Development of a Methane Emissions Estimation Model for the Heavy-Duty Transportation Sector

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ABSTRACT

Compressed natural gas (CNG) and liquefied natural gas (LNG) fueling stations serving heavy-duty (HD) vehicles were characterized for methane emissions. Losses from LNG delivery to a station averaged 0.128% of the fuel dispensed. Continuous station emissions averaged 0.0001% for LNG and 0.009% for CNG. Average observed emissions from LNG nozzle disconnects were 0.011% and CNG nozzle losses were 0.003%. CNG compressors emitted 0.075% of their methane throughput. Manual venting of LNG truck tanks was projected at 0.25% if one in twenty tanks vented before refueling. Methane emissions from HD vehicles were quantified on-road and using a chassis dynamometer. Values averaged by vehicle type and activity for High Pressure Direct Injection (HPDI) and stoichiometric spark-ignited (SI) engines showed that the amount of methane in the exhaust ranged from 0.1% to 1.41% of methane consumed as fuel. Fuel-specific emissions of SI crankcases and HPDI dynamic vents were similar over a range of 0.5% to 2.2%. Emissions factors were developed for 2035 using measured data and projections of fleet growth, technology change, and practice changes. High, medium, and low scenario total fueling station and vehicle emission projections for 2035 were 0.67%, 0.33% and 0.15%.

BACKGROUND

Natural gas, from traditional, tight shale and renewable sources, is offered as an alternative fuel for heavy-duty (HD) transportation1 and has lower carbon content per unit of energy than does diesel fuel. Production of natural gas in the USA has now surpassed 24 trillion cubic feet per year2. Natural gas vehicles and their associated fueling infrastructure currently release methane into the atmosphere. There is concern that fugitive methane from production and use has climate change implications3,4. Methane is a substantially more potent greenhouse gas (GHG) than carbon dioxide. If overall methane emissions are sufficiently low or if the gas is certified as an ultra-low carbon fuel (sometimes referred to as renewable natural gas), then potential GHG advantages exist from increased adoption of natural gas as a HD transportation fuel. This study provides comprehensive data on methane emissions from recent model year natural gas trucks and buses, along with limited data sets for losses from the fueling infrastructure. These data support a projection of methane emissions for 2035.

Current studies supported by the Environmental Defense Fund and industry are addressing methane emissions from the transmission, distribution, storage, and processing of natural gas5,6. The study reported here addresses methane emissions from the fueling infrastructure for HD vehicles and from the vehicles themselves, without considering sources that are upstream of the fueling station and that have been the focus of other studies3,7. In this study, fugitive emissions were quantified from recent technologies and current practices to provide data and insight for predictions for 2035. Substantial supplemental information has also been provided to augment material in this paper.

TECHNOLOGY AND EMISSIONS REVIEW

Methane emissions associated with fueling of vehicles and fuel stations are not well documented in the literature, although values are available in the GREET model8. Compressor leaks can occur during CNG production at fueling stations. Emissions are associated with bulk fuel deliveries to LNG stations. Underutilized LNG facilities may vent methane. Although there is literature related to boil-off of cryogenic liquids9-12 and standards for LNG tank hold times13,14, no literature predictions of in-use boil-off rates are reported.

Natural gas from wells or renewable resources has been used to fuel internal combustion engines, both stationary and mobile15,16. Throttled lean and stoichiometric spark ignited engines have been used17,18 and unthrottled HPDI engines are also in service19. Truck engines may be retrofitted with kits that displace part of the diesel fuel with natural gas20.

Natural gas engines without a closed crankcase system will also emit methane: blowby fraction may be 0.5 to 1% of the intake flow21, and blowby gas will be high in methane for homogenous charge engines. EPA regulations already limit GHG emissions, including crankcase methane emissions22, from HD vehicle engines. HPDI engines emit methane via a dynamic vent to the atmosphere, and their diesel-like operation suggests that little methane is lost from the crankcase.

