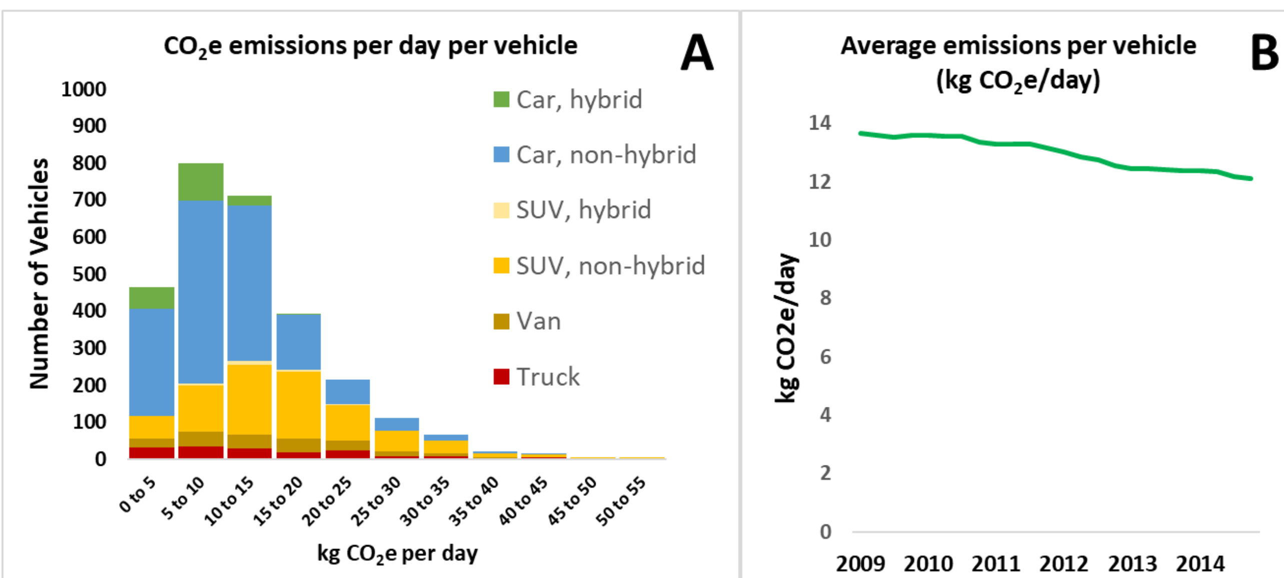


Figure 8. A) Distribution of emissions per day per vehicle by class of vehicle (Q2 of 2014) B) Change in average CO2e emissions per vehicle, 2009-2014.

Using this information, assuming 4981 vehicles in total in Lincoln in 2017 and extrapolating forward to 2017 the linear trend seen from 2009-2014 in average CO_2 emissions per vehicle per day leads to an emissions estimate for 2017 of 4981 vehicles × 11.4 kg CO_2e per day per vehicle = ~20,700 tons of CO_2e/year. Future updates of the MAVC should allow further validation of this estimate and its extension to future years.

3.1.1.1. Electric Vehicles

While adoption of hybrid cars has contributed to reducing emissions, more dramatic reductions in per-vehicle emissions have begun to occur in the last few years due to the adoption of electric vehicles (EVs). Only a few electric vehicles are seen in the MAVC dataset for Lincoln (14 vehicles by the end of 2014) but adoption of EVs has mainly occurred since 2014, so statistics from the MOR-EV program (a Massachusetts program of rebates for newly purchased or leased EVs) were consulted as a proxy to get a sense of more recent EV adoption[10]. While the absolute numbers have been small so far, judging from MOR-EV rebates, Lincoln has been a leader in EV adoption when compared to other neighboring communities on a per capita basis (Table 4).

	Population	MOR-EV rebates (2014-2019)	rebates per 1000 people
Lincoln	6696	106	15.8
Bedford	14105	103	7.3
Concord	19357	238	12.3
Lexington	33339	469	14.1
Sudbury	18697	171	9.1
Waltham	62832	76	1.2
Wayland	13700	177	12.9
Weston	12027	177	14.7
Massachusetts	6789319	15417	2.3

(**Table 4**. MOR-EV rebates issued to residents of Lincoln and neighboring towns. Source: https://mor-ev.org/program-statistics. Population estimates from American Community Survey.)

Rebates were issued for 36 vehicles registered in Lincoln by the end of 2017; this would represent less than 1% of the total vehicle count for 2017. Accordingly, emissions from the electricity used to charge these vehicles was not reported separately from electricity use in buildings, but would likely account for less than 0.3% of total emissions from electricity use in 2017[11]. As EVs become a larger portion of the vehicle fleet in Lincoln, accounting separately for the electricity used in charging will become more important, and will require information about the charging behavior of Lincoln EV owners (where vehicles are being charged and using what source of electricity).

3.1.2. Air Travel

[10] https://mor-ev.org/ Not all eligible owners will have applied for rebates, and not all models of EV were eligible for rebate throughout the course of the program, so this measure only provides a lower bound on EV numbers.
[11] Assuming .33 kWh/mile EV efficiency, average 27 miles/day/vehicle, and that all charging takes place in Lincoln.

