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Influence of Methane Emissions and Vehicle Efficiency on the Climate Implications of Heavy-Duty Natural Gas Trucks

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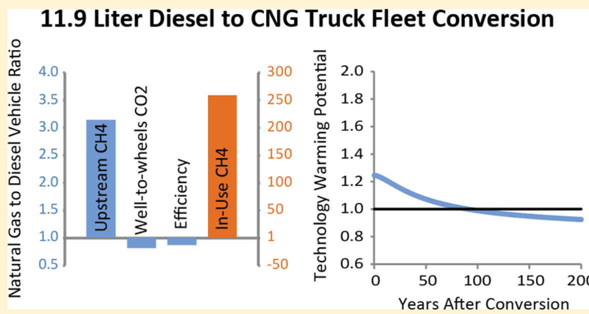
Supporting Information

ABSTRACT: While natural gas produces lower carbon dioxide emissions than diesel during combustion, if enough methane is emitted across the fuel cycle, then switching a heavy-duty truck fleet from diesel to natural gas can produce net climate damages (more radiative forcing) for decades. Using the Technology Warming Potential methodology, we assess the climate implications of a diesel to natural gas switch in heavy-duty trucks. We consider spark ignition (SI) and high-pressure direct injection (HPDI) natural gas engines and compressed and liquefied natural gas. Given uncertainty surrounding several key assumptions and the potential for technology to evolve, results are evaluated for a range of inputs for well-to-pump natural gas loss rates, vehicle efficiency, and pump-to-wheels (in-use) methane emissions. Using reference case assumptions reflecting currently available data, we find that converting heavy-duty truck fleets leads to damages to the climate for several decades: around 70−90 years for the SI cases, and 50 years for the more efficient HPDI. Our range of results indicates that these fuel switches have the potential to produce climate benefits on all time frames, but combinations of significant well-to-wheels methane emissions reductions and natural gas vehicle efficiency improvements would be required.



■ INTRODUCTION

Making natural gas a near-term fuel of choice in the United States has been championed by many, as it provides a number of advantages over other fossil fuel options. Recent technological innovations in extracting natural gas have led to significant expansions of U.S. natural gas reserves. The resulting shale gas boom not only represents a significant source of domestic energy production, thus satisfying pressure for energy independence, it does so at relatively low costs (in fact, low prices in recent years have already contributed to a significant shift toward natural gas in the U.S. electric power industry).[1] In addition, since natural gas has relatively low carbon intensity, releasing less carbon dioxide (CO_2) per unit of usable energy than other fossil fuels, it is often assumed that switching to natural gas is comparatively beneficial for the climate.

As recent literature suggests, the latter statement deserves a closer look. While it is true that natural gas emits less CO_2 than other fossil fuels during combustion, potential climate benefits could be reduced or even delayed for decades or centuries,[2−4] depending on the magnitude of methane (CH_4) loss from the natural gas supply chain—an area of active research.[5−10] Although CH_4 decays more rapidly than CO_2 in the atmosphere, it is a more powerful greenhouse gas (GHG), and its influence on the climate is significant on decadal time frames (Supporting Information, section S3). Even small amounts of CH_4 can potentially overwhelm large CO_2 reductions to increase radiative forcing in the short run. Taking CH_4 emissions into consideration is critical: short-term radiative forcing will determine the rate at which climatic changes occur,[11,12] and it is crucial to address both short and long-term net radiative impacts in order to minimize social and ecological disruptions from climate change.

Alvarez et al. proposed a framework to compare the time-dependent cumulative radiative forcing of a conventional technology, such as a diesel truck or a coal power plant, to a substitute powered by natural gas.[2] This framework deployed Technology Warming Potentials (TWP), which consider the radiative efficiency of both CO_2 and CH_4 and their atmospheric fate as a function of time, thereby providing a view of climate impacts from fuel switching across both short and long time frames. Relying on Environmental Protection Agency (EPA) estimates of CH_4 emissions for 2010,[13] they found that switching from coal to natural gas in the power sector would reduce radiative forcing across all time frames, yet a switch of heavy-duty trucks (HDTs) from diesel to natural gas would result in greater radiative forcing for more than 200 years.[2]

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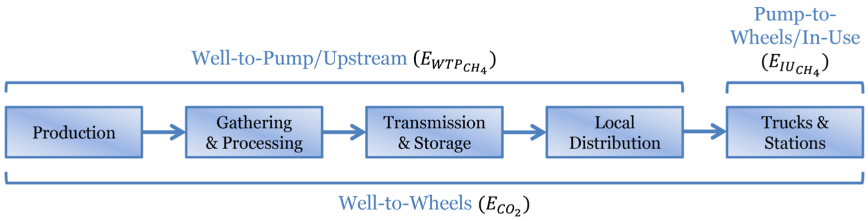

Figure 1. Natural gas value chain schematic. The aggregations of the value chain in this paper include estimates for all CH_4 and CO_2 emissions (fugitive, vented, and combustion) from all equipment in each industry segment (Supporting Information, section S4).

