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Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles

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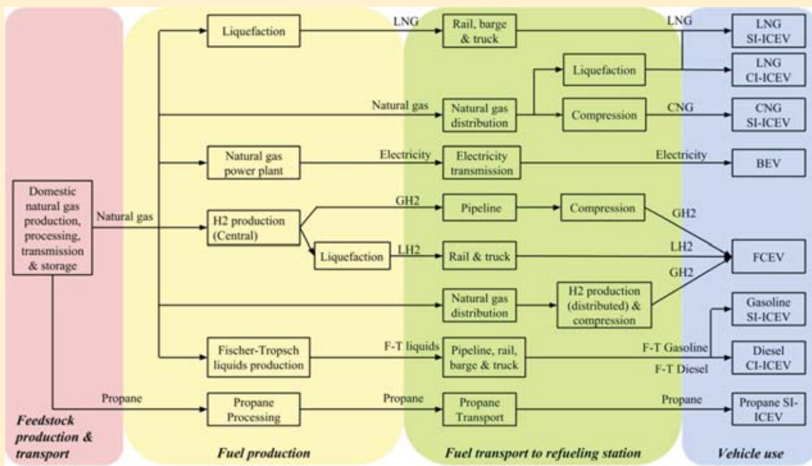
Supporting Information



ABSTRACT: The low-cost and abundant supply of shale gas in the United States has increased the interest in using natural gas for transportation. We compare the life cycle greenhouse gas (GHG) emissions from different natural gas pathways for medium and heavy-duty vehicles (MHDVs). For Class 8 tractor-trailers and refuse trucks, none of the natural gas pathways provide emissions reductions per unit of freight-distance moved compared to diesel trucks. When compared to the petroleum-based fuels currently used in these vehicles, CNG and centrally produced LNG increase emissions by 0−3% and 2−13%, respectively, for Class 8 trucks. Battery electric vehicles (BEVs) powered with natural gas-produced electricity are the only fuel-technology combination that achieves emission reductions for Class 8 transit buses (31% reduction compared to the petroleum-fueled vehicles). For non-Class 8 trucks (pick-up trucks, parcel delivery trucks, and box trucks), BEVs reduce emissions significantly (31−40%) compared to their diesel or gasoline counterparts. CNG and propane achieve relatively smaller emissions reductions (0−6% and 19%, respectively, compared to the petroleum-based fuels), while other natural gas pathways increase emissions for non-Class 8 MHDVs. While using natural gas to fuel electric vehicles could achieve large emission reductions for medium-duty trucks, the results suggest there are no great opportunities to achieve large emission reductions for Class 8 trucks through natural gas pathways with current technologies. There are strategies to reduce the carbon footprint of using natural gas for MHDVs, ranging from increasing vehicle fuel efficiency, reducing life cycle methane leakage rate, to achieving the same payloads and cargo volumes as conventional diesel trucks.

INTRODUCTION

In recent years, the successful combination of technologies, such as hydraulic fracturing, horizontal drilling, and seismic mapping have led to significant production of unconventional natural gas resources, which in turn has attracted industrial interests in using natural gas as a transportation fuel.[1−18] While economic considerations have dominated this discussion, environmental impacts of natural gas-based fuels are likely to be of interest to multiple stakeholders.[17,19,20] A recent NRC report[17] analyzed the impacts of natural gas to fuel medium- and heavy-duty vehicles (MHDVs) and concluded that "more studies and data are needed to determine the well-to-tank GHG emissions of NG vehicles."

There are several approaches to evaluate the GHG emissions of MHDVs. Both vehicle simulation[21−29] and vehicle tests[30−42] provide estimates of emissions from the use phase. These tests are limited in that they fail to account for emission sources beyond tailpipe. Thus, vehicle simulations and tests may not be appropriate for making generalized recommendations regarding GHG emissions. Life cycle assessment (LCA) studies[5,40,43−55,62−65] overcome this shortcoming as they account