Emissions from air travel are not generally included in community inventories, and fall outside of the scope of what is included in BASIC level GPC reporting. However, it was decided that based on the principles of relevance, completeness, and especially consistency, an attempt should be made to estimate emissions associated with flights by Lincoln residents. Flights for personal purposes are for the most part under a similar degree of discretionary control by Lincoln residents as are their on-road trips in vehicles. Accordingly, given that a resident activity method that includes all travel (inside and outside of Lincoln) is being used for vehicles, it would seem inconsistent to exclude similar travel by air. This is particularly highlighted by envisaging the scenario in which a Lincoln resident is choosing between alternative means of travel; if air travel is excluded from the inventory, then while emissions from (for example) driving to and from Washington D.C. in a vehicle would appear in the community inventory as vehicle miles traveled, emissions from flying to make the very same trip would not. Another argument in favor of considering air travel is that Lincoln has a high median household income ($134,211 compared to a US average of $57,652[12]); since air travel increases with income (Figure 9A), emissions from air travel would be expected to be higher for residents of Lincoln than for those of other towns, increasing their saliency.

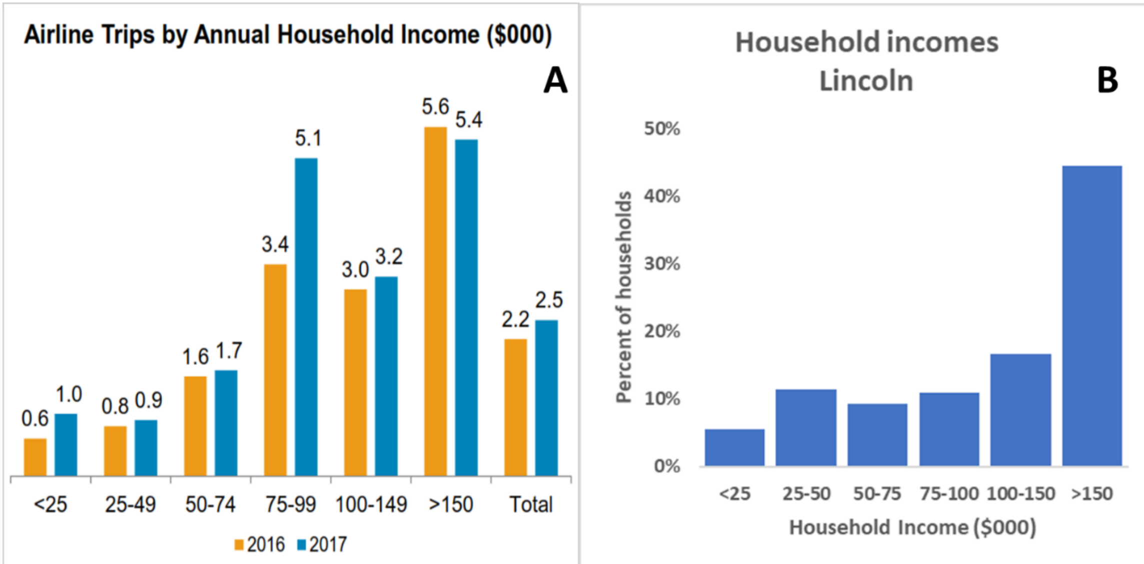
The major limitation in estimating emissions from air travel is limited information. In the absence of Lincoln-specific polling data, which may be conducted for future updates, this will necessarily be an approximation with large uncertainties; nonetheless, it will serve to give a sense of the possible magnitude of emissions from air travel relative to those from vehicular transportation.

The GPC suggests that Scope 3 emissions from air travel for the extended BASIC+ level of reporting can be estimated by considering only departing flights from regional airports serving a community. However, such an approach seemed inconsistent with the resident activity method used for passenger vehicles that includes <u>all</u> vehicular travel. Accordingly, for this inventory the estimate seeks to consider all roundtrip flights taken by Lincoln residents.

Annual polling studies conducted by IPSOS for Airlines for America[13] have found that air travel by US adults varies by household income level (Figure 9A).

[12] 2013-2017 American Community Survey 5-year estimates

[13] IPSOS online survey. https://www.airlines.org/wp-content/uploads/2018/02/A4A-AirTravelSurvey-20Feb2018-FINAL.pdf



Source: Ipsos survey for Airlines for America

Source: American Community Survey 2013-2017 5 year-estimates

Figure 9. Air Travel. A: Airline trips per year as function of household income from US survey. B: Distribution of Household incomes in Lincoln.

This information was combined with data on the household income distribution for Lincoln (Figure 9B) to estimate flights by Lincoln residents by making the following simplifying assumptions:

- adults in Lincoln fly the same average amount as U.S. survey respondents with the same household income
- the fraction of Lincoln adults at each household income level is the same as the fraction of households in each level
- children don't fly (the survey was of US adults)

Under these assumptions, the average number of "trips" annually per adult in Lincoln is calculated to be 3.8. The survey question posed asked respondents to "count each roundtrip as a trip", so it is assumed that all "trips" are roundtrips. Respondents reported that 71% of all trips were for personal reasons. If we choose to count only personal trips (on the principle that emissions should be allocated to the party that paid for the flights and assuming that most business travel by Lincoln residents is conducted for companies housed outside of Lincoln), this reduces the average number to 2.7 personal trips per adult.

