

Article

Natural Gas, a Mean to Reduce Emissions and Energy Consumption of HDV? A Case Study of Colombia Based on Vehicle Technology Criteria

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Abstract: In this study, the use of compressed and liquefied natural gas is evaluated for heavy-duty passengers (HDPV) and freight vehicles (HDFV). The evaluation is conducted considering the socioeconomic and vehicle fleet characteristics of Colombia. The energy consumption, the CO₂, and the pollutant emissions of a baseline and four natural gas penetration scenarios are analyzed. The results show that the inclusion of natural gas reduces the energy consumption per capita of the HDPV and HDFV by up to 40% by 2050. Furthermore, PM_{2.5} emissions per capita are reduced up to 77% for HDPV and 90% for HDFV, while CO emissions per capita decreased by 82%. Additionally, the technological renovation of HDFV emerges as an effective way to reduce pollutant emissions in the medium term. The establishment of strategies to make HDFV cleaner and more efficient is imperative for the long term. Finally, a sensitivity analysis is conducted to evaluate the influence of the gross domestic product per capita (GDPc) over the indicators analyzed. The results show that higher GDPc demands more ambitious actions to decarbonize the transportation sector, since a considerable increase in energy consumption and emissions from heavy-duty vehicles is identified.

Keywords: natural gas vehicles; heavy-duty vehicles; socioeconomic criteria; emissions reductions; energy consumption projections



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1. Introduction

Transport is one of the key economic sectors to propose strategies for reducing emissions. It is one of the primary producers of pollutants and greenhouse gases (GHG) emissions. In 2018, this sector produced about 25% of CO₂ global emissions [1]. Likewise, the transport sector is one of the primary generators of pollutant gases that affect air quality in urban areas. Chemical species like particulate matter (PM), tropospheric ozone (O₃), nitrogen oxides (NO_x), and sulfur oxides (SO_x), are intricately linked to the operation of the transport sector. The use of cleaner fuels as hydrogen, biofuels, electricity, natural gas, and carbon synthetic fuels emerges as a strategy to achieve environmentally sustainable transport [2].

In this sense, socioeconomic parameters are simulated to evaluate the possible consequences of the introduction of new transport technologies in existing transport systems. [3]. Nevertheless, not all fuels are competitive in terms of performance or availability. The penetration of electric vehicles has been slow, principally in countries with developing economies [4]. Today, natural gas has emerged as a possible transition fuel to substitute the use of diesel and gasoline in road transport vehicles, since its carbon content is lower. Generally, natural gas can be employed in transport as compressed natural gas (CNG) or liquefied natural gas (LNG) [5]. A change from petroleum-based energy chains to natural gas-based energy chains could be a good strategy to both reduce emissions of fuels used

today as well as maintain a high grade of flexibility regarding the development of future technologies due to three principal reasons: (i) carbon emission per unit of energy in combustion is lower for natural gas; (ii) in time, natural gas can be substituted for climate-neutral energy carriers, such as hydrogen; and (iii) natural gas is the cleanest and most environmentally acceptable primary fossil fuels regarding its combustion products [6].

It has been identified that the substitution of diesel fuel for natural gas is a viable alternative, from both an economic and environmental point of view [7]. Nevertheless, it is not sensible to apply a general rule for all cases without considering the specific conditions of each country. From an environmental perspective, natural gas vehicles can produce between 70% and 85% fewer pollutant emissions than gas or diesel vehicles, and a reduction of the GHG of 10% compared to diesel [8]. Today, natural gas has facilitated energy security and diversification in transport, as well as generated profit for users and companies of the transport sector, as the cost of natural gas is less than diesel fuel [9].

Specifically, in heavy-duty passengers vehicles (HDPV) and heavy-duty freight vehicles (HDFV), one of the most-profiled alternatives to substitute diesel fuel is LNG, as it presents a greater energy density than CNG. LNG gives vehicles greater autonomy during their routes, being much more attractive for commercial transport [10]. Generally, LNG is stored in a cryogenic liquid phase, after which it passes through an evaporator where a phase change from liquid to gas occurs [11]. From here, it is directed to the engine where, as is with gas engines, there is a spark ignition system [12]. Some important advantages of LNG vehicles include an increase in the vehicle's performance, weight reduction, and less time spent refueling compared to CNG [13]. Because of these advantages, the use of LNG is recommended in fleets comprised of heavy-duty vehicles (HDV) that operate on long or cyclical routes (intercity trucks, urban trucks, and semi-tractor trucks) where fueling takes place upon departure or arrival—until a network of service stations is available to supply the automotive fleet [14].

