



ASSESSMENT OF HEAVY-DUTY NATURAL GAS VEHICLE EMISSIONS: IMPLICATIONS AND POLICY RECOMMENDATIONS

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ACKNOWLEDGEMENTS

This project was supported by the Pisces Foundation and the ClimateWorks Foundation. The authors thank Nic Lutsey, Fanta Kamakaté, and Nigel Clark for their critical input and review of the report.

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EXECUTIVE SUMMARY

Recent assessments indicate that natural gas vehicles could constitute up to 20 percent of the new 2025 heavy-duty vehicle market, potentially displacing a significant amount of diesel-fuel-burning vehicles. Considering the relative lack of regulatory guidance in the existing regulation, there are many ways in which the U.S. heavy-duty vehicle “Phase 2” greenhouse gas rulemaking could influence the new fuel/engine technology and its deployment in the fleet. The possibilities range from provisions that promote natural gas use in trucks, with minimal protection against increased methane emissions, to those that promote only the lowest-carbon natural gas technology and can provide even greater carbon and oil-saving benefits.

Inherently, natural gas, which consists largely of methane, contains about a quarter less carbon per energy unit than diesel; therefore, if the fuel supply chain is managed properly, natural gas could be instrumental in the shift to a lower-carbon heavy-duty vehicle fleet. However, recent studies on natural gas supply chain leakage and emissions indicate that even low levels of methane emissions can turn natural gas truck technology from an asset into a liability for the United States’ long-term climate mitigation planning.

This assessment analyzes the implications of a growing natural gas vehicle fleet on the potential emission benefits of Phase 2. The approach includes a synthesis of data from leading sources on upstream emissions, vehicle emissions, and efficiency technology. The assessment involves a stock turnover model analysis of the U.S. medium- and heavy-duty vehicle fleet. The analytical results are presented in terms of the total potential carbon dioxide equivalent (CO₂e) emissions across scenarios with varying vehicle efficiency, methane emissions, and natural gas penetration among the fleet.

As shown in Figure ES-1, on a *fleetwide basis*, a number of developments concerning natural gas vehicles and fuel supply and handling could substantially determine the success of the Phase 2 standards. The figure illustrates how the potential emissions from a heavy-duty vehicle fleet in which natural gas is increasingly common vary dramatically depending on a number of critical variables including vehicle efficiency, the global warming potential of methane, and cumulative “well-to-wheels” methane emissions in the fuel’s supply chain. The figure shows several possible Phase 2 GHG outcomes based on a range of different natural gas vehicle scenarios. The reference case assumes that the new vehicle fleet sees efficiency improvements of 3.5 percent per year and that natural gas-fueled trucks retain about a 1 percent market share into the future, with natural gas leakage assumed to be 1.1 percent, and natural gas trucks continuing to have a 10 percent efficiency loss versus diesel. That reference case would result in emission reductions of approximately 140 million metric tons of CO₂ equivalent per year in 2040. Other scenarios in the figure are shown with greater and lesser GHG benefits. With natural gas truck penetration of 20 percent of new vehicle sales in 2025, best practices could increase the Phase 2 regulatory program’s 2040 benefits by 11 million tons of CO₂e, or 7 percent. On the other hand, inadequate attention to technologies designed to limit methane leakage, and using 20-year climate impact accounting rather than 100 years, would diminish the program benefits by as much as 38 percent (55 million tons of CO₂e per year). The impact of changes in natural gas engine efficiency versus conventional gasoline and diesel trucks was also analyzed, but the overall impact was smaller than that of methane leakage or the choice of accounting time frame.

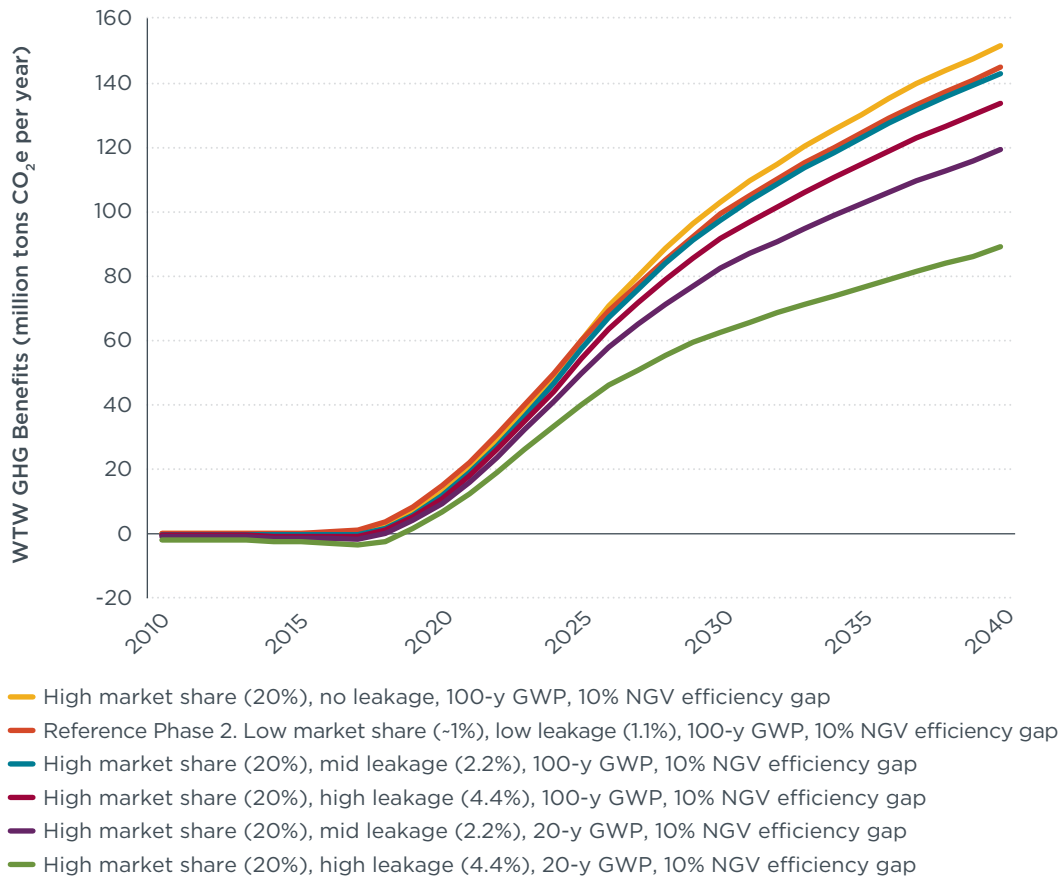


Figure ES1. Well-to-wheels greenhouse gas (GHG) benefits across different scenarios

The analytical results from the GHG scenarios point to several high-level conclusions. First, minimizing the overall well-to-wheels leakage is the key determinant in whether trucks using natural gas will offer long-term benefits as part of an overall shift toward a more efficient and lower-carbon heavy-duty vehicle fleet. As has been stated elsewhere, keeping well-to-wheel natural gas leaks at or below 1 percent throughout the supply chain is critical to ensuring that the fuel offers a climate benefit. Second, innovation will be needed in order for natural gas trucks to keep pace with diesel and gasoline engine efficiency improvements and thus to maintain their carbon reduction benefits, although the effect is less critical than reducing methane leakage. Finally, the decision as to which global warming potential (i.e., 100-year or 20-year) to use is approximately as important as an additional 1 percent methane leak, indicating the importance of considering both GHG time accounting metrics.

Based on this assessment of the range of emission impacts, best practice technologies, and policy design options, there are four recommendations that should be considered in the heavy-duty vehicle greenhouse gas (GHG) emissions rulemaking process to avoid the potential problems resulting from greater deployment of natural gas trucks in the 2015-2030 time frame.

1. Ensure uptake of available technologies that significantly lower tailpipe and crankcase methane emissions

The carbon dioxide/methane trading flexibility provisions in the Phase 1 GHG rulemaking allow for high tailpipe and crankcase methane emissions from natural gas vehicles. Current certification data show that stoichiometric natural gas engines (which currently dominate the market for sales of natural gas engines) are emitting at 10 to 20 times the regulatory limit. There is currently little incentive for manufacturers to use available technologies such as closed crankcase ventilation systems or improved methane oxidation catalyst systems. In addition, it is possible to reduce or eliminate dynamic venting from high-pressure direct injection engines through design changes or dynamic vent capture solutions.

2. Use full life-cycle GHG emissions, via both a 20-year and a 100-year time horizon, in the benefits assessment for natural gas vehicles in Phase 2

There is currently a regulatory push at the federal level to mitigate methane leakage and emissions from the well-to-pump segment of the value chain. There is also active research that will provide more up-to-date information on actual leakage and emissions rates. Owing to methane's status as a short-lived climate pollutant, it is necessary to understand fully both the short- and long-term impacts of its emissions compared with carbon dioxide. In the benefits assessment for Phase 2, regulatory agencies would do well to acknowledge the leading science in this area by including both long-term (i.e., 100 years) and short-term (20 years) time horizons for greenhouse gases, including methane.

3. Set a clear signal to reduce other known emissions associated with natural gas trucks within the Phase 2 rulemaking time frame

Natural gas trucks can yield climate benefits; however, it is difficult to make that case today because of their higher upstream emission impacts. The regulation would ideally be executed in such a way as to allow the natural gas vehicle market to grow yet to avoid significantly undermining the heavy-duty regulatory program's GHG reduction objectives as the industry and government work expeditiously to shore up known emission leaks through the fuel supply. It is important to set a clear signal that within the period in which the regulation is expected to be in force—by 2025 or so—there will be limits for liquefied natural gas tank venting, natural gas fueling station venting and emissions, and other methane emission sources that are identified over time. It will be important to factor in average upstream emission impacts as part of the vehicle or engine certification emission level within the rulemaking time frame. Increased collaboration between natural gas vehicle manufacturers and fuel providers will be needed to address such issues. Stipulating a default upstream methane emissions level will encourage such collaboration in the service of a lower-carbon fuel supply.

4. Set fuel-neutral greenhouse gas standards

The adoption of fuel-neutral standards is the most appropriate way to credit the relative carbon dioxide emission advantages of natural gas vehicles versus their gasoline and diesel counterparts. A fuel-neutral, level playing field is important to ensure that technologies compete based on their GHG emission performance and their cost-effectiveness. Fuel-neutral standards as part of the regulation would provide the clearest incentive for the introduction of natural gas trucks with the lowest GHG attributes (i.e., highest efficiency, lowest methane emissions).

1. INTRODUCTION

Approximately one million heavy-duty vehicles (HDVs) are sold in the United States every year, and currently less than 1 percent are powered by natural gas. But the booming shale gas industry guarantees abundant resources and has brought prices of natural gas to as low as one-third the price of diesel. With natural gas this cheap and available, the commercial trucking industry is poised to invest in new natural gas-powered trucks over the coming decades. The U.S. Energy Information Administration's *Annual Energy Outlook 2015* projects that natural gas will be the fastest-growing fuel in the transportation sector, with an average annual demand increase of 10 percent from 2012 to 2040 (US EIA, 2015). Heavy-duty vehicles are the leading edge of this projected expansion, with a projected average annual growth rate for natural gas of 14 percent. This rapid growth raises questions about climate change since methane, a potent greenhouse gas (GHG), is the primary constituent of natural gas. The lower carbon content of methane could provide climate benefits when natural gas vehicles are compared with diesel vehicles. However, their lower energy efficiency and their methane emissions may erode this advantage.

The Obama administration is aware of the broad climate implications of the shale gas boom and is developing a plan to contend with upstream methane emissions, those emissions that occur from production, processing, and transmission of natural gas (White House, 2014). However, little attention has been given to transport sector methane emissions that occur downstream, at the fuel station and during vehicle operation (i.e., pump-to-wheels). A comprehensive series of 16 studies that quantify methane losses and leaks across the natural gas supply chain is ongoing (EDF, 2015). The series includes a study by researchers at West Virginia University on methane emissions from the operation of natural gas vehicles, as well as from refueling stations. Results from this study are expected to be made publicly available sometime in the middle of 2015. Meanwhile, the second phase of GHG emissions and efficiency standards for HDVs (Phase 2) was recently proposed by the U.S. Environmental Protection Agency. As the agencies seek to adopt Phase 2 standards by early 2016, a near-term opportunity has opened up to examine methane emissions from natural gas-fueled HDVs, a major source of transport sector methane emissions.