The distance of these trips was not specified, though it was elsewhere noted in the survey that two-thirds of all trips are domestic. We assume that each trip is a return flight from Boston to Chicago, a distance of ~900 miles. The estimated emissions from each such trip is ~0.5 tons CO_2e (see Appendix). This is roughly three times the emissions from a short roundtrip to New York City and about 1/3 of the emissions from a roundtrip to San Francisco, and thus lies in the middle of the range of lengths of possible domestic flights. The total emissions from flights by Lincoln adults is then broadly estimated as 2.7 trips × 0.5 tons CO_2e/trip × 4802 adults in Lincoln, which gives an estimate of ~7000 tons of CO_2e.

3.1.3. Commuter Rail

Lincoln is served by the MBTA Fitchburg line commuter rail stop at Lincoln Station. The GCP recommends assessing Scope 1 emissions from rail by using the extent of track length that falls within the geographic boundaries of a community. A total of 12,651,108 gallons of diesel fuel were used by the commuter rail system in 2017 and 3.05 miles of the 388 miles of system track length lie within the town of Lincoln, leading to an estimate of ~1020 tons of CO_2e.

3.1.4. Other transportation

Emissions from inter-city rail and bus travel by Lincoln residents (e.g. Amtrak, Greyhound) were not included, but were assumed to be smaller than the uncertainty in the estimate of emissions from air travel. Similarly, Scope 3 emissions from use by Lincoln residents of vehicles not garaged in Lincoln (e.g. rental cars) or public transit other than the Fitchburg commuter rail line were not considered.

3.2. Stationary Sources

3.2.1. Natural Gas

Natural gas is supplied to residents of Lincoln by National Grid. Natural gas is mainly used for space heating, though water heating, dryers and gas cooking also account for a portion of natural gas consumption. Total usage of natural gas in Lincoln in 2017 was obtained from usage data reported by National Grid to masssavedata.com, and totaled 2.24 million therms, resulting in emissions of ~11,900 tons CO_2e.

Usage is classified in the masssavedata.com records as either “Residential & Low Income” or “Commercial & Industrial”. Residential gas usage in recent years was compared for several nearby communities that are also served by National Grid (Figure 10).

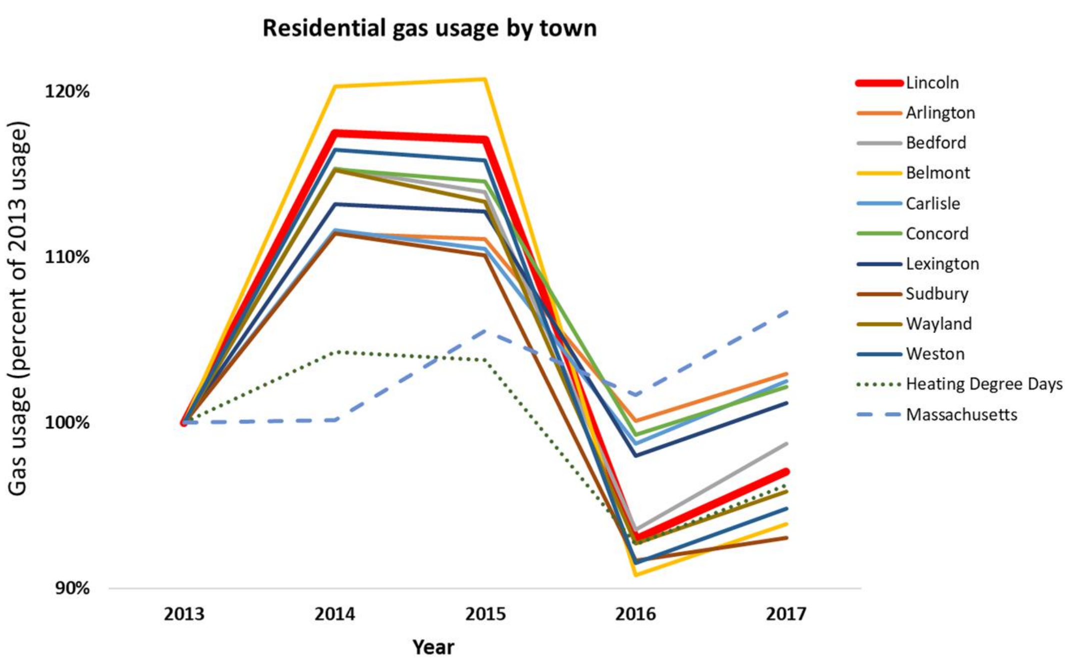


Figure 10. Residential natural gas usage in several towns served by National Grid, 2013-2017.[14]

Reported residential usage in each town fluctuated from year to year in parallel with each other and with the number of heating degree days, a measure of heating load demand. There is more variability from year to year than is seen for total natural gas usage in Massachusetts, but this is to be expected in that about half of the Massachusetts usage is for electricity generation and industry, while most residential use is for home heating, the need for which varies with the severity of winters. It is not obvious why the annual fluctuations are larger in some towns like Lincoln and Belmont than in others like Arlington and Carlisle. One possibility is that this may reflect a higher fraction of use of natural gas for heating in the former two towns.

Usage classified as "Commercial & Industrial" accounted for 37% of total gas usage in Lincoln in 2017. This value is higher than might be expected given Lincoln's largely residential character, which is due at least in part to the fact that some multiunit housing complexes with a central heating supply are classified under the "commercial" heading.

