UC Davis
Working Papers

Title
The Carbon Intensity of NGV C8 Trucks

Permalink
https://escholarship.org/uc/item/9n2963pg

Author
Dominguez-Faus, Rosa

Publication Date
2015-03-01

eScholarship.org Powered by the California Digital Library
University of California

Working Paper – UCD-ITS-WP-15-01

The Carbon Intensity of NGV C8 Trucks

March 2015
(revised February 2016)

Rosa Dominguez-Faus

Institute of Transportation Studies ◦ University of California, Davis
1605 Tilia Street ◦ Davis, California 95616
PHONE (530) 752-6548 ◦ FAX (530) 752-6572
www.its.ucdavis.edu

Abstract

Natural gas vehicles have been favored by U.S. air quality agencies for the cleaner burning properties of natural gas. However, the climate consequences of a switch to natural gas vehicles for long distance, heavy-duty applications has been less clear. The radioactive forcings of short-lived methane leakage must be weighed against any long term benefits of emitting less CO2. The scientific literature reports a variety of results and conclusions, thus policy makers often find it hard to make science-based, sound decision-making. But there is inherent natural variability in the system and virtually any result can be justified based on a given choice of input values. Some scholars deal with this variability with probabilistic distributions of inputs to produce probabilistic distributions of results. But this treatment of uncertainty might not resound with decision makers, who might prefer the simplicity of one single estimate. In this study, we attempt to tackle and communicate uncertainty in a simplified way in which a transparent base case scenario is modified one input at a time to determine the distinct parameters that are critical to assessing the climate impact of natural gas as a transportation fuel. Instead of focusing on a specific number, this analysis shows what makes a natural gas fuel a better option versus a bad option, so policy makers and agencies can focus on promoting these best practices among the interested parties. We utilize Argonne's GREET1 2014 model to test sensitivities for the life cycle carbon intensity of natural gas versus diesel fuel under a range of scenarios for upstream and in vehicle methane leakage, fueling and storage technologies, and operational performance of various kinds of class 8 engines. We evaluate the relative importance of engine technology, natural gas fuel storage choice, upstream methane leakage (i.e., well-to-tank), and vehicle methane slip (i.e., tank-to-wheel). We find that: 1) Upstream methane leakage contributes between 7 and 11% and vehicle methane leakage (i.e., methane slip) contributes between 5 and 9% to the total carbon intensity of natural gas in long haul trucks; 2) Variability factors include whether natural gas fuel is stored as compressed (CNG) or liquefied (LNG) and whether a natural gas vehicle uses spark ignition or compression ignition. Natural gas engines typically being spark ignition, which are around 10% less efficient than compression ignition diesel engines; 3) If no efficiency penalty is assumed (as in the case of the currently out of market HPDI model), NGVs offer a climate advantage compared to diesel only if well-to-tank methane leakage remains under 5%; and 4) CNG storage is more sensitive to leakage than LNG storage. This analysis allows us to identify the most important strategies to reduce the carbon intensity of NGVs.

Introduction

In terms of climate pollution, tailpipe emissions from burning natural gas in heavy-duty trucking applications will produce between two-thirds and three-fourths the emissions of burning gasoline or diesel[1], but there are other issues that affect the well-to-wheels carbon intensity of natural gas in transportation. The variables that impact the environmental performance of natural gas include the level of methane and carbon dioxide venting and leakage from upstream production (i.e., non-combustion related); the methane and carbon emissions associated with fuel processing (e.g., gas production, gas compression or liquefaction, etc.); and also methane emissions from the vehicle.

Natural gas vehicles have been favored by U.S. air quality agencies for the cleaner burning properties of natural gas. However, the climate consequences of a switch to natural gas vehicles for long distance heavy-duty applications has been less clear.

