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Methane (CH₄) is an important greenhouse gas emitted by vehicles. This study provides estimates of emissions of this important and often not well characterized greenhouse gas (GHG) emission related to transportation energy use. It aims to assist urban community planners and policymakers to prioritize and choose implementation strategies for low carbon cities. The paper focuses on emissions of CH₄ from vehicles. Unlike emissions of CO₂, which are relatively easy to estimate, emissions of CH₄ are a function of many complex aspects of combustion dynamics and depend on the type of emission control systems used. In this context, they cannot be derived easily and instead must be determined through the use of published emission factors for each combination of fuel, end-use technology, combustion conditions, and emission control systems. Emissions of CH₄ play a significant role with regards to the relative CO₂-equivalent GHG emissions of the use of alternative transportation fuels, in comparison with the use of conventional fuels. By analyzing a database based on literature review this study analyzes all the factors affecting the creation of CH₄ emissions from different vehicle types. Statistical analysis indicated "r" values ranging from 0.10 to 0.85 for all vehicles.

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Article

New Aspects to Greenhouse Gas Mitigation Policies for Low Carbon Cities

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Abstract: Methane (CH₄) is an important greenhouse gas emitted by vehicles. This study provides estimates of emissions of this important and often not well characterized greenhouse gas (GHG) emission related to transportation energy use. It aims to assist urban community planners and policymakers to prioritize and choose implementation strategies for low carbon cities. The paper focuses on emissions of CH₄ from vehicles. Unlike emissions of CO₂, which are relatively easy to estimate, emissions of CH₄ are a function of many complex aspects of combustion dynamics and depend on the type of emission control systems used. In this context, they cannot be derived easily and instead must be determined through the use of published emission factors for each combination of fuel, end-use technology, combustion conditions, and emission control systems. Emissions of CH₄ play a significant role with regards to the relative CO₂-equivalent GHG emissions of the use of alternative transportation fuels, in comparison with the use of conventional fuels. By analyzing a database based on literature review this study analyzes all the factors affecting the creation of CH₄ emissions from different vehicle types. Statistical analysis indicated “r” values ranging from 0.10 to 0.85 for all vehicles.

Keywords: methane emissions; air pollution; climate change; low carbon cities

1. Introduction

Air quality constitutes a very important issue for public health, economy and environment. Poor air quality as a result of air pollution is a major environmental health risk, contributing to respiratory disease, cardiovascular disease, and lung cancer. In addition to the health effects, air pollution has considerable economic impacts, cutting short lives, increasing medical costs, and reducing productivity through lost working days across the economy. As climate change and air pollution stemming in urban areas from Greenhouse Gas Emissions (GHG) are closely linked, it is of great significance to investigate all interrelations of GHG for a low carbon urban environment.

In 2010, 82% of all European Union’s greenhouse gas emissions were CO₂-related. About 94% of the carbon dioxide (CO₂) released to the atmosphere stemmed from combusting fossil fuels and the remaining 6% from industrial processes. Methane is considered a major GHG that accounted for 14% of the world GHG emissions and 8.6% of the European Union GHG emissions in 2010. Over the last

two hundred and fifty years, the concentration of methane (CH_4) in the atmosphere has increased by 151% [1]. To be more specific, since the pre-industrial period, the global mixing ratios of CH_4 emissions in the atmosphere have more than doubled, rising from around 750 parts per billion (ppb) in 1800 [2,3] to the current level of around 1770 ppb [4]. The rate of increase slowed to 5–10 ppb year by the late 1980s and continued to decline into the 1990s, though with considerable annual growth variation [4].

Atmospheric CH_4 originates from both non-biogenic and biogenic sources. Non-biogenic CH_4 includes emissions from fossil fuel mining and burning (natural gas, petroleum and coal), biomass burning, waste treatment and geological sources. Alternatively, CH_4 sources can be divided into anthropogenic and natural. The anthropogenic sources include rice agriculture, livestock, landfills and waste treatment, some biomass burning, and fossil fuel combustion. Natural CH_4 is emitted from sources such as wetlands, oceans, forests, fire, termites and geological sources.

Regarding the anthropogenic emissions of CH_4 , it is noted that these can contribute significantly to total CO_2 -equivalent emissions of GHG from the lifecycle of conventional and alternative transportation fuels and technologies. Internal combustion engines (ICE) operate by burning fossil fuel derivatives. Exhaust emissions are their major contribution to environmental pollution. Typical emissions contain primary greenhouse gases—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). All criteria pollutants—carbon monoxide (CO), total nitrogen oxides (NO_x), sulfur dioxide (SO_2), non-methane volatile organic compounds (NMVOC) and particulate matter (PM) are the other major components. CH_4 is emitted from gasoline, diesel, methanol, ethanol, Liquefied Petroleum Gas (LPG), and natural gas internal-combustion-engine vehicles. Methane is emitted from light duty vehicles due to the incomplete combustion of fuel in the vehicle engine and the incomplete oxidation of engine-out methane in current catalytic after treatment systems. Emissions of CH_4 are a function of the type of fuel used, the design and tuning of the engine, the type of emission control system, the age of the vehicle, as well as other factors. Given that the transportation sector is a main source for emitting CO_2 , accounting for 13.5% of worldwide global warming [5] it is imperative to investigate CH_4 emissions resulting from this sector.