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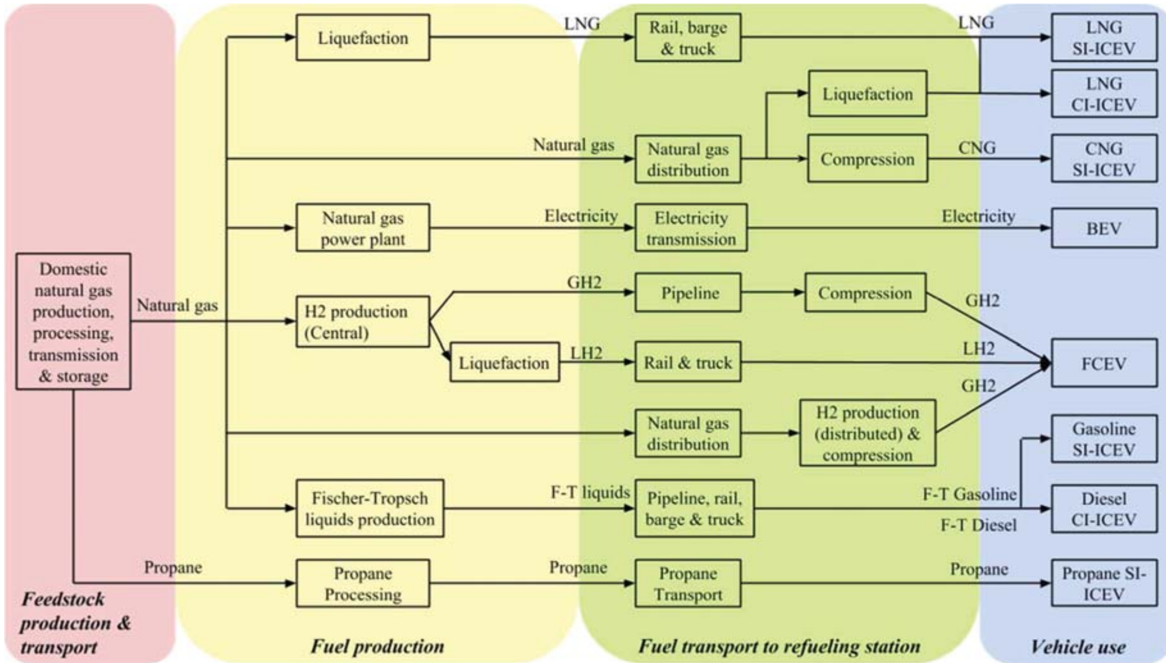

Figure 1. Study system boundary of natural gas pathways. Different colored areas correspond to different life cycle stages: natural gas upstream (pink), fuel production (yellow), fuel transport (green), and vehicle operation (blue) (indicated by engine technologies). Both feedstock and energy carriers are marked along each pathway. LNG = liquefied natural gas; CNG = compressed natural gas; H2 = hydrogen; GH2 = gaseous hydrogen; LH2 = liquid hydrogen; F-T = Fischer−Tropsch; LPG = liquefied petroleum gas, or propane; ICEV = internal combustion engine vehicle; SI = sparking ignition; CI = compression ignition; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle.

for several phases of the vehicle life and can include data from vehicle simulations and tests. However, existing studies were generally focused on specific fuel pathways for some MHDVs, especially compressed natural gas (CNG) and liquefied natural gas (LNG) for transit buses and heavy-duty trucks, relied on outdated data, ignored payload differences, and presented contradictory conclusions. Outdated data about methane emissions from the natural gas sector is particularly concerning as there are several recent field studies[56−61] that performed on-site measurements to estimate methane leakage rates. Similarly, natural gas vehicle technologies have undergone recent improvements in fuel efficiency,[52] which previous studies could not account for. Finally, the contradictory results from recent studies suggest further analysis is needed: TIAX[62] found more than 20% reductions for CNG and LNG trucks compared to diesel; Meyer et al.[63] found a 5% reduction for CNG trucks; Santini et al.[52] found an 8% reduction for LNG trucks and a 3% reduction for CNG trucks; Volvo[64] found a 2−30% increase for lean-burn CNG trucks. For transit buses, conclusions from the same consulting agency were contradictory when one study[65] reported CNG buses emit slightly less than diesel buses while the other[40] reported the opposite. Clark et al.[48] found CNG and ultrasulfur diesel were comparable for year 2007, but a more recent load-based life cycle GHG emission calculator[53] found a 14% reduction for CNG buses.

A fundamental characteristic of the MHDV market is that MHDV fleets are extremely heterogeneous and their environmental performance is highly dependent on the use patterns (such as truck configurations, payloads, drive cycles, etc.).[17,55,66−68] The complexity of modeling the MHDV market has posed serious barriers to understanding the magnitude of life cycle GHG emissions attributed to MHDVs. Existing studies generally differed from each other by considering different MHDV segments, or by using different vehicle configurations, payloads, or drive cycles. Moreover, MHDVs have only recently been added to the Corporate Average Fuel Efficiency (CAFE) standards,[69] so researchers and policy-makers are still learning how to characterize MHDVs emissions and how to assess the consequences of different fuels and technologies in this market. Unlike light-duty vehicles (LDVs), where authoritative sources (such as fueleconomy.gov) provide comparable fuel economy estimates for the same drive cycle and test specifications, test-based fuel economy estimates of MHDVs are limited. Furthermore, a non-negligible portion of existing studies neglected methane emissions from natural gas trucks (in the form of incomplete combustion and direct leaks from MHDVs),[31] though some recent work attempts to bridge this gap.[70]

This paper aims to fill a specific knowledge gap in terms of GHG emissions estimates from MHDVs. More specifically, we evaluate the relative comparison of different ways of using natural gas for different types of MHDVs. To achieve this goal, we perform a LCA on a comprehensive set of natural gas-derived fuels, engine technologies, and vehicle types. The contribution of this paper is not methodological; instead we address an important gap in current policy discussions such as the Low Carbon Fuel Standard (LCFS)[71] in California, U.S. and the CAFE standards set to reduce fuel consumption and GHG emissions of MHDVs in the U.S.[72] While the CAFE standards for MHDV only consider use phase emissions, it is of key relevance to identify whether the best strategies in terms of emissions reductions still hold when one accounts for the full life cycle emissions in order to avoid unintended negative consequences that may be derived from a use-phase-only policy design—as it becomes apparent in our results and analysis section. We follow a bottom-up attributional LCA approach