Because of high compression ratios and compression-ignited combustion, diesel engines achieve higher fuel efficiencies than spark-ignited gasoline and natural gas engines (the efficiency of natural gas trucks with spark-ignited internal combustion engines are largely on par with their gasoline counterparts).[14] This, in addition to higher torque capabilities of diesel engines in low revolutions per minute (RPM) environments, has contributed to making diesel engines the industry standard in heavy-duty commercial trucking. However, the lower cost of natural gas has led to increased interest in using trucks fueled by both compressed natural gas (CNG) and liquefied natural gas (LNG) for certain operations, and as a result several natural gas-fueled heavy-duty truck engines are now commercially available. More specifically, 8.9 and 11.9 L spark ignition (SI) HDTs are in common use; manufacture of 15 L high-pressure direct injection (HPDI) engines, previously conducted by Westport Fuel Systems Inc., has currently halted,[15] but the HPDI technology is slated to return to the market.[16]

Our analysis uses the TWP methodology to examine in greater depth the climate effects of switching from diesel fuel to natural gas in the HDT sector. We modify the TWP methodology to differentiate upstream and in-use CH_4 emissions, and broaden the scope of the analysis by looking at different engine technologies and fuel types (SI and HPDI; LNG and CNG). We conduct sensitivity analyses to better understand climate implications under a range of assumptions for key parameters: well-to-pump (upstream) CH_4 emissions, efficiency differences between natural gas and diesel engines (efficiency penalty), and pump-to-wheels (in-use) CH_4 emissions.

Our results show which combinations of these input parameters produce climate benefits on all time frames when switching diesel truck fleets to natural gas. We determine whether fuel switch scenarios produce net climate benefits based on cumulative radiative forcing over specific time frames for a natural gas fleet relative to the diesel fleet it replaces. A fuel switch produces climate benefits on all time frames if cumulative radiative forcing is reduced immediately.

This work can inform state and federal policymakers considering methane emission regulations for well-to-pump natural gas industry segments as well as how to treat natural gas trucks and associated infrastructure in energy policy or clean air rules.

METHODS

Equation 1 is a modification of the original TWP formulation in Alvarez et al.[2] that differentiates CH_4 emissions occurring upstream from those occurring during vehicle use, including any potential natural gas losses during truck refueling (Supporting Information, section 2). The TWP of switching from a diesel to a natural gas technology is given by

$$\mathrm{TWP}(t) = \frac{(E_{\mathrm{WTP}_{1\mathrm{CH}_4}} + E_{\mathrm{IU}_{1\mathrm{CH}_4}})\mathrm{TRF}_{\mathrm{CH}_4}(t) + E_{1_{\mathrm{CO}_2}}\mathrm{TRF}_{\mathrm{CO}_2}(t)}{E_{2_{\mathrm{CH}_4}}\mathrm{TRF}_{\mathrm{CH}_4}(t) + E_{2_{\mathrm{CO}_2}}\mathrm{TRF}_{\mathrm{CO}_2}(t)} \quad (1)$$

where the terms are defined as follows: Technology 1 (represented by subscript 1) is the natural gas case, with well-to-wheels CO_2 emissions $E_{1_{CO_2}}$ (including vented and fugitive CO_2 emitted during natural gas production, processing and transportation), and well-to-wheels CH_4 emissions broken out explicitly into two parts, upstream (or well-to-pump) CH_4 emissions $E_{\mathrm{WTP}_{1\mathrm{CH4}}}$ and in-use (or pump-to-wheels) CH_4 emissions $E_{\mathrm{IU}_{1\mathrm{CH4}}}$. Technology 2 (represented by subscript 2) is the diesel case, with well-to-wheels CO_2 emissions $E_{2_{\mathrm{CO2}}}$ and CH_4 emissions $E_{2_{\mathrm{CH4}}}$. $\mathrm{TRF}_{\mathrm{CH4}}(t)$ and $\mathrm{TRF}_{\mathrm{CO2}}(t)$ represent the total radiative forcing values of each GHG as a function of time, and are calculated with the functions for Fleet Conversion TWP in Table 3 of Alvarez et al. (2012).[2] The E values represent the emission burden associated with each unit of energy consumed at a specific point in the supply chain. The segments of the natural gas value chain and corresponding E values from eq 1 are illustrated in Figure 1.

The $E_{\mathrm{WTP}_{1\mathrm{CH4}}}$ and $E_{\mathrm{IU}_{1\mathrm{CH4}}}$ implicitly reflect the upstream and in-use loss rates of CH_4, respectively, and can be derived through simple unit conversions. For example, in the case of the upstream emissions factor

$$E_{\mathrm{WTP}_{1\mathrm{CH}_4}} = \frac{L_{\mathrm{WTP}}\theta_{\mathrm{CH}_4}\rho_{\mathrm{CH}_4}}{\varepsilon \mathrm{LHV}_{\mathrm{NG}}} \quad (2)$$

where L_{WTP} is the natural gas loss rate from the well to the pump, that is, the ratio of natural gas emitted to the atmosphere relative to natural gas throughput (vol/vol); θ_{CH_4} is the average CH_4 content in natural gas across the supply chain (90% vol/vol, as described in Supporting Information, section S1);[17] ρ_{CH_4} is the mass density of CH_4 at standard conditions of 60 °F and 1 atm (19.2 g CH_4/scf); ε is the efficiency of a natural gas truck in miles/mmBtu fuel consumed (47 and 47.4 miles/mmBtu for the 11.9 and 15 L engines respectively, as converted from the miles per gallon values in Table S5 of the Supporting Information); and $\mathrm{LHV}_{\mathrm{NG}}$ is the lower heating value of natural gas (9.30×10^{-4} mmBtu/scf). The latter is based on the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, with an adjustment in the standard conditions used by GREET from 32 to 60 °F (and 1 atm pressure).[18]

The loss rates discussed in this paper are throughput-based rates, defined as the ratio of the volume of natural gas emitted upstream of the point of use relative to the amount of natural gas consumed at the point of use. Stated differently, these loss