LNG is considered the cleanest form of natural gas. This is because before the liquefaction process several impurities are removed from natural gas to conduct the liquefaction safely and efficiently [15]. As a result, LNG contains up to 98% methane [16]. Being such a pure fuel, LNG combustion, compared to traditional fossil fuels, has less NO_x , SO_x , and PM emissions [17]. Moreover, CO emissions are practically null [16]. For said reasons, diverse studies have found that by operating HDV with LNG, low levels of pollutant concentrations can be achieved without the need to employ costly emissions control systems, as are required for diesel vehicles [18]. It is estimated that an LNG truck, as compared to conventional diesel trucks, can consume up to 7% more energy, given that these vehicles are approximately 18% less efficient. However, the sale price of LNG is less than that of diesel; therefore, the fleet operating costs could be considerably reduced [19].

On the other hand, it has been confirmed that employing buses that operate with CNG in public transport diminish the negative impact on the environment due to the reduction of emissions of toxic substances, particles, and GHG [20,21]. Likewise, the use of CNG buses contributes to a cleaner operation and supports the objectives of sustainable development. Natural gas has been studied extensively and used in the transport sector in several countries, as presented in Table 1.

Even though the use of natural gas has been analyzed widely, and some environmental and economic advantages have been demonstrated, Latin America still requires an analysis of social, geographical, and technical factors that directly influence the penetration of technologies to identify the viability of the implementation of this type of energy in the transport sector. Moreover, the low quality of public transport, poor planning practices, and highly populated and polluted cities emerge as some of the challenges that the new technologies must overcome. Likewise, the mountainous geography in countries like Bolivia, Colombia, Peru, and Ecuador requires high mechanical performance from engines. The weak vehicle and quality emission standards and fuel savings mean vehicles in the region tend to have a higher level of pollutant and GHG emissions. This shows potential in reducing emissions through the use of natural gas in the region.

Table 1. Studies related to the evaluation of natural gas in HDV in the world.