The EU's methane emissions have dropped from around 595 $\text{MtCO}_2\text{eq.}$ in 1990 to 405 $\text{MtCO}_2\text{eq.}$ in 2010 (a reduction of more than 30%). This reduction was attributed to lower emissions from enteric fermentation and less waste disposal on land [6]. Viewed over a longer timeframe, the decrease in methane emissions in the period 1990–2010 resulted from lower fugitive emissions from coal mining and post-mining activities, and lower emissions from managed waste disposal on land. Methane from enteric fermentation in the agricultural sector also fell significantly, partly due to reduced livestock numbers but also due to changes in the agricultural management of organic manures. Despite the fact that methane is not toxic, it has a global warming potential that is 25 times higher than that of CO_2 [7,8]. As far as legislation is concerned, EU tackles methane emissions together with other GHG emissions through the Climate and Energy Package aiming at reducing the EU's greenhouse gas emissions by 20% in 2020 compared to 1990 [9].

The usage of natural gas as an automotive fuel seems bound to increase over the next few years as the demand for natural gas for use in European road vehicles is projected to double between 2015 and 2020 [10]. A recent techno-economic analysis of a broad range of fuel types revealed Compressed Natural Gas-CNG to outperform gasoline in terms of fuel economy, with a vehicle purchase cost that was close to that of a gasoline vehicle [11]. Based on the above and in conjunction with the fact that road transport is responsible for about 75% of GHG emissions (CO_2 , CH_4 and N_2O) [12,13], estimating and measuring CH_4 emissions by road traffic is a key-issue for air pollution management as it introduces a good additional method for the environmental evaluation of transportation system scenarios. Furthermore, city-based research literature on road emissions is in broad agreement that the energy efficiency improvement in urban transport sector has large potentials to address carbon mitigation. Nonetheless, a key gap in the existing literature remains on analyses involving the opportunity to mitigate CH_4 emissions.

In this context, the purpose of this study is to provide an estimation of CH_4 emissions of different vehicle types, so as to identify all the factors affecting methane emission, as well as the ratio of methane

to total hydrocarbons emissions by passenger cars. We focus on CH₄ because for many energy-use technologies—and particularly alternative fuel vehicles—emissions of CH₄ are not well characterized, whereas emissions of CO₂ from fuel combustion are relatively easy to estimate. In order to address the abovementioned issues the method of statistical analysis was selected. The results of this study indicate that CH₄ emissions from the road sector are affected by various vehicle's characteristics, such as the engine volume, horsepower, compression ratio, temperature, exhaust after treatment system as well as the fuel injection system. In addition, the paper argues that the results of this study should be interpreted in regards to a low carbon transportation system and to be considered in policy and planning strategies. The paper is structured as follows: Section 2 describes the data, variables and methodology used. Section 3 presents the main results, whereas Section 4 includes the concluding remarks.

2. Materials and Methods

A statistical analysis was performed in order to determine the direct relationships of CH₄ emissions from different vehicles. Based on references concerning a number of commercial vehicles makes such as Chrysler, Ford, GM, Honda and Toyota a database was designed. The database includes a sample of 1000 vehicles that were distributed between the period of 1986–2005 [14–81]. It should be noted that in regards to the methodological approach, some other methodologies, such as patent analysis [82], could have been used in a study, which focus on providing guideline regarding climate change mitigation; nonetheless due to the large number of data it was decided that in this study a statistical analysis could have better results, as it will clearly depict the correlations between different vehicle parameters and CH₄ emissions.

The literature review focused on finding useful data for grouping and analyzing the vehicles as well as on finding statistical issues and analytic methods associated with vehicle emissions data. This included notably numerous cars with mileages far higher than 1,000,000 km. The vehicles under examination were assumed to cover a wide range of engine conditions. The emission records used were for vehicles speeds between 20 and 58 km/h and accelerations between 0 and 2.8 m/s², so as to avoid irregular emission behavior at deceleration, high instantaneous acceleration, and top speeds. Furthermore, to ensure statistical validity an F-test (99% confidence level) was carried out to validate the regression model. In order to perform the comparative analysis the following vehicle characteristics were assessed:

- Engine Volume: L
- Horsepower: hp
- Torque: Nm/rpm
- Distance travelled: km
- Fuel consumption: L/100 km
- Emissions of CO₂, CO: g/km
- Emissions of NO_x, THC, CH₄: mg/km
- Emissions of PM: Particle Number/km

The driving test cycles examined, included the ECE and EUDC test cycle—also known as the MVEG-A cycle [EEC Directive 90/C81/01]. The European transient cycle (ETC) is the regulatory test cycle for heavy-duty diesel vehicles. In 2000, that idling period has been eliminated, *i.e.*, engine starts at 0 s and the emission sampling begins at the same time. This modified cold-start procedure is referred to as the New European Driving Cycle (NEDC) or as the MVEG-B test cycle, which was also taken into consideration. NEDC is the regulatory test cycle for light and medium-duty vehicles. The full test starts with four repetitions of the ECE cycle. The ECE is an urban driving cycle, also known as UDC. It was devised to represent city driving conditions, e.g. in Paris or Rome. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature. In addition, the EPA Federal Test Procedure, commonly known as FTP-75 for the city driving cycle was also included in the statistical analysis. Finally from the US cycles, which include a variety of test cycles from the USA including their type approval cycles—cars, HGVs and buses the US06 test cycle was taken into consideration.