The Phase 2 rule will cover new HDVs for the next 10-15 years, and, while there may be other supplemental opportunities to deal with HDV methane emissions, Phase 2 offers the most comprehensive and immediate policy window. Thus, in order to avoid lock-in of technologies and practices that allow excess methane emissions, action needs to be taken under this rulemaking. This paper presents GHG emissions scenarios under different assumptions about natural gas vehicles' market penetration, methane leakage, methane global warming potential, and efficiency. Then, the paper discusses critical areas that may be addressed and policy-related approaches to the regulatory framework that will allow the natural gas vehicle industry to get a strong footing in the heavy-duty vehicle market while simultaneously safeguarding against any negative climate impacts resulting from the widespread adoption of natural gas vehicles.

As depicted in Figure 1, there are a number of opportunities across the natural gas supply chain for methane leakage. Upstream, or well-to-pump, methane emissions include leakage and venting during production, processing, transmission, storage, and distribution to fuel stations. For the transportation sector, the end-use, or pump-to-

wheel, methane emissions include leakage and venting from the fueling stations and refueling operations and emissions and leakage from the vehicle itself. Leakage rates differ between compressed natural gas (CNG) and liquefied natural gas (LNG) since they follow different upstream processes and utilize different types of equipment during storage, refueling, and vehicle operations.

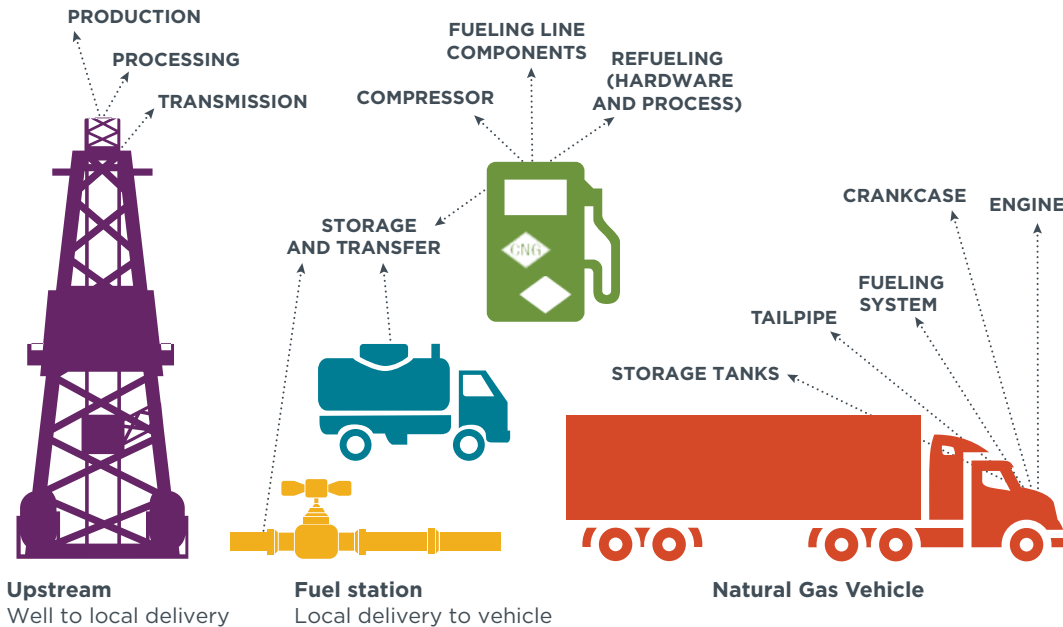


Figure 1. Methane emissions across the natural gas value chain

Different engine technologies can have significant consequences for GHG emissions. Natural gas engines can be either stoichiometric, spark ignited (SI) or lean-burn, compression-ignited, high-pressure direct injection (HPDI). A third technology, not explored in this paper, is lean-burn SI; this technology is currently being adopted elsewhere in the world but is not under consideration for use in the U.S. heavy-duty transportation sector. SI natural gas engines operate similarly to gasoline engines and in turn produce similar engine-out emissions that require a three-way catalyst for after-treatment. HPDI engines, which use compression ignition along with a small (around 5 percent) amount of diesel fuel to pilot the ignition, operate similarly to diesel engines and require after-treatment systems composed of a diesel particulate filter (DPF) and selective catalytic reduction (SCR).

The diesel-like combustion of HPDI systems (direct injection of natural gas with a pilot injection of diesel fuel, unthrottled, and lean combustion) makes them more efficient than throttled SI engines, particularly at part load. Tailpipe methane emissions are similar in magnitude between the two technologies. Without the use of closed crankcase ventilation systems, crankcase methane emissions are expected to be lower for HPDI engines than for SI engines since with HPDI only air is present inside the cylinder during most of the compression stroke. However, it is in the nature of the HPDI fueling system that a small amount of gas may occasionally need to be vented to the atmosphere through a pipe. This is a result of the dynamic behavior of the fuel rail pressure control system and is termed “dynamic venting.” SI engines can use either CNG or LNG as fuel. Owing to the high injection pressures required, HPDI engines only use LNG fuel

systems (Perez Souto, Ferrera, Leclercq, Matchett, and Magnusson, 2014). Because LNG has a higher energy density per unit volume than CNG, it can be more readily used in long-haul trucking operations. LNG is stored on board in insulated tanks as a cryogenic liquid.¹ If the fuel warms up (resulting in more evaporation) and pressure builds beyond a certain limit, natural gas is vented through a pressure relief valve. The time the tank can hold the LNG without venting is called the “holding time.” Tanks are designed for a holding time of five days (SAE, 1997).

Because of the lack of consensus on well-to-wheels methane emissions, this study begins with a review of the literature, which is summarized below and in Table 1. The emissions data used for scenario analysis are discussed in greater detail in section 2.2. Measurement of these losses is typically challenging. Upstream leakage rates estimates are uncertain and difficult to compare, and the incidence of events such as pressure relief venting is hard to quantify. There is a lack of standardization of accounting methodologies, which creates discrepancies in the reported results. Also, there is limited literature available for end-use methane leakage in the transportation sector.

Table 1. Well-to-wheels methane emissions

Location in Value Chain	Category	Sources / Description	Magnitude (references to studies)
Upstream	Production	Horizontal drilling, hydraulic fracturing, well completion, liquid uploading, equipment	0.49% (US EPA, 2013) 0.3%-4.3% (Howarth et al., 2011) 0.30%-0.37% (Burnham et al., 2014)
	Processing	Processing equipment	0.18% (US EPA, 2013) 0.13% (Burnham et al., 2014) 2.4% (processing and transmission) (Allen et al., 2013)
	Transmission	Compressors, pipeline systems, storage facilities	0.42% (US EPA, 2013) 0.39% (Burnham et al., 2014) 2.4% (processing and transmission) (Allen et al., 2013)
	Distribution	Pipeline systems, gas metering and regulating stations	0.46% (US EPA, 2013) 0.30% (Burnham et al., 2014)
Fuel Station	Storage and Transfer	Underutilized station's LNG tank boil-off venting	0.03-0.08% of volume/day (Chen, et al., 2004)
	Compressor	Crankcase losses	0.30% from leakage and venting at the station (Burnham et al., 2014)
	Fueling Line Components	Continuous or intermittent leaks in valves, piping, and fittings	0.30% from leakage and venting at the station (Burnham et al., 2014)
	Refueling	Intentional venting of tank prior to refueling, nozzle connection/disconnection losses	0.30% from leakage and venting at the station (Burnham et al., 2014)
Vehicle	Tailpipe	Unburned methane in the exhaust	0.6-1.1%* (US EPA, 2014)
	Crankcase	Methane leaks past piston rings; open crankcase vent to the atmosphere	0.1-0.6% (Johnson and Covington, 2014)
	Storage	Vehicle's LNG tank boil-off vents	2.6% of the initial mass of liquid in the tank (Ursan, 2011)
	Fueling System	HPDI system dynamic venting	0.15% (Dunn et al., 2013)

* Certification data include tailpipe and crankcase emissions combined.

¹ Cryogenic liquids include liquefied gases that boil at temperatures at or below -150 °F under normal atmospheric pressure. LNG boils at -258 °F.

This assessment uses existing data on methane emissions throughout the natural gas value chain, engine certification data, and efficiency technology potential to analyze the emission implications of greater natural gas penetration among the U.S. heavy-duty fleet. The analysis includes the development of a stock turnover model that is updated from the VISION model of Argonne National Laboratories (ANL) to include the latest data on vehicle efficiency, fuel carbon intensities, and natural gas market share. To model the latest science on upstream methane emissions, the study draws upon the leading literature on fuel supply methane leakage and associated greenhouse gas intensity. ANL's GREET model is used to calculate the well-to-wheels carbon intensity of different fuels. In addition, acknowledging the short-term climate impact of methane emissions, it is important to analyze scenarios with methane's global warming potential (GWP) over both 100-year and 20-year time horizons.

The report is organized as follows. Section 2 describes the assumptions made and analysis performed to develop different GHG emissions scenarios based on varying market penetration rates, well-to-wheel emissions, engine efficiency, and global warming potential. Section 3 presents the results and analysis in the context of the ongoing Phase 2 GHG rulemaking in the United States. Section 4 summarizes regulatory considerations and areas where further research work is needed in preparation for the ongoing rule. Finally, section 5 presents the conclusions and recommendations based on the analysis.

2. SCENARIO DEVELOPMENT

Natural gas contains less carbon than any other fossil fuel. The carbon intensity (in units of grams of CO₂e per megajoule) of compressed natural gas is 28 percent lower than diesel (ANL, 2014b). However, on a well-to-wheels basis, this benefit may be reduced or even eliminated by methane emissions, methane leaks, and differences in engine efficiency. Emissions scenarios were developed to estimate potential consequences of methane emissions and leakage from heavy-duty natural gas vehicles against the overall greenhouse gas benefits of the newly proposed second phase of HDV GHG and efficiency regulations. This section discusses the steps taken to model a range of variables according to the modified VISION stock turnover framework.

Argonne National Laboratory's VISION model (ANL, 2014a) was employed to estimate energy use and GHG emission impacts under different scenario assumptions. The model proved valuable for analyzing many variations on natural gas vehicles' market penetration, methane leakage, methane global warming potential, and engine efficiency. The scope of the analysis is strictly limited to heavy-duty vehicles, so nothing can be concluded for light-duty passenger vehicles. The VISION model calculates total carbon-equivalent emissions based on "carbon coefficients," which account for full fuel cycle emissions per unit energy (units of million metric tons of carbon per quadrillion BTU of fuel). These values are based on Argonne National Laboratory's GREET model (ANL, 2014b). These "reference" fuel cycle emissions were used to analyze varying upstream characteristics.

The modifications made to VISION and the data assumptions built into the customized version included:

- » New natural gas vehicles entering the Class 3–6 fleet (these are classified, according to gross vehicle weight rating, as medium duty) displace diesel and gasoline vehicles in equal proportions (50/50 percent).
- » New natural gas vehicles entering the Class 7 and Class 8 fleet (heavy duty) displace diesel vehicles according to the vehicle type (straight units displace straight units, and combination trucks displace combination trucks)
- » All the correction factors in the stock model (vehicle stock, vehicle miles traveled, fuel efficiency, and energy consumption correction factors) were set to 1.
- » Vehicle miles traveled for natural gas vehicles were changed to those of their diesel counterparts. This was done to avoid the artificial advantage of replacing a diesel vehicle with a natural gas vehicle that travels fewer miles per year.
- » Carbon coefficients (fuel carbon intensity) were calculated based on the GREET 2014 model.
- » Class 3 to 6 natural gas vehicles and Class 7 and 8 straight units were assumed to use spark-ignited engines and CNG as fuel supply, and Class 7 and 8 combination trucks were assumed to use HPDI engines and LNG as fuel supply.
- » When modeling an efficiency gap between NG engines and diesel engines, it was assumed that all vehicles (SI and HPDI) had the same value for the gap

Although methane decays faster than carbon dioxide in the atmosphere, it has a more powerful climate effect (short-term radiative forcing), so its influence on the climate is evaluated assuming two different time horizons (20 years and 100 years).