Codes, standards, and recommended practices for on-board vehicle fuel systems and natural gas dispensing and storage systems can be found in NFPA 5223. CNG tanks are vessels that typically store fuel at a pressure of 3,600 psig at 70⁰F, whereas LNG tanks are cryogenic containers that contain pressures up to 230 psig. Losses can occur due to manual or pressure relief venting from on-board LNG tanks.

METHODOLOGY

The measurements and modeling results in the study represent recent natural gas transport, storage, and utilization technology. They do not include the entire mix of technologies still being employed in 2015, and cannot be used directly for a 2015 inventory predictions.

All emissions from delivery of fuel to a station (by pipeline or tanker truck) to use of that fuel by a vehicle were examined. For tailpipe and crankcase emissions and for fuel consumption, a conservative relative measurement uncertainty (MU) for an engine under power and at idle was +/-5% and +/-15% (respectively) of the reported value. For methane emissions measured using a full-flow dilution sampling system, the MU was +/-4.4% of the reported value. Where a reported value is the average of many measured points, the MU is reduced to the extent that the single value errors are not systematic. It is not possible to estimate uncertainty due to small sample effects or representativeness of assumptions. Substantial detail on measurement methods and accuracy is provided in the supporting information.

Quantifying Emissions at Stations. Methane emissions from fueling stations were gathered during research visits to six LNG stations, all fed by cryogenic tanker truck deliveries. Methane emissions from eight CNG stations, seven fed directly from pipelines and one fed from an LNG station (termed L-CNG), were also characterized. The LNG stations were all commissioned in the two years before the study. The CNG stations represented cascade fast fill (CFF), buffer fast fill (BFF), and time fill (TF) stations and represented a broader range of ages than for the LNG stations.

Leaks were detected using a hand held RKI Eagle 2. Methane emissions were quantified using a full flow diluter, similar in concept to the constant volume sampler used for automobile emissions characterization. A blower drew air through an automotive mass airflow sensor from a sampling hose. Sample methane concentration was measured with a Los Gatos Research Ultraportable Greenhouse Gas Analyzer. The methane detector also was used to examine vehicle fuel systems for leaks. Methane emissions detection and quantification are detailed in Section 14 of the Supporting Information.

LNG Thermodynamic Model. A fundamental storage tank pressure rise model recognized heat delivery to the station by heat transfer to the tank, vehicles returning vapor to the station, heat generated when LNG was sent intermittently to the dispenser, pumping energy, and delivery of fresh product to the system. Tank pressure, fuel dispensing, and delivery data were gathered during three-week observation periods at two LNG stations for model validation. The model used the design configurations and the fueling use data from the two observed stations. Model results were compared to pressure rise rates measured over contiguous time periods (37 to 91.5 hours) where activity did not include fuel deliveries to the station or venting. The model, on average, overpredicted pressure rise by 19.7% with error from 0.7% underprediction to 37% overprediction. Model error was attributable to incomplete knowledge of station specifications, errors in estimating the mass/quality of vent gases returned to the station, and physical factors such as stratification in the tank. Losses due to transient cooling of lines are only approximately modeled. The model was subsequently used to predict the behavior of a reasonably representative station at different utilization levels, with the 19.7% correction applied. Details of the LNG station model are provided in Section 15 of the Supporting Information.

Tank Venting Measurement and Analysis. Cryogenic LNG tanks incorporate a pressure relief valve (PRV) to vent “boil-off” methane to prevent tank overpressurization. Venting emissions could not be characterized using the traditional leak detection methods. In a laboratory setting, the methane mass emitted during a venting event was inferred from the fill level of the tank and the pressures in the tank before and after the event. Pressure, level, and mass were measured during eight manual ventings from a 150 gallon capacity tank and five from a 120 gallon capacity tank in the laboratory. Five additional data points were available from industry24,25. Figure 1 shows the relationship between the mass vented, in kg., and a function of tank pressure before venting (Pi), pressure vented from the tank (dP), and tank fill level (%Fill).