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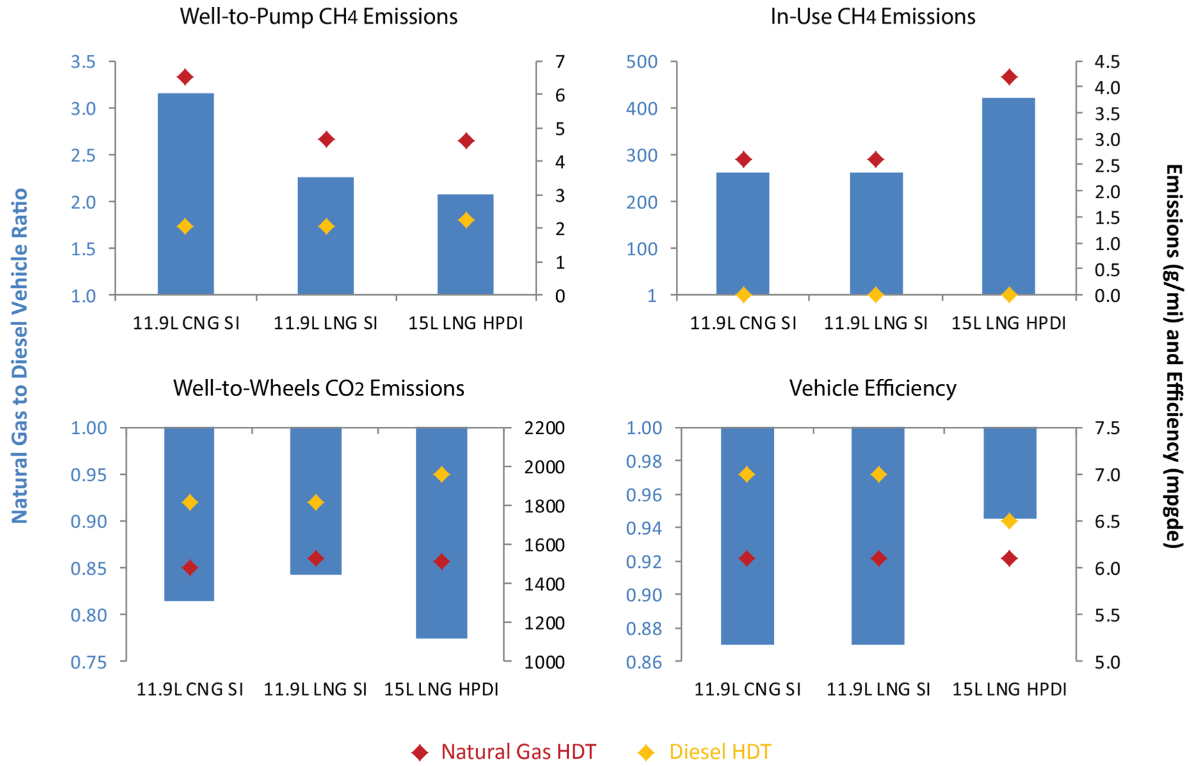

Figure 2. Reference case assumptions for all three natural gas fuel switching scenarios. Assumptions are expressed as absolute values (yellow and red points, right axis) and as the ratio of natural gas over diesel HDT values (bars, left axis).

rates represent the emissions burden associated with each unit of natural gas fuel consumed. The Supporting Information (Section S4) provides further detail about this throughput-based approach, which we follow due to its transparency and direct relationship to emission rates used in life-cycle analyses.[19]

We use the Fleet Conversion TWP, which considers the cumulative radiative forcing of continuous emissions streams resulting from the permanent conversion of a diesel fleet to natural gas, and assumes that the converted natural gas fleet emits continuously and indefinitely; that is, each natural gas truck is replaced by an identical unit at the end of its service life.[2]

We use eq 1 and eq 2 to calculate the critical loss rates, defined as the maximum natural gas loss rates at which natural gas technologies produce lower cumulative radiative forcing than diesel technologies, that is, where TWP $(t) < 1$, on all time frames.[2] As we cannot simultaneously solve for both the well-to-pump and in-use critical loss rates simultaneously, we focus on the upstream portion of the natural gas value chain. It should be noted that the upstream and in-use loss rates are affected by the decisions and practices of economically distinct industries. The pace of change is likely to differ between natural gas operators in one case, and engine manufacturers, component manufacturers, fuel providers, and fleet managers in the other. It is therefore important to modify the TWP equation to account for well-to-pump and in-use emissions separately.

Substituting eq 2 into eq 1 and following the steps in Alvarez et al.,[2] we solve for L_{WTP} when TWP = 1 to obtain a relationship between the crossover time (t^* = the time at which the two technologies have equal cumulative radiative forcing) and the natural gas loss rate that makes this happen (L^*_{WTP}):

$$L^*_{\mathrm{WTP}} = \frac{\varepsilon \mathrm{LHV}_{\mathrm{NG}}}{\theta_{\mathrm{CH_4}}\rho_{\mathrm{CH_4}}}\left\{E_{2_{\mathrm{CH_4}}} - E_{\mathrm{IU}_{1\mathrm{CH_4}}} + \frac{\mathrm{TRF}_{\mathrm{CO_2}}(t^*)}{\mathrm{TRF}_{\mathrm{CH_4}}(t^*)}(E_{2_{\mathrm{CO_2}}} - E_{1_{\mathrm{CO_2}}})\right\} \quad (3)$$