3.2.1.1. Fugitive emissions (Gas leaks)

An additional source of Scope 1 emissions associated with natural gas is emissions of methane (the main component of natural gas) into the atmosphere from the gas distribution system due to leakage. There are many gas leaks that have been identified within the town of Lincoln (Figure 11).

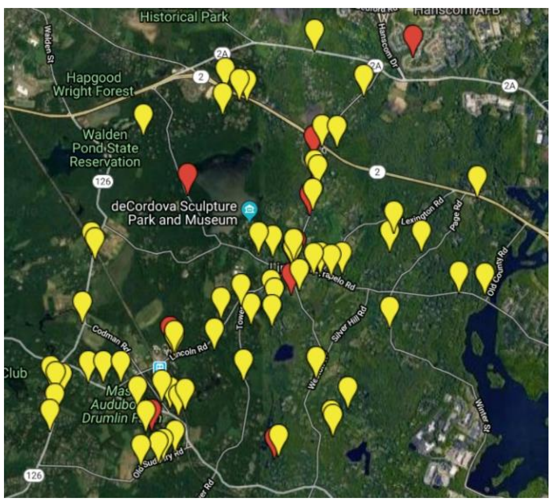


Figure 11. Gas leaks in Lincoln.

Yellow pins identify 68 unrepaired gas leaks in 2018. Source: HEET. heetma.org/gas-leaks/gas-leak-maps/

Methane itself is a much more potent heat-trapping gas than the CO_2 that is produced when the methane is burned, so leaked methane has a disproportionately large effect on the climate even if the volumes leaked are a small percentage of the total.

[14] Data for Massachusetts from US. Energy Information Agency : https://www.eia.gov/dnav/ng/hist/na1490_sma_2a.htm
Data for towns from Masssavedata.com: 2013-2015 from "Usage, Savings and Incentives" tab; 2016-2017 from "Usage by Month" tab; accessed 12/23/2019. Heating Degree days from weatherdatadepot.com.

Exactly how big a problem for the climate are methane leaks? Two factors make this a complicated question to answer. One is uncertainty about how much gas is actually released through leakage; a second is the fundamental differences between methane and CO_2 as heat-trapping gases.

Extent of leakage: Several recent studies have found substantially higher release of methane from the natural gas supply chain than had earlier been estimated, both at sites of natural gas production[15] and distribution[16]; quantifying the extent of release is an active area of research[17]. A 2015 study estimated release of methane from the natural gas system in the Boston area to be 2.7% of all natural gas delivered to the area[18]. It should be noted that the location of this methane release was not identified — both gas leaks from pipes and release of unburned methane at sites of final use might have contributed.

Comparing Methane and CO_2. Methane and CO_2 both trap heat in the atmosphere, but they are different gases. Methane is much more potent at trapping heat than CO_2, but it stays in the atmosphere for much shorter times than CO_2: methane has a residence time of only ~10 years, while CO_2 emitted today remains in the atmosphere for decades to centuries. This means that "how bad" methane is in terms of warming depends on the time frame one is looking at. In order to be able to make a comparison with CO_2 (the principal heat-trapping gas driving climate change) the standard approach used in inventories is to "convert" amounts of methane or other heat-trapping gases to units of "CO_2 equivalent" (CO_2e) using the gas's Global Warming Potential (GWP). The GWP is computed based on considering the amount of warming that would result from an instantaneous release of the gas (in this case methane) relative to warming that would result from release of the same amount of CO_2, integrated over some defined time period, most commonly 100 years. However, the common use of CO_2e should not obscure the facts that methane and CO_2 really are different gases and the choice of a 100-year time horizon for computing GWP is somewhat arbitrary. How important one considers methane depends on the relative importance one ascribes to effects on global temperature over the short term versus over longer time periods, which is a complex and value-laden question[19].

With these caveats in mind, for this inventory a 2.7% leakage rate (as a fraction of total natural gas delivered) is assumed based on the Boston-area findings of McKain *et al* and a standard 100-year GWP for methane is used to calculate the emissions of leaked natural gas as ~3300 tons of CO_2e, which is "equivalent" (in the specific sense described above) to about a quarter of the CO_2 emissions from combustion of natural gas.

3.2.2. <u>Fuel oil and propane</u>

Estimating use of fuel oil and propane is challenging in that there is a multiplicity of suppliers rather than a single regulated utility from which information can be obtained. An estimate was made based on the number of households in Lincoln using each fuel as derived from census data (601 households for oil and

[15] Alvarez *et al*, Science 361: 186 (2018) "Assessment of methane emissions from the U.S. oil and gas supply chain"
[16] McKain *et al*, PNAS 112:1941 (2015) "Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts"
[17] For recent research into developing new methods to efficiently identify important leaks, see http://heetma.org/gas-leaks/large-volume-leak-study/
[18] McKain *et al*, op. cit.
[19] For an article exploring these complexities, see https://thebreakthrough.org/issues/energy/howarth-natural-gas

130 for propane in 2017[20]), and data on average oil or propane usage per household for Massachusetts. These lead to estimates of ~4200 tons CO_2e from use of fuel oil and ~460 tons CO_2e from use of propane.

Oil use has declined in recent years, going from 30.4% of households in 2012 to 23.7% in 2017 as households have converted to heating with gas or electricity.

As for use of oil in non-residential settings, examination of records in the Lincoln assessors' database suggests that few buildings in the non-residential sector are heated with oil, so these were not considered. In particular, municipal accounting shows that there has been no use of oil in municipal buildings since 2013.