Unlike any physical property (e.g., temperature, which can be measured with a thermometer) there are no instruments that can measure the carbon intensity of a fuel. It is an abstract concept that we quantify with models, and as with any modeling effort, it is subjected to considerable uncertainty. The scientific literature[2] describes the following types of uncertainty in modeling: 1) data uncertainty, and 2) model uncertainty. Data uncertainty, also known as parameter uncertainty, refers to the problem of not using the most accurate data, either due to lack of a measurement or lack of granularity. Model uncertainty is related to the possible options in the formulation in the model. Some examples of model uncertainty include whether or not to include indirect land use change in the case of biofuels or the choice of allocation method among co-products, such as in the case of oil and gas co-production. Parameter uncertainty is easier to deal with than model uncertainty. Probabilistic simulations such as Monte Carlo analysis, scenario modeling, and fuzzy analysis have been used to establish parameter uncertainty in outputs. As for modeling uncertainty, the best that can be done is to use all reasonable existing models to establish bounds on model results.

Understanding uncertainty in modeling is key to robust policies but it complicates decision-making. Kocoloski and colleagues write "*Recognizing uncertainty complicates a decision maker's task of choosing among fuel types: however, neglecting uncertainty in favor of (relative) simplicity leads to less robust decisions on policy.*" For example, they estimated that the carbon intensity of gasoline ranges from 84 to 100g CO2e/MJ depending on the methodology used. In the case of corn ethanol, a range of 40-100 gCO2e/MJ can be expected due to parameter uncertainty, but when model uncertainty (in this case related to land use change) was introduced, the range expanded to -40 to 150gCO2e/MJ.

[1] Zhao et al. 2013
[2] Kocoloski and others

The question of the climate performance of natural gas compared to diesel for heavy duty truck applications has been tackled by several researchers and agencies recently. For Californian's Low Carbon Fuel Standard (LCFS), the California Air Resources Board (ARB) produces a point estimate. It is calculated using the CA-GREET, which is a version of GREET developed by Argonne National Lab (ANL) where adjustments are made for efficiency, distribution distances, and upstream petroleum emissions that reflect the state averages rather than national averages. However, the LCFS calculation is designed to create one representative point estimate that does not necessarily reflect individual types of variability based on drive cycle, vehicle engine, class of vehicle and other on road factors.

ARB's LCFS carbon intensity number reflects that of the average fuel sold in the state and does not reflect the individual performance of any specific application. It is a weighted average based on the current mix of applications (transit, taxis, trucks) rather than a single application. Currently, the LCSF calculation does not specifically and singly calculate the greenhouse gas emissions from long haul, heavy duty trucking with natural gas fuels in the state. Rather, LCFS estimate for natural gas reflects average operations which include many transit buses and other fleets that have been early adopters in the state. For this reason, the ARB calculations are not comparable to scientific conclusions specifically studying long haul, heavy duty natural gas trucking, such as the one presented here.

The LCFS metric for natural gas is up for revision in 2016. The original LCFS lookup tables calculate gasoline, diesel, CNG and LNG at a carbon intensity of 95.86, 94.71, 68, and 72.38 gCO2e/MJ (not EER adjusted) respectively[3]. In more recent public hearings, ARB is considering a modification to 98.38, 98.03, 75.56, 80.42 g/MJ (not EER adjusted) or 100.53, 102.76, 88.29, 96.19 g/MJ respectively if EER adjusted[4]. Depending on what report is used and compared with diesel natural gas provides a carbon reduction of 12 or 28%, based on revisions in the case of CNG, and 24% or 6% in the case of LNG.

Comparatively speaking, the carbon intensity calculation provided by petroleum products reported by ARB is higher than the number obtained with GREET or CAGREET. The difference is in both the approach and the input data. ARB does use CAGREET, which is structurally equal to GREET, to simulate the natural gas pathways, so any difference in natural gas estimates between ARB results and others that use GREET is due to parameter variability (i.e., parameter uncertainty[5]). However, ARB models upstream petroleum emissions with OPGEE rather than GREET or CAGREET. For this reason, in

[3] http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf
[4] http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040115_pathway_ci_comparison.pdf
[5] Data can be varied (e.g., regional differences) or uncertain (e.g., we can't estimate). However, the term "parameter uncertainty" is often used in modeling to reflect both uncertainty and variability in data, and that is the meaning used in this paper.

addition to potential parameter uncertainty, differences might arise from differences in the modeling approach for petroleum (i.e., model uncertainty).