If we then take the limit of L^*_{WTP} as t^* goes to zero, when the ratio of the two TRF terms approaches 1/RE (where RE = 120 is the radiative efficiency of CH_4 relative to CO_2, derived from values in IPCC AR5 Table 8.A.1 and following the IPCC convention that the direct radiative efficiency of CH_4 is enhanced by 65% to account for indirect forcing effects),[20] we derive an expression for the critical well-to-pump loss rate $L_{o,\mathrm{WTP}}$ below which the natural gas case leads to less radiative forcing on all time frames

$$L_{o,\mathrm{WTP}} = \frac{\varepsilon \mathrm{LHV}_{\mathrm{NG}}}{\theta_{\mathrm{CH_4}}\rho_{\mathrm{CH_4}}}\left\{E_{2_{\mathrm{CH_4}}} - E_{\mathrm{IU}_{1\mathrm{CH_4}}} + \frac{(E_{2_{\mathrm{CO_2}}} - E_{1_{\mathrm{CO_2}}})}{\mathrm{RE}}\right\} \quad (4)$$

With the IPCC's new parameters describing the decay of CO_2 and CH_4 emissions, $L_{o,\mathrm{WTP}}$ occurs immediately upon fleet conversion, as L^*_{WTP} increases monotonically with t^*.

We evaluate two engine types commonly used within the HDT sector. The first is the 11.9 L configuration, available as both diesel compression ignition (CI) and natural gas SI types. The 11.9 L diesel CI and natural gas SI engines share many components, and are generally fungible based on utility and torque output. The second engine configuration we examine is the 15 L heavy-duty engine, which is currently the largest commercially available diesel engine for use in long-haul heavy-duty trucking. In addition to the diesel fuel version of the 15 L engine, an HPDI natural gas-based fueling system version has

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been developed. This HPDI engine uses a small amount of diesel as a pilot ignition source, allowing it to operate as a CI diesel engine while using natural gas as the primary fuel. The HPDI technology allows the engine to take full advantage of the inherent benefits of current diesel technology (high compression ratio, lack of throttling losses), and minimizes the fuel economy loss that has historically been present when comparing diesel to SI natural gas engines. We include it to understand how more efficient existing natural gas engines can compare to their diesel counterparts. In addition to the two engines above, we examine in the Supporting Information (section S7) the 8.9 L heavy-duty engine, also available both as diesel CI and natural gas SI type (this engine is included for completeness and to enable direct comparison to other studies).

For our reference cases, we use EPA certification dynamometer data to estimate relative vehicle fuel economy values for engine types considered, as illustrated in the bottom right panel of Figure 2 (see Table S5 and Supporting Information for values and detailed explanation of these calculations).[21,22] The 11.9 L engines considered are model year 2014 engines, while the 15 L engines are model year 2012 (manufacture of the natural gas HPDI engines halted in 2013). All engines were tested on EPA's "on-highway heavy-duty diesel engine" federal test procedure.

The 11.9 L SI natural gas engine is estimated to be on average 13% less efficient (in other words, exhibiting a 13% efficiency "penalty") compared to its counterpart, the 11.9 L diesel CI engine (based on fuel consumption data in gallons per brake horsepower-hour from the 2014 EPA engine certification database).[22] This relative efficiency value is in the range of those found in recent literature. Meyer et al. found efficiency penalty values of 20.7% for the CNG SI and 20.2% for the LNG SI; however, these values were representative of older 8.9 L transit buses (EPA data suggests the 8.9 L natural gas SI truck has a higher efficiency penalty when compared to its diesel counterpart than the 11.9 L SI).[22,23] More recently, Santini et al. have estimated an efficiency penalty of 14% for the natural gas SI truck, based on values published by Deal.[24,25] As for the 15 L engine configuration, we estimate that the LNG HPDI engine is on average 5.5% less efficient than the 15 L diesel CI engine (derived using relative CO_2 emissions from the 2012 EPA engine certification database, see Supporting Information, section S5).[21] This value is similar to that of Santini et al., who assume a 4% efficiency difference between the two trucks.[24] We emphasize that efficiency values are highly dependent on the duty-cycle to which trucks are subjected. We address this issue partly by using the EPA engine certification test data, which guarantees that the engines were tested on the same simulated duty-cycle (see Supporting Information, section S5). However, because certain duty-cycles favor some engine types over others, we also run a sensitivity analysis around the relative efficiency assumption. We note that absolute fuel economy values (in miles per gallon) have far less impact on the TWP calculations than the diesel to natural gas relative fuel economy assumptions, because all emissions factors, except for the in-use CH_4 emissions of natural gas engines ($E_{IU_{1CH4}}$), scale proportionally to changes in absolute fuel economy (Supporting Information, section S5, provides a more detailed discussion, as well as our reference absolute fuel economy assumptions).

We use GREET 1 2013, a vehicle fuel cycle model which is broadly utilized for academic studies and by industry, to generate upstream emissions factors for CH_4 and CO_2 for all engine types considered in the analysis (Supporting Information, section S5).[18] We make adjustments to GREET 1 2013 consistent with CH_4 emissions data from the 2014 EPA Greenhouse Gas Inventory (Table S6 in the Supporting Information).[19,26] Our analysis covers estimates for all CO_2 and CH_4 emissions, whether fugitive, vented or from combustion, including venting from LNG tanks along the supply chain and at the vehicle refueling station.