3.2.3. Electricity

Eversource is the supplier of electricity for most residents in Lincoln. Data on total electricity use were obtained from submissions by Eversource to masssavedata.com. Electricity use reported for Lincoln totaled 34,489 MWh of consumption in 2017, with 39% being classified as "Commercial & Industrial" (this may include multi-unit residential usage as is the case for gas). It should be noted that there are irregularities in the reported electricity data, with large year-to-year fluctuations in previous years. This data issue should be addressed in consultation with the electricity supplier in order to allow electricity usage to be tracked consistently in the future.

In the absence of an Eversource-specific emissions factor for electricity, the 2017 average for the regional independent system operator ISO-New England of 682 lbs CO_2e/MWh was used. This reflects the use of fossil fuels (mainly natural gas) as a component of electricity generation in the region. Using this emissions factor, total emissions are estimated as ~10,700 tons CO_2e. It should be noted that under Community Choice Aggregation, Lincoln residents could select zero-carbon electricity in the future, thereby reducing emissions associated with electricity use.

Local production of emissions-free electricity (e.g. by residential solar installations) results in generation of renewable energy certificates (RECs). In most cases these are sold by homeowners, meaning the clean electricity that is delivered onto the electric grid does not affect the level of emissions attributable to electricity use in Lincoln, as the renewable attributes of those installations have been sold to outside parties. Locally-produced electricity for which RECs are retained within Lincoln could contribute to lowering the emissions factor for electricity. Locally-produced clean electricity that is directly consumed on-site will be reflected as a reduction in use of grid-derived electricity.

3.2.3.1. Electricity system losses

Electricity system losses are assessed based on an estimate from the U.S. Energy Information Agency for losses in Massachusetts of 5.4%, leading to an estimated loss of 1876 MWh of electricity, with associated emissions of ~580 tons of CO_2e.

[20] ACS

3.3. Waste

3.3.1. Waste Incineration

Lincoln's trash is sent for incineration by Wheelabrator in North Andover. This results in emissions at the site of incineration, which are included in BASIC reporting as Scope 3 emissions under the GPC. In total, 859 tons of waste were delivered to the transfer station in 2017, leading to an estimated ~360 tons of CO_2e emissions.

3.3.2. Wastewater treatment

Wastewater treatment in Lincoln is via septic systems. Methane emissions from these systems was estimated based on the population of the town to amount to ~810 tons of CO_2e.

3.4. Municipal Emissions

Municipal emissions are tracked a consequence of Lincoln's status as a Green Community. These are shown in Figure 12, displayed by source of emissions and using the same emissions factors as for the inventory as a whole.

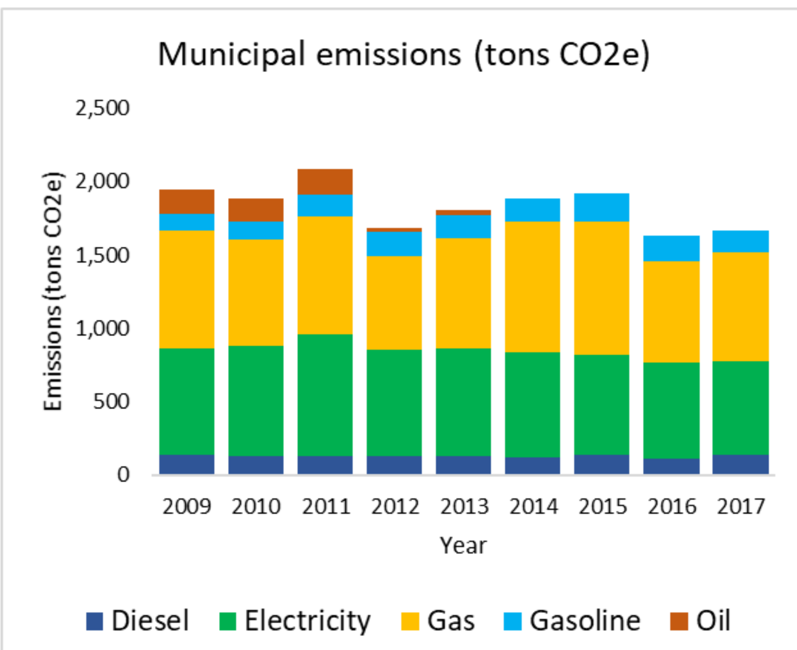


Figure 12. Municipal emissions by source, 2009-2017.

Municipal emissions in 2017 were 1666 tons CO_2e in total, representing 3% of the town's overall emissions. While this is a small fraction, reducing municipal emissions provides an important opportunity for Town operations to lead by example.

4. Opportunities for emissions reductions

To halt the rise in global temperature and minimize the damages that will result from global warming, collectively we will need to reach zero net emissions of greenhouse gases. The more rapidly that greenhouse gas emissions are reduced, the less global temperature will rise. The sections below consider opportunities for reductions of emissions in the town of Lincoln.

4.1. Electrification as an overarching strategy

There is an emerging consensus that the most likely pathway to deep cuts in greenhouse gas emissions is through electrification[21].