Another important point is that the LCFS analysis is designed to measure the life cycle carbon intensity of the fuel itself and not the operation of specific vehicles or applications. Thus, the LCFS number is given in gCO2e/MJ. Unless otherwise noted, this metric does not reflect the relative efficiency of the alternative vehicle. Fuels used in spark ignition engines must factor in a 10% (on average) fuel efficiency penalty when compared to fuels used in compression ignition diesel engines. The Energy Efficiency Ratio (EER) is the relative gain or penalty in energy efficiency between incumbent and alternative engines. In heavy duty trucking natural gas substitutes diesel, which is burned in efficient compression ignition engines, thus an EER of 0.9 typically applies. In taxis it substitutes gasoline, and since both gasoline and natural gas are burned in spark ignition engines, the EER is 1, which is the same as to say that no EER adjustment is necessary. Given these differences, in its most recent reports, ARB has shown both EER-adjusted and non EER-adjusted numbers.

Another peer-reviewed scientific approach to the question was conducted by the Environmental Defense Fund (EDF) and Columbia University and found that "converting heavy-duty truck fleets (to natural gas) leads to damages to the climate for several decades". Instead of using static 20y or 100y global warming potentials (GWP) that most researchers and agencies use, the EDF-Columbia University study uses radiative forcings of each greenhouse gas as a function of time. In other words, this research shows the time it takes for a fleet conversion to natural gas to offset the shortcoming of emitting more short-lived methane with the long term benefit of emitting less CO2. The researchers find that the immediate release of methane rather than CO2 is material and that only on a very long dated basis is it appropriate to conclude that natural gas is a preferred fuel to diesel given the relative inefficiency of natural gas vehicles and the higher emissions damage of methane compared to CO2 in the short run. After some period of time, 72 years (CNG) and 90 years (LNG) in the case of the SI NGV trucks, and 51 years in the case of the HPDI truck (LNG), a climate benefit occurs as the initial warming created by methane dissipates and the benefits of lower CO2 emissions are reaped.

The EDF-Columbia University study assumes relative efficiencies of the SI and HPDI natural gas engines are 13% and 5.5% lower than diesel, respectively. They consider the difference in the engine efficiencies of natural gas 8.9L and 11.9L spark ignition (SI) engines and include a 15L high-pressure direct injection (HPDI) engine technology that is still not marketed. Due to uncertainty related to these parameters, the study conducts a detailed sensitivity analysis of relative efficiency assumptions. For methane slip (i.e., methane from the vehicle) this study uses 4.2 gCH4/mi for HPDI and 2.6 g/CH4 for the SI. Another parameter in this study that creates variation from other studies, are assumptions about upstream methane leakage rates and methane emitted in the vehicle which are calculated based on national averages, and therefore will vary from any studies specifically on California based studies.

An important study by Carnegie Mellon University (CMU) offers probabilistic ranges rather than point estimates in order to account for the variety in fuels and transportation systems. The CMU study includes the addition of payload differences, and researchers model new vehicles rather than the fleet of vehicles currently existing in the market. The study uses a probabilistic approach in which probabilistic distributions of input parameters are created from a variety of data sources. Thus, instead of using one value for methane leakage, their probabilistic approach shows a right skewed distribution of natural gas upstream emissions, justified by the existence of a few super emitters. For the WTW emissions, in addition to the variability in feedstock systems, they include variability in vehicles and fuel options. Significantly, the scientists conclude that "for Class 8 tractor-trailers and refuel trucks, none of the natural gas pathways provide emissions reduction per unit of freight-distance moved compared to diesel trucks"[6]. When compared with petroleum fuels, CNG and centrally produced LNG emissions increased by 0-3% and 2-13%, respectively.

These studies demonstrate that there is a wide variability in conclusions when comparing natural gas to incumbent fuels. As discussed, much of the variety arises from variations of data and of methodology. We also contribute to the scientific debate by utilizing Argonne's GREET 2014 model and testing the same questions. In this paper, we do not intend to focus attention on specific carbon intensity values, because we understand the uncertainty associated with one point estimate. Rather, we consider scenarios around an initial point estimate to understand the dynamics of the system, and to provide policy-makers an understanding of how the different factors affect directionality and uncertainty of results. Other than endorsing one fuel type or the other, we intend to show the sensitivities for the use of the specific natural gas application in long-haul trucking to provide additional information for policy analysis. This effort is not intended to be compared to the methodology of the Low Carbon Fuel Standard which, as discussed, applies to the fuel only and not the application of the fuel in specific vehicles, drive trains and/or applications.