Short-term radiative forcing has an effect on the rate at which climate changes occur (Shoemaker, Schrag, Molina, and Ramanathan, 2013). In this study, methane emissions are converted to carbon dioxide equivalents using the latest Intergovernmental Panel on Climate Change (IPCC) report's global warming potential (GWP) numbers of 28 (100 years) and 84 (20 years). (Myhre et al., 2013).

Figure 2 compares well-to-wheels GHG emissions for heavy-duty trucks powered by diesel, CNG, and LNG from the most recent data available from the GREET model, which assumes a methane leakage rate (percent volume of methane relative to natural gas throughput) of 1.14 percent for conventional natural gas and 1.21 percent for natural gas extracted from shale. Figure 2-a shows that, on an energy-specific basis (grams of CO₂e per million BTU), according to the GREET model natural gas emits 4 to 5 percent lower levels of GHG emissions than diesel throughout the fuel life cycle under a 100-year GWP time horizon and 19 to 24 percent higher levels of GHG emissions than diesel under a 20-year time horizon. If these results are expressed in a distance-specific metric (grams of CO₂e per mile), which takes into account the differences in vehicle efficiency, assuming a 10 percent efficiency gap between natural gas and diesel engines, the use of natural gas results in 6 percent higher GHG emissions than diesel under a 100-year time horizon and more than 30 percent higher GHG emissions than diesel under a 20-year time horizon. Note that most of the emissions come from vehicular rather than upstream operations.

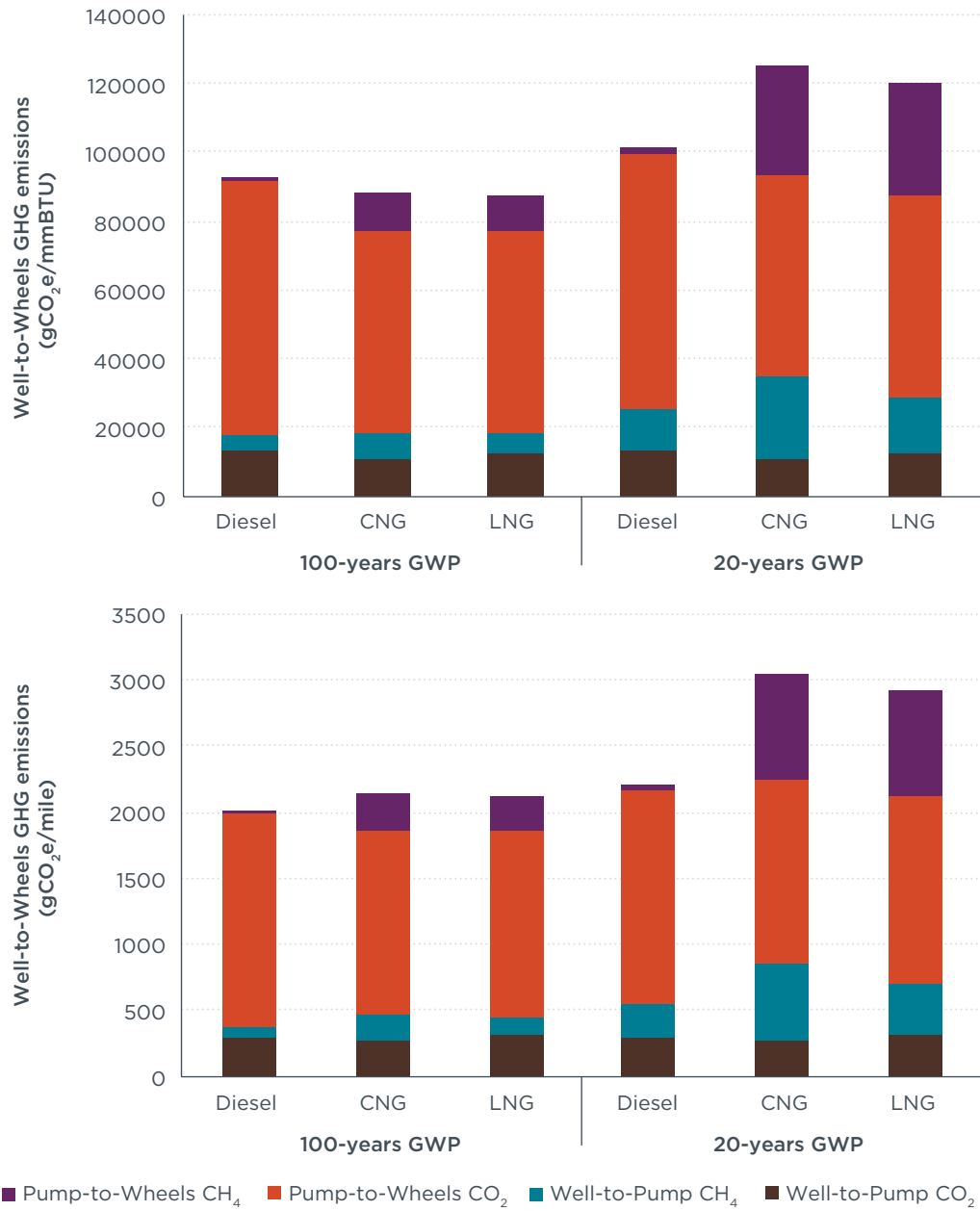


Figure 2. GREET model default WTW GHG emissions for diesel, CNG, and LNG: a) in energy-specific units; b) in distance-specific units. WTW: well-to-wheel, PTW: pump-to-wheel, WTP: well-to-pump

In this analysis, Class 3–6 natural gas-powered vehicles and Class 7 and 8 straight units were assumed to use spark-ignited engines and CNG fuel supply, and Class 7 and 8 combination trucks were assumed to use HPDI engines and LNG as fuel supply. Although it is understood that there will be SI units that utilize LNG as a fuel, this simplification seemed justified for the purposes of this study. The VISION model was modified in order to account for different methane leakage rates. Carbon coefficients for CNG and LNG were estimated using the GREET model under different methane leakage rates to develop linear functions as illustrated in Figure 3. Those linear functions were then input into the VISION model to modify its default carbon coefficients. Figure

3 demonstrates that, depending on which methane leakage rate (and methane GWP) is used, results with natural gas can vary from offering an incremental improvement over diesel fuel (in terms of GHG intensity) to being a substantially worse choice. These linear functions were developed under the assumption that natural gas vehicles have the same efficiency as diesel vehicles, so the effects of differential vehicle efficiency were implemented only in the VISION model to avoid double counting. Note that the GREET model indicates that CNG is more sensitive to the effects of leakage. CNG requires distribution via local natural gas pipelines, which are prone to significant leakage, to the refueling stations where it is compressed, whereas LNG is transported in liquid form from an LNG plant to a refueling station by truck. LNG boil-off assumptions will affect the aforementioned sensitivity.

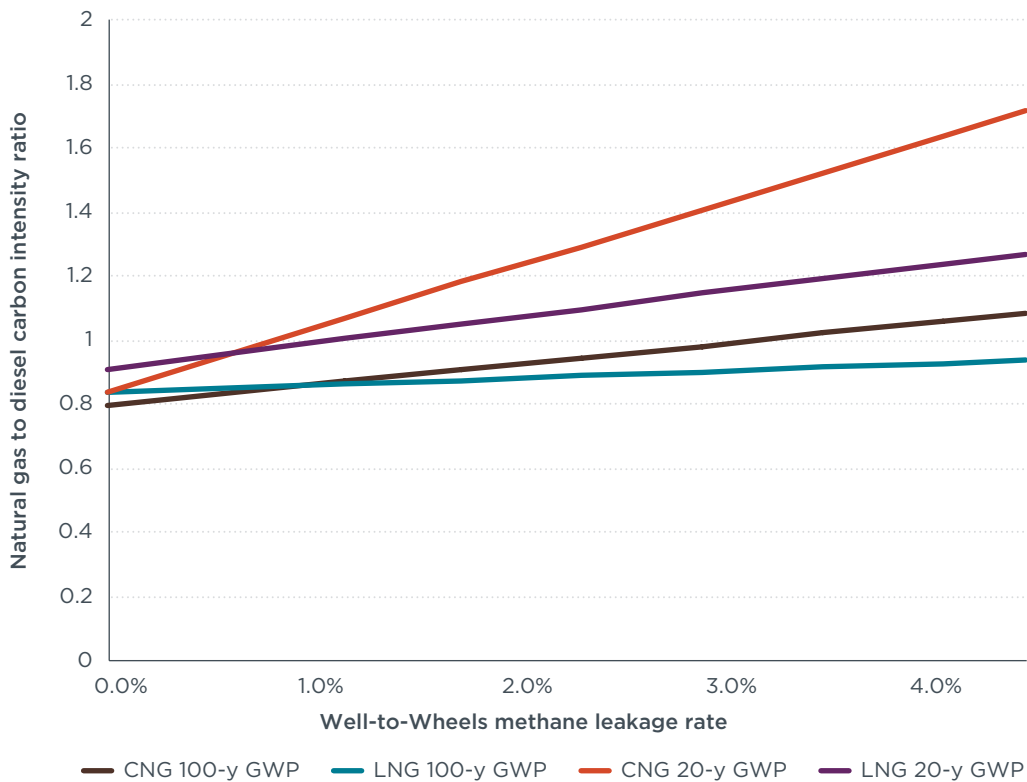


Figure 3. Natural gas to diesel carbon coefficient ratios as a function of methane leakage rates in the GREET model

In this analysis, a series of assumptions were made related to natural gas-powered vehicle market penetration, vehicle efficiency, methane leakage, and the global warming potential of methane. Table 2 summarizes the set of parameters that were analyzed for scenario development, as well as the range of numbers used. Sections 2.1 to 2.4 below describe each parameter in detail.

Table 2. Assumptions for scenario development

Parameter	High estimate	Low estimate
Natural gas vehicle penetration among the new HDV fleet by 2025	20%	1%
Well-to-wheels methane leakage	4.6%	1.1%
Carbon dioxide equivalence (GWP) of methane	84 (20-year)	28 (100-year)
Natural gas vehicle efficiency gap (with respect to diesel)	15%	0%
Diesel efficiency improvement (2018–25)	3.5%/year	

2.1. NATURAL GAS VEHICLE MARKET PENETRATION

Several forecasts exist for the penetration rate of natural gas-powered vehicles (NGVs) into the heavy-duty fleet. Natural gas adoption is mainly driven by lower cost versus diesel fuel, but it faces several barriers such as limited fueling station infrastructure, the additional cost and weight of natural gas equipment, and the need for upgraded maintenance facilities. It is still unclear how fast the market will develop. The *Annual Energy Outlook 2015* (US EIA, 2015) projects that natural gas will be the fastest-growing fuel in the transportation sector, with an average annual demand increase of 10 percent from 2012 to 2040. Heavy-duty vehicles are the leading edge of this projected expansion, with an average growth rate of 14 percent per year. Despite those high growth rates, NGVs are projected by the U.S. Energy Information Administration to account for just 0.5 percent of the overall HDV fleet stock and 1 percent of new vehicle fleet sales by 2025. In contrast, a report by ACT Research (2012) suggests that, if certain conditions favorable to natural gas persist, it could power up to 50 percent of the new Class 8 trucks produced for the U.S. market by 2025. However, that report’s assumptions were revised in 2014 (ACT Research, 2014), and the projections of market penetration were lowered by about 50 percent.

Other studies’ projections suggest that natural gas-fueled vehicles can achieve market penetration rates of about 15 to 20 percent in the 2020–35 time frame. Frost & Sullivan, a consultancy and market research firm, estimates a 12–14 percent NGV market share in 2020 (Kar, 2012). The National Research Council projects that, by 2025, 20 percent of new trucks sold could be fueled by natural gas (NRC, 2014). TIAX, a technology development company, projects that NGVs will make up about 14 percent of the total heavy-duty fleet by 2025, assuming that government incentives for vehicles, infrastructure, and fuel are in place (TIAX, 2012). The National Petroleum Council (NPC) estimates market share with a model that mimics market competition by assigning higher market shares to more cost-effective solutions. The model calculates the new vehicle market share based on a series of economic trade-offs as seen from the perspective of the new-truck-buying population. NPC points to a natural gas market share of about 20 percent by 2025 under the “reference” scenario, which represents a midpoint between low and high oil price scenarios (NPC, 2012).