Country	Comparison and Method	Results, Benefits, and Obstacles Encountered	Ref
Canada	Life cycle analysis (LCA) and dynamic simulation of LNG and CNG as alternatives to diesel in buses.	Through a life cycle analysis (LCA), when diesel was changed for CNG and LNG, there were GHG reductions of 4.8% and 8.1%, respectively.	[22]
Poland	Cost-benefit analysis with the use of CNG in public transport buses.	Purchasing CNG buses is more profitable when the price of CNG per m ³ is 55% below the m ³ cost for diesel. The LCA of a CNG bus is reduced by 400 kg of GHG and 52.5 kg of PM. The environmental benefits are sufficient to justify the use of CNG in buses by transport companies.	[20]
Taiwan	Study of the carbon footprint of an urban bus in the city of Taiwan, based on the international regulation ISO/TS 14067:2013.	Carbon footprints in the lifecycle of buses measured from highest to lowest: LNG 63.14 g CO _{2e} /km; diesel, 54.6 g CO _{2e} /km; liquefied petroleum gas, 47.4 g CO _{2e} /km; plugin electric, 37.82 g CO _{2e} /km, and hydrogen gas cell, 29.17 g CO _{2e} /km.	[23]
China	Identification of polluting emissions of buses using a mean distribution deviation (MDD) for different fuels on the road.	On the road, bus stops, and intersections, the diesel vehicles with standard Euro IV and Euro V have higher CO and NO _x emissions than natural gas buses. Nevertheless, for CNG buses, the levels of CO ₂ and HC are higher. There is no significant difference in velocity or acceleration.	[7]
	LCA of LNG and CNG in HDV, taking into account the gas leakage in the supply chain.	Trucks that use LNG and CNG can reduce GHG emissions by 11.17% and 5.8%, respectively, in comparison to diesel vehicles in the lifecycle.	[24]
	CO ₂ , NO _x , CO, THC emissions analysis in real operating conditions using a portable emission measuring system (PEMS) in semi-trucks that use diesel and LNG in China.	The emission factors of THC of the LNG vehicles were 2.01 to 10.63 g/km higher than diesel vehicles (0.03 to 0.19 g/km). Likewise, vehicles operating with LNG had higher NO _x and CO ₂ emissions than diesel vehicles.	[25]
	Engine combustion and emission fueled with natural gas: A review	Compared to gasoline, natural gas vehicles have a lower production of THC, CO, CO ₂ , and PM. However, NO _x emissions are higher. In natural gas vehicles, methane is the main component of THC emissions. It can be reduced by the addition of hydrogen and after-treatment technology.	[26]
United States	Optimization of the impact of the evaluation of the lifecycle of bus fleets using alternative fuel.	CNG vehicles had 23% less GHG emissions than diesel vehicles.	[27]
	Analysis of GHG reductions that can be achieved through increasing engine efficiency and transition to low-carbon fuels.	Compared to gasoline, natural gas provides a 20% reduction of GHG emissions in the internal combustion engine and up to 50% when it is used as a raw material to produce hydrogen or electricity.	[24]
	Comparison of the complete lifecycle of transit autobuses with diesel engines and five types of buses using alternative fuels.	The number of buses fueled with B20, CNG, and LNG has high participation in today's transit operations, but their CO ₂ emissions do not reveal a significant reduction compared to diesel buses. LNG-fueled transit buses showed the worst results in terms of CO _{2e} emissions during their lifetime of 12 years for the Manhattan operation cycle compared to other cycles.	[25]
Brazil	Economic analysis and regulation barriers for the inclusion of natural gas as a fuel in HDFV.	The availability of LNG vehicles on the market reduces the possibility of including natural gas as a combustible in HDFV. The cost of fuel makes it possible to incur investments of up to 17% higher than in diesel fuel vehicles.	[8]
	Analysis of the increase of use of LNG in the transport sector in different parts of the world.	The use of CNG and LNG have increased in different types of vehicles in various countries, among them Italy, New Zealand, the United States, Australia, Iran, and France. Italy is the country with the most developed program using natural gas as a fuel, where almost 300,000 vehicles circulate with CNG. Countries like Brazil, Egypt, Canada, and Bangladesh implemented programs to use natural gas for internal transport needs.	[28]
United Kingdom	Energy and environmental well-to-wheel analysis of LNG as a transition fuel in heavy-duty vehicles.	GHG emissions reductions of the LNG trucks only happen when there are efficiency improvements in the vehicles. The LNG vehicles perform 17% less efficiently than diesel, provoking 7% more GHG emissions.	[10]
South Korea	General vision about the LNG and CNG characteristics for automobiles.	For a tank of fuel of a determined capacity, a vehicle that runs on LNG can travel up to 2.4 times the distance of its CNG counterpart.	[16]
Colombia	Energy and emission impact of natural gas in heavy-duty vehicles: A case of study of Colombia based vehicle technology criteria	The introduction of natural gas for HDPV and HDFV reduces energy consumption by up to 40% by 2050. Pollutant emissions such as CO and PM _{2.5} decrease up to 80 and 90%, respectively. The use of LNG in HDFV increases NO _x emissions by 30% in 2050.	-

In this article, the authors want to assess if natural gas can be considered as a transition fuel in the transport sector in Colombia based on the energy and environmental effects that result from the inclusion of this fuel in the operation of the HDPV and HDFV fleet. For this, models that relate the socioeconomic, energy, pollutant emissions, vehicle technology, and energy supply infrastructure parameters are proposed for road transport systems. The models are applied in the case study of Colombia; nevertheless, they can be replicated in any region based on data of the fleet composition, population, and the use of the energy sources in the transport sector.

An estimate and projection are made of the number of commercial transport vehicles and tank-to-wheel (TTW) pollutant emissions resulting from the operation of the HDPV and commercial vehicle fleet in the country through the year 2050. The above provides an evaluation of the environmental and energetic effectiveness of the use of passenger buses

powered by CNG in public transport and HDFV powered by LNG, considering the current HDV technologies, based on diesel and gasoline fuels, that are being commercialized in Colombia. Based on the model, several scenarios of the inclusion of natural gas in HDV can be proposed and analyzed. The results could be used to draw insights, support, and argue the development of national and regional policies, as well as to project the required actions in the medium and short term.