Methodology

In our analysis, we utilize GREET 2014[7] and assume national averages of methane leakage of 1.14%[8] to test scenarios for the life cycle carbon intensity of natural gas versus diesel fuel in the operations of various kinds of engines used in class 8 vehicles for long distance trucking.

[6] Tong F., Jaramillo P., Azevedo I.M.L. (2015) Comparison for Life Cycle Greenhosue Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles. Environ. Sci. and Tech. 49, 7123-7133.
[7] Rood Werpy M., Santitni D., Burnham A., and Mintz M., Argonne National Laboratory "White Paper on Natural Gas Vehicle: Status, Barriers, and Opportunities" September 2009 which found that in-use emissions reductions varied by region, fuel composition and engine configurations. The authors conclude that light duty natural gas vehicles can offer up to a 15 percent reduction in greenhouse gas emissions
[8] Dominguez-Faus, R. The Carbon Intensity of C8 NGV trucks. Working paper.

We test the effect of: 1) Vehicle efficiency; 2) Vehicle methane emissions; and 3) Upstream methane emissions. To accomplish that we use GREET1 2014 to simulate a baseline case representative of the status quo based on a literature review and conversations with vehicle manufacturers and oil and gas industry, and alternative scenarios to test the effect of plausible changes in the abovementioned parameters.

The baseline case is defined as:

- 2010 Model Vehicle with 5.9 mpdge (Diesel), 89% efficiency for natural gas spark ignition engine, 100% efficiency for compression ignition engine
- 0.07 gCH4/mi (Diesel), 3.6 gCH4/mi for the natural gas Si model, 6.3 gCH4/mi for the natural gas HPDI model
- 1.14% well to tank methane leakage rate.

The alternative cases will test:

- 0% upstream methane leakage (i.e., well-to-tank)
- 0% vehicle methane slip (i.e., tank-to-wheel)
- Zero penalty in fuel economy for natural gas trucks.

Detailed methodology description as well as data sources can be found in the methodology section in Appendix A.

Results and Discussion

In the baseline case scenario where the more efficient HPDI engine is used in long distance trucking using LNG fuel, we find system-wide methane leakage from natural gas production and distribution cannot exceed 5% for natural gas to break even in carbon intensity as compared to diesel engines (Figure 1). For a scenario where LNG trucks are equipped with the less efficient spark ignition engine, we calculate that methane leakage would need to be eliminated entirely for natural gas to match the carbon intensity of more efficient diesel engines (Figure 1).

Using these scenarios and applying them to class 8 vehicles using CNG fuel instead of LNG fuel, we also find that upstream methane leakage impacts CNG more than LNG[9]. CNG requires distribution via leaky natural gas local pipelines to the refueling stations where it is compressed, whereas LNG is transported as LNG from LNG plant to refueling station by truck. For these reasons, we do not find carbon pollution advantage in cases where NGV trucks are equipped with the less-efficient SI engine technology and the more methane leakage-prone CNG.

[9] These results are based on national natural gas supply chain assumptions. In California, results can be different due the lower leakage in the pipeline infrastructure and the higher energy efficiencies in upstream processes.