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Table 1. Vehicle Specifications for Different Fuel Pathways and Different Vehicle Applications[a]

		Class 2b Pick-up truck/van 	Class 4 Parcel delivery van 	Class 6 Box truck 	Class 8 Transit bus 	Class 8 Refuse truck 	Class 8 Tractor trailer local-haul 	Class 8 Tractor trailer line-haul
Unit of fuel economy+		MPG/ L/100km	MPG / L/100km (diesel gallon/liter equivalent)					
Gasoline (SI-ICEV)		14.0/16.8*	-	-	-	-	-	-
Diesel (CI-ICEV)		16.1/14.6	11.5/20.5*	7.0/33.6*	4.0/58.8*	3.3/71.3*	4.3/54.7*	6.5/36.2*
Gasoline-HEV(SI-ICEV)		16.8/14.0	10.9/21.5	-	-	-	-	-
Diesel-HEV (CI-ICEV)		19.3/12.2	14.4/16.4	9.3/25.3	4.8/49.0	3.6/64.8**	5.2/45.6	7.2/32.9
CNG (SI-ICEV)		14.0/16.8	10.8/21.8	6.6/35.7	3.6/65.3	2.9/81.0	3.9/60.8	5.9/40.2
LNG (SI-ICEV)		-	-	-	3.6/65.3	2.9/81.0	3.9/60.8	5.9/40.2
LNG (CI-ICEV)		-	-	-	-	-	4.2/55.8	6.4/36.9
Propane (SI-ICEV)		14.0/16.8	-	-	-	-	-	-
BEV		42.0/5.6	34.5/6.8	21.0/11.2	16.8/14.0	-	-	-
H_2-FCEV		-	-	-	7.6/30.9	-	-	-
Conventional truck	Gross weight (lbs.)	8,501-10,000	16,000	19,501-26,000	39,980	60,000	80,000	80,000
	Empty weight (lbs.)	5,000-6,300	9,700	11,500-14,500	27,730	16,627	30,500	35,550
	Payload (lbs.)	3,700	6,300	11,500	12,150	43,373	49,500	44,450
Alternative fuels #	Weight penalty for payloads (lbs.)	Gasoline/Diesel HEV: 350 CNG: 200 BEV: 600	Gasoline/Diesel HEV: 0 CNG: 0 BEV: 200	HEV: 1200 CNG: 515 BEV: 200	Gasoline/Diesel HEV: 0/750 CNG: 900 LNG: 1150 H_2-FCEV: 5,400 BEV: 4,800	Hybrid: 400 CNG: 915 LNG (SI): 265	HEV: 880 CNG: 502 LNG (SI): 252 LNG (CI): 1249	HEV: 880 CNG: 2042 LNG (SI): 1142 LNG (CI): 2541
	Volume penalty	Reduced cargo space	No difference (except for transit buses) because fuel tanks are mounted on the chassis, behind the cabin, or atop the vehicle. For transit buses, volume penalty has been factored into weight penalty.					

[a]Acronyms: CNG = compressed natural gas. LNG = liquefied natural gas. SI-ICEV = sparking ignition internal combustion engine vehicle. CI-ICEV = compression ignition internal combustion engine vehicle. HEV = hybrid electric vehicle. BEV = battery electric vehicle. H_2−FCEV = hydrogen fuel cell electric vehicle. MPG = mile per gallon. +Different vehicle segments have different baseline petroleum fuels (gasoline for Class 2b and diesel for Class 3−8) so the same "gallon" has a different meaning in different vehicle segments. *The baseline petroleum fuel pathway is marked and highlighted in gray. **A diesel refuse truck with hydraulic hybrid system is assumed. #Details on how to determine weight and volume penalties in payloads of alternative fuel pathways are discussed in the Supporting Information. The vehicle cartoon figures come from NREL (2013)[95]

with latest available data and a consistent system analysis boundary. We perform detailed reviews regarding the assumptions related to natural gas production, fuel production, fuel delivery, and vehicle specifications, to ensure consistency and transparency throughout the analysis. We include a Monte Carlo analysis to explicitly account for the variability and uncertainty in emissions along the life cycle of natural gas pathways. In addition, we estimate the break-even life cycle methane leakage rates for CNG and LNG pathways that would make them net emissions reducers or net emission contributors to understand the relative importance of methane leakage and vehicle fuel efficiency.

■ METHODS AND DATA

System Boundary. We define a *pathway* as a way of using natural gas for road transportation. Figure 1 illustrates the different pathways considered. We assume that natural gas used to produce these transportation fuels is derived from shale gas resources in the U.S., as shale gas is expected to account for the majority of natural gas produced in coming decades.[73] The baseline fuel pathways are conventional gasoline (Class 2b) and conventional (ultralow-sulfur) diesel (Class 3−8 MHDVs). The geographic scope of the study is the contiguous U.S.