In-use emissions factors are also generated in GREET 1 2013, except for the CH_4 in-use factor applicable to natural gas trucks. Our reference value of 2.6 gCH_4/mi for 11.9 L SI in-use emissions is based on the EPA 2014 engine certification database (Table S6 in the Supporting Information).[22] The EPA engine certification database does not include CH_4 emissions data for HPDI engines however. Consequently, for the HPDI case, we use a reference estimate of 4.2 gCH_4/mi based on Graham et al.[27] This is the only published value we could find and it should be viewed with caution as it is based on a model year 2004 diesel engine converted to run on LNG with diesel fuel pilot ignition, and tested on the Urban Dynamometer Driving Schedule which may not correspond to the test cycle used in the EPA certification database. Because we could find no published data on venting from LNG tanks on trucks, we use the above emissions factors as proxies for total in-use emissions; the range of in-use CH_4 emissions in the sensitivity analysis can accounts for potential venting from truck tanks.

Estimates for the emissions factors of each technology considered, expressed in g/mile, can be found in Table S7 and are explained in the Supporting Information. Reference case emissions assumptions are illustrated in Figure 2, which emphasizes the fact that natural gas engines emit less CO_2, but more CH_4 than their diesel counterparts. Our methodology is designed to account for the temporal complexities associated with the emissions of these gases and examine whether (and on what time frame) a transition to natural gas could result in climate benefits.

RESULTS

In this section, we present TWP and critical well-to-pump loss rate results for a switch from diesel to natural gas-fueled HDT fleets. Figure 3 plots, as a function of time, the TWPs of choosing one of three natural gas truck options (CNG SI, LNG SI, or LNG HPDI) as a replacement for diesel HDTs. As detailed previously, it is assumed that each of these three options replaces a diesel heavy-duty technology equivalent in engine size and in duty-cycle.

Reference case results reflect what we believe are reasonable input estimates based on currently available data, characteristic of existing technology and operations (these results are represented by the blue dashed lines in Figure 3; assumptions are informed by literature estimates and detailed in Figure 2, as well as Table S5 and S7 of the Supporting Information). However, our intent is not to present reference case results as definitive. Because of the uncertainty surrounding several key assumptions and the potential for them to evolve over time with new data, technology improvements, policy changes, or market dynamics, we use reference values primarily as points for comparison, emphasizing results of our sensitivity analyses instead (shaded areas in Figure 3). We test the sensitivity of TWP results to a range of values for upstream CH_4 emissions from 0 to 4% of natural gas throughput, and to a range of diesel to natural gas engine efficiency penalty values from 0 (or equal

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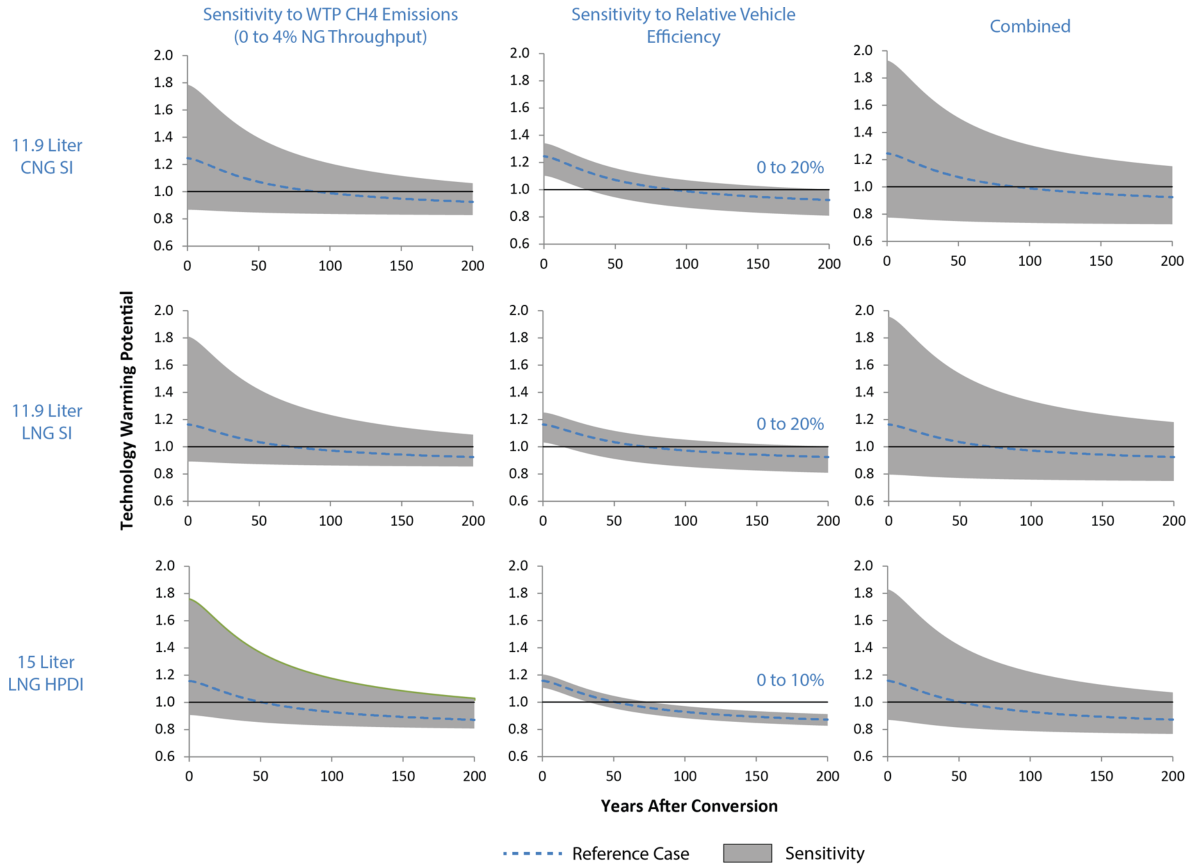