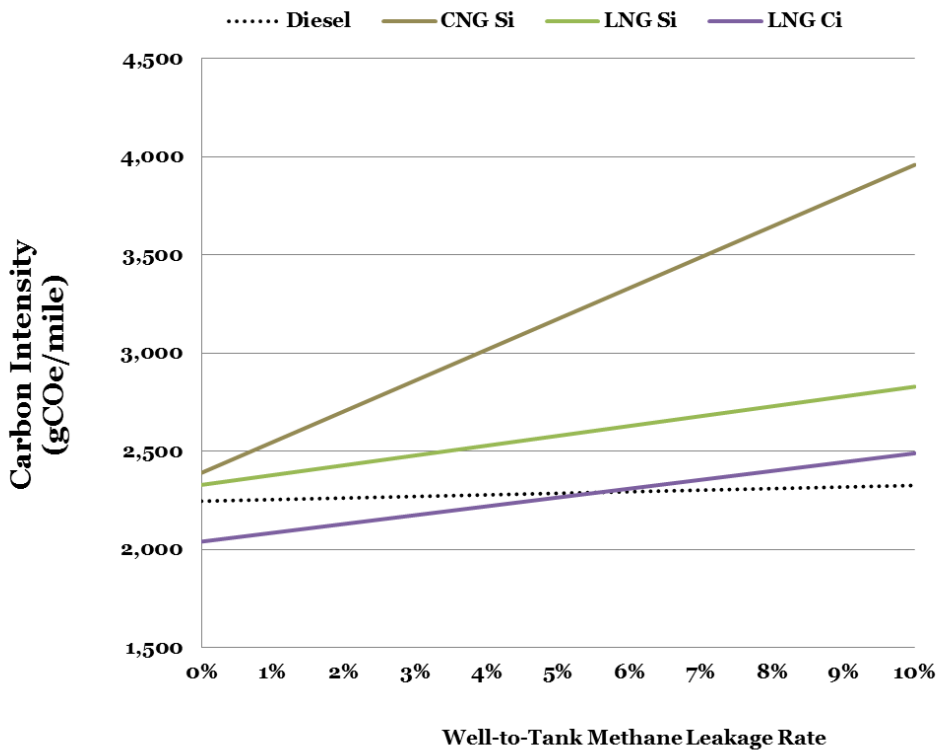

Figure 1. 100-year carbon intensity (gCO2e/mile) of C8 diesel and natural gas under different leakages rate. Dashed line represents diesel, brown line is CNG on a SI engine, green line is LNG on a SI engine, and purple is LNG on the HPDI model. The crossing of NGV lines with diesel line indicates breakeven leakage rates.

Utilizing our scenario results and applying the most recent 100 year carbon intensity standard parameter used by the United Nations, Figure 2 compares the contribution in grams of CO2 per mile to the 100 year carbon intensity (CI) of diesel and three configurations of NGV Class 8 trucks. This comparison reveals that the high-efficiency HPDI CI engine using LNG is the best performing vehicle-storage technology combination that would provide a beneficial carbon reduction with respect to diesel under the currently accepted Environmental Protection Agency (EPA) official methane leakage rate of 1.14%.