**Figure 1**. Mass vented as a function of pressure and fill level for on-board 120/150 gallon capacity tanks.

Data were gathered on pressure rise from both these tanks in the laboratory and from additional tanks on in-use vehicles. These supported estimates of whether tanks would vent if a specified use were defined. The pressure research also supported estimation of mass emitted during manual tank venting.

Limited data were acquired for cases where drivers vented LNG tanks to the atmosphere prior to fueling, and the relationship in Figure 1 was used to interpret these measurements. Details of on-board LNG tank pressure rise and venting behavior are provided in section 16 of the Supporting Information.

*Vehicle Emissions.*On-road tailpipe and crankcase methane emissions were measured using a portable emissions measurement system (Horiba OBS-2200 flame ionization detector). For chassis dynamometer testing vehicle exhaust was diluted in a full-scale sampling system with a Horiba MEXA 7200D. Chassis dynamometer crankcase emissions were measured using a separate full-flow dilution sampling system. Two refuse trucks and two OTR tractors were provided by program sponsors. The remaining vehicles were obtained from public, private, and rental fleets. The variety of sources and ability to compare data between trucks assured that the test fleet was unbiased. The vehicles examined included five refuse trucks (9 liter SI), four transit buses (9 liter SI), three OTR tractors (9 liter SI), three OTR tractors (12 liter SI), four OTR tractors (15 liter HPDI), and three OTR tractors with dual-fuel retrofit (DFR) diesel-natural gas engines. Additional details on tailpipe and crankcase emissions measurement methodology are included in section 17 of the Supporting Information.

RESULTS AND DISCUSSION

*LNG Delivery Losses.* From six observed LNG deliveries to one station that employed most recent refueling technology, the measured methane emissions represented 0.128% of the estimated delivered fuel and were associated primarily with release from the hose couplings after disconnection. The fuel-specific emissions were computed to be 0.071%, 0.076%, 0.077%, 0.078%, 0.086%, and 0.381%. The high value included vented gas. Additional minor losses occurred but were below pre-defined study measurement thresholds. LNG delivery loss estimation methods are provided in section 1 of the Supporting Information.

*LNG Station Boil-off Emissions.* Venting from station tanks was observed during the study, but measurements were beyond the study design. The LNG station model provided an estimate of the fraction of methane lost by underutilized stations assuming a 25,000 gallon storage tank dispensing to SI and HPDI powered vehicles. The model predicted no station venting if 2,000 (for SI) or 3,000 (for HPDI) gal/day or more were dispensed. For the case of a severely underutilized station (1,500 gal/day) serving current HPDI vehicles, about 2% of the methane fuel would be vented.

*LNG Station Continuous and Nozzle Emissions.* Emissions rate measurements of detected leaks at six LNG stations ranged from 0.01 to 53.1 g/hr (average 12.7 g/hr; MU < ±0.6 g/hr: 0.002% of station utilization). LNG fueling nozzle emissions were quantified from 43 refills: only recent technology dispensers were monitored as per study design. The largest methane mass emitted during a single refill exceeded the sampling system measurement range. This mass was estimated to be larger than the 330.4g that was captured, and represented more than 43% of the total LNG nozzle emissions quantified in the program. Including this event the average emitted methane was 17.7 g/event (MU < ±0.8 g/event, fuel-specific methane emissions rate of 0.096% for estimated 185 kg tank fill). These emissions rate measurements are detailed in section 1 of the Supporting Information.

*CNG Fuel Station Compressor, Component, and Nozzle Emissions.* Emissions were measured from eight CNG stations (Table 1).