The LCA boundary starts at natural gas extraction and ends with the use of the natural-gas-derived fuel during vehicle operation. In general, there are four stages in the life cycle of any fuel pathway: feedstock (natural gas) production and transport, transportation fuel production, transportation fuel delivery, and vehicle use. In pathways that rely on distributed transportation fuel production, the natural gas transport stage of the life cycle includes both interstate and distribution pipelines. Pathways that include centralized production of the transportation fuel only account for GHG emissions from the interstate pipeline network, where natural gas is assumed to be drawn directly from. Emissions related to manufacturing of batteries and fuel cells for electric vehicles are included, while emissions with manufacturing of other vehicle components are assumed to be similar among pathways. Emissions from building the infrastructure needed to deploy different fuels and vehicle end-of-life are outside of the scope of this study. Existing studies found that emissions associated with infrastructure construction and decommissioning contribute to less than 1% of the life cycle emissions for electricity and hydrogen production,[74,75] and we anticipate that the values for the natural gas infrastructure would be in the same ballpark.

This paper focuses on estimating emissions of three GHGs, CO_2, methane (CH_4), and N_2O, which are converted to CO_2-equivalent emissions using the probabilistic distribution for the latest global warming potential (GWP) values. We build a bottom-up model in accounting for all emissions defined in this system boundary. Details of the LCA model and discussions on the quality of the data sources can be found in the Supporting Information (SI).

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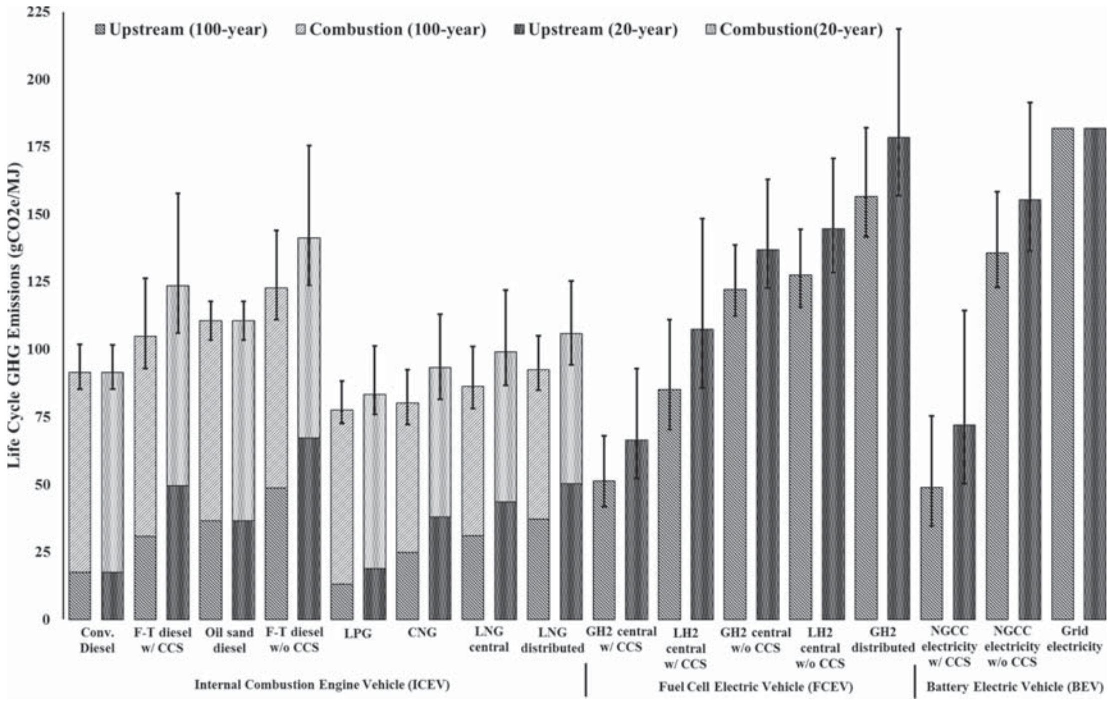

Figure 2. Life cycle GHG emissions from natural gas-derived fuels and existing liquids with 100-year GWP (left bar in each pair) and 20-year GWP (right bar in each pair). The functional unit is 1 MJ (lower heating value) of fuel delivered to end use. Upstream emissions include all emission sources until the fuel is dispensed into the vehicle. Combustion emissions are estimated based on fuel characteristics, as described in the Supporting Information. Error bars represents the 95% confidence interval of the life cycle GHG emissions.

Given that natural gas-powered MHDVs are still emerging, we model new vehicles available in the market rather than existing vehicles. We use functionally equivalent vehicles for different fuel pathways within a specific vehicle segment.[19] We follow the weight-based classification method for on-road vehicles,[67] which is used by industry and U.S. federal agencies (e.g., U.S. Federal Highway Administration (FHWA), and U.S. Environmental Protection Agency (EPA)). We consider seven types of MHDVs:[67,76] Class 2b pick-up truck, Class 4 parcel delivery truck, Class 6 box truck (such as beverage delivery truck), Class 8 transit bus, Class 8 local-haul tractor-trailer, Class 8 long-haul tractor-trailer, and Class 8 refuse truck. Finally, we include five vehicle engine technologies: sparking ignition internal combustion engine vehicle (SI-ICEV), compression ignition internal combustion engine vehicle (CI-ICEV), hybrid electric vehicle (HEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV). The interaction between fuel pathways, vehicle engine technologies and types of MHDVs are shown in Table 1, along with key parameters, such as vehicle fuel efficiencies and vehicle payloads. The Supporting Information includes a detailed discussion of vehicle-side assumptions (such as fuel economy, payload, lifetime, battery and fuel cell sizes, and tailpipe methane and N_2O emissions).