Emission standards for passenger cars and light commercial vehicles were also taken into consideration. Since the Euro 2 stage, EU regulations introduce different emission limits for diesel and petrol vehicles. Diesel vehicles have more stringent CO standards but are allowed higher NO_x emissions. Petrol-powered vehicles are exempted from particulate matter (PM) standards through to the Euro 4 stage, but vehicles with direct injection engines are subject to a limit of 0.005 g/km for Euro 5 and Euro 6. The type of testing also played a role in determining if a given study should be included in this analysis. There were a number of cases in which data from one study were repeated in another study. This might occur if the authors published the same data set in multiple scientific journals to maximize exposure, or if the authors presented a previously-published set of data in a new publication for the purpose of comparing the two datasets. These publications were excluded from our database. The variables examined are the type of fuel, horse power, engine power, compression ratio as well as mileage.

The statistical analysis consisted of a series of statistical procedures applied to the data in each vehicle type. These included both Regression and Pearson Correlation Analysis (PCA), in order to identify the relationship between a dependent variable and one or more independent variables. Pearson correlation coefficients (*r*) were also calculated. A model of the relationship is hypothesized, and estimates of the parameter values are used to develop an estimated regression equation. Various tests are then employed to determine if the model is satisfactory. If the model is deemed satisfactory, the estimated regression equation can be used to predict the value of the dependent variable given values for the independent variables. It is noted that the correlation and regression analysis are related in the sense that both deal with relationships among variables.

3. Results and Discussion

Based on the methodology presented in Section 2, statistical analysis was performed for the vehicles that are included in the database. The results of the positive correlations were “*r*” values ranging from 0.10 to 0.85 for all vehicles’ whereas for negative correlations the results of “*r*” values were ranging between −0.08 to −0.9. Methane emissions vary with the engine load and with vehicle characteristics. The variables examined are distinguished to the following categories: Vehicles’ Characteristics (engine volume, horsepower, compression ratio, temperature, exhaust after treatment system as well as fuel injection system), Fuel Properties, Exhaust Emissions, Driving Cycles, Emissions standards, Three Way Catalyst—TWC, Total Hydrocarbons (THC).

The findings of the statistical analysis performed for the category of vehicle’s characteristics are summarized in Table 1. The engine volume was examined for 482 vehicles, the horsepower for 101 vehicles, and the temperature for 110 and finally the exhaust after treatment system for 409 vehicles.

Table 1. Correlation between CH₄ emissions and different vehicle’s variables.

Variable: Vehicles’ Characteristics	Number of vehicles	Pearson’s Correlation Coefficient (<i>r</i>)
Engine Volume		
All vehicles	482	−0.04
EURO 4, EURO 5, Otto engine, Gasoline or gasoline blended fueled with exhaust after treatment system	35	−0.04
Average of data regarding vehicles after 2000, TWC, Gasoline fueled, NEDC, EUDC, FTP-75, US06	10	0.241
Average of vehicles after 2000, Diesel engine, Diesel fueled, EUDC, UDDS	5	0.855
Average of data regarding vehicles before 2000, TWC, Gasoline fueled, NEDC, EUDC, FTP-75, US06	13	0.045

Table 1. Cont.

Variable: Vehicles' Characteristics	Number of vehicles	Pearson's Correlation Coefficient (<i>r</i>)
Horsepower		
All vehicles	101	−0.265
Test Temp. >10 °C, TWC	82	−0.327
Test Temp. >10 °C, TWC, FTP-75, NEDC, EUDC	55	−0.231
Compression Ratio		
All vehicles	217	−0.162
Cold test, Liquid fueled vehicles	136	0.107
No Cold test, Liquid fueled vehicles, FTP-75, NEDC, ECE, EUDC	72	−0.195
Temperature		
All vehicles	117	0.03
Otto engine, Gasoline or gasoline blended fueled	110	−0.12
Hyundai Sonata-2011; Volvo S40-2011; Chrysler Town & Country-2001; Gasoline fueled	21	−0.78
Renault Express—1994	3	−0.90
Exhaust after treatment system		
All vehicles	409	0.30
Vehicles with Otto engine, with exhaust after treatment system	409	0.33
Vehicles after 2000 with Otto engine, with exhaust after treatment system	57	0.60
Vehicles after 2000 with Otto engine, with exhaust after treatment system—performing testing at ambient temperature	37	0.97
Vehicles with Diesel engine—performing testing at ambient temperature	39	0.21
Vehicles with Diesel engine—performing testing at ambient temperature—EUDC driving cycle	11	0.68

3.1. Vehicle's Characteristics

It is noted that the engine volume is strongly correlated with the average of methane emissions of Otto engine vehicles with distribution year after 2000, which are gasoline (or gasoline blended), fueled. This is also noted in the case of diesel powered vehicles with correlation efficiency reaching $r = 0.855$. The strong correlation is attributed to the fact the fuel consumption increases as the engine volume increases. Highest dispersion emissions values compared to engine volume, are indicating the existence of more important factors that affect emissions of older vehicle technologies (for instance vehicle's emission standards).