**Table 1**. CNG station audit and emissions measurement summary (MU < +/- 4.4 %).Leaks and emissions from fittings or valves and can be eliminated through repair. Losses are operational in nature. Fuel nozzle emissions are not included in Table 1.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Station** | **Type** | **Vehicle** | **Number of****Compressors** | **Operational****Losses (g/hr)** | **Dryer Losses (g/hr)** | **Leaks Identified**1 | **Leaks Quantified** | **Total Rate****for Leaks (g/hr)** | **Average Rate per Leak (g/hr)** |
| **Type** | **Count** |
| 1 | TF | Refuse | 53 | 2 | 0.0 | 0.0 | 1 | 1 | 0.9 | 0.9 |
| 2 | BFF | Transit | 252 | 3 | 90.02 | 3.6 | 11 | 05 | n/a | n/a |
| 3 | BFF | Public | variable | 1 | 0.0 | 0.0 | 12 | 6 | 41.3 | 6.9 |
| 4 | CFF | Public | variable | 3 | 13.53 | 35.5 | 15 | 5 | 27.2 | 5.4 |
| 5 | CFF | OTR | 29 | 3 | 165.63 | 83.3 | 33 | 13 | 11.0 | 0.9 |
| 6 | CFF | Transit | 61 | 3 | 0.0 | 0.0 | 29 | 11 | 67.8 | 6.2 |
| 7 | CFF4 | Public | variable | 1 | 0.0 | n/a | 9 | 2 | 0.6 | 0.3 |
| 8 | CFF | OTR | 27 | 3 | 0.0 | 0.0 | 19 | 19 | 33.2 | 1.7 |
| CFF: Cascade Fast Fill; BFF: Buffer Fast Fill; TF: Time Fill; OTR Over the road1: Leaks discovered during station audit including those too small to quantify and those on compressors and dryers2: Continuous loss emanating from controlled sources (e.g. Continuous gas analyzers)  | 3: Transient losses originating at priority panel due to use of natural gas operated actuated valves/ flow controllers4: CNG portion of LCNG facility, no gas dryer required5: Leaks were detected at this facility but not quantified as they were well below the quantification limits of the measurement equipment |

The average methane mass emitted during fast-fill CNG refueling was 3.0 g/event from the nozzle vent, 0.4 g/event from nozzle disconnection (dead volume), and 0.3 g/event for refueling system actuators: total 3.7 g/event (MU < 0.15g). Section 2 of the Supporting Information includes additional detail on methane emissions measurements at CNG stations.

*Manual Venting of LNG Tanks to Atmosphere.* An empirical model was developed to relate methane mass emitted from vehicle tanks to initial tank pressure, initial fill level and, pressure reduction during venting (see Figure 1). This model was applied using data from observed manual venting of tanks on six in-use vehicles. The model estimated the vent mass emitted to the atmosphere equaled 4.88% of the average fuel mass filled from the station. Manual venting should be avoided as a practice: the current fraction of tanks that are manually vented nationally is not known. Details on manual tank vent emissions estimations and model development are included in section 5 of the Supporting Information.

*LNG Truck Tank Boil-off.* Boil-off from tanks of underutilized vehicles requires additional research, although data were gathered for static and in-use HPDI LNG pressure rise. A truck out of service for far longer than the tank design five day hold time would lose a high fraction of its fuel unless the fuel in the tank were recovered.

*Vehicle Fuel System Leaks.* No continuous leaks were found from subject CNG vehicles; one LNG system leak was too small to quantify.

*Crankcase and Tailpipe Emissions.* Tailpipe emissions were characterized for different engine and vehicle types and for different vehicle activity using both chassis dynamometer and on-road measurements.Crankcase emissions were measured and modeled by engine type and activity. Data were divided into short periods of activity termed microtrips26 classified as Idle (< 0.2 mph), City (0.2-10 mph), Arterial (10-40 mph), or Freeway (>40 mph). Figure 2 shows the average values for crankcase plus tailpipe emissions of each microtrip for 9 liter SI engines in three different vehicle types.

**Figure 2.** Fuel specific methane emissions (tailpipe & crankcase) during distinct microtrips for all vehicles powered by 9 liter stoichiometric natural gas engines (n=1482).