Finally, a sensitivity analysis is executed to identify what factors influence the projections of energy consumption and pollutant emissions in the case study, and medium and long-term regulatory recommendations are established.

2. Methodology

An analysis of HDV is conducted, since this fleet is one of the primary causes of NO_x , SO_x , CO, and PM emissions in urban areas [29]. Currently, Colombia has about 341,100 HDV (26% HDPV and 74% HDFV) in operation. 11% of HDPV uses gasoline fuel, meanwhile 86% and 3% uses diesel and natural gas respectively. On the other hand, 9% of HDFV uses gasoline and 91% uses diesel.

2.1. Vehicle and Population Projections

The size of the HDV fleet in Colombia by 2050 is projected through the Gompertz function. It has been widely used for modeling the growth of vehicle fleets considering the market and the socioeconomic characteristics of a specific population. This function models the relation between the number of vehicles and the economic development of a country. It establishes the number of vehicles per capita in the function of the gross domestic product per capita (GDPc), as shown in Equation (1) [30].

$$V = \gamma e^{\alpha e^{\beta(\text{GDPc})}} \quad (1)$$

where:

V is the motorization index, in number of vehicles per capita.

α and β establish the form of the Gompertz function. These parameters are determined using a linear regression method that allows the curve to be adjusted according to the specific conditions of the region, based on the historical data of the vehicle fleet.

β : is known as the saturation level and determines the maximum point of growth of the fleet. It is expressed in vehicles per 1000 inhabitants and depends, principally, on the population density and urbanization rate of the country [30]. Initially, it is determined for Light-Duty Vehicles (LDV), according to Equation (2) [30]. Later, the saturation level of HDPV and HDFV are determined based on the relation between the number of automobiles and the number of vehicles in each category.

$$\gamma = \gamma_{max} - 0.388 \bar{D}_i - 7.765 \bar{U}_i \quad (2)$$

where:

γ_{max} is the maximum saturation level of automobiles. As a reference, it is considered the γ_{max} of the United States, with 652 automobiles for every 1000 inhabitants [30].

$\bar{D}_i$ and $\bar{U}_i$ relate population density and the urbanization rate, respectively, and are calculated according to Equations (3) and (4), respectively.

$$\bar{D}_i = D_i - D_{US} \text{ if } D_i > D_{US} \quad \bar{D}_i = 0 \text{ if } D_{US} > D_i \quad (3)$$

$$\bar{U}_i = U_i - U_{US} \text{ if } U_i > U_{US} \quad \bar{U}_i = 0 \text{ if } U_{US} > U_i \quad (4)$$

where:

D_{US} and D_i are the population densities of the United States and the country of study, in this case, Colombia. For these, values of 36 and 45 inhabitants/km² are considered, respectively [31].

U_{US} and U_i are the urbanization rates of the United States and the case study, Colombia. Values of 82.7 and 81.4% are considered respectively [32].

Once the saturation level is determined for LDV, the saturation level of HDPV and HDFV is estimated according to the historic relationship between the number of automobiles and the quantity of HDPV and HDFV. In the last 15 years, an average relation of 3.2 HDPV and 8.47 HDFV per 100 automobiles is established.

Table 2 shows the parameters of the Gompertz function. The level of saturation γ is established based on the ratio between the number of automobiles of the country and the quantity of HDPV and HDFV, knowing the level of saturation of automobiles in the country. It is calculated based on what Dargy, Gately, and Sommer [30] established.

Table 2. Parameters of the Gompertz function.

Parameter	γ	α	β
HDPV (buses and small buses)	21 ^a	−3.46	-6.29×10^{-2}
HDFV (trucks and semi-tractor trailer trucks)	55 ^b	−3.87	-9.22×10^{-2}

^a Ratio of HDPV/automobiles of 3.2%. ^b Ratio of HDFV/automobiles of 8.5%. Level of saturation of automobiles: 648 vehicles for every 1000 inhabitants.

From this model, the quantity of HDPV and HDFV from 2020 to 2050 is projected, based on the actual data from 2010 to 2020, and assuming an average annual growth of GDPc of 4% each year as established in the report “The World in 2050” [33]. In Figure 1, the projection of the number of vehicles per capita is presented. In which an elevated growth is identified from 2030 and greater growth for HDFV than for HDPV, reaching 28 vehicles per 1000 inhabitants by the year 2050 for HDFV as compared to a total of 7 per 1000 inhabitants of HDPV by the year 2050.