Figure 3. TWP results for diesel to natural gas HDT fleet conversions. Technology Warming Potential (TWP) for three diesel to natural gas heavy-duty fleet conversion cases (rows from top to bottom: 11.9 L diesel to 11.9 L SI CNG; 11.9 L diesel to 11.9 L SI LNG; 15 L diesel to 15 L HPDI LNG), with each column showing the sensitivity to alternative ranges of upstream CH_4 emissions, relative vehicle efficiency and the combination of the two. "The "Sensitivity to WTP CH_4 Emissions" case" assumes a range of upstream emissions between 0 and 4% of natural gas throughput, with vehicle efficiency fixed at reference case levels. The "Sensitivity to Relative Vehicle Efficiency" case assumes a range of diesel to natural gas vehicle efficiency penalty values between 0% and 20% (or equal efficiency) for the SI fleets and between 0% and 10% for the HPDI fleets, with upstream emissions fixed at reference case levels. The "Combined" cases show the sensitivity of the TWP results to both the upstream CH_4 emissions and the assumed vehicle efficiency penalty, with the most optimistic scenario assuming zero upstream emissions and equal vehicle efficiency and the most pessimistic scenario assuming 4% upstream loss and upper bound vehicle efficiency penalty for the natural gas trucks. Pump-to-wheels CH_4 emissions are held constant at 2.6 g/mile for the SI fleet conversion cases and 4.2 g/mile for the HPDI case (see Supporting Information, section S5),[22,27] which equals approximately 0.6% and 1% of natural gas fuel consumption respectively (sensitivity to pump-to-wheels emissions are examined in Figure 4).

efficiency) to 20% for the SI cases and 0 to 10% for the HPDI case. The upper bounds of these ranges are meant to represent worst case scenarios for both variables and are consistent with recent literature estimates.[6,23−25] The lower bounds illustrate hypothetical future best case scenarios. A more detailed discussion of the basis for the sensitivity ranges is available in the Supporting Information, section S6.

The horizontal line in Figure 3 graphs, which equals a TWP of 1, denotes where diesel and natural gas technologies produce equal cumulative radiative forcing. TWP values greater than 1 indicate net climate damage t years after switching a diesel fleet to natural gas; values less than 1 indicate net climate benefits. The shape of the blue TWP curve (given by eq 1) results from the counterbalancing effects of CH_4's large radiative forcing and its short atmospheric lifetime relative to CO_2. In early years, the influence of the well-to-wheels CH_4 emissions in the natural gas fuel cycle outweighs the lower CO_2 from natural gas fuel use. Over longer time frames, the effect of fresh CH_4 emissions is outweighed by the forcing due to accumulated CO_2 from prior years (because atmospheric CH_4 concentrations from continued fleet operation reach a steady state, whereas CO_2 concentrations continue to accumulate in a roughly linear fashion). At sufficiently long time frames, TWP values will asymptotically approach the value that results if well-to-wheels CH_4 emissions were zero. The TWP approach was proposed to draw attention to this time-dependent behavior.[2]

Overall, both upstream natural gas loss and relative vehicle efficiency values are shown to have a significant impact on whether a switch toward a natural gas HDT fleet produces net benefits or net damages to the climate, both in the short and long-term. This is illustrated by the large, time-dependent range of results in all three of the combined sensitivity cases. At $t = 0$, maximum TWP results are roughly 2.5 times higher than the minimum value; at $t = 200$ years, maximum values are 1.6 times higher. Our results suggest that the climate implications of fleet conversion appear to be more sensitive to the likely range of upstream emissions values than the likely range of efficiency loss values.

The third column of Figure 3 illustrates that certain combinations of improved efficiency joined with reduced upstream CH_4 emissions, relative to reference case levels, could result in all three engine fleet conversions achieving

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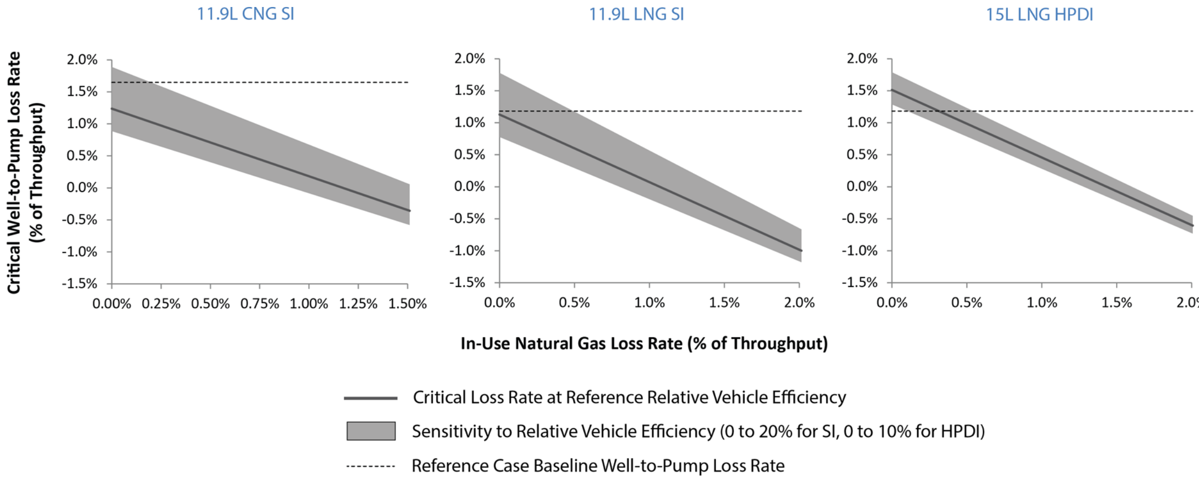