Based on the above, the analysis here considers three levels of NGV market penetration for scenario development:

1. A high-market-share scenario that follows the NPC reference case figure of 20 percent natural gas market share for new vehicles by 2025.

2. Market penetration at half the level of the high-market-share scenario, or a 10 percent natural gas market share in 2025.
3. A low-end case based on the *Annual Energy Outlook 2013* (US EIA, 2013), which projects limited market penetration of NGVs, at about 1 percent ten years from now.

2.2. WELL-TO-WHEELS METHANE EMISSIONS

This subsection details how the range of well-to-wheels methane emissions was determined for use in scenario modeling. These values take into account the literature values that were summarized in section 1.

Upstream (well-to-pump)

Calculating exactly what quantity of fugitive methane emissions occur during production, processing, transmission, and distribution of natural gas is freighted with difficulty. Various well-to-pump estimates are reported and range from 1.4 percent (US EPA, 2013) to 7.9 percent (Howarth, Santoro, and Ingraffea, 2011). Adam R. Brandt and colleagues (2014) reviewed a comprehensive set of top-down and bottom-up studies and concluded that leaks of methane from drilling sites were 50 percent (+/-25 percent) higher than the U.S. Environmental Protection Agency (EPA)'s emissions inventory estimates. The Brandt study estimates a national leakage rate of 1.9–2.6 percent and describes a high-end estimate of 7.1 percent (on an end-use basis) that can be considered an unlikely worst-case scenario. This study contrasts with the one from Robert W. Howarth, Renee Santoro, and Anthony Ingraffea (2011), which estimates emissions at 1.7–6.0 percent for conventional methane production (well site leakage, liquid uploading and gas processing, transport, and storage) and 3.6–7.9 percent for methane extracted from shale. Gabrielle Pétron and coauthors (2012) conducted measurements of methane emissions over the Denver-Julesburg Basin in Colorado and estimated emission rates from the gas field at 2.3 to 7.7 percent of the gas produced in the region. For scenario development, this study assumes a well-to-pump methane leakage rate of 1.4 percent as a lower limit. A leakage rate of 2.6 percent based on the Brandt study is used as an upper bound.

Fueling station

CNG fueling station losses may include continuous methane leaks through piping and fittings, gas escape during nozzle connection and disconnection, and compressor losses. LNG station losses may include methane boil-off in storage tanks, manual venting of vehicle fuel tanks prior to refueling, spills, and nozzle connection and disconnection escapes. Data on fueling station methane leakage are scarce. A report by Andrew Burnham, Jeongwoo Han, Amgad Elgowainy, and Michael Wang (2014) estimates fueling station methane losses from leakage and venting at 0.30 percent, which is the figure used for this project.

Tailpipe emissions

Tailpipe methane emissions can be estimated from available literature, in which both methane and carbon dioxide emissions are reported. For example, Patrick E. Meyer, Erin H. Green, James J. Corbett, Carl Mas, and James J. Winebrake (2014) report CNG tailpipe emission factors of 0.015 grams of methane per metric ton-mile and 80 grams of CO₂/ton-mile. Under the simplified assumption that natural gas composition is 100 percent methane (i.e., one mole of carbon dioxide is produced per mole of fuel burned), 0.05 percent of the fuel is lost through the tailpipe. In a similar manner, Table 3 shows the greenhouse gas emission rates and the global warming potential comparison

between vehicles with stoichiometric, natural gas engines; lean-burn, high-pressure direct injection (HPDI) engines; and diesel engines compliant with US EPA 2010 emission standards, based on a report by West Virginia University (Carder, Gautam, Thiruvengadam, and Besch, 2014). The table also shows estimated tailpipe methane loss at 0.21 percent and 0.33 percent for the stoichiometric and HPDI engines, respectively. The same report presents results from a sanitation truck (which are not shown in the table), and the estimated methane loss is 0.74 percent of the fuel.

Mark E. Dunn, Gordon P. McTaggart-Cowan, and James Saunders (2013) report that engine dynamometer tests over the Supplemental Emissions Test (SET) cycle (equivalent to the European Stationary Cycle) reveal tailpipe methane at 0.65 to 0.75 grams per kilowatt-hour (kWh) and 503 g/kWh of carbon dioxide emissions, which translates to a 0.48 percent methane loss. Tim Frazier (2013) registers carbon dioxide levels at 506 grams per brake-horsepower-hour (bhp-hr) and methane levels at 1.7 g/bhp-hr, which translates to a 0.92 percent tailpipe methane loss. EPA 2014 GHG certification data (US EPA, 2014) for two stoichiometric natural gas engines show methane emissions of 1.06 and 1.97 g/bhp-hr, with carbon dioxide emissions of 506 and 463 g/bhp, respectively. This translates to methane emissions rates of 0.6–1.2 percent, although it should be noted that these values include both tailpipe and crankcase emissions.

The variability observed in the results above is expected because of differences in technology, vehicle age, catalyst age, engine and catalyst temperature, gas composition, and duty cycle. For reference, the European methane emissions standard (Euro VI) is 0.5 g/kWh (0.37g/bhp-hr), while the current US limit is 0.1 g/bhp-hr (0.13 g/kWh). Assuming engine emissions of about 500 gCO₂/kWh, those numbers translate to methane losses of 0.27 percent and 0.07 percent of the fuel, respectively. Based on the numbers discussed so far, this project used 0.1 percent and 0.9 percent as low and high estimates of tailpipe methane emissions.

Table 3. Comparison of greenhouse gas emissions of natural gas–fueled and diesel-powered vehicles (based on Carder et al., 2014)

	CO ₂ emissions (g/mile)	CH ₄ emissions (g/mile)	CH ₄ burned (g/mile)	CH ₄ leakage (%)	GHG 20-y (g/mile)	GHG 100-y (g/mile)
Natural Gas (Stoichiometric, TWC)	2250	1.7	818.2	0.21	2297.6	2392.8
Natural Gas (HPDI, DPF/SCR)	2150	2.6	781.8	0.33	2222.8	2368.4
Diesel (DPF/SCR)	2420	0.0	0.0	0.00	2420	2420

Crankcase emissions

Crankcase emissions, also known as “blow-by” emissions, are released directly from the engine into the atmosphere through a vent. Literature values for crankcase emissions are scarce. Derek Johnson and April Covington (2014) conducted methane leak and loss audits of large-bore engines at natural gas compressor stations, and the crankcase emissions represent a loss of 0.1 to 0.6 percent. EPA certification data for natural gas engines show that combined tailpipe and crankcase emissions for stoichiometric natural gas engines range from 0.6 to 1.2 percent of the fuel (US EPA, 2014).

Heinz W. Ebner and Alfred O. Jaschek (1998) conclude that typical piston ring blow-by losses are in the range of 0.5 to 1 percent. A more recent paper (Koszalka, Niewczas, and

Guzik, 2008) on diesel engine blow-by losses suggests that 0.5 percent is a reasonable number. Andrew H. Rose and Ralph C. Stahman (1961) measured composition of blow-by gases for carbureted gasoline engines and found that blow-by emissions for gasoline engines contain from 75 to 85 percent carbureted fuel-air mixture, with the remainder being combustion products. This indicates that crankcase gas emission composition would be very close to the composition of the intake mix for a natural gas engine. Assuming for a SI stoichiometric natural gas engine an average of 20 percent exhaust gas recirculation, the percentage of methane lost to the crankcase vent would be between 0.4 and 0.8 percent.

Donald Stanton (2014) states that closed crankcase ventilation systems could reduce GHG by 5 percent from a 2017 GHG-compliant engine over the regulatory cycle. The 2017 standard for vocational engines (engines for vehicles such as dump trucks, garbage trucks, or cement mixers) is 555 gCO₂/bhp-hr, which means that the carbon dioxide equivalent of methane (CH₄) released at the crankcase is 27.75 gCO₂e/bhp-hr, or 1.11 gCH₄/bhp-hr. From the EPA certification database for a 12L ISX G engine (US EPA, 2014) and carbon dioxide values reported in Stanton (2014), about 180 gCH₄/bhp-hr are consumed over the Federal Test Procedure (FTP), so crankcase emissions represent an approximate 0.6 percent loss. Note that this value is at the midpoint of this analysis's estimate range.

It is expected that HPDI engines, like diesel engines, will lose little fuel as crankcase discharge because no fuel is introduced into the cylinder until just before ignition, and that fuel does not penetrate the crevice between the piston and cylinder. However, HPDI vehicles vent methane to the atmosphere through their fueling process and fuel storage systems, as discussed in the next two subsections. This project used a range of 0.4 to 0.8 percent for methane emissions from the crankcase. For modeling purposes, assume that the given range applies to HPDI engines as well and that CNG crankcase emissions are similar in magnitude to LNG dynamic venting plus boil-off venting, which are discussed below.

Storage

CNG is stored in tanks at high pressure. Venting of methane is not an issue during storage in a CNG tank except during a maintenance blowdown, if a recovery mechanism is not used. However, LNG is stored in double-walled, vacuum-insulated tanks as a cryogenic liquid. Because of atmospheric heat penetrating the tank, a part of the LNG continuously evaporates. Once this "boil-off" gas achieves a certain pressure level, it is vented (for safety reasons) to the atmosphere through a pressure relief valve. The time the tank can hold LNG without venting is called the "holding time." Tanks are typically designed for holding times of five days (SAE, 1997). However, boil-off rates depend on fuel temperature and pressure, ambient temperature, and tank characteristics that can make a tank vent in a shorter or larger period of time. The magnitude of vented emissions per venting has been estimated at 2.6 percent (by mass) of the initial amount of liquid in the tank (Ursan, 2011). It is difficult to generalize, though, since the amount vented depends on many parameters (tank size, fuel level, pressures, and temperatures, among others). Owing to data limitations on the magnitude of vented emissions and the frequency of these ventings for the heavy-duty fleet, this project does not make any assumption about methane emissions from natural gas storage on board the vehicle except, as noted above, that it is assumed that the CNG crankcase emissions are similar in magnitude to LNG dynamic venting plus boil-off venting.

Fueling system

It is in the nature of the HPDI fueling system that a small amount of gas may occasionally need to be vented during highly transient operation (sudden shifts in torque and speed) of the engine. This is a result of the dynamic behavior of the fuel rail pressure control system and is termed “dynamic venting.” Dunn et al. (2013) present a tank-to-wheel analysis showing that HPDI engines have 22.9 percent lower GHG emissions than their diesel counterparts over a combined FTP and SET engine cycle (weighted 30 percent and 70 percent, respectively). The contribution of dynamically vented methane in the study is 1.3 percent of the carbon dioxide equivalent, while tailpipe methane contributes 3 percent of the carbon dioxide equivalent. Based on these numbers, methane leakage due to dynamic venting can be estimated at approximately 0.15 percent, in comparison with 0.34 percent for the tailpipe. As noted earlier, this project assumes that methane emissions from HPDI dynamic venting are similar in magnitude to CNG crankcase emissions, and it does not assume any other leakage from the natural gas fueling systems (such as leaks from valves or fittings in the fueling lines).

Well-to-wheels summary

In this study, well-to-wheels methane leakage is estimated to be nominally between 2.2 and 4.6 percent of the fuel used. That being said, a few scenarios outside this range were chosen for the analysis, specifically, one with no methane leakage at all and one with the latest methane leakage estimates from the EPA (1.1 percent). Table 4 summarizes the low and high estimates for leakage rates used.