This means a strategy resting on two pillars:

- "Electrify everything"
- Move electricity use to carbon-free sources

"Electrify everything" means transitioning from fossil fuel-driven technologies to electrically-driven ones. In the context of this inventory for Lincoln, the main two areas this encompasses are vehicles and heating of buildings. This strategy reflects recognition of the fact that while there can be incremental improvements in the efficiency of fossil fuel-burning end uses — burning gasoline in vehicles and oil and gas in houses — CO_2 emissions will inevitably remain. In contrast, there are ways to produce electricity without carbon emissions. As such, electrification of transportation and heating provides a pathway to zero emissions.

An additional reason to focus on electrification is that vehicles and especially heating systems have long lifespans. Vehicles in Lincoln stay on the road for around ten years (Figure 4B), and heating systems can last decades; purchasing new fossil fuel-using equipment thus locks in many years of further emissions. Lincoln residents make dozens of individual decisions every day that affect the climate, but in terms of overall magnitude of impact on climate these decisions pale in comparison to the momentous decision to purchase a new vehicle or heating system. These purchasing decisions are key moments of opportunity for emissions reduction.

In the sections below, opportunities for emissions reduction are further considered by sector.

4.2. Vehicles

One approach to reducing vehicle emissions is to reduce the total vehicle miles traveled through increased walking, biking, use of transit, and carpooling. While over 200 people a day board the MBTA Commuter Rail at Lincoln Station, 70% of Lincoln commuters still commute by driving in a vehicle alone[22], suggesting there remains significant potential for reducing vehicle miles traveled through transit use or carpooling. Average miles driven per vehicle did decline during the time period covered by the MAVC, albeit only by ~1%/year (Figure 6B). There are important non-climate co-benefits to reduced vehicle use, including effects on health, local air quality and traffic.

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[21] See https://www.vox.com/2016/9/19/12938086/electrify-everything and references therein, and https://www.rff.org/publications/explainers/electrification-101/

[22] American Community Survey 2017.

That being said, Lincoln's semi-rural nature and location put limits on the reductions that can plausibly be expected to occur in personal vehicle use through modal shift; significant personal vehicle use is very likely to persist. Switching to electric vehicles offers the potential for immediate large reductions in emissions, especially if residents of Lincoln move to carbon-free electricity sources (see further discussion below in section 4.5), in which case EVs allow for emissions-free mobility.

It is worth noting that even when powered by today's New England grid mix of electricity, in which about half the electricity is produced by burning natural gas, driving an EV already results in a large reduction in emissions relative to driving a gasoline-burning car (Table 5). This is largely because of the dramatic inefficiency of internal combustion engines, where most of the energy content of the gasoline is wasted as heat, as compared to an electric vehicle, where most of the electrical energy used for charging the battery is converted into forward motion of the vehicle.

Electric technology	**Fossil fuel comparison**	**CO2e emissions relative to fossil fuels, using current NE grid electricity**	**CO2e emissions relative to fossil fuels, using carbon-free electricity**
Electric vehicles	Gasoline car (29 mpg)	31%	0%
Air-source heat pump	Gas furnace, 95% efficient	65%	0%
Ground-source heat pump	Gas furnace, 95% efficient	33%	0%

Table 5. Emissions benefits of electrification

Assumptions: Efficiency of EV: 0.33 kWh/mile. Coefficient of Performance for ASHP: 2.5. Coefficient of Performance for GSHP: 5. Emissions from operation only, not full lifecycle. Does not include emissions from gas leaks in emissions factor for natural gas.

4.3. Commuter Rail

In general terms, increasing transit use helps reduce emissions. Moreover, if an individual Lincoln resident decides to take a trip on a commuter rail train that is "already going", the marginal increase in emissions this causes is clearly negligible (one extra body does not significantly impact the fuel use of the train). Nonetheless, it is important to recognize that our collective use of the commuter rail system does have a climate impact; on a per-passenger-mile basis, CO_2 emissions from commuter rail operation at current ridership levels are roughly equivalent to those generated by a passenger driving alone in a vehicle with 50 mpg fuel efficiency[23]. This underscores the point that while transit use is an important way to reduce emissions, to achieve deep regional emissions reductions goals the MBTA will need to transition its operations toward emissions-free technologies, presumably through electrification.

4.4. Air Travel

Reducing emissions from air travel is challenging, inasmuch as at the moment there are not zero-emissions alternatives as there are for on-road vehicles. It should be noted though that flying is very unevenly distributed among Americans, with over half of all trips being taken by the seven per cent of US adults who take nine or more trips per year (with members of this group taking on average over 18

[23] https://willbrownsberger.com/transit-energy-efficiency/

trips a year[24]). Accordingly, changes in behavior in this small segment of the population could have a large impact on emissions from air travel.

4.5. Electricity

While continuing to decarbonize the entire New England grid stands as a major challenge for the coming decades, Lincoln does not need to wait for the system as a whole to go green. Community Choice Aggregation offers Lincoln residents the opportunity to choose their sources of electricity. This would allow both for reducing or eliminating emissions from existing in-home electricity use (e.g. lighting and appliances), and also zero-emissions transportation and heating through electrification of both sectors (see discussion in sections 4.2 and 4.6).

4.6. Heating

One important opportunity to reduce emissions associated with heating buildings is improvements in building envelopes, e.g. increased insulation and air sealing. This has been an area of ongoing efforts in Lincoln, including the Lincoln Energy Challenge, and will be important to continue.