Figure 4. Critical well-to-pump loss rate: Sensitivity to in-use CH_4 emissions and relative vehicle efficiency. Maximum well-to-pump natural gas loss rates that produce climate benefits on all time frames are plotted as a function of vehicle in-use CH_4 emissions for all three fleet conversion cases, and for a range of natural gas to diesel vehicle efficiency penalty values (0−20% for SI cases, 0−10% for the HPDI case). The dashed line indicates the reference case loss rate (1.65% and 1.2% well-to-pump natural gas loss for the CNG and LNG cases respectively, implied by the reference upstream emissions factor $E_{WTP_{1CH_4}}$, expressed as a percent of natural gas throughput using eq 2). Results consider in-use emissions between 0% and 1.5% of natural gas throughput for the CNG case and between 0% and 2% for the LNG case, consistent with a range of estimates found in the literature (see Supporting Information, section S6, for a more detailed discussion). The dark lines represent results at the reference vehicle efficiency values detailed in Figure 2 and Table S5 of the Supporting Information. Note that our reference cases assume in-use CH_4 emissions of 2.6 g/mile for the SI cases and 4.2 g/mile for the HPDI case,[22,27] which equal approximately 0.6% and 1% of natural gas throughput, respectively.

climate benefits sooner, or even at all time frames. This emphasizes the importance of making improvements to both the emissions from the natural gas fuel supply chain and the efficiency of natural gas trucks in order to ensure and maximize net climate benefits for all three fleet conversion cases.

Based on reference assumptions for all cases examined, converting HDT fleets from diesel to natural gas damages the climate for decades before any climate benefits occur. TWPs decline with time because of the short-lived properties of CH_4. Because of higher upstream CH_4 loss in the CNG fuel cycle as compared to LNG (due primarily to higher levels of CH_4 loss at the transmission stage), conversion toward a CNG fleet results in slightly steeper TWP curves in the earlier years. A diesel CI to natural gas SI fleet conversion damages the climate for 90 and 72 years for the 11.9 L CNG and LNG cases, respectively. On longer time frames, the climate implications of switching to CNG and LNG SI fleets become comparable due to larger CO_2 emissions in the LNG fuel cycle compared to the CNG fuel cycle. The impact of these additional CO_2 emissions (occurring from liquefaction and transportation of LNG by truck, rail or barge) is more prevalent on longer time frames. A conversion to the LNG HPDI fleet is beneficial to the climate on a relatively shorter time frame, after 51 years, which is a function of a lower assumed efficiency penalty than for the SI engines. Note that in-use CH_4 emissions are assumed to be about 60% higher in the HPDI case than in the SI cases (see Supporting Information, section S5).[22,27] This undermines some of the potential benefits of the relatively higher efficiency of the HPDI engine.

While TWP results for all three engine types are similar in our reference cases, the dynamics that cause these results are different. Figure 2 helps shed light on these differences: while the SI engines incur a larger efficiency penalty, they have less in-use CH_4 emissions compared to the HPDI engine. In turn, the significantly higher in-use emissions of the HPDI case are offset by relatively lower upstream CH_4 and CO_2 emissions compared to the CNG SI case, as well as lower efficiency penalty compared to both SI cases. For the SI vehicles, the LNG case has higher well-to-wheels CO_2 emissions, but these are offset by lower upstream CH_4 emissions compared to the CNG case (due primarily to the GREET assumption that natural gas travels through hundreds of miles of transmission and distribution pipelines between the well and CNG refueling stations).[18,19] Being aware of these underlying dynamics is important to understand what combinations of variables are needed to ensure that natural gas trucks are beneficial to the climate at all time frames.

Figure 4 shows the effect of vehicle in-use CH_4 emissions on the well-to-pump loss rate necessary for each diesel to natural gas fleet conversion to ensure net climate benefits on all time frames, under a range of natural gas vehicle efficiency assumptions relative to diesel (using eq 4). The difference between the dashed line and the solid line represents the change in well-to-pump loss rate necessary for the diesel to natural gas fleet conversion to have zero radiative forcing impact at $t = 0$ and at reference diesel-to-natural gas efficiency penalties (in the LNG HPDI reference case, increased upstream loss rates, relative to the reference case, would be possible for in-use CH_4 loss values below approximately 0.3%). For example, with reference case assumptions for in-use CH_4 emissions (0.6% on the x-axis for the CNG and LNG SI cases, and 1% for the HPDI case) and relative vehicle efficiency (solid black line), reference case upstream CH_4 loss would need to be reduced by approximately 65% in the CNG SI case (from 1.65% to 0.6%) and 60% in the LNG SI case (from 1.2% to about 0.45%). Converting to an LNG HPDI fleet under reference case assumptions also results in a critical well-to-pump loss rate of approximately 0.45%, again about 60% below the 1.2% reference case loss rate.

We note that EPA's *Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Phase I)* caps exhaust CH_4 emissions from HDTs

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at 0.1 g/bhp-hr starting with model year 2014. Such low emissions are included in this paper's sensitivity analyses to in-use CH_4 emissions. However, natural gas engine manufacturers are able to offset CH_4 emissions by using CO_2 credits earned as a result of low CO_2 emissions from these vehicles.[31] This provision is likely to help engines comply without reducing their CH_4 exhaust emissions. In addition, vehicle tank venting of CH_4 is not regulated under the standard.