Table 4. Methane leakage rate estimates, as a percentage of fuel delivered, used in this study

	This study's low estimate	This study's high estimate
Well-to-pump	1.4	2.6
Fueling station	0.3	0.3
Tailpipe	0.1	0.9
Crankcase (or HPDI dynamic venting)	0.4	0.8
Storage	-	-
Fueling system	-	-
Total	2.2	4.6

2.3. GLOBAL WARMING POTENTIAL

The differing characteristics of methane and carbon dioxide contributions to global warming make the choice of a precise time horizon for analysis difficult. Methane emissions are converted to carbon dioxide-equivalent units by means of global warming potential (GWP). This concept measures the radiative forcing (the difference between the energy of sunlight absorbed by the Earth and heat energy radiated back into space) property of a gas over a chosen time horizon relative to that of carbon dioxide (whose GWP is standardized to one). The latest GWP values for methane are provided in the latest IPCC assessment. They are 28 for a 100-year span and 84 for a 20-year span (Myhre, et al., 2013).

While many regulatory agencies opt simply to calculate methane's “carbon dioxide equivalence” using a 100-year GWP, climate scientists disagree with the validity of that

simplified approach (Rogelj et al., 2014; Shoemaker et al., 2013). Using this method could lead to an underestimation of the true strength of the short-term climate impact of methane and could thus discourage action toward methane mitigation. For this reason, a range of scenarios using both 20- and 100-year methane GWPs was selected for this study for well-to-wheels methane emissions.

2.4 VEHICLE EFFICIENCY

Diesel efficiency

There are available, cost-effective technologies to achieve a 30–40 percent reduction in fuel consumption from diesel vehicles (Delgado and Lutsey, 2015 and Meszler, Lutsey, and Delgado, 2015). Diesel engine technology can contribute a significant share of the expected reductions. Stanton (2013) illustrates a powertrain technology pathway that can deliver a greater than 20 percent fuel consumption reduction. Wayne Eckerle (2015) estimates 9 to 15 percent fuel consumption reduction potential from 2017 standards for tractor diesel engines and 5 to 11 percent for vocational diesel engines. Anthony Greszler (2015) estimates that vehicle efficiency can be improved by 14 percent for tractor-trailers and 4 percent for vocational trucks by 2021, and by 20 percent for tractor-trailers and 7 percent for vocational trucks by 2024.

Based on these findings, and in order to model the effects of the potential Phase 2 GHG and fuel efficiency regulations, diesel vehicle fuel efficiency was assumed to increase at a rate of 3.5 percent per year, applied to all diesel HDVs from 2018 until 2025. We emphasize that this reference Phase 2 scenario is a simplification and does not reflect the precise details of the proposed July 2015 rulemaking according the particular proposed requirements across the many dozens of regulatory categories. This assumption was based on the available technology and the approximate rate of improvement that the first phase of HDV regulations generated. Under this scenario, the second phase of regulations is expected to realize at least the same degree of efficiency improvements as the first, but the new regulation's timeline and stringency have yet to be finalized.

Natural gas efficiency

Because it has relatively low carbon content, when combusted, natural gas releases 28 percent less carbon dioxide per unit of heat than diesel fuel (NRC, 2014). However, spark-ignited stoichiometric engine efficiency is considerably lower than diesel engine efficiency because throttling is needed at part load and the compression ratio (the ratio between the volume of the combustion chamber when the piston is at the bottom of its stroke and the volume when the piston is at the top of its stroke) is limited to avoid knock. This partially offsets the benefits of fuel switching. The environmental consulting firm MJ Bradley & Associates (2013) compared measured fuel economy from diesel and CNG transit buses (model years 2010–2012), which indicated a 7 to 46 percent fuel economy penalty for natural gas-fueled vehicles, depending on the test cycle. John J. Kargul (2012) finds that CNG engines are around 15 percent less efficient than diesel engines. Zhiming Gao, Tim LaClair, C. Stuart Daw, and David E. Smith (2013) compared a Class 8 truck's fuel consumption from diesel and natural gas vehicles using ANL's Autonomie model. The results show that natural gas-propelled trucks have 6 to 13 percent lower fuel economy relative to diesel trucks. NRC (2014) reports that spark-ignited combustion systems are less efficient than compression-ignited engines by roughly 15 percent. The efficiency gap seems to be larger for older-technology natural

gas vehicles. For example, a study comparing different lean-burn CNG and diesel buses in operation in the Washington metropolitan area reveals that the average energy-equivalent fuel economy of the CNG buses was 18 percent lower than that of the diesel buses (Chandler, Eberts, and Melendez, 2006).

High-pressure direct injection natural gas engines avoid some of the limitations of SI engines and are approaching diesel-like energy efficiency, with peak efficiency in excess of 42 percent, as reported by Dunn et al. (2013). Note that the fuel economy gap does not necessarily imply higher GHG emissions for NGVs. For example, a recent study (Carder, et al., 2014) finds that natural gas vehicles' distance-specific carbon dioxide emissions were 7 percent and 11 percent lower than diesel vehicles for the case of stoichiometric and HPDI engines, respectively (see Table 4). The National Research Council (NRC, 2014) determines that natural gas vehicles generally emit about 5 to 20 percent less carbon dioxide than diesel vehicles, the advantage being dependent on the drive cycle. Max Kofod and Trevor Stephenson (2013) estimate that HPDI LNG trucks' well-to-wheels GHG emissions can be 17–25 percent lower than diesel. It should be noted that some studies look only at carbon dioxide, not factoring in total GHG emissions, which would include methane.

There are significant opportunities for fuel efficiency improvement and carbon dioxide emissions reduction for engines designed to run on natural gas. Potential improvements include (Frazier, 2013):

- » Improved air handling with high-efficiency turbochargers
- » Low-pressure loss exhaust gas recirculation (EGR) loops
- » Low-restriction ports
- » Higher-energy ignition
- » Reduced friction and parasitic losses
- » Improved combustion (with optimized bowl geometry, fuel swirl, and squish)
- » Improved after-treatment (with better methane oxidation and increased oxygen storage)
- » Improved controls (with air/fuel ratio dithering strategies, advanced sensors, and adaptive algorithms)
- » Higher compression ratios (if gas quality is ensured)

The conference paper by Stanton (2014) showcases a natural gas engine and powertrain technology roadmap beyond Phase 1 GHG regulation and discusses the potential for a nearly 25 percent reduction in carbon dioxide from a 2017 GHG-compliant baseline in the 2020–27 time frame. Eckerle (2015) estimates that new engine technologies such as brake thermal efficiency improvements, close-coupled after-treatment systems, enhancements to the three-way catalyst and air handling controls, and additional EGR can provide a 10 to 15 percent GHG emissions benefit with respect to 2017/2018 standards.

Based these results and the scope for efficiency improvements for vehicles using natural gas, it is reasonable to assume a range of efficiencies from 0 to 15 percent relative to diesel vehicle efficiency. For modeling purposes, most of the scenarios presented here assume that natural gas vehicles will follow the efficiency trend of diesel vehicles but at 10 percent lower efficiency, without regard to engine technology or fuel type. NGVs' efficiency is expected to increase as a result of the regulations, but

it is assumed that the natural gas-diesel efficiency gap is going to remain constant over the time horizon of the analysis. Each scenario also assumed a single fleetwide efficiency gap (i.e., the same efficiency gap for all, both SI and HPDI engines). HPDI engines are closer to in efficiency to diesel engines than their SI counterparts, but at this point in time the HPDI option is not available in the market. (Production of HPDI engines stopped in 2013, but an enhanced version of the engine is under development.) (Westport Innovations, 2014).

We recognize that relative efficiency values are highly dependent on the duty cycle that trucks are put through. For example, the differences between SI natural gas- and diesel engines are going to be higher at part-load operation (i.e., urban driving) than at full-load operation (highway driving), thanks to the lower throttling losses in the latter case.

3. RESULTS

This section summarizes the results of the scenario analysis.

METHANE EMISSIONS AND GLOBAL WARMING POTENTIAL

In order to analyze the potential emissions impact of methane leakage rates under different GWP time horizons, a set of ten scenarios was developed, using varying assumptions. Table 5 summarizes the assumptions made for the different scenarios, their GHG emission impacts through 2040, and the percentage change relative to the reference scenario. VISION's "base case," which is grounded in the Energy Information Administration's projections in its *Annual Energy Outlook* (US EIA, 2014, was used as the baseline for referencing GHG benefits for the different scenarios. Note that the natural gas-fueled vehicle efficiency gap is assumed at 10 percent for all the scenarios in Table 5. The effect of varying NGV market penetration and leakage rates and the selection of the time horizon to account for global warming potential is significant. It can be seen that moderate to high levels of methane leakage would be detrimental in climate terms. The magnitude of the impact goes from a 1 percent to an 8 percent increase in GHG emissions under a 100-year time horizon and from a 10 percent to a 39 percent increase under a 20-year time horizon. Only the scenarios with no leakage show climate benefits, in the range of 2 to 5 percent.

Table 5. Emission scenarios under different methane leakage rates and methane GWP*

No.	Name	NGV market share	WTW leakage (%)	Methane GWP	NGV efficiency gap	GHG benefits (millions of metric tons CO ₂ e)	Percentage change from reference
R	Reference (Phase 2)	1%	1.1%	28	10%	144.9	-
1	High MS, no leak, 100-y	20%	0.0%	28	10%	151.7	5%
2	Mid MS, no leak, 100-y	10%	0.0%	28	10%	147.1	2%
3	High MS, mid leak, 100-y	20%	2.2%	28	10%	143.1	-1%
4	Mid MS, mid leak, 100-y	10%	2.2%	28	10%	142.7	-2%
5	Mid MS, high leak, 100-y	10%	4.6%	28	10%	137.9	-5%
6	High MS, high leak, 100-y	20%	4.6%	28	10%	133.6	-8%
7	Mid MS, mid leak, 20-y	10%	2.2%	84	10%	130.5	-10%
8	High MS, mid leak, 20-y	20%	2.2%	84	10%	119.3	-18%
9	Mid MS, high leak, 20-y	10%	4.6%	84	10%	115.1	-21%
10	High MS, high leak, 20-y	20%	4.6%	84	10%	89.1	-39%

* MS:market share

A subset of the scenarios (those with high NGV market share) presented in Table 5 is shown in Figure 4. The figure illustrates the implications of methane leakage and choice of GWP time horizon for climate impact accounting in situations where natural gas propulsion achieves a 20 percent share of new heavy-duty vehicle sales in 2025. The reference case assumes that the new vehicle fleet sees efficiency improvements of 3.5 percent per year, and that the share of natural gas-fueled trucks remains at about 1 percent of the market, with methane leakage assumed to be 1.1 percent and natural gas trucks continuing to have a 10 percent efficiency loss versus diesel. That reference case would result in approximately 140 million metric tons of CO₂ emissions avoided per year in 2040. With greater natural gas penetration of 20 percent and inadequate methane leak technologies, under 20-year climate impact accounting, as much as 39 percent of the program benefits could be lost in 2040 (56 million tons of CO₂e per year). On the other

hand, the unlikely scenario of no leakage could increase the Phase 2 regulatory program’s 2040 benefits by 7 million tons of CO₂e, or 5 percent from the reference case emissions. Understanding that the prospect of reducing levels of methane leakage to zero is likely unattainable, both well-to-wheels methane emissions reduction and natural gas vehicle efficiency improvements will be required in order to enable the NGV market to develop without adverse consequences for the benefits of the regulation. The following subsection analyzes the GHG emission impacts of vehicle efficiency in more detail.