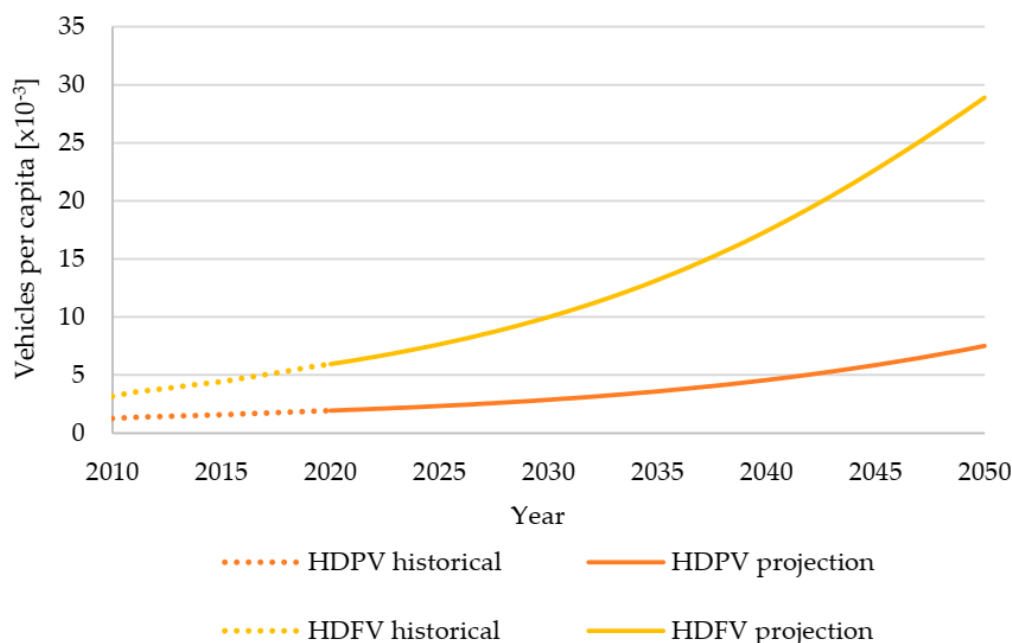


Figure 1. Projection of HDPV and HDFV per 1000 inhabitants by 2050—Colombia.

The substitution of diesel fuel and gasoline for natural gas is considered, specifically HDPV powered by CNG, and HDFV powered by LNG. Four scenarios of natural gas penetration are proposed:

- The baseline scenario follows the current trend of natural gas use in HDV. Therefore, it considers a minimal penetration of natural gas, with a participation of 95% diesel and 5% natural gas by 2050.

- In a low scenario, greater participation of diesel compared to natural gas by 2050 is assessed (75% diesel–25% natural gas).
- In the medium scenario, equal participation of both fuels diesel and natural gas is considered by 2050.
- In the high scenario, greater participation of natural gas compared to diesel fuel is analyzed (25% diesel–75% natural gas).
- Finally, the total gas scenario considers that all the HDV fleet uses natural gas by 2050.

In all the analyzed scenarios, the withdrawal of used vehicles with more than 20 years of useful life is considered. To this end, an historical assessment of the registrations of new HDPV and HDFV in Colombia is conducted. Besides, the penetration of natural gas vehicles is analyzed progressively, considering a linear growth for each year.

Under the Gompertz model, a projection of 260,000 HDPV is expected by 2050. In the base scenario, about 13,000 vehicles will use CNG. For the low, medium, and high penetration scenarios of natural gas, about 65,000; 130,000; and 195,000 vehicles will operate using natural gas. In addition, the total gas scenario will consider all the vehicles operating with CNG by 2050.

On the other hand, about 1.27 million HDFV are projected by 2050. In the base scenario, 63,700 vehicles will use LNG by 2050. In the low scenario, about 318,500 LNG-HDFV are projected; about 637,000 for the medium; and 955,500 for the high penetration scenario.