It is noticed (Table 1) that the compression ratio (CR) is negative correlated with CH₄ emissions, having a low correlation coefficient. This can be attributed to the fact the majority of the vehicles in our database with high CR refer to either diesel engine or OTTO engine direct injection vehicles, which can extract maximum possible mechanical efficiency from the engine. The temperature of the combustion chamber will also increase and that is beneficial for complete combustion reducing CH₄ emissions. The horsepower is negatively correlated with methane emissions; this is attributed to the technological progress of vehicles.

Methane emissions appear to be higher at lower ambient temperatures. This is expected because before the engine is warmed up the temperature of the fuel going into the engine is close to the ambient temperature, and at lower temperatures a liquid fuel does not vaporize as completely, and hence does not burn completely. If CH₄ emissions are related to temperature, such that lower combustion and exhaust temperatures cause them to increase, then one would expect that CH₄ emissions also would be related to the driving cycle, which can affect engine and exhaust temperatures. The dependence between methane emissions and temperature is not linear but exponential decay.

The exhaust after treatment systems seem to have a positive influence on engine performance and reduce CH₄ exhaust emissions. On the contrary, it seems that the existence of after treatment systems in diesel powered vehicles, does not have an effect on methane emissions. This can be attributed to lower diesel engine methane emissions as well as to the fact that after treatment systems in diesel engines such as Diesel Particulate Filter (DPF) or NO_x Storage Reduction (NSR) aim to reduce emissions such as PMs and NO_x respectively. In general, exhaust gas after treatment systems using catalytic converter systems, secondary air injection, insulation of exhaust manifold and exhaust system, filters (traps) etc, can reduce the CH₄ emissions.

Figure 1, illustrates that technology progress in the field of vehicle's fuel injection system has led to significant CH₄ emissions reduction. For instance Gasoline Direct Injection (GDI) technology has decreased the percentage of CH₄ emissions approximately 170%, compared to Multi Port Injection (MPI) technology. The maximum percentage of methane emissions is noted at older technology systems (Sequential Fuel Injection system (SFI) of the Ford Crown Victoria [83] and classic carburetor system with no after treatment system of the Volkswagen Golf [84]). Methane emissions seems to increase as the engine and the emission-control system deteriorate. The data of Table 1 suggest that for most vehicles CH₄ emissions increase with the age of the catalyst.

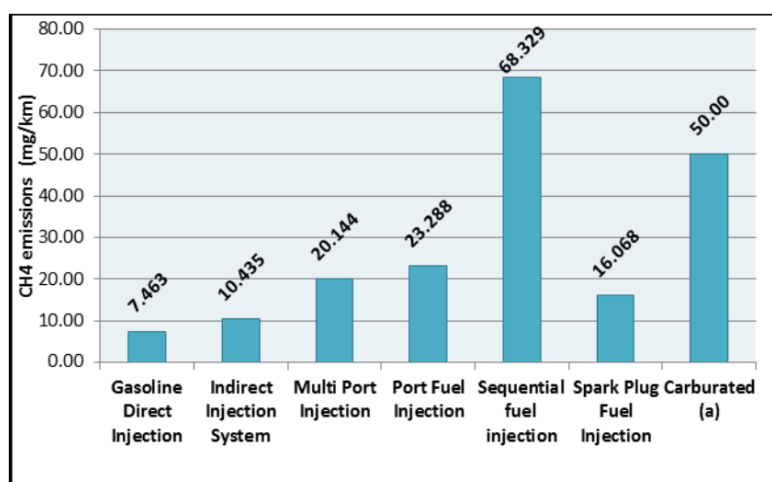


Figure 1. Average CH₄ emissions of different OTTO gasoline fueled of gasoline-blended fueled vehicles equipped with exhaust after treatment system and standard driving conditions. (a No exhaust after treatment system).

3.2. Emission Standards

Figures 2 and 3 depict average methane emissions for Otto and Diesel engine vehicles for several European and non-European regulations of commercial vehicles tested. In the case of Otto engine vehicles, a constant decrease is observed for the vehicles of EURO 1 to EURO 5 emission technology. In the case of non-European regulations average gasoline CH₄ emissions decrease from US87 to US94 regulations. It is noted that as in commercial vehicle engines, the Selective Catalytic Reduction (SCR technology) became the norm for the most part in Europe since the introduction of Euro IV vehicle technology, the reduction of CH₄ emissions from EURO3 to EURO4 is impressive.