Similar data were obtained for other engine types. Variability of emissions data is due to vehicle age, catalyst temperature, engine speed, load, transient behavior, and emissions diffusion between neighboring microtrips9,10. Average speed of a microtrip does not define average load: road grade, acceleration, fan power demand, vehicle weight, drivetrain design, wind speed, and frontal area affect load as well. The ratio of average power demand to engine rated output affects efficiency. These variations are separate from measurement uncertainty. The methane emitted as a percentage of natural gas consumed for each vehicle type during idle, city, arterial, and highway operation are shown in Figure 3. Emissions differences between engine types are due in part to different duty cycles.

**Figure 3**. Activity-averaged tailpipe, crankcase vent, and HPDI fueling system vent methane emissions as a percentage of natural gas fuel consumed for all of the vehicle types characterized in the study.

Vehicle methane emissions measurements and measurement methodology are more fully detailed in Section 6 of the Supporting Information.

Scenarios

The methane emissions scenarios were estimated assuming that the 2035 hardware would reflect a range of standards, technologies and practices. To estimate the fraction of methane emitted, each scenario required assumptions about the relative size of the infrastructure and fleet components, and the energy efficiency of the vehicles. Tables 2 and 3 show the 2035 vehicle population assumptions. Background for development of vehicle emissions, activity and population scenarios are included in sections 8 and 9 of the Supporting Information.

**Table 2**. Heavy-duty natural gas OTR tractor total market share and distribution scenarios for 2035.

|  |  |  |  |
| --- | --- | --- | --- |
| **Vehicle Category** | **Short Haul (≤320 hp)** | **Long Haul (>320 hp)** | **Total** |
| Population Fraction of HD NG OTR Market | 50% | 50% | 100% |
| HD NG Engine Technology | SI | SI | SI | HPDI | SI | -- |
| Fuel Type | CNG | LNG | CNG | LNG | LNG | -- |
| Population Fraction of Vehicle Category | 60% | 40% | 25% | 50% | 25% | -- |
| Population Fraction of Total OTR Tractors | 30% | 20% | 12.5% | 25% | 12.5% | 100% |
| Low | 132,360 | 88,240 | 55,150 | 110,300 | 55,150 | 441,200 |
| Medium | 231,960 | 154,640 | 96,650 | 193,300 | 96,650 | 773,200 |
| High | 331,590 | 221,060 | 138,162 | 276,325 | 138,163 | 1,105,300 |

**Table 3**. Projected heavy-duty natural gas vehicle population in 2035, with fraction of vehicle class population in parentheses.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Low | Medium | High |
| Refuse Trucks | 80,000 (50.0%) | 104,000 (65.0%) | 128,000 (80.0%) |
| Transit Buses | 21,000 (30.0%) | 31,500 (45.0%) | 42,000 (60.0%) |
| OTR Tractors | 441,200 (19.4%) | 773,200 (34.1%) | 1,105,300 (48.7%) |
| Total Fleet | 542,200 (21.7%) | 908,700 (36.0%) | 1,275,300 (51.0%) |

The projected population of natural gas fuel stations for the HD vehicle sector (Table 4) is developed from assuming that a station will refuel 50 refuse trucks, 80 transit buses, or 80 OTR tractors.

**Table 4.** Projected natural gas fuel station populations for the heavy-duty natural gas vehicle sector in 2035.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Low | Medium | High |
| CNG Stations | 3,945 | 6,189 | 9,341 |
| LNG Stations | 3,172 | 5,559 | 9,168 |
| Total | 7,117 | 11,748 | 18,509 |

The EPA MOVES model27 for diesel-powered trucks suggests that 2035 natural gas trucks in service would be represented by at least ten model years of production. Infrastructure would also exhibit a range of technologies, commissioning years, and retrofit campaigns. The relative contributions of sources were assessed by matching the number of CNG and LNG vehicles to the number of fueling stations. This in turn implied the number of CNG and LNG fueling events and LNG station delivery events. The relative numbers of CNG and LNG vehicles, types, and associated fueling infrastructure were taken in the same ratio as projected for 2035 (Table 2).