However, as with vehicles, deep reductions in emissions will ultimately require moving away from combustion of fossil fuels in heating end uses. Air-source heat pumps and ground-source heat pumps (sometimes called geothermal) are efficient, electrically-driven heating technologies. Recent technical improvements mean that these technologies can provide heating even in cold New England winters[25]. Switching from heating with oil or natural gas to heat pumps allows for the possibility of emissions-free heating when powered by carbon-free electricity. Also, as was discussed for EVs above, heat pumps already result in lower emissions than heating with gas even when using today's New England grid mix of electricity (Table 5). This is due to their inherent efficiency: heat pumps work by simply moving heat between the inside and outside of a building, which requires as little as one-fifth of the electricity to provide the same amount of heating as inefficient electric resistance heating (baseboard heaters).

4.7. Gas leaks

A study examining gas leaks in Metro Boston found that just 7% of leaks accounted for fully half of the total methane released[26]. In light of these and similar findings, a 2017 summit between non-profit organizations HEET and Mothers Out Front and utilities Columbia Gas, Eversource, and National Grid led to agreement on a shared action plan for prioritizing and repairing leaks[27]. Ensuring these repairs take place will be important for reducing this significant and costly source of greenhouse gas emissions.

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[24] inferred from IPSOS online survey. https://www.airlines.org/wp-content/uploads/2018/02/A4A-AirTravelSurvey-20Feb2018-FINAL.pdf

[25] See https://neep.org/ashp

[26] Hendrick *et al*, Environ Pollut. 213:710 (2016). "Fugitive Methane Emissions from Leak-prone Natural Gas Distribution Infrastructure in Urban Environments." doi: 10.1016/j.envpol.2016.01.094

[27] https://heetma.org/gas-leaks/fix-big-gas-leaks/shared-action-plan/

5. Indirect emissions and consumption-based accounting

This inventory is a "sector-based" inventory that focuses primarily on greenhouse gas emissions that result in a relatively direct manner from the actions of residents (e.g the CO_2 produced by an oil-burning furnace or by a gasoline-burning car), which is the standard approach taken for community inventories as outlined in the GPC. An alternative framework for thinking about emissions is consumption-based accounting[28], in which all of the emissions resulting both directly *and indirectly* from individual actions are estimated using economy-wide input-output models to connect "activities" (e.g. purchasing of goods) to the emissions that ultimately result elsewhere from these activities. In this framing, a community's emissions are then considered to be the aggregate of all the emissions ascribed to the residents of that community.

An example of an online tool that estimates household emissions including such indirect emissions is the coolclimate calculator developed at UC Berkeley (coolclimate.org). These emissions include those from transportation and home energy use, overlapping with the direct emissions reported in this inventory but also including the emissions that occur upstream in the fossil fuel production system. They also include emissions that arise elsewhere in the economy as a consequence of a household's purchases of Food, Goods and Services. Of note, total indirect emissions from these latter three categories are typically comparable in magnitude to those from the more direct activities of transportation and home energy use.

Lincoln residents may also wish to reduce these indirect emissions. To this end, there are some rules of thumb that can be followed. Meat is particularly carbon-intensive, so a diet with reduced meat consumption lowers indirect emissions from agriculture. Essentially all goods in our current fossil fuel-reliant economy result in associated emissions, so buying less in general (or products that last longer) will also reduce overall climate impact. In general, though, and particularly when it comes to services (e.g. items like health care or entertainment), it is not straightforward for an individual to know how their behaviors could impact ultimate emissions. One could argue that for addressing these emissions, a concerned individual's efforts could best be spent working toward broader systemic change, e.g. by promoting adoption of supportive policies at the level of state or federal government.

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[28] https://www.c40.org/researches/consumption-based-emissions

Appendix – Technical addendum

Summary of data sources and calculations

Note: All tons are metric tons.

Inputs (units)	Value	Source
		Vehicles
number of vehicles	4981	a) Lincoln excise tax, 1st commitment period 2017
avg. emissions per vehicle (kg CO_2e/vehicle/day)	11.4	b) extrapolation of best fit linear trend 2009-2014 (Fig. 8B) to Q2 2017; emission factor of 9.1 kg CO_2e/gallon of gasoline: https://www.mapc.org/learn/data/
Emissions (tons CO_2e)	**20726**	calculated: a × b × 365/1000
		Commuter Rail
track length in Lincoln (miles)	3.05	a) Google Maps
total track length in system (miles)	388	b) http://www.nerailroadclub.com/wp-content/uploads/2018/12/RCoholan_NERRC.pdf
diesel use by MBTA commuter rail system (gallons)	12651208	c) https://www.transit.dot.gov/ntd/data-product/2017-fuel-and-energy
kg CO_2e/gallon diesel	10.18	d) https://www.eia.gov/environment/emissions/co2_vol_mass.php
Emissions (tons CO_2e)	**1012**	calculated: a/b × c × d/1000
		Air Travel
number of adults in Lincoln	4802	a) ACS 2017 https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml
estimated trips per adult	3.83	b) sum across income ranges of: (fraction of Lincoln households in income range from ACS) × (trips/person for that range from Ipsos survey) (Fig. 9)
fraction of trips for personal reasons	0.71	c) average from survey: https://www.airlines.org/wp-content/uploads/2018/02/A4A-AirTravelSurvey-20Feb2018-FINAL.pdf
average tons CO_2e/trip	0.5	d) based on roundtrip flight from Boston to Chicago; see below
Emissions (tons CO_2e)	**6529**	calculated: a × b × c × d
		Gas
total usage (therms)	2241709	a) masssavedata.com, accessed 12/23/2019
tons CO_2/therms of gas combusted	0.00531	b) https://www.eia.gov/environment/emissions/co2_vol_mass.php
Emissions (tons CO_2e) (from combustion)	**11903**	calculated: a × b
GWP for methane	28	c) IPCC AR5, 100 year GWP
CO_2 produced per ton of methane burned (tons)	2.74	d) calculated: molecular weight of CO_2 (44.01) / molecular weight of CH_4 (16.04)
CO_2e/therm of leaked gas (tons)	0.0543	e) calculated: b × c/d
leak fraction	0.027	f) McKain *et al*
Emissions (tons CO_2e) (from leaks)	**3284**	calculated: a × e × f