We use two functional units: vehicle distance traveled (gCO_2-equiv/km) and freight-distance moved (gCO_2-equiv/km-metric-ton). The first functional unit is simple but fails to reflect the functionality of MHDVs. While heavier trucks have lower fuel economy than their lighter substitutes, they are more efficient in moving the same weight of load, thus getting lower load-normalized fuel economy (gallons per cargo-ton-mile) than lighter vehicles.[67,77] We thus include the second functional unit to address this issue, at the expense of adding an additional set of assumptions (payloads of MHDVs).

RESULTS

Life Cycle Inventory. Methane emissions have been shown to play an important role in the life cycle emissions of natural gas but the methane leakage rate in the U.S. natural gas systems remains a subject of debate. In particular, there is a wide gap between bottom-up studies (including this study) and top-down studies.[78] To account for a potential bias in methane leakage rate estimates, and also to account for choices to use GWPs with different time frames, we consider four scenarios: (1) a baseline methane estimate with 100-year GWP (baseline scenario), (2) a baseline methane estimate with 20-year GWP, (3) a pessimistic estimate with 100-year GWP, and (4) a pessimistic estimate with 20-year GWP.

For the baseline estimate, our mean estimate of natural gas upstream GHG emissions is 17.2 gCO_2-equiv/MJ_{LHV}, with a 95% confidence interval (C.I.) of 10.2−29.3 gCO_2-equiv/MJ_{LHV}. This estimate uses 100-year GWPs, and implies a methane leakage rate of 1.0−2.2% for a 95% C.I. The distribution of natural gas upstream emissions is right-skewed, which is likely the results of superemitters.[78] Our baseline mean estimate falls within the range of other recent bottom-up estimates.[79] However, to account for the differences between bottom-up and top-down estimates,[78,80] we multiply the baseline methane emission estimate by 1.5. The Supporting Information includes a detailed description of the data and assumptions used to develop the life cycle inventory.

Figure 2 shows the life cycle GHG emissions (also called "carbon intensity") of the natural gas-based fuels that can be used in MHDVs. It should be noted that this figure is not meant to be used for a fuel comparison, as the carbon intensity

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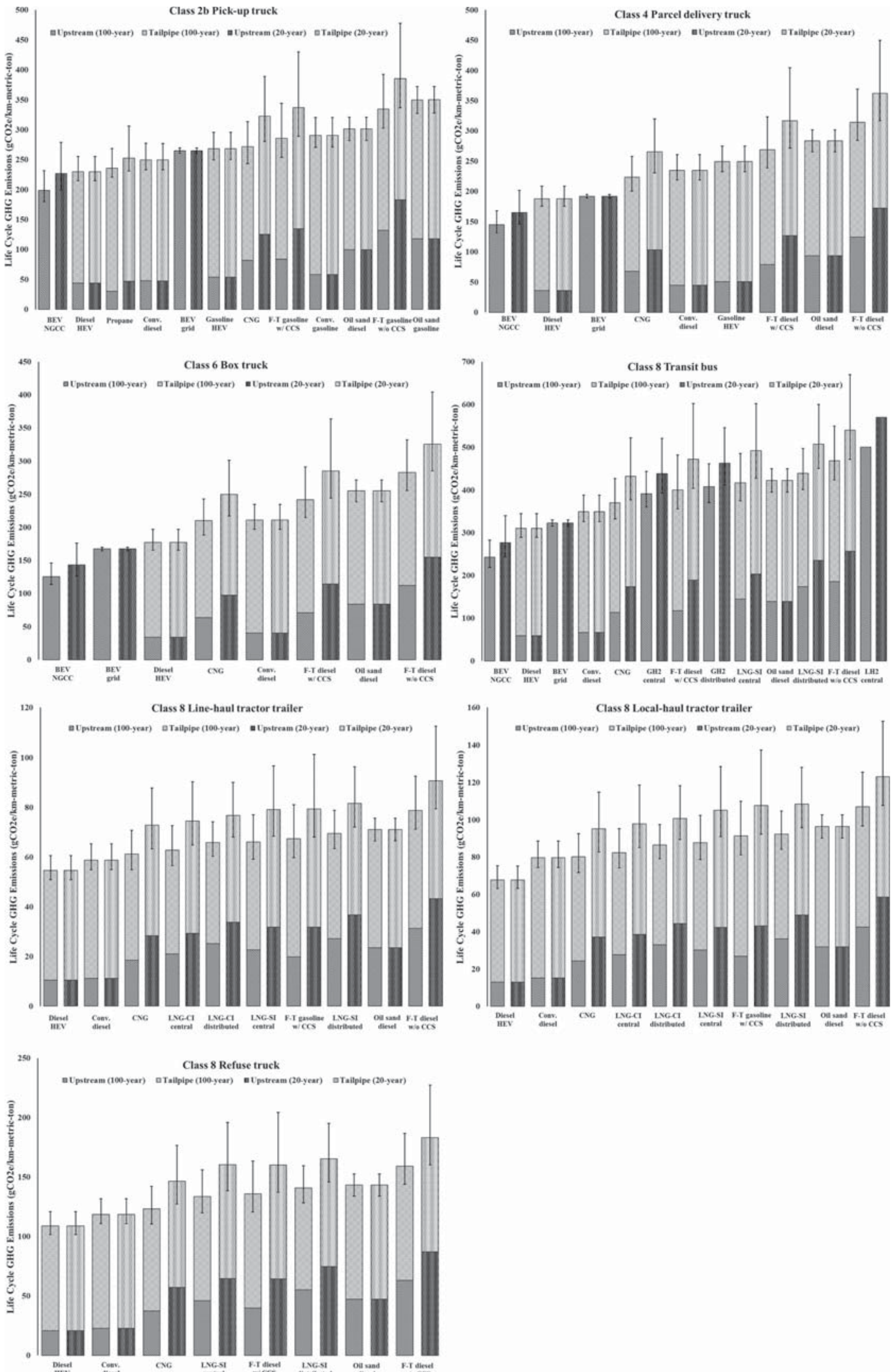