In the stasis scenario, results were combined with the medium 2035 fleet and infrastructure prediction to suggest the relative contributions of sources if there were no change from the technology and practices measured and observed in this program. The stasis scenario acknowledges retirement of today’s older technology.

Methane emissions will be reduced through technology and practice changes, so that emissions will be below the stasis scenario by 2035. These changes may be driven by regulation or by establishing industry best practice programs28 and are represented in the high, medium, and low scenarios described below as percentages of the measured or assumed stasis value. Rapid technology turnover, rapid growth of the natural gas transportation sector, technology breakthroughs, and adoption or enforcement of best practices, would all favor the low scenario, whereas a moribund market would favor the high scenario.

*LNG Delivery Losses.* The stasis scenario was set at the average measured LNG fuel loss, 0.128% of delivered fuel. There were few study observations, but eliminating the highest emissions event from offload events suggests that the percentage emitted could drop readily from 0.13% to 0.08%. The high value was set to reflect consistent good practice, at 60% of stasis. Assuming that connector volume emissions could be reduced or captured, medium and low values were 40% and 20% of stasis.

*LNG Station Boil-off.* Modeling demonstrated that severe under-utilization led to station boil-off, but did not quantify this effect nationally because utilization rates are not known. Methane emissions of 0.1% were selected for the stasis scenario, corresponding to about 1 in 20 stations being underutilized while fueling HPDI vehicles. Growth of natural gas transportation will serve to increase station utilization, and LNG station modeling shows that modest increases in station use will reduce the boil-off emission by a factor of five, so that 20% of the stasis scenario was used as a high value. Currently, there are methods to prevent boil-off, use boil-off gas for other purposes, re-direct gas to a supply line, or oxidize (burn, catalyze) the boil-off gas. Methane emissions from an oxidizer are probably 1% of the methane burned. If half of the 2035 stations have boil-off reduction technology, a representative medium value is 10% of today’s value. Assuming full adoption of boil-off abatement, with 95% technology availability, and 1% in combustion exhaust, the low is 2%.

*CNG and LNG Fuel Station Continuous Emissions.*In the stasis scenarios, based upon a medium fuel efficiency scenario, LNG station continuous emissions were set to zero as the estimated value was below the third decimal place (0.00007%) while for CNG, all continuous emissions were set at the average estimate of 0.009% of station utilization. The low scenario assumes that continuous emissions would be reduced through improved practice in eliminating plumbing leaks, through improved component technology, employment of compressed air (versus methane) for station pneumatic controls, and by routing vent flows to an oxidizer. However, methane emissions from station leaks are generally low, and inspections are already frequent. The three scenario values were 80%, 50% and 20% for CNG stations, and were irrelevant for LNG losses that were below the reporting level for this study.

*CNG Station Compressor Losses.* CNG stations in this study represented two decades of technologies, and the range of compressor emissions measured suggest that substantial reductions from the average are possible. For the stasis scenario, based upon a medium fuel efficiency scenario of fuel throughput, average fuel-specific compressor emissions of 0.075% were used. Emissions can be captured and recycled or oxidized. However, there may still be old technology compressors in service in 2035. The scenario values chosen were 50%, 20%, and 5%.

*CNG and LNG Fueling Nozzle Losses.*Methane emissions from CNG nozzles consist of vent emissions, which could be routed to an oxidizer, and disconnection emissions, which are smaller than vent emissions. For the stasis scenario, CNG nozzle losses were 0.003%, and for LNG 0.011% for estimated 185 kg tank fill. For CNG the values chosen were 50%, 20%, and 10%.Only new technology LNG nozzles demonstrated high event variability in methane emissions. The ability to prevent high emissions events through training and technology improvement is critical to the future reduction. The scenario values were set at 50%, 20%, and 10%.