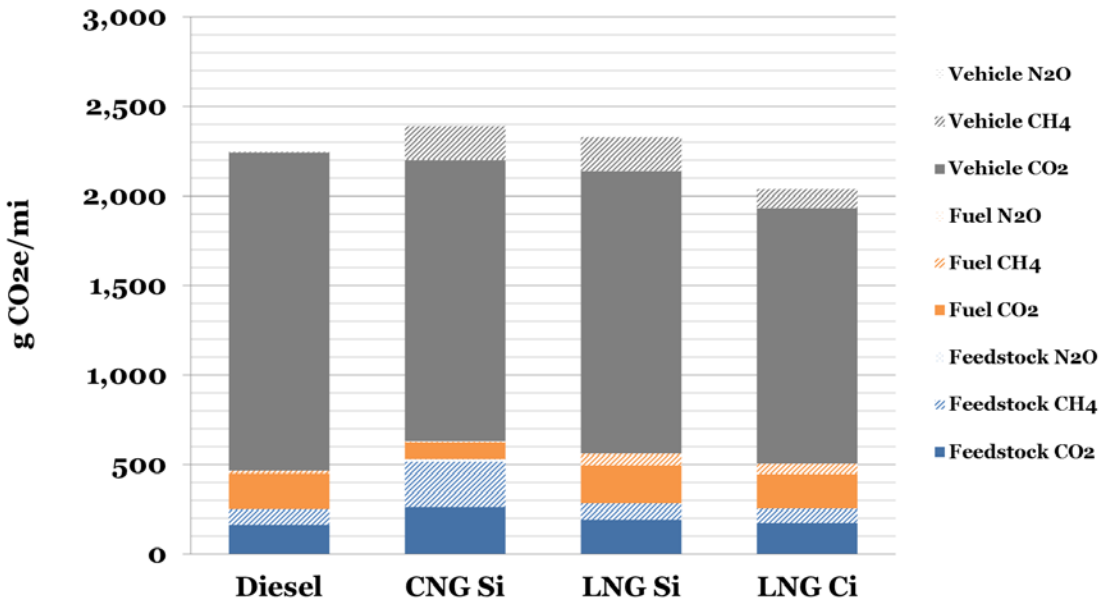

Figure 2. Carbon intensities of diesel and natural gas vehicles under baseline conditions. The graph shows the contribution of the different greenhouse gases and life cycle segments to well-to-wheels Carbon Intensity of Diesel. Blue indicates emissions from feedstock procurement, Orange indicates emissions from conversion of feedstock to fuel, and Grey indicates vehicle emissions. Solid box refers to CO2 and striped box refers of CH4. Percentages in parenthesis show change respect to diesel.

Technologies exist for industry to curb upstream methane leakage significantly. In 2012 EPA ruled that all new oil and gas wells must use green completions beginning in 2015. The rule only applies to existing or modified wells, and affects an estimated 13,000 wells every year. While designed to control smog-contributing pollutants, green completions are also able to control methane emissions at oil and gas production sites. A study by the Environmental Defense Fund (EDF) found that a large number of operators are using

these best practice technologies already.[10] According to official estimates, between 2012 and 2015, when green completions were only voluntary, methane emissions were reduced by 16%, despite the increase in oil and gas production. Technologies exist to bring wellhead methane leakage to zero. However, these technologies only reduce leakage at field operations. Additional technologies will be required to eliminate leaks at processing facilities, transmission lines and local distribution pipelines which can often be leakier.

EPA is now in the process of drafting methane-specific regulations to be issued sometime in 2016. The new regulations will apply to new and modified infrastructure, and will potentially cover production and distribution operations, not just drilling. According to EPA estimates, the new regulations could achieve reductions of methane leaks in natural gas and oil systems of 40% to 45% by 2015, using 2012 as baseline.

Still, our scenario analysis suggests that the largest potential improvements in the carbon intensity of NGVs running on fossil natural gas will come from gains in natural gas vehicle efficiency. As discussed above, NGVs equipped with HPDI engines compare favorably to diesel if leakage is below 5%. Using the same parameters, we find that NGVs using HPDI engines (5.36 miles per dge) would provide an 8% reduction in carbon emissions compared to diesel. Under very high methane leakage rates of 3% or higher, under our modeling parameters, a SI engine (4.8 miles per dge) would produce no significant benefits and in fact, would create significant increases in carbon emissions compared to operations of high efficiency diesel engines. It is possible that the carbon intensity of natural gas fuel could be lowered, especially by co-mingling fossil natural gas supplies with lower carbon intensity renewable natural gas from bio-waste sources or hydrogen.

[10] http://www.edf.org/methaneleakage; also see A R Brandt et al, (2014) Science Vol 343, "Methane Leaks from North American Natural gas systems,"