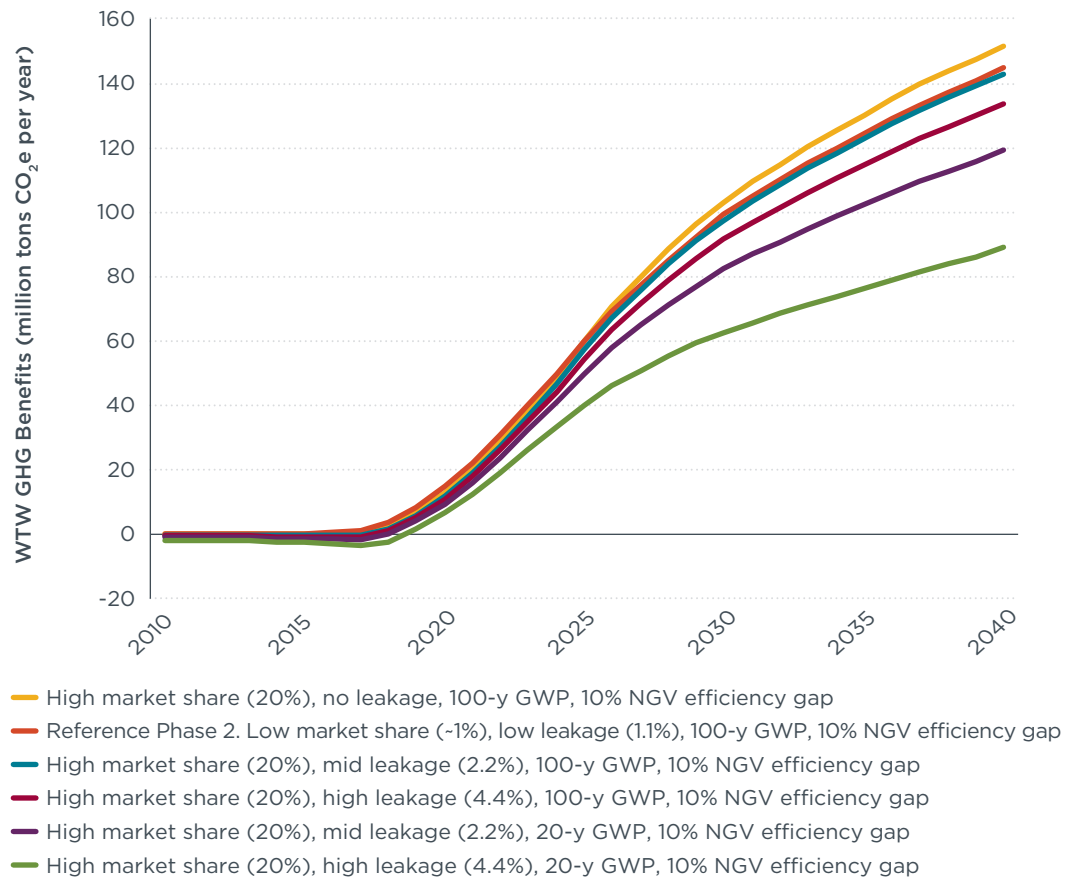


Figure 4. WTW GHG benefits of different emissions scenarios (scenarios 1, 3, 6, 8, and 10 in Table 5)

VEHICLE EFFICIENCY

In order to understand the GHG emissions impacts of natural gas vehicle efficiency improvements, a set of scenarios was conceived varying the NGV efficiency gap from 0 to 15 percent. As illustrated in Table 6, these scenarios were analyzed under the assumption of a 1.1 percent well-to-wheels leakage rate and a 100-year time horizon. The table shows that, under these low methane emission assumptions, if the natural gas-powered vehicle fleet were to close the efficiency gap to 5 percent, GHG emission benefits in the range of 2 to 7 percent could be obtained. Note that scenario 12 in Table 6 (low methane leakage and a 5 percent NGV efficiency gap) provides GHG emission benefits equivalent to scenario 1 in Table 5 (no methane leakage and a 10 percent efficiency gap). Hence, a combination of vehicle efficiency improvements and reasonable efforts to control methane leaks can obtain the same benefits as (in the absence of any more than incremental vehicular technology advances) mounting a prohibitively expensive campaign to eliminate completely methane emissions through the natural gas value chain.

Table 6. Emission scenarios under different natural gas-powered vehicle fuel efficiency gaps*

No.	Name	NGV market share	WTW leakage (%)	Methane GWP	NGV efficiency gap	GHG benefits (MMTCo ₂ e)	Percentage change from reference
R	Reference (Phase 2)	1%	1.1%	28	10%	144.9	-
11	High MS, low leak, 100-y, 0% gap	20%	1.1%	28	0%	155.6	7%
12	High MS, low leak, 100-y, 5% gap	20%	1.1%	28	5%	151.7	5%
13	Mid MS, low leak, 100-y, 0% gap	10%	1.1%	28	0%	149.0	3%
14	High MS, low leak, 100-y, 10% gap	20%	1.1%	28	10%	147.4	2%
15	Mid MS, low leak, 100-y, 5% gap	10%	1.1%	28	5%	147.1	2%
16	Mid MS, low leak, 100-y, 10% gap	10%	1.1%	28	10%	144.9	0%
17	High MS, low leak, 100-y, 15% gap	20%	1.1%	28	15%	142.5	-2%
18	Mid MS, low leak, 100-y, 15% gap	10%	1.1%	28	15%	142.4	-2%

* MS:market share

A subset of the scenarios (those with high NGV market share) presented in Table 6 is shown in Figure 5. The figure illustrates the implications of making substantial improvements in NGV efficiency in a situation where natural gas propulsion achieves a 20 percent share of new heavy-duty vehicles sales in 2025. Best-practice natural gas vehicle efficiency advances (those sufficiently comprehensive or radical to close the gap with diesel) could increase the benefits of the program by 11 million metric tons of CO₂e, or 7 percent from the reference case emissions.

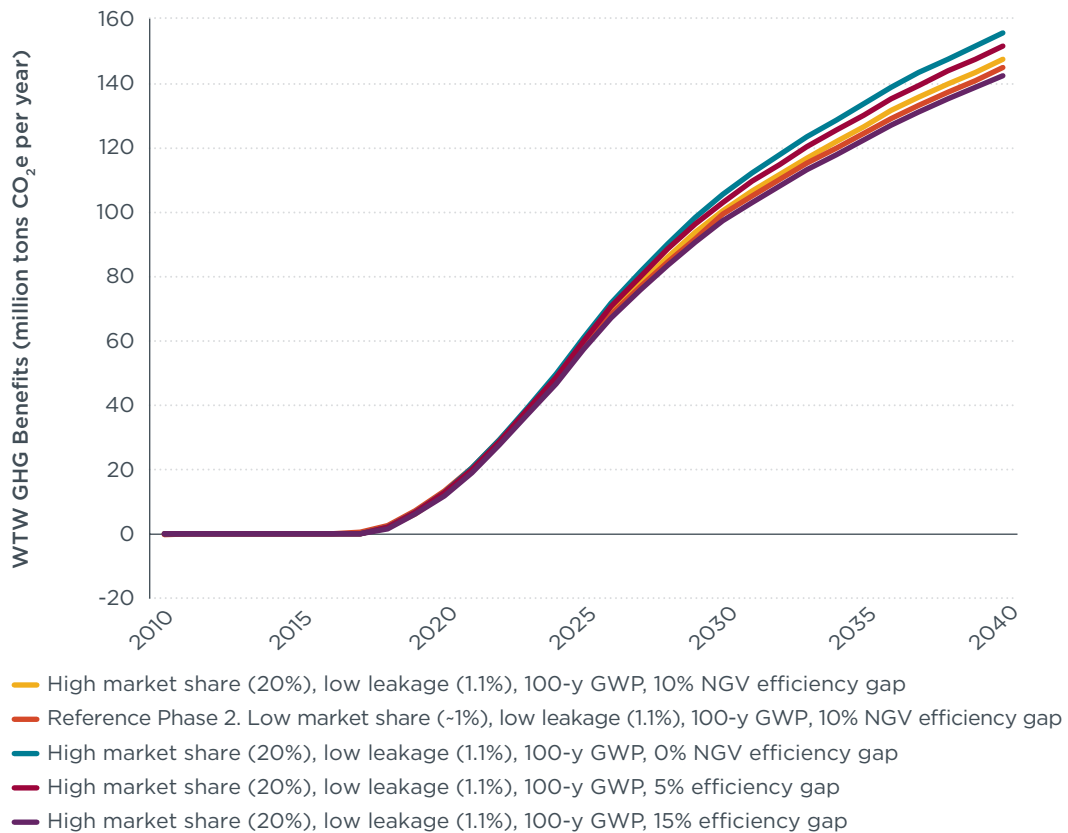


Figure 5. WTW GHG benefits of different emissions scenarios (scenarios 11, 12, 14, and 17 in Table 6)

Figure 6 compares emission trends in units of millions of metric tons of CO₂e per year through 2040 for (1) business as usual (the absence of any standards at all), (2) Phase 1 GHG HDV standards, and (3) potential Phase 2 GHG HDV standards showing the highest (scenario number 10) and lowest (scenario number 11) emission estimates of the scenarios analyzed, as well as the reference scenario. It is evident that high natural gas vehicle market penetration without measures to prevent methane emissions from supply leakages can adversely affect the climate benefits of the second phase of HDV GHG regulations.

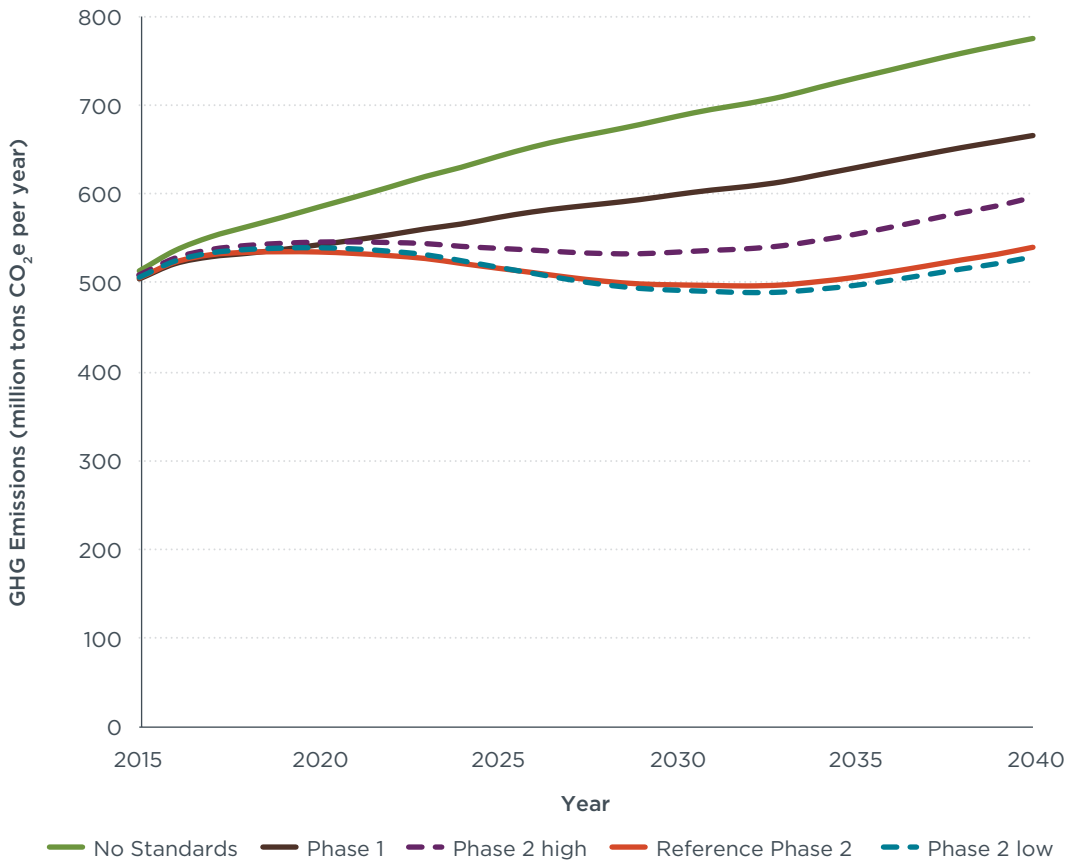


Figure 6. GHG HDV emissions for Phase 1 and potential Phase 2 scenarios

4. POLICY CONSIDERATIONS

Based on the preceding analysis, four main areas for regulatory review or cooperation with industry can help curb methane emissions under the Phase 2 HDV GHG rulemaking.

4.1. ENSURE LOWER TAILPIPE AND CRANKCASE EMISSIONS

Based on the research presented above, crankcase and tailpipe emissions are the two largest sources of downstream methane from stoichiometric natural gas vehicles. For HPDI engines, the largest sources are from the tailpipe, dynamic venting, and venting from the LNG storage tank. Stoichiometric NGVs are currently dominating the new sales market; fortunately, technology is currently available to eliminate crankcase emissions entirely and to significantly reduce tailpipe emissions from these vehicles. Therefore, the primary proposal presented here is to rethink the flexibility provisions that were allowed in the Phase 1 GHG rulemaking, which allow for high tailpipe and crankcase emissions from stoichiometric NGVs. A tailpipe limit (tailpipe limits include tailpipe plus crankcase emissions) of 0.1 gram per brake-horsepower-hour was set under Phase 1 of the HDV GHG regulation. A flexibility mechanism was also introduced that allows for carbon dioxide emission credits to be used to offset methane emissions in excess of the 0.1 g/bhp-hr limit. Under the regulation, excess methane emissions can be traded with carbon dioxide credits using a multiplier of 25 (the number 25 was selected based on the best understanding of the 100-year GWP of methane when Phase 1 was written).