*LNG Manual Venting to Atmosphere.*Manual venting of vehicle tanks to atmosphere will be reduced by the ability of most LNG stations to accept all return product from a vehicle tank, and through adoption of better practices at time of refueling. For the stasis scenario, manual venting was estimated to be 0.250% of fuel volume, assuming that one in every twenty truck tanks was manually vented, based upon observations of venting and measurements of vehicle tank pressure data prior to refueling. The high scenario value was set at 50% of the stasis scenario, based on better practices and colder stations due to higher utilization. The medium value, 25%, and the low value, 3%, were based on the fraction of stations having boil-off reduction technology, which would aid in accepting returned warm product from truck tanks.

*Crankcase Losses.*For engine emissions certification, crankcase methane and tailpipe emissions are measured and regulated together. Future joint regulation could be met with varied combinations of crankcase and exhaust reductions. Stasis scenario values were based upon average measured values (Figure 3). The technology for closing the crankcase is already available, providing one pathway for SI reduction. For the high scenario, it is assumed that the oldest 25% of the fleet still has open crankcase operation because the timing of a standard or voluntary closure is unknown. This leads to a high scenario of 25% of the stasis scenario. The medium value was taken as 10%, and the low value was taken as 2%. These methane reductions are fuel mass specific.

*LNG Truck Tank Boil-off.*This is a corollary to station boil-off, but some of the station technologies (cooling; running power generators) are not available on-board trucks. For the stasis scenario, it was assumed that 1% of trucks might lose 10% of their fuel from extended periods out of service, so that a fuel fraction loss of 0.1% was adopted in the absence of empirical data. Some stationary boil-off reduction technology might be transferrable to mobile sources. Design improvements for LNG tanks and fuel systems, such as improved insulation and reduction in heat loads will lengthen hold times. The high, medium, and low scenario values selected were 75%, 50%, and 25%.

*HPDI Venting.*Stasis scenario values were based upon average measured values (Figure 3). The HDPI dynamic venting reduction would be dependent on future fuel system design or capture and use of the vent gas. Scenario values of 50%, 20% and 10% were used. These methane reductions are fuel mass specific.

*Tailpipe Emissions*.Historical trends in both diesel and gasoline engine emissions reduction suggest that both in-cylinder and catalyst strategies will be successful for SI and HPDI engines. The 2035 fleet will include older technology that does not achieve emissions reductions levels of the newest vehicles. Also, at cold temperatures, benefits of advanced catalyst systems may be reduced. Stasis scenario values were based upon average measured values (Figure 3). The high, medium, and low values were taken as 75%, 35%, and 15%.These methane reductions are fuel mass specific.

*Fuel Efficiency.*It was assumed that less fuel would be used per mile, both through legislation-driven engine efficiency improvements and vehicle efficiency improvements (including drivetrain loss, aerodynamic drag, and tire rolling resistance reductions)29,30. However, heating catalysts during low power operation will increase fuel use. Reduction of natural gas fuel must be compounded with the fuel-specific crankcase, dynamic vent, and tailpipe methane reductions discussed above. For the stasis scenario, an overall efficiency for both methane and diesel was used for HPDI vehicles. Pilot diesel fuel use estimates for HPDI vehicles, provided by the manufacturer, were 10% by energy fraction while under power and 42.5% at idle. For the scenarios, high fuel use was combined only with high emissions, medium with medium, and low with low. Penetration of idle reduction and stop-start technology is anticipated, and is more easily included as a reduction in fuel use than by adjusting vehicle activity: it is included in the low value for idle. For power operation the reductions for 2035 were 90%, 75% and 50%. For idle the values were 100%, 90% and 60%.

**Overall 2035 Scenario**

The scenario contributions were combined to yield estimates of methane emissions associated with vehicles, and an estimate of the overall quantity of methane used by vehicles as fuel. The stasis and 2035 scenarios are shown in Table 5 for CNG and LNG, using a medium proportion of HPDI vehicles in the fleet, and without retrofit vehicles. Whereas directly quantified losses can be modeled as a function of usage and design, the national distribution of boil-off losses is not known.