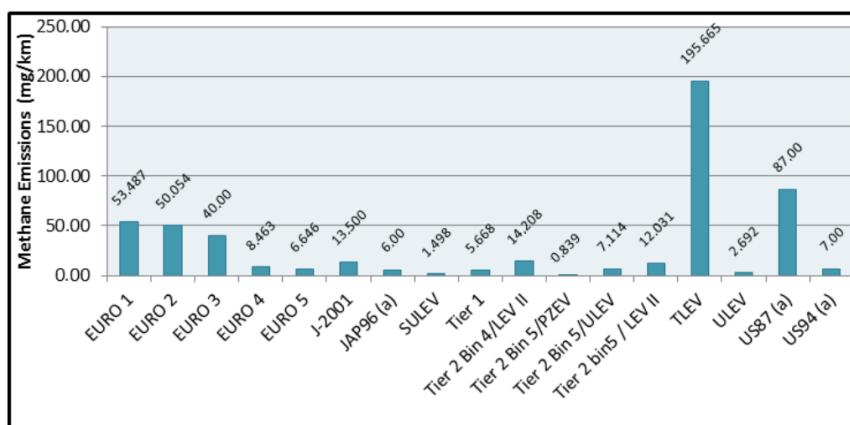


Figure 2. Emissions Standards—methane emissions for Otto engine vehicles, gasoline fueled with after treatment exhaust.

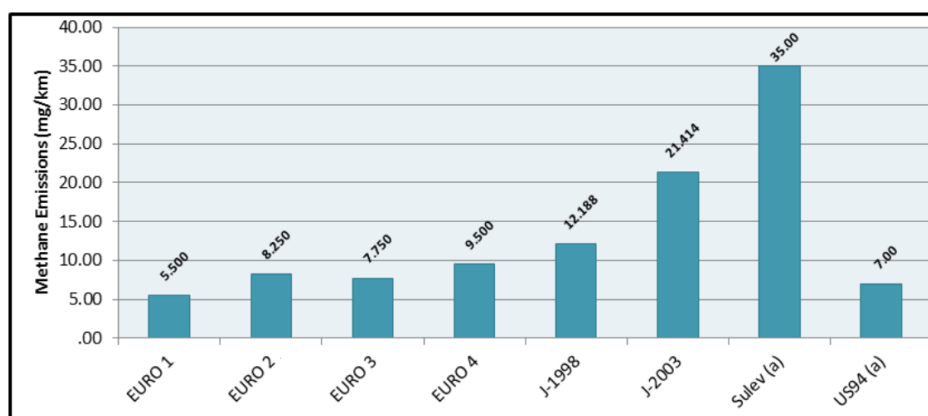
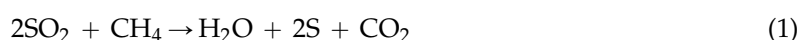


Figure 3. Emissions Standards—Methane emissions for Diesel engine vehicles.

As far as diesel engine vehicles are concerned, a decrease is observed from EURO 1 to EURO 3 emission technology; whereas EURO 4 emission technology seems to have slighter higher emissions than EURO 3. The latter can be attributed to the tax incentives. In the case of non-European regulations, average diesel CH₄ emissions increase in the case of SULEV to US94.

3.3. Fuel Properties

Table 2 illustrates the correlation between CH₄ emissions and different fuel properties. It is obvious that CH₄ emissions are positive correlated to the percentage of aromatic hydrocarbons, as well as gasoline's content of olefins and paraffins; whereas CH₄ emissions are negative correlated to the percentage of Methyl ter-butyl-ether (MTBE) in gasoline–MTBE blends, as well as to the percentage of oxygen in gasoline. It is also deducted that there is no correlation between CH₄ emissions and diesel's sulfur content ($r = -0.47$); whereas are correlated with gasoline's octane number ($r = 0.51$). The latter can be attributed to the reduction of produced SO₂, from the CH₄ produced during the following reaction:



It should be noted that with diesel fuel, ignition quality is also a main performance criterion. Diesel fuel ignitability is specified by its cetane number which, like octane number, is measured in a stationary engine and specified by comparison to reference fuels. Whereas gasoline must be resistant to auto ignition, diesel fuel is required to auto ignite readily. This is because combustion proceeds without spark ignition, *i.e.*, burning must commence spontaneously as the fuel is injected into a gas

mixture that has been heated adiabatically by piston compression. Whereas gasoline ignition quality is dictated by performance at severe, high load conditions, diesel ignition quality is most critical under cold start and light load conditions—the fuel must ignite easily enough to allow start-up and smooth running under cold condition.

CNG vehicles have higher emissions than gasoline and diesel cars (Figure 4). This is due to the unburned fuel which is mainly methane, while this pollutant is mainly formed during the combustion process from the higher hydrocarbons in gasoline and diesel powered vehicles. Methane emissions from CNG vehicles decrease with technology, but there is no clear trend in the case of gasoline and diesel. As per data analysis, it is shown that emissions from natural gas fueled vehicles, decrease with model year (later models emit less) and increase with vehicle mileage, and generally are about an order of magnitude higher than methane emissions from gasoline vehicles of similar technology and age.

Methane emissions increase significantly with ethanol content, having a strong correlation of $r = 0.89$ (Table 2). The abovementioned is significant as it indicated that show that vehicles running on ethanol have very different CH_4 emission characteristics compared to vehicles running on methanol. The results show that CH_4 emissions tend to increase with ethanol content, which is the reverse of what occurs with methanol. This can be attributed to the fact that adding ethanol to gasoline results to oxygenate the fuel. The higher the ethanol blend, the higher the oxygen content in the fuel. The increased oxygen in the fuel changes the stoichiometric air/fuel ratio of the fuel. The stoichiometric air/fuel ratio is the chemically correct or theoretical air to fuel ratio which provides the minimum amount of oxygen for the conversion of all the fuel into completely oxidized products. For a hydrocarbon-based fuel, this means that all the carbon in the fuel is converted to CO_2 and the hydrogen to water, H_2O .