Phase 1 GHG engine certification data for 2014 are available, and thus far two natural gas engine designs have been certified under the GHG rule (US EPA, 2014). These are 9- and 12-liter Cummins stoichiometric engines. Figure 7 shows a plot of methane versus carbon dioxide emissions for the two 2014 GHG engine certifications. It can be seen that the two natural gas-propelled engines are emitting methane at rates 10 to 20 times higher than the tailpipe standard of 0.1 gCH₄/bhp-hr. However, thanks to the Phase 1 flexibility provisions discussed above, the pair are still easily able to meet the relevant 2014 and 2017 GHG engine standards with room to spare, as can be seen in Figure 8. That figure illustrates the inherent advantage of natural gas, with carbon dioxide emissions that are well below 2017 standards but also with the risk that methane emissions from supply and operations can negate that advantage over diesel. It also demonstrates how taking into account methane's nearer-term (20-year) climate effects only emphasizes the need to curb emissions. There is currently no regulatory incentive for manufacturers to close the engine crankcase or improve the methane oxidation activity of the exhaust catalyst.

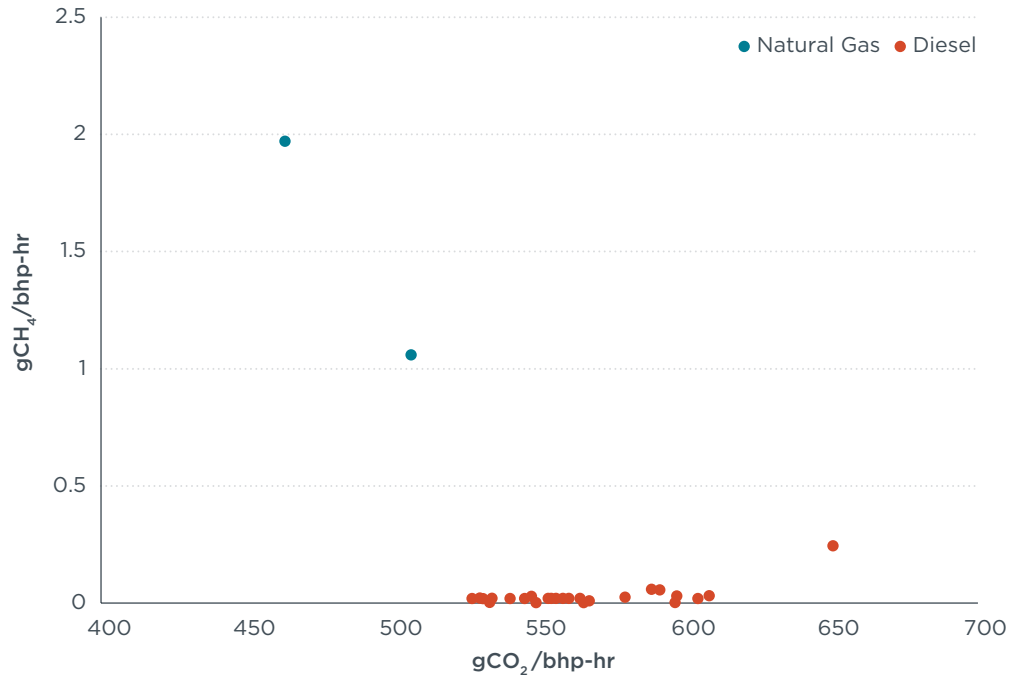


Figure 7. Methane versus carbon dioxide emissions for 2014 GHG engine certifications

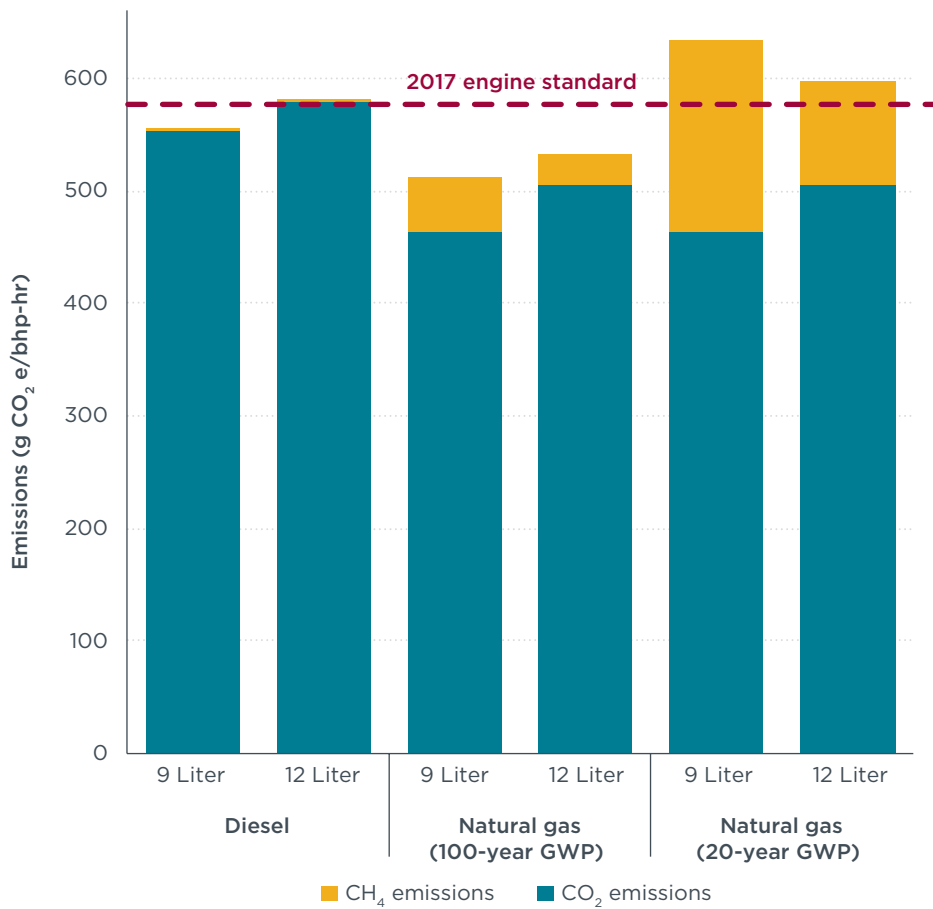


Figure 8. Certification GHG emissions for diesel- and natural gas-powered engines

There are a number of provisions that could be considered for adoption in the final Phase 2 regulation to ensure that crankcase plus tailpipe emissions of methane are significantly reduced and that existing technologies are adopted:

1. Eliminate the flexibility provision that allows trading of credits between methane and carbon dioxide;
2. Alternatively, choose a larger multiplier for exchanging carbon dioxide credits for methane emissions;
3. Reduce total GHG emissions limits significantly;
4. Enforce closed crankcase technology.

Eliminating the flexibility provision that allows trading between methane and carbon dioxide would be a straightforward solution to ensure low emissions from the crankcase/tailpipe of natural gas vehicles. There is a significant precedent for barring flexibility for NGV methane emissions. In Europe, methane is regulated under the progressively tighter “Euro” emission standards, so there is no option for trading. The tailpipe limit in the European Union for Euro VI is 0.5 g/kWh under the World Harmonized Transient Cycle (WHTC) for NGVs. The EU standard compels the use of closed crankcase ventilation systems. These systems capture the blow-by gas, return it to the crankcase, and then redirect these gaseous emissions back to the intake system for combustion instead of allowing them to escape into the air. For example, Cummins ISL G Euro V engines have closed crankcase ventilation systems for all sales in Europe, whereas the same model for the U.S. market has an open crankcase (Perez Souto et al., 2014). In addition, many climate scientists have gone on record speaking against methane/carbon dioxide trading, reasoning that lenience with respect to non-carbon dioxide GHGs could actually increase peak temperature change and that carbon dioxide-related regulatory actions should be separated from those for non-CO₂ climate forcers (Rogelj et al., 2014; Shoemaker et al., 2013).

Eliminating the possibility of trading would also induce progress toward better-functioning methane oxidation catalysts. Three-way catalysts used in stoichiometric NGVs become ineffective at the low temperatures that can be encountered during extended idling or low-power operations. Methane oxidation is particularly difficult at low exhaust temperatures because it typically requires a higher light-off temperature (the temperature at which catalytic reactions are initiated) than other hydrocarbons (Perez Souto et al., 2014; Li and Hoflund, 2003). That said, there are ways to improve the conversion of methane in three-way catalysts. One solution is to use additional fuel or sophisticated engine controls to keep the catalyst active at light loads (this involves a carbon dioxide/fuel penalty, however, and as a result might not reflect actual fuel use accurately). In addition, improved catalyst formulations can effectively be utilized to reduce the light-off temperature. These catalyst formulations typically involve an increase in precious metal content in the catalyst (Johnson, 2014; Hajbabaei, Karavalakis, Johnson, Lee, and Durbin, 2013).

Employing a larger multiplier for trading credits between methane and carbon dioxide, as a measure short of banning such exchanges outright, would still guarantee that further action is taken to lower tailpipe emissions. In Figure 7 it can readily be seen that selecting a multiplier that is closer to the 20-year GWP of methane would mean that the two Cummins engines discussed above would no longer be able to meet the 2014 and 2017 GHG standards. Therefore, the manufacturer would need to take remedial

steps, which would likely involve closing the crankcase or making improvements to the methane oxidation catalyst, or both.

Reducing the GHG limits significantly without altering the flexibility provisions could also ensure that suitable technology adoption takes place. Nonetheless, as indicated by the Phase 2 proposal, Phase 2 GHG limits will likely be based on what the agency sees as a reasonable annual percentage improvement and will not themselves be used as a ceiling to force sweeping reductions in methane emissions in natural gas-powered engines. In the absence of any alternative, the EPA could consider mandating that all natural gas engines come equipped with closed crankcases.

The discussion thus far applies mainly to stoichiometric engines. As mentioned previously, for HPDI engines, the largest emission sources are from the tailpipe, dynamic venting, and venting from the LNG storage tank. The strategies already suggested should result in lower tailpipe emissions and dynamic venting emissions from HPDI engines as well. It is possible to reduce or eliminate dynamic venting in HPDI engines through design changes or dynamic vent capture solutions. Reduction in dynamic venting is an area of ongoing technological improvement for HPDI fuel systems (Dunn et al., 2013).

4.2. INCLUDE FULL LIFE-CYCLE ANALYSIS IN REGULATORY ASSESSMENT

As noted, there is currently a federal regulatory push to mitigate methane leakage and emissions from the well-to-pump fraction of the value chain (White House, 2014). In addition, new research is being published that gives more up-to-date results for actual leakage and emissions rates. It is critical that the best available information be used to calculate well-to-wheels GHG emissions for natural gas vehicles as part of the benefits analysis for Phase 2. Since a 100-year GWP is not always sufficient by itself to make policy decisions, it is also important that total GHG emissions are (at a minimum) calculated using both the 100- and 20-year GWP for non-carbon dioxide GHGs. Such an approach is currently being pursued in California to aid policymakers in crafting regulations that address both the short- and long-term climate impacts of that state's GHG inventory (ARB, 2014). This recommendation does not itself have any direct GHG benefit, but taking the time to do a rigorous well-to-wheels analysis of natural gas vehicles will enable stakeholders to understand the true climate implications as such vehicles are seen more frequently on roads and highways. The calculations and research undertaken to determine life-cycle GHG emissions can be used down the road to incorporate these values into the vehicle certification procedure (as discussed in the next subsection).