Emissions associated with vehicles and vehicle operations are significantly higher contributors than station related emissions for the stasis and 2035 totals. Section 12 of the Supporting Information includes substantial detail on how fuel-specific emissions rates for the stasis, high, medium and low scenarios of Table 5 were developed.

**Table 5**. Methane estimations for both CNG and LNG using the medium population/medium HPDI penetration with stasis, high, medium and low fuel specific emissions/fuel efficiency scenarios.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Stasis | High | Medium | Low  |
|  | CNG | LNG | Combined | CNG | LNG | Combined | CNG | LNG | Combined | CNG | LNG | Combined |
| Delivery |  | 0.128% | 0.068% |  | 0.077% | 0.042% |  | 0.051% | 0.029% |  | 0.026% | 0.016% |
| Station Tank BOG |  | 0.100% | 0.053% |  | 0.020% | 0.011% |  | 0.010% | 0.006% |  | 0.002% | 0.001% |
| Station Continuous | 0.010% | 0.000% | 0.005% | 0.009% | 0.000% | 0.004% | 0.007% | 0.000% | 0.003% | 0.004% | 0.000% | 0.002% |
| Compressor | 0.075% |  | 0.035% | 0.038% |  | 0.017% | 0.015% |  | 0.007% | 0.004% |  | 0.001% |
| Fueling Nozzle | 0.003% | 0.011% | 0.007% | 0.001% | 0.006% | 0.004% | 0.001% | 0.003% | 0.002% | 0.001% | 0.002% | 0.001% |
| Vehicle Fuel Tank |  | 0.100% | 0.053% |  | 0.075% | 0.041% |  | 0.050% | 0.028% |  | 0.025% | 0.015% |
| Vehicle Manual Vent |  | 0.109% | 0.058% |  | 0.092% | 0.050% |  | 0.063% | 0.035% |  | 0.030% | 0.019% |
| Engine Crankcase | 0.698% | 0.356% | 0.516% | 0.177% | 0.087% | 0.128% | 0.072% | 0.032% | 0.049% | 0.014% | 0.005% | 0.009% |
| Dynamic Vent |  | 0.226% | 0.120% |  | 0.119% | 0.065% |  | 0.052% | 0.029% |  | 0.031% | 0.019% |
| Engine Tailpipe | 0.390% | 0.417% | 0.404% | 0.291% | 0.315% | 0.304% | 0.135% | 0.149% | 0.143% | 0.058% | 0.066% | 0.063% |
| Total | 1.177% | 1.447% | 1.321% | 0.517% | 0.790% | 0.665% | 0.230% | 0.411% | 0.331% | 0.081% | 0.187% | 0.146% |
| CH4 (MMT) | 0.222 | 0.310 | 0.532 | 0.088 | 0.161 | 0.249 | 0.033 | 0.076 | 0.109 | 0.008 | 0.029 | 0.037 |
| Fuel (MMT) | 18.840 | 21.452 | 40.292 | 17.127 | 20.321 | 37.448 | 14.386 | 18.544 | 32.931 | 9.591 | 15.476 | 25.067 |

*Separate Consideration of Retrofit Technology.* Fuel-specific tailpipe methane emissions from three retrofit vehicles (two manufacturers) over individual tests (chassis and on-road) ranged from 3% to 47%. Fuel substitution averages over microtrips ranged from 4% to 34%.**Average fuel specific crankcase methane emissions from the retrofit vehicles were 1%. These emissions values are high in comparison to SI and HPDI engines.**

**Estimation of future retrofit emissions levels is difficult. First, a range of years of retrofit would be in use in 2035. The retrofit regulations may vary by year. Second, each of those years of retrofit will be populated by a range of original model years, potentially encompassing a range of original certification levels for carbon dioxide, methane, and air pollutants. Third, the retrofit emissions levels may also vary if the retrofits are conducted at separate levels of engine useful life. The number of retrofit vehicles in service today is small: they were not included in either the stasis or 2035 scenarios.**

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