2.2. Energy Consumption

To estimate the energy consumed (EC), vehicle fuel consumption, and lower heating value (LHV) of fuels must be considered. These variables are related to the vehicle kilometers traveled (VKT) using Equation (5), through which the EC by class and vehicle technology is obtained. The VKT is calculated knowing the average of kilometers traveled per vehicle (AVKT) and the quantity of vehicles (Veh), as is shown in Equation (6). For this study, the AVKT is calculated based on the registry of total trips each year made by vehicles on the country's roads, and the number of kilometers traveled on each of the roads. Thus, the AVKT has been established at 40,576 km for HDPV and 37,877 km for HDFV [34]. Table 3 presents the mean fuel consumption of diesel and gasoline HDV fleet in Colombia under real operational conditions. In addition, this table reports the mean fuel consumption (FC) of LNG HDFV for China [19]. Table 4 presents the lower heating value of fuels and CO₂ (EF CO₂) emission factors.

$$EC = VKT * FC * LHV \quad (5)$$

$$VKT = AVKT * Veh \quad (6)$$

Table 3. FC of vehicles by technology [19,35].

Class	Technology	FC [L/100 km]
HDPV	Gasoline	51.49
	Diesel	27.47
	CNG	18.52×10^3 ^a
HDFV	Gasoline	29.87
	Diesel	25.97
	LNG	26.55

^a Standard conditions.

Table 4. Lower heating value of fuels [36].

Fuel	LHV [MJ/L]	EF CO ₂ [gCO ₂ /MJ]
Gasoline	33.098	70.08
Diesel	36.540	73.81
GNC	34.79×10^{-3} ^a	55.88
LNG	21.322	55.75

^a Standard conditions.

2.3. Pollutant and CO₂ Emissions

The pollutant emissions (PE) generated by a vehicle fleet depend on the VKT and the emission factors (EF). The EF refers to the total emissions of a pollutant and can be expressed per unit of energy (g/MJ) or distance traveled (g/km). For this study, emission factors (g/km) are used, based on available information regarding emission standards with which vehicles must comply, which are presented in the Appendix A.

Therefore, as each vehicle of the fleet can accomplish a specific emission standard (ES), the PE is determined by Equation (7). It considers the participation of each ES in the fleet, in which the counter $n = 1$ is equivalent to the Euro I standard, through $n = 6$, equivalent to the Euro VI standard, for diesel and gasoline vehicles, respectively.

$$PE = VKT * \sum_{n=1}^6 (\% ES_n * EF_n) \quad (7)$$

The actual participation percentage of ES is obtained from the baseline, and its projection is estimated assuming a vehicle lifespan of 20 years, as is indicated by the regulations of the case study country. Moreover, it is assumed that the EF in vehicles does not vary over the lifespan of the vehicle. These two considerations are made based on Colombia's regulations, which establish that diesel HDV must accomplish the Euro II standard since 2010, Euro IV since 2015, and Euro VI since 2023. On the other hand, gasoline HDV must accomplish the Euro II standards since 2015, Euro IV since 2025, and Euro VI since 2030 [29,37].

Furthermore, for the study, Euro VI is the maximum reference standard because of the lack of information on the values and implementation dates of forthcoming standards.

Carbon dioxide emissions (E CO₂) are calculated using Equation (8). It relates the CO₂ emission factors of (EF CO₂) in g/MJ, as shown in Table 4, and the used fuel through the energy consumption (EC) of the vehicles.

$$E CO_2 = EC * EF CO_2 \quad (8)$$

3. Results

Despite the use of natural gas has been analyzed widely, several authors have found controversial results related to the benefits of its use. This is because results are closely linked to the characteristics of the vehicle fleet under analysis and its operational conditions. Particularly for Colombia, Table 5 shows the behavior of energy consumption and CO₂, CO, NO_x, and PM_{2.5} emissions per capita in the proposed scenarios compared to the baseline scenario for HDPV and HDFV by 2050. In general, the use of natural gas generated a positive impact on energy consumption and pollutant emissions is evidenced for HDPV and HDFV by 2050.

Table 5. Reduction of emissions and energy consumption by 2050.