Figure 3. Life Cycle GHG emissions of MHDVs (gCO_2-equiv/km-metric-ton), with baseline methane emission estimate. In each panel, results 100-year GWP (left bar in each pair) and 20-year GWP (right bar in each pair) are shown side by side. Error bars are based on the 95% confidence interval of life cycle GHG emissions.

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is not functionally equivalent or comparable unless the efficiency of end-use technologies is considered. Thus, this figure is only meant to summarize the range of estimates for each pathway.

Life Cycle GHG Emissions. We report results of the life cycle GHG emissions of natural gas-based transportation fuels for MHDVs in Figure 3. These results are based on 100-year GWPs, the baseline estimate of natural gas upstream emissions, and are presented in the functional unit considering payloads of MHDVs (gCO_2-equiv/km-cargo-metric-ton). In the Supporting Information, we present bar plots and cumulative distribution plots for results in other scenarios (with both functional units). The Supporting Information data file includes statistics for these scenarios, such as means, standard deviations, 95% confidence intervals, and ranks of fuel pathways.

Class 2b, Class 4, and Class 6 vehicles are "medium-duty trucks" with similar life cycle GHG emissions rankings among fuel pathways. As shown in Figure 3, we find that BEVs with natural gas-based electricity achieve the largest (31−40%) mean emission reductions compared with the baseline petroleum fuels (gasoline for Class 2b, and diesel for Class 4 and 6). CNG trucks achieve 0−6% mean emission reductions for these three MHDV segments, and are better than the baseline petroleum pathway for over 80% of time (except Class 6). In our LCA model, propane is only available for Class 2b pick-up trucks, for which it achieves the largest emission reductions (19% on average) among natural gas pathways with ICEV technologies. However, the supply of propane may be regional (where wet natural gas is abundant) and could be limited due to competitions from other demands (such as residential heating).[81]

For Class 8 transit buses, BEVs with natural gas electricity emit the lowest life cycle GHG emissions, achieving 31% reductions compared to diesel bus. Thanks to the large fuel efficiency benefits (3.2 times better than diesel), BEVs powered with U.S. current grid electricity still achieve 8% emission reductions. Other natural gas pathways that are available for transit buses, such as CNG, hydrogen FCEVs, LNG, and F-T liquids, increase GHG emissions by 6−43% on average compared to conventional diesel. For Class 8 trucks, CNG emits lowest among natural gas pathways but it cannot reduce emissions (0−3% higher for three types of Class 8 trucks) on average compared with conventional diesel. LNG and F-T liquids increase GHG emissions by 2−34% for Class 8 trucks when compared to the baseline.

The distributions of life cycle emissions from natural gas pathways are found to be wider than those from petroleum pathways and exhibit highly asymmetrical shapes skewed to the right. Thus, when we calculate relative emission changes compared to petroleum fuels, the resulting distributions are also skewed to the right. An important factor in determining the relative benefits of natural gas pathways is the choice of baseline fuel and vehicle technology. While conventional gasoline and diesel used in ICEs still appear to be appropriate baselines for MHDVs, we also include hybrid technologies (7−21% less emissions than baseline) and crude oils derived from Canadian oil sands (21% more emissions than baseline).

Moving payloads or passengers is the primary goal of MHDVs, and the differences in payloads from different pathways appear to be important. We find that all natural gas fuel pathways incur payload penalties for all MHDVs (Table 1) and the issue of payload loss is more severe for pick-up trucks and transit buses than for other MHDVs. For pick-up trucks, any changes in the payload are relatively large since the bassline payload is small. For transit buses, alternative fuel buses see large drops (40−45%) in the maximum number of bus riders (determined from vehicle tests) compared to diesel buses.