4.3. ADDITIONAL REGULATIONS AS THE MARKET DEVELOPS

A regulatory NGV sales cap, whereby once the cap is met, additional standards will be imposed or explored, is advisable as a policy option. Because NGVs, under the right conditions, confer a climate benefit compared with conventional HDVs, the trigger mechanism should ideally function in a way that would allow NGVs to reach a reasonable market share prior to additional regulation, avoiding the unintended consequence of discouraging the development of lower-GHG-emitting vehicles. The EPA could follow a scheme similar to the one that was enacted for light-duty electric vehicles, in which, once a reasonable sales volume is reached, additional regulations kick in. For methane emissions, measures such as setting stringent limits for LNG tank venting, fueling station venting and emissions, and upstream emissions should be considered as part of the vehicle certification process.

Limits for LNG venting

For safety reasons, LNG tanks on natural gas vehicles vent methane to the atmosphere once the fuel boil-off exceeds a certain pressure level. Venting is difficult to predict and is a product of holding time, ambient temperature, fuel temperature, and tank design. Boil-off and venting can be high if trucks are allowed to sit for several days with a full tank. There may be also manual venting of vehicle tanks prior to refueling, in order to lower the vapor pressure in the tank to a suitable level.

Technological fixes and certain operational practices could be adopted or mandated to prevent some of these emissions. Vented emissions could be recaptured or flared, and manual venting to the atmosphere could be banned. Evaporative testing is not required of natural gas vehicles, as evaporative methane standards were deferred under the Phase 1 rulemaking. A mandatory evaporative certification test could help accelerate the adoption of new technology and encourage sounder operational practices, as well as serving to confirm stated LNG tank holding time. Gasoline vehicles are already subject to evaporative emissions controls that are enforced via a SHED (sealed housing evaporative determination) test (ARB, 2012), in which the vehicle temperature is controlled and hydrocarbon emissions are monitored. An identical approach could be used to monitor continuous or intermittent losses from NGVs, although it is likely that new facilities would need to be built that are capable of measuring the fugitive emissions from large trucks.

To minimize the burden of these tests, a modified SHED test could be performed to determine fuel system integrity, while LNG tank holding time could be determined using current practices. In addition, LNG tanks may deteriorate over time or become damaged, thus losing their vacuum insulation. In-use compliance could include a mandatory minimum holding time for LNG tanks, coupled with a regular vacuum check for LNG tanks. Developing a set of policies to mitigate venting-based emissions from LNG tanks will require research and development and should be conducted once it is determined that LNG-fueled vehicles will become a significant proportion of the fleet.

Limits for fueling station venting and emissions

Continuous and intermittent methane emissions from fueling stations can occur at many junctures, including storage tanks, piping, nozzles and fittings, the connections and disconnections associated with refueling, and intentional venting to atmosphere, among others. The majority of these leaks are preventable. For example, natural gas can be recaptured and either recompressed or used to power on-site generators. There is precedent for EPA regulation of the environmental impact of fueling stations (maintenance of underground storage tanks and emissions control at the gasoline pump). While air pollution permit programs may be controlled by the individual states, the EPA has influence here as well. Further research is required to determine the best pathway for regulating methane emissions from fueling stations. These studies should be conducted once a predetermined number of natural gas fueling stations have been opened. Currently the United States has more than 1,500 CNG fueling stations, of which more than 800 are public, and it has 111 LNG stations, of which 73 are public. (US DOE, 2014).

Life-cycle emissions incorporated into the certification level

The upstream GHG emissions for diesel and natural gas (both LNG and CNG) are different and subject to change over time. Without a complete leakage assessment, the precise averages for the various natural gas pathways' upstream GHG emissions

are unclear. It is thus recommended that EPA include a full well-to-wheels analysis of GHG emissions as part of the benefits analysis for Phase 2 with at least one analysis that includes significant penetration of natural gas vehicles. If upstream GHG emissions are being properly accounted for, they could be incorporated into vehicle compliance values as well.

Notwithstanding uncertainty over how quickly the natural gas industry adopts best practices or the EPA issues regulations to eliminate egregious instances of leakage in the fuel supply, with a number of new initiatives in place to reduce upstream methane emissions significantly, it is likely that crediting these emissions in the certification process will end up benefiting the industry in the long run. Therefore, thinking of the 2015–25 time frame as a transitional period for regulation, when vehicles are just coming onto the market and the fuel supply is rapidly changing, is warranted. A system for moving in stages to regulatory incorporation of upstream methane emissions, perhaps based on the sales cap applied to electric vehicles in the U.S. light-duty vehicle efficiency standards (2017–25), would be sensible. With those light-duty standards in effect, the EPA credits all-electric vehicles, plug-in hybrids, and fuel cell vehicles as emitting 0 grams of CO₂e per mile until the per manufacturer vehicle sales caps are reached (US EPA and NHTSA, 2012). The cap for model-years 2021 to 2025 is either 600,000 for companies that sell 300,000 of these vehicles from model-year 2019 to model-year 2021 or 200,000 otherwise. Beyond that cap, manufacturers need to account for the electric vehicles' upstream emissions. Considering a similar mechanism to phase in the inclusion of the upstream GHG emissions in the certification for natural gas HDVs in the 2015–30 time period would be appropriate, acknowledging that the new technology is still early in its development.

4.4. ESTABLISH FUEL-NEUTRAL STANDARDS

Under the prevailing first phase of GHG regulations, natural gas-fueled engines can be subject to either the spark-ignited engine standards (generally for gasoline) or the more stringent compression-ignition engine standards (generally for diesel). Available natural gas engines larger than a 7-liter displacement that are derived from compression-ignition diesel engines (even if spark ignited) have to comply with the compression-ignited engine standards, beginning with the 2014 models. Natural gas engines that are derived from gasoline engines are subject to less stringent standards, beginning with the 2016 models. These separate standards put existing and in-development natural gas engines into one of two distinct bins that have different emissions and efficiency requirements.

A report from the National Research Council (NRC, 2014) recommends that “NHTSA and EPA should develop a separate standard for NG vehicles.” This suggestion to create a third emission standard further opens the door to unintended consequences. Using separate standards in such a way incentivizes nonoptimal technologies in the fleet by assigning distinct regulatory standards to engines and vehicles that have comparable utility characteristics and compete in the same marketplace. Isolating natural gas from gasoline and diesel engines, as the NRC suggests, hinders the development and adoption of NGV engines with the best efficiency and low-emissions characteristics by regulating them against only other engines that run on natural gas.

Instead, by placing natural gas-fueled engines in the same regulatory category as gasoline and diesel engines, the best of them would be directly compared against leading gasoline and diesel engine technologies, all of which will be improving greatly

between now and 2030. This heightens the motivation of the developers of all engine types to improve by measuring against the same yardstick, allowing comparison of similar engines with similar attributes. Also, a fuel-neutral standard would simplify matters by applying the same regulatory requirements to diesel-derived and gasoline-derived natural gas engines.

The adoption of fuel-neutral standards for the second phase of the GHG regulations is the most appropriate way to credit the relative carbon dioxide emission impact of natural gas-propelled vehicles versus their gasoline and diesel counterparts. Emissions and efficiency regulations would ideally require the same performance levels for engines using diesel, natural gas, or gasoline if those engines competed in the same market and offered comparable functionality. Depending on the efficiency of the engines and on how the methane leakage emissions are accounted for, natural gas trucks could already be significant compliance credit generators under the prospective regulation.

5. CONCLUSION

This assessment analyzes the implications of a growing natural gas vehicle fleet on the emission benefits of the U.S. heavy-duty vehicle Phase 2 rulemaking. The approach includes a synthesis of data from leading sources on upstream emissions, vehicle emissions, and efficiency technology. The assessment involves in part stock turnover model analysis of the U.S. medium- and heavy-duty vehicle fleet.

The findings of the report indicate that the treatment of natural gas emissions in the heavy-duty vehicle rulemaking could have substantial implications for greenhouse gas emissions. Natural gas-fueled heavy-duty vehicles may come to represent a substantial proportion of the fleet beyond 2020. The analysis presented here demonstrates that by 2040 as much as 39 percent of the expected climate benefits from the newly proposed Phase 2 rule could be offset by uncontrolled methane emissions from the natural gas value chain. At the same time, it suggests that if NGVs are treated appropriately in this regulation, and if the market for them takes off, they could provide climate benefits that exceed those promised by the Phase 2 rule by up to 7 percent.

Based on this assessment of the range of emission impacts, best practice technologies, and policy design options, there are four recommendations that should be considered in the heavy-duty vehicle greenhouse gas (GHG) emissions rulemaking process to avoid the potential problems resulting from greater deployment of natural gas trucks in the 2015–30 time frame.

1. Ensure uptake of available technologies that significantly lower tailpipe and crankcase methane emissions

The carbon dioxide/methane trading flexibility provisions in the Phase 1 GHG rulemaking allow for high tailpipe and crankcase methane emissions from natural gas vehicles. Current certification data show that stoichiometric natural gas engines (which currently dominate the market for sales of natural gas engines) are emitting at 10 to 20 times the regulatory limit. There is currently little incentive for manufacturers to use available technologies such as closed crankcase ventilation systems or improved methane oxidation catalyst systems. In addition, it is possible to reduce or eliminate dynamic venting from high-pressure direct injection engines through design changes or dynamic vent capture solutions.

2. Use full life-cycle GHG emissions, via both a 20-year and a 100-year time horizon, in the benefits assessment for natural gas vehicles in Phase 2

There is currently a regulatory push at the federal level to mitigate methane leakage and emissions from the well-to-pump segment of the value chain. There is also active research that will provide more up-to-date information on actual leakage and emissions rates. Owing to methane's status as a short-lived climate pollutant, it is necessary to understand fully both the short- and long-term impacts of its emissions compared with carbon dioxide. In the benefits assessment for Phase 2, regulatory agencies would do well to acknowledge the leading science in this area by including both long-term (i.e., 100 years) and short-term (20 years) time horizons for greenhouse gases, including methane.

3. Set a clear signal to reduce other known emissions associated with natural gas trucks within the Phase 2 rulemaking time frame

Natural gas trucks can yield climate benefits; however, it is difficult to make that case today because of their higher upstream emission impacts. The regulation would ideally be executed in such a way as to allow the natural gas vehicle market to grow yet to avoid significantly undermining the heavy-duty regulatory program's GHG reduction objectives as the industry and government work expeditiously to shore up known emission leaks through the fuel supply. It is important to set a clear signal that within the period in which the regulation is expected to be in force—by 2025 or so—there will be limits for liquefied natural gas tank venting, natural gas fueling station venting and emissions, and other methane emission sources that are identified over time. It will be important to factor in average upstream emission impacts as part of the vehicle or engine certification emission level within the rulemaking time frame. Increased collaboration between natural gas vehicle manufacturers and fuel providers will be needed to address such issues. Stipulating a default upstream methane emissions level will encourage such collaboration in the service of a lower-carbon fuel supply.

4. Set fuel-neutral greenhouse gas standards

The adoption of fuel-neutral standards is the most appropriate way to credit the relative carbon dioxide emission advantages of natural gas vehicles versus their gasoline and diesel counterparts. A fuel-neutral, level playing field is important to ensure that technologies compete based on their GHG emission performance and their cost-effectiveness. Fuel-neutral standards as part of the regulation would provide the clearest incentive for the introduction of natural gas trucks with the lowest GHG attributes (i.e., highest efficiency, lowest methane emissions).

This study focuses on the greenhouse gas emission implications of an increasing population of natural gas trucks in the U.S. fleet, but of course there are other considerations related to natural gas-fueled vehicles and policy. As alluded to in the final recommendations, getting U.S. policy right for natural gas-powered vehicles involves going beyond the heavy-duty vehicle rulemaking, engaging with fleet operators and fuel providers. This requires industry and policy actions to minimize leakage and emissions throughout the natural gas fuel supply. Also, it is important to recognize that, beyond greenhouse gas emissions, NGVs offer air quality benefits thanks to their very low nitrogen oxide emissions, the cost-saving benefits for vehicle fleets, and the reduced dependence on foreign oil. These are surely important objectives and reasons to support a shift toward a natural gas-fueled fleet. The policy considerations in this report are meant to provide some guidance to ensure that natural gas is a contributor to reducing transport greenhouse gas emissions over the long term.

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