Methanol vehicles emit less CH_4 compared to gasoline vehicles. For instance, Figure 4 indicates that methanol vehicles generally emit less CH_4 than do gasoline vehicles of the same model. Data analysis suggests that dedicated M85 vehicles (which use a mixture of 85% methanol and 15% gasoline) emit about 2/3 as much CH_4 as gasoline vehicles.

Table 2. Correlation between CH_4 emissions and fuel properties.

Variable: Fuel Properties	Number of vehicles	Pearson's Correlation Coefficient (r)
Gasoline Composition		
% aromatic hydrocarbons, standard driving conditions	37	0.69
% paraffin, standard driving conditions	4	0.90
% olefins, standard driving conditions	28	0.60
% O_2 , standard driving conditions	6	−0.88
% MTBE, standard driving conditions	3	−0.46
Gasoline		
% Methanol, Standard driving conditions	18	−0.10
Octane number, Vehicles with after treatment exhaust systems, Standard driving (no cold starts- cold conditions), Gasoline- gasoline blended fueled	21	0.51
Sulfur content	18	−0.10
Ethanol Blends		
% Ethanol, Standard driving conditions	7	0.89
Diesel		
Sulfur content (ppm)	9	−0.47
Cetane number	19	0.63

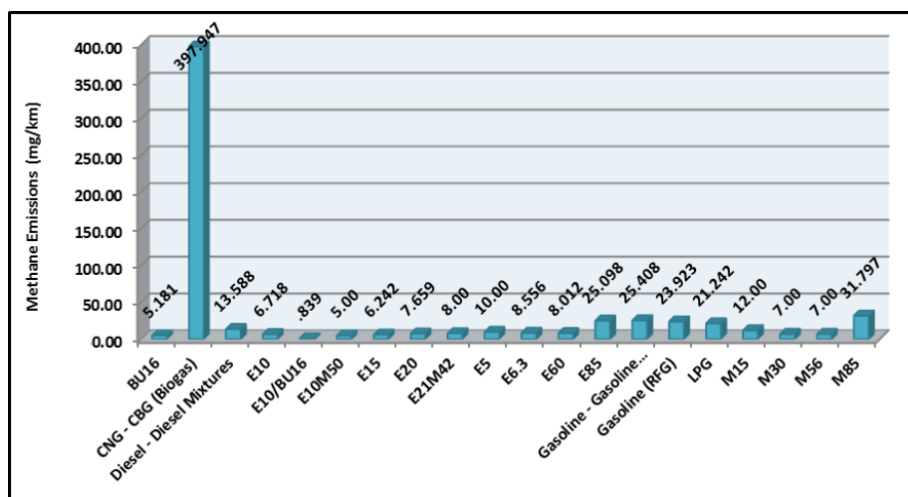


Figure 4. Average Methane Emissions per different fuel types of vehicles with after treatment exhaust systems. (*Gasoline - Gasoline blended fueled).

3.4. Exhaust Emissions

Table 3 examines the relation between exhaust emissions and CH₄ emissions. The variables examined include the following emissions: CO₂, CO, NO_x as well as THC. In regards to CO₂, CO and NO_x emissions, 482 vehicles were examined, whereas in regards to assessment of TCH emissions 647 vehicles were examined.

Table 3. Correlation between CH₄ emissions and exhaust emissions.

Variable: Exhaust Emissions	Number of vehicles	Pearson's Correlation Coefficient (<i>r</i>)
CO₂ emissions		
All vehicles	482	0.14
Vehicles with Otto engine, Gasoline or gasoline blended fueled with exhaust after treatment system, after 1998	110	0.58
Vehicles with Otto engine, Gasoline or gasoline blended fueled with exhaust after treatment system, after 1998, NEDC & F driving cycles	42	0.65
Vehicles with Diesel engine	100	0.14
Vehicles with Diesel engine, with exhaust after treatment system	56	0.19
CO emissions		
All vehicles	482	0.526
Vehicles with Otto engine	481	0.797
Vehicles with Otto engine and exhaust after treatment system	263	0.724
Vehicles with Otto engine and exhaust after treatment system. ECE, EUDC, NEDC, FTP75 driving cycles	133	0.427
Vehicles with Otto engine and exhaust after treatment system, distributed after 2000, FTP75 & US06 driving cycles	54	0.347
Vehicles with Otto engine and exhaust after treatment system, distributed before 2000, FTP75 & US06 driving cycles	61	0.546
Vehicles with Diesel engine	91	0.13
Vehicles with Diesel engine and after treatment exhaust system	53	0.236

Table 3. Cont.