The implications of payload differences depend on the actual operations of MHDVs. For instance, transit buses might only operate at full loads in certain time periods and along specific routes, in which case the functional unit that includes the payload is most appropriate. At other times, especially in nonrush hours, all transit buses should be able to operate functionally the same, in which case the maximum payload is not the limiting factor and the other functional unit (gCO_2-equiv/km) is more representative. In the bus example, when payload differences do not affect service levels (such as in nonrush hours), hydrogen FCEVs using gaseous hydrogen could achieve an emission reduction of more than 35%, hydrogen FCEVs using liquid hydrogen could reduce emissions by 20%, and CNG could reduce emissions by 2% compared with diesel buses for mean estimates.

As for trucks, highway statistics[82] show that not all on-road Class 8 trucks reach the federal weight limits (i.e., carrying full payloads). For trucks that are limited by the cargo space rather than cargo weight,[8] considering payload differences may result in biased results. Moreover, the consideration of payload differences not only determines which functional unit is better but may also change the operation schedules of MHDVs (for instance, less payloads mean more trips) and thus affect total GHG emissions from freight movement. The attributional LCA framework does not account for these system responses. As a result, we are limited to reporting the results for both functional units.

In addition to payload, the choice of GWPs and methane emission estimates are other important factors for absolute emission levels and relative rankings of natural gas fuel pathways. Using 20-year GWPs instead of 100-year GWPs increases life cycle GHG emissions by 7−21% for natural gas pathways. While the pessimistic estimates of methane leakage from the natural gas system increase baseline methane emission estimates by 50%, this effect is attenuated to only 5−7% for the life cycle emissions since the majority of GHG emissions are emitted during vehicle operations. While more studies are needed to improve our understandings of battery and fuel cell manufacturing emissions and tailpipe methane emissions, we find that both emission sources are small (1−4%) for BEVs, as well as CNG and LNG pathways across all possible MHDVs.

While carbon capture and sequestration (CCS) technologies are not mature, they may be available in the future for some of the fuel pathways in this analysis. We include CCS technologies for natural gas electricity generation, central hydrogen production, and F-T liquids production. When comparing life cycle GHG emissions for pathways with CCS and without CCS, there are significant reductions for electricity generation (64% for mean estimate) and hydrogen production (46% for liquid hydrogen, and 58% for gaseous hydrogen), but much smaller reductions for F-T liquids (Figure 2). As a result, F-T liquids even with CCS technologies still increase emissions compared to conventional diesel (Figure 3). On the other hand, if CCS technologies are available, BEVs and gaseous hydrogen FCEVs could reduce emissions by 67% and 53%, compared to petroleum-based systems, for transit buses considering the payload differences.

Break-Even Life Cycle Methane Leakage Rates. One of the key uncertainties that drives natural gas pathways to be net

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emissions reducers or not is the assumed methane leakage. We presented the LCA results across fuels, vehicle engine technologies, and MHDVs, but important insights on the trade-off between vehicle fuel efficiency and methane leakage rate may have been buried behind the scene. Here we present a break-even analysis on methane leakage rates for two pathways, CNG and distributed LNG, as these fuels seems to currently be the focus on intense interest.[2,4,9,10,17,52] Break-even methane leakage rate is defined as the mole or volume percentage of all dry natural gas produced that is lost through fugitive emissions at which the life cycle GHG emissions of the natural gas-based transportation fuels are comparable to the life cycle GHG emissions of incumbent petroleum fuels. We find that a linear relationship exists between break-even methane leakage rate and the relative fuel efficiency of the vehicles (Supporting Information includes mathematical derivations). As shown in Figure 4, distributed LNG allows for a smaller break-even

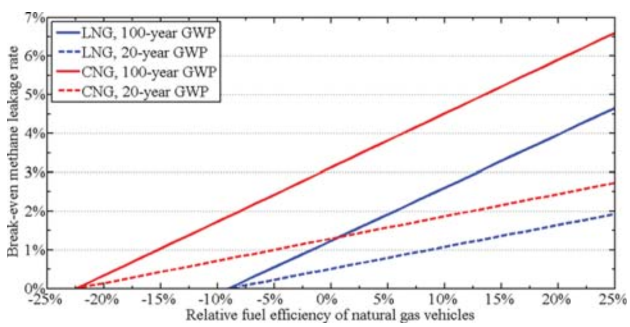

Figure 4. Relationship between break-even life cycle methane leakage rate and relative fuel efficiency of natural gas vehicles. The break-even life cycle methane leakage rate identifies the methane leakage rate for the life cycle at which the natural gas fuel would have the same life cycle emissions as the incumbent petroleum fuel, which in this case is conventional diesel. Further, the leakage rate is calculated as the volumetric percentage of natural gas produced that is lost through venting or fugitive leaks in the life cycle. Finally, the relative fuel efficiency is represented as the percentage difference between the efficiency of the petroleum-based vehicle and the natural gas-fueled vehicle. A negative relative fuel efficiency means the efficiency of the natural gas vehicle is lower than the efficiency of the petroleum-based vehicle.

methane leakage rate than the CNG pathway for the same relative vehicle fuel efficiency. We find that there are lower bounds on the relative vehicle fuel efficiency for CNG and LNG pathways (77.5% and 91% relative to diesel vehicles, respectively) below which carbon dioxide emissions in the life cycle would already make CNG and LNG pathways worse than incumbent petroleum fuels. If the carbon intensity of the baseline petroleum pathway changes, then break-even methane leakage rates will shift accordingly.