Oil		
households with fuel oil	601	a) ACS 2017
estimated average household usage for MA, 2016-17 (gallons)	707	b) https://www.mass.gov/info-details/household-heating-costs#projected-household-heating-costs-for-2019/2020-by-average-consumption-for-each-fuel-
estimated average household usage for MA, 2017-18 (gallons)	679	c) https://www.mass.gov/info-details/household-heating-costs#projected-household-heating-costs-for-2019/2020-by-average-consumption-for-each-fuel-
estimated gallons/household for 2017	693	d) calculated: average of b and c
kg CO2e/gallon of oil	10.16	e) https://www.eia.gov/environment/emissions/co2_vol_mass.php
Emissions (tons CO2e)	**4232**	calculated: a × d × e
Propane		
households with propane	130	a) ACS 2017
estimated average household usage for MA, 2016-17 (gallons)	565	b) https://www.mass.gov/info-details/household-heating-costs#projected-household-heating-costs-for-2019/2020-by-average-consumption-for-each-fuel-
estimated average household usage for MA, 2017-18 (gallons)	564	c) https://www.mass.gov/info-details/household-heating-costs#projected-household-heating-costs-for-2019/2020-by-average-consumption-for-each-fuel-
estimated gallons/household for 2017	564.5	d) calculated: average of b and c
kg CO2e/gallon of propane	5.76	e) https://www.eia.gov/environment/emissions/co2_vol_mass.php
Emissions (tons CO2e)	**423**	calculated: a × d × e
Electricity		
total usage (MWh)	34489	a) masssavedata.com, accessed 12/23/2019
emissions factor (kg CO2e/MWh)	309	b) ISO-New England 2017 average (682 lb CO2e/MWh) https://www.iso-ne.com/static-assets/documents/2019/04/2017_emissions_report.pdf
Emissions (tons CO2e)	**10657**	c) calculated: a × b / 1000
Electricity system losses		
estimated loss rate	0.054	d) https://www.eia.gov/electricity/state/massachusetts/
Emissions (tons CO2e)	**580**	calculated: c × d
Waste		
amount of trash in 2017 (tons)	859	a) Town of Lincoln DPW
waste incinerated at Wheelabrator site in 2018 (tons)	456852	b) https://www.wtienergy.com/plant-locations/energy-from-waste/wheelabrator-north-andover
CO2e emissions from Wheelabrator site in 2018 (tons)	191392	c) https://ghgdata.epa.gov/ghgp/service/html/latest?et=undefined&id=1004101
emissions factor (tons CO2e/tons waste)	0.42	d) calculated: c/b
Emissions (tons CO2e)	**360**	e) calculated: a × d
Wastewater treatment		
population of Lincoln	6696	a) ACS
CO2e emissions from septic systems (tons/person/year)	0.121	b) calculated using Eq WW.11(alt), ICLEI community protocol, Appendix F = 0.09×0.6×0.22×365.25/1000×28 http://icleiusa.org/publications/us-community-protocol/
Emissions (tons CO2e)	**813**	c) calculated: a × b

For emissions from air travel, an estimate of ~ 0.5 tons/roundtrip flight to Chicago was used based on the range of values given for this flight by multiple carbon calculators:

Calculator:	tons CO2
https://www.carbonfootprint.com/calculator.aspx	0.38
http://www.carbonzero.ca/	0.47
https://co2.myclimate.org/en/portfolios?calculation_id=2999859	0.53
https://www.offsetters.ca/education/calculators/flight-emissions-calculator	0.44
https://www.terrapass.com/carbon-footprint-calculator	0.51

Analysis of data from Massachusetts Vehicle Census

The MAVC Complete Public Access Files were obtained from MAPC. The 7 GB spreadsheet of microdata was split into 50 smaller spreadsheets using gsplit software for ease of manipulation. From these, records pertaining to vehicles in Lincoln were obtained by filtering on muni_id (muni_id for Lincoln = 157), leading to recovery of 32,147 records, which were assembled in a new spreadsheet.

For breakdown of vehicles by vehicle type, all records with vehicle classifications were used. For analyses of miles driven, fuel efficiency and CO_2 emissions, analysis was limited to those records for which overlap between the period used for mileage estimate and registration record (inspdays_p) was greater than 90% (varying this threshold from 0 to 95% had little qualitative effect on the distributions).

Average fuel efficiencies for each vehicle class in Lincoln were computed on a straight per-vehicle basis (not weighted by distance traveled) by computing gallons/mile consumption for each vehicle (1/mpg_adj), averaging these values, then inverting to obtain mpg.