Variable: Exhaust Emissions	Number of vehicles	Pearson's Correlation Coefficient (<i>r</i>)
NOx emissions		
All vehicles	482	−0.11
Vehicles with Otto engine and exhaust after treatment system	243	0.558
Vehicles with Otto engine and exhaust after treatment system, distributed after 2000, FTP75 driving cycle	25	0.649
Vehicles with Otto engine and exhaust after treatment system, distributed before 2000, FTP75 driving cycle	42	0.61
Vehicles with Diesel engine	91	0.06
THC emissions		
All vehicles	647	0.484
Vehicles with Otto engine and exhaust after treatment system, gasoline fueled	481	0.750
Vehicles with Otto engine and exhaust after treatment system, CNG	19	0.996
Vehicles with Otto engine and exhaust after treatment system, LPG fueled	8	0.341
Vehicles with Otto engine and exhaust after treatment system, gasoline-ethanol fueled	55	0.967
Vehicles with Otto engine and exhaust after treatment system, FTP75 driving cycles	27	0.579
Vehicles with Otto engine and exhaust after treatment system, gasoline-ethanol fueled, T < 0 °C	10	0.982
Vehicles with Otto engine and exhaust after treatment system, gasoline-methanol fueled	10	0.886
Vehicles with Otto engine and exhaust after treatment system, gasoline fueled, ECE, EUDC, NEDC driving cycles	50	0.573
Vehicles with Diesel engine	104	0.214
Vehicles with Diesel engine, manufactured after 2000	30	0.598

Table 3 indicates a positive correlation between methane emissions and CO₂, CO, NO_x emissions, in all types of vehicles. Correlation coefficients are higher for Otto engine vehicles compared to Diesel engine vehicles. Especially, in the case of Diesel engine vehicles, correlation coefficient increases for vehicles that have been manufactured after 2000. In addition, the data of Table 3 show that as THC is reduced, methane is also reduced in a proportional manner. Thus, as vehicle technology advances to meet stricter organic compound emission standards, it is reasonable to expect that methane emissions will also decline. Hydrocarbons derive from the incomplete combustion of fuel, lubricating oil and pyrosynthetic reactions, presents a large variety of compounds, including alkanes, alkenes, aromatics as well as oxygenated organic compounds.

Statistically significant relations between both CH₄ and THC are found. From total HC emitted, more than 60% correspond to methane in the case of gasoline engine vehicles. The emissions ratio of CH₄/THC increases as the percentage of ethanol increases in gasoline-ethanol blends (Figure 5). As indicated by Figure 6, the emission ratio of CH₄/THC is not correlated to temperature.

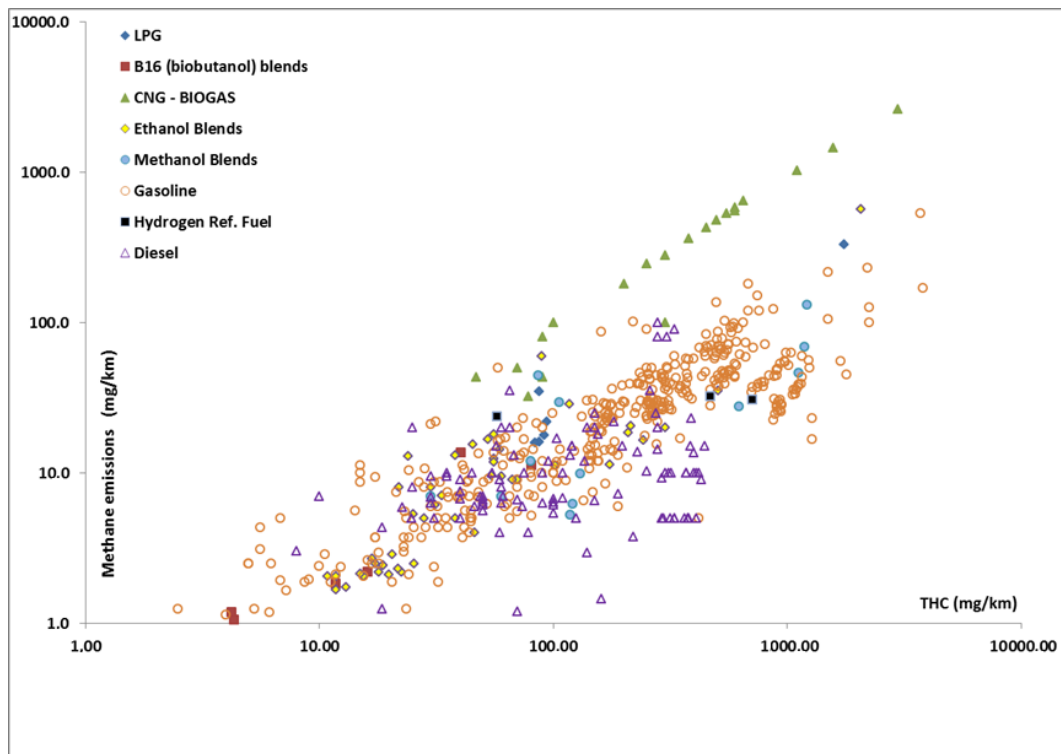


Figure 5. Methane emissions and THC emissions per different fuel type.