In this Policy Analysis, we systematically analyze the life cycle GHG emissions of natural gas pathways for a comprehensive combination of natural gas-derived fuel, engine technologies, and vehicle types of MHDVs using a bottom-up LCA approach. The contribution of this paper is not methodological. Instead, we address an important gap in current policy discussions, such as the Low Carbon Fuel Standard (LCFS) in California and the CAFE standards of MHDVs in the U.S. To understand the sensitivity of the emission reductions, we calculate break-even methane leakage rates of the CNG and LNG pathways as a function of the relative fuel efficiency of natural gas vehicles (compared to baseline petroleum fuels).

We find that the emissions reduction potentials of natural gas pathways vary sharply between non-Class 8 MHDVs (e.g., pick-up trucks, parcel delivery trucks, and box trucks), Class 8 transit buses, and Class 8 MHDVs (e.g., refuse trucks and tractor-trailers). BEVs, LPG, and CNG pathways could reduce life cycle GHG emissions for non-Class 8 MHDVs compared to the baseline petroleum fuels. Similarly, BEVs achieve emission reductions for transit buses. On the other hand, none of natural gas pathways, CNG, LNG, and F-T liquids, achieve any emission reductions for Class 8 trucks compared to conventional diesel.

Choice of natural gas pathway, relative fuel efficiency of natural gas vehicles (relative to petroleum counterparts), and life cycle methane leakage rate are important factors determining rankings of natural gas pathways. Payload losses in natural gas-fueled MHDVs compared to conventional MHDVs are also an important consideration. For instance, transit buses with alternative fuels see large drops in payloads (measured by the maximum numbers of bus riders). Excluding these payload differences in the comparison may incorrectly result in larger emission reduction potentials than could actually be achieved. While we note that the payload losses we considered might only occur in certain conditions, our results still highlight the importance of considering payload differences when assessing emissions of MHDVs. Furthermore, we find that choices of baseline petroleum fuels and global warming metrics play important roles in determining emission reduction potentials of natural gas pathways for MHDVs.

Our results could be important inputs to current policy debates, such as the Low Carbon Fuel Standard (LCFS)[71] in California, the CAFE standards of MHDVs,[72] as well as methane regulations in the U.S. In addition to the exact emission estimates, large uncertainties shown with natural gas pathways should be considered and discussed in the LCFS-type regulations. In terms of methane regulations, more transparent reporting requirements (such as EPA's GHGRP program[83]) and more on-site measurements on natural gas systems and natural gas vehicles (such as EDF's efforts[70]) are crucial to solve the ongoing debates regarding methane leakage and to identify emission reduction opportunities which can then be implemented via cost-effective technologies or stringent regulations.[84−88]

We acknowledge that there are several limitations to this study. Our analysis focuses on GHG emissions and we use the global warming potential of non-CO_2 gases. Recent literature suggests that GWP has serious limitations. For instance, GWP treats all emissions as if they are pulse emissions at the beginning of the time horizon considered, thus completely ignoring different effects of emissions happening at different time.[49,89−92] Further, while GWP is closely related to radiative forcing, GWP does not consider other drivers of climate change, such as the rate of change, and variations in surface temperature response.[93] Some research is ongoing to develop more appropriate climate impact metrics,[89−92] but there is no consensus about the use of these metrics for LCA and a comparison of such metrics is beyond the scope of this study. In the future, as more appropriate metrics are identified, we can use the inventory results in this paper to re-evaluate the climate impacts of natural gas-based transportation fuels.

This analysis is also limited by our inability to consider real-world conditions in actual operations of MHDVs, especially the

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drive cycles (e.g., speed, idling, road grade)[40,53,68] and payload profiles,[53,55] as such information is limited. As more vehicle tests and innovative methods to factor duty cycles into the assessment of vehicle emissions become available, further analysis could refine our estimates of the life cycle GHG emission of natural gas-based transportation fuels.

Finally, while this Policy Analysis focuses on GHG emissions, there are other environmental benefits from using natural gas for road transportation, such as health benefits from reduced air pollutants and lower operating noises,[35,50,62,63,94] which could be significant. There are also other types of MHDVs beyond those included in this paper; for instance, we do not include school buses, port drayage trucks, and all off-highway MHDVs. We also exclude dual-fuel pathways (such as CNG and diesel, and plug-in hybrid electric vehicles) because of limited data, though these vehicles may serve as near-term options to meet the long-term goals of oil independence and emission reductions. While this Policy Analysis is the most up-to-date and comprehensive analysis of the potential environmental benefits of natural gas-based transportation fuels for the MHDV fleet, future analysis should be performed as data becomes available and analytical methods improve.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed information about the assumptions related to the upstream emissions of natural gas and petroleum resources, production and delivery of natural gas-derived transportation fuels, and vehicle technologies and specifications, detailed results of the life cycle inventory and sensitivity analysis, and additional results. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/es5052759.

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Notes

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