		Total Amount on Baseline Scenario	Reduction Compared to the Baseline Scenario [%]			
			Moderate	Medium	High	Total Gas
HDPV						
Energy	3.00 [GJ per capita]	7.29	16.40	25.52	34.63	
CO ₂	219.92 [kg per capita]	10.55	23.74	36.93	50.12	
CO	92.86 [g per capita]	17.32	38.97	60.62	82.26	
NO _x	112.36 [g per capita]	5.89	13.24	20.60	27.96	
PM _{2.5}	0.31 [g per capita]	16.23	36.52	56.82	77.11	
HDFV						
Energy	10.18 [GJ per capita]	8.23	18.53	28.82	39.12	
CO ₂	746.66 [kg per capita]	11.30	25.42	39.55	53.67	
CO	564.39 [g per capita]	0.60	1.34	2.09	5.61	
NO _x	430.18 [g per capita]	−(6.91)	−(15.54)	−(24.18)	−(30.47)	
PM _{2.5}	13.22 [g per capita]	17.88	40.23	62.59	90.07	

Nevertheless, results show a “negative” reduction in NO_x emissions of HDFV fleet for each analyzed scenario. It means that the use of LNG may cause the NO_x emissions rates to increase by up to 30% in 2050 when compared to the baseline scenario. This behavior could be related to the fact that in real operating conditions the NO_x emission factor is greater for LNG HDFV than Euro VI diesel ones. It occurs because the higher exhaust temperature of LNG vehicles affects the efficiency of the selected catalytic reduction system, causing a great rise in NO_x emissions [25]. Nevertheless, there are ample benefits related to PM_{2.5} emissions, given that LNG is considered the cleanest form of natural gas and has a lower sulfur content than gasoline and diesel [38]. Therefore, studies have shown that the use of LNG has generated reductions between 90% and 97% in PM emissions [39,40].

Figure 2 presents CO, NO_x, and PM_{2.5} emissions per capita in both vehicle categories between 2010 and 2050. From this, a direct relationship between emissions and the technological renewal of the fleet is identified. Since new emissions standards are required, there are considerable reductions in this parameter. It illustrates the renewal of technology in HDPV, showing a considerable reduction in pollutants. The projected CO emissions are reduced from 0.95 kg per capita in 2020 to less than 0.1 kg per capita by 2050. PM_{2.5} emissions have projected reductions from 26 g per capita in 2020 to less than 0.5 g per capita in 2050. Additionally, NO_x emissions present reductions of about 1 to 0.1 kg per capita. The results show that actions taken on HDPV in the case study country could generate considerable benefits regarding pollutant emissions in the transport sector.

On the other hand, when considering HDFV, there are reductions in CO, NO_x, and PM_{2.5} emissions until approximately 2035, after which emissions begin to increase again. This is due to the close relationship between emissions and the number of vehicles, where the increase of the HDFV vehicle fleet based on the GDPc represents a significant number, and the renewal of technology is not sufficient to maintain a reduction in emissions, as opposed to what happens for HDPV. It is relevant to point that out, even though the total inclusion of LNG contributes, in great measure, to the reduction of CO and PM_{2.5} emissions. In the other scenarios, similar reductions of emissions are evident, which is due to the inclusion of vehicle technologies with more responsible ES. For the case of NO_x in the HDFV, emissions of this pollutant are reduced until 2035, as a result of stopping the operation of vehicles with low ES. Nevertheless, from the said year, there is a considerable increase of the PE of this chemical species, as a product of an increase in the number of vehicles in circulation and the greater LNG contribution in NO_x emissions, in comparison with diesel fuel.