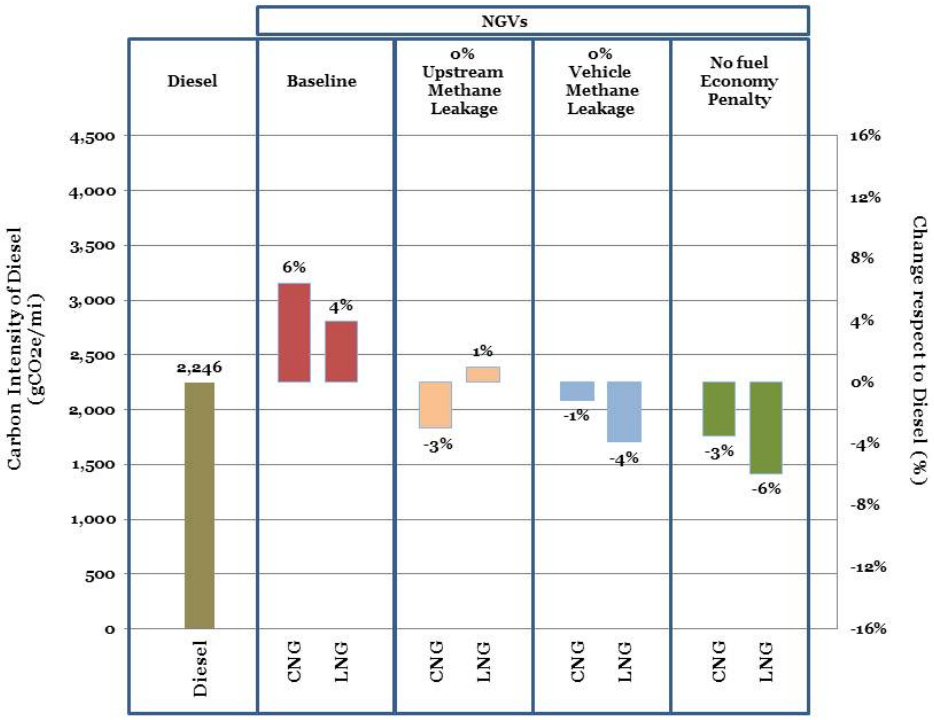

Figure 3. Difference (%) in carbon intensity between NGVs and Diesel vehicles under baseline and alternative scenarios.

Figure 3 shows the difference between the carbon intensity of NGV trucks and the baseline diesel truck according to simulations using Argonne's 2014 version of the GREET1 life cycle assessment model and different assumptions of methane leakage and vehicle fuel economy (baseline indicates a 10% fuel economy penalty in Si and no penalty for HPDI).

Our analysis suggests that improving efficiencies in vehicle engine and during upstream processes can be more effective at reducing the carbon intensity of natural gas in transportation than a strategy based in controlling methane leaks alone.

Conclusions and Implications for Policy

Policy makers at the state and federal level have expressed an interest in promoting natural gas as a transport fuel in commercial fleets. There are substantial commercial benefits since domestic natural gas supplies are abundant and located in geographically diverse locations. However, the environmental performance of natural gas as a direct fuel will be a major consideration of such policies. The United States' recent commitment to reduce greenhouse gas emissions by 25% to 28% from 2005 levels by 2030 includes stringent regulation of methane emissions, venting and flaring from U.S. domestic oil and gas production. System-wide emissions of methane will be a variable in the climate performance of natural gas as a transportation fuel.

We find that: 1) Upstream methane leakage contributes between 7 and 11% and vehicle methane leakage (i.e., methane slip) contributes between 5 and 9% to the total carbon intensity of natural gas in long haul trucks; 2) Variability factors include whether natural gas fuel is stored as compressed (CNG) or liquefied (LNG) and whether a natural gas vehicle uses spark ignition or compression ignition. Natural gas engines typically being spark ignition, which are around 10% less efficient than compression ignition diesel engines; 3) If no efficiency penalty is assumed (as in the case of the currently out of market HPDI model), NGVs are better than diesel only if well-to-tank methane leakage remains under 5%; and 4) CNG storage is more sensitive to leakage than LNG storage. Thus, reducing upstream leakage as a strategy to reduce the carbon intensity of NGVs is effective if natural gas is used as CNG but has a minimal effect if LNG is used. The higher sensitivity of CNG to leakage is due to a supply chain that includes local natural gas distribution networks for distribution to the gas station, where it is compressed, whereas in the case of LNG distribution occurs from centralized liquefaction plants to the stations by trucks. Even when LNG boil-off in the truck is taken into account, the fugitive methane emissions in the LNG supply chain are of a smaller magnitude than in CNG.

A significant insight from our sensitivity study lies in the identification of some important strategies that would best reduce the carbon intensity of NGVs. These strategies include first and foremost, reducing the engine efficiency penalty of NGVs and reducing methane slip in the vehicle. Other strategies that will be less effective if taken alone without improving vehicle efficiency include reducing upstream methane leakage. We argue that, from an LCA point of view, it is more important to control emissions in the vehicle than in the upstream. Also, vehicle efficiency is the normalizing factor and the relatively lower fuel efficiency of NGVs plays against it in terms of climate effect, even if the fuel is a lower carbon fuel.