All else equal, higher in-use CH_4 loss (moving from left to right on the *x*-axis) means that greater reductions must occur in the upstream part of the supply chain if net climate benefits are to be achieved at all time frames. At sufficiently high levels of in-use emissions, critical well-to-pump loss results can reach negative values, indicating that the effect of the in-use emissions at such magnitudes can no longer be compensated by upstream loss reductions. In other words, if in-use emissions are high enough, it is possible that no combination of upstream loss reductions and efficiency improvements could result in climate benefits on all time frames. Figure 3 displays a higher upper bound for CH_4 in-use emissions in the LNG cases to account for LNG station boil-off or venting from HDT tanks.[28,29] Note that while we do not specifically evaluate after-market natural gas retrofit kits for diesel engines, which may have larger in-use CH_4 emissions, our sensitivity analysis encompasses scenarios with high vehicle-level emissions. Further research on these engine configurations is needed.

The likely range of relative vehicle efficiency values also has a significant effect on critical well-to-pump loss rates. Conversions to a fleet with small diesel to natural gas efficiency penalties allow for higher upstream CH_4 emissions. For example, at equal efficiencies and reference upstream loss rates, a fleet conversion from diesel to LNG trucks produces net climate benefits at all time frames provided the in-use CH_4 emissions of the LNG fleet are below approximately 0.5% of natural gas throughput (about 2 g/mile) for both the SI and HPDI cases. This number goes down to 0.2% (0.8 g/mile) for fleet conversions to CNG SI trucks. The combination of values that produce net climate benefits immediately is represented by the gray shaded segments above the black dashed line in the three cases illustrated in Figure 4.

We also provide TWP and critical loss rate results for 8.9 L engines in section S7 of the Supporting Information. Although these results highlight dynamics similar to the 11.9 L cases, the reference case TWP values are higher in the 8.9 L cases due to both greater assumed natural gas to diesel engine efficiency penalty and larger in-use CH_4 emissions.

We emphasize that the critical loss rates presented in this paper are not directly comparable to those in Alvarez et al. because we are reporting throughput-based loss rates instead of rates relative to gross production. Figures S3 and S4 in the Supporting Information enable an approximate comparison of throughput and gross production values in the 8.9 L CNG SI case.

■ DISCUSSION

Whether a switch from diesel to natural gas HDT fleets produces net climate benefits or net climate damages for a chosen time horizon hinges considerably on several critical factors. These include, but are not limited to the type of fuel used, the natural gas engine and its efficiency penalty relative to the diesel engine it replaces, and well-to-wheels emissions of CH_4 (i.e., the magnitude of loss through the supply chain and in-use). The results of our sensitivity analyses shed light on the climate implications of these factors by highlighting a likely range of impacts under different assumptions; further research and improved data are needed to estimate with confidence the current GHG footprint of HDTs (simulated by our reference cases, which are based on available data but not definitive). First and foremost, a better understanding of CH_4 loss along the natural gas well-to-wheels cycle is needed. Significant research is underway to update estimates of CH_4 loss across the U.S. natural gas system from production through local distribution and natural gas fueling stations and vehicles.[5−10,30]

This paper utilizes national-level assumptions for truck and emissions data. Outcomes could vary for localized or regional applications, which may result in different emissions due to fuel pathways and other factors unique to an area. These could include different distances between production and end use (affecting transmission and distribution emissions) or state-specific emissions regulations (which could affect both upstream and vehicle operation emissions). Geographical sensitivity analyses could therefore provide a more precise picture of the implications of diesel to natural gas truck fleet conversion for particular applications.

Our analysis does not address the broader question of how increased use of natural gas can produce the greatest climate benefits—though evidence from other analyses suggests it may be more beneficial for it to be consumed in the electricity sector rather than in transportation.[2] Neither does our analysis speak to the relative effects of other vehicle fuel alternatives (for example, electricity or biofuels) or policies which could result in fewer vehicle miles traveled—all of which may have the potential to produce lower overall emissions and radiative forcing, and therefore reduce the climate impacts of HDTs. In addition, we do not examine induced demand effects. In theory, low natural gas prices could influence fleet conversion to natural gas or increase miles traveled—though in reality there may be other factors affecting such changes in behavior, but none of these potential impacts are considered here. Finally, our analysis does not consider the potential nonclimate air pollution (e.g., particulates) reduction benefits of transitioning from diesel fuel toward natural gas. Additional analyses could be useful for policymakers to make informed decisions regarding incentives for specific technologies in energy policies or clean air rules.

Our results show that under our reference case assumptions, reductions in CH_4 losses to the atmosphere are needed to ensure net climate benefits on all time frames when switching from diesel to natural gas fuel in the heavy-duty sector. By combining such reductions with engine efficiency improvements for natural gas HDTs, it may be possible to realize substantial environmental benefits. However, until better data is available on the magnitude of CH_4 loss, especially for in-use emissions, the precise climate impacts of a switch remain uncertain in this sector. Therefore, policymakers wishing to address climate change should use caution before promoting fuel switching to natural gas. Furthermore, diesel engine efficiency is likely to improve in the future (particularly as a result of current and upcoming HDT standards),[32] and if this occurs without similar improvements in natural gas engine efficiency, a growing spread between these engines could worsen the impacts of diesel to natural gas fuel switching. Fleet owners and policymakers should continue to evaluate data on well-to-wheels CH_4 losses and HDT efficiencies and work to ensure that the potential climate benefits of fuel switching are realized.

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ASSOCIATED CONTENT

Supporting Information

Further methodological details and results. This material is available free of charge via the Internet at ACS Publications website at DOI: 10.1021/acs.est.5b00412.

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