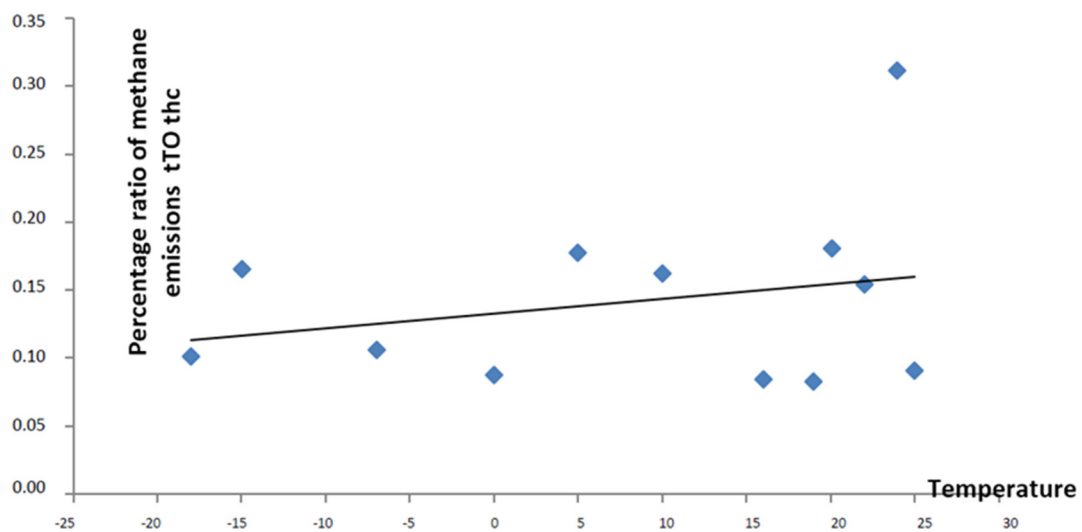


Figure 6. Percentage of average emissions ratio of CH₄/THC per different test temperature.

4. Conclusions

About half of the world’s population lives in urban areas and the future population growth will happen mostly in urban areas. How urban dwellers choose their infrastructure, technology, consumption and lifestyle will determine the global GHG emissions. To support the global GHG mitigation, several new strands of research for developing a better understanding of mitigation opportunities, governance and incentives systems for urban areas are necessary. The goals of research and actions in urban areas should be to reduce the overall urban carbon footprint, taking into a broader system perspective. In order to advance the urban research on GHG mitigation, we identified a number of key research issues.

The findings of this study indicated that natural gas vehicles can play a significant role in reducing emissions in the transportation sector. When used in vehicles, natural gas the fossil fuel (predominantly methane) result in reduced emissions of almost all regulated and non-regulated emissions compared to gasoline and diesel-fuelled vehicles possibly with one exception: total hydrocarbons. Nonetheless it should be mentioned that although CH₄ emissions from gasoline vehicles (in terms of global warming potential) are lower than N₂O emissions, these are increased in natural gas-fueled vehicles (given that methane is the primary component of natural gas). It should be noted that the results of this study could be verified with the use of other methods like artificial intelligence (AI), so as to translate descriptive factors into functions [85].

On light-duty gasoline vehicles, modern three-way catalyst-based emission control technology is effective at reducing all hydrocarbon exhaust emissions including methane. Tightening of hydrocarbon emission standards over time with the parallel introduction of more effective emission control systems have resulted in lower emissions of methane from today's vehicles compared to older vehicles certified to less stringent standards. Catalyst designs can also be optimized in concert with engine control strategies to oxidize methane exhaust emissions from motor vehicles including vehicles that operate exclusively on natural gas or bi-fuel vehicles that can operate on either natural gas or gasoline. Natural gas could also be important for cutting CO₂ emissions from heavy-duty vehicles (HDVs). Moreover natural gas vehicles can contribute to a low carbon transportation sector by: improving air quality and reducing noise in urban areas; diverting oil from domestic consumption to export; improving energy security; and reducing government spending on road fuel subsidies. Nevertheless it should be noticed that despite the fact that natural gas can play a significant role in cutting vehicle carbon dioxide (CO₂) emissions, over the long term there will need to be a commitment to transition to very low CO₂ gas sources, such as biogas or bio-synthetic gas.

The analysis of this study can play a significant role in the development of a low carbon city by identifying policies and programs for energy saving and carbon emissions reduction across the transportation sector. The dissemination of the abovementioned information will give the ability to local governments not only to gather resources, but also the legislative power to devise plans and enforce them. These are crucial factors for low carbon governance across the cities. In this direction, regulatory conditions should be changed and financial incentives should be provided. Additionally, the public sector cans co-ordinate stakeholders to align their expectations and actions towards a common goal of an energy transition to a low carbon city. The adoption of alternative fuel vehicles is not possible to take off without co-ordination between automakers, fuel suppliers and governments. Co-ordination is essential on pilot region selection, target market, vehicle portfolio selection, asymmetric incentives for urban and rural stations, other incentive packages and standardization. Government intervention will also be required to break through the technological lock-in of existing technologies or path dependence. In view of the abovementioned, the findings of this study can be further developed by investigating the combined use of other alternative transportation fuels, so as to provide a useful policy tool for decision-makers, in order to develop a sustainable transport system.

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