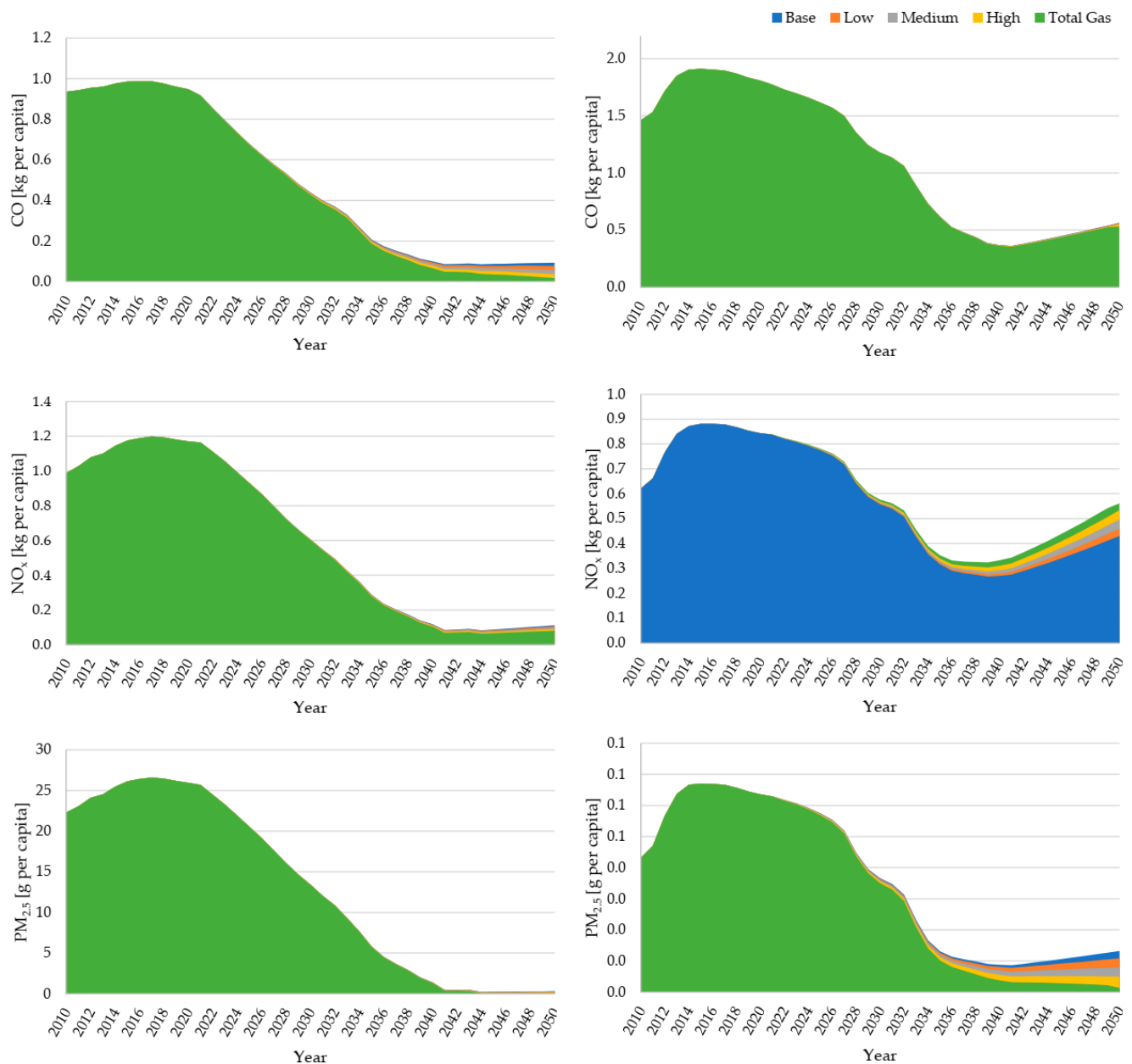


Figure 2. Pollutant emissions by 2050.

Likewise, the results reveal that from the year 2035, proposing complementary actions to significantly reduce NO_x and CO emissions is important, principally, in HDFV. In other words, for this class of vehicles, a quicker transition to zero-emissions than for the HDPV is necessary, where new technologies like hybrid, electrical, or fuel cell trucks, not only could reduce emissions, but also provide economic benefits and fuel savings [41–44].

4. Sensitivity Analysis

The results represent the impact in emissions and energy consumption as a product of the inclusion of natural gas in heavy vehicles, varying the percentage of participation of fossil fuels. Nevertheless, a variation in the GDPc values, population growth, vehicle fuel efficiency, or emission factors can directly influence the results. Therefore, in this section, a sensitivity analysis of the GDPc and emission standards is executed to observe the impact of the number of vehicles, EC, and emissions.

The GDPc is directly related to the number of existing vehicles in a population, as the greater the economic development of a country the greater the purchasing power of its inhabitants. For effects of analysis, the average annual growth percentages of the GDPc were varied, with values of 2%, 4%, and 6%. Thus, it was observed that with an average annual growth of 6%, the total fleet analyzed would come close to its saturation value by 2050, with 61 heavy vehicles for every 1000 inhabitants. On the other hand, with a growth of 2% of the GDPc, there would be 16 heavy-duty vehicles for every 1000 inhabitants by 2050. Said behavior can be observed in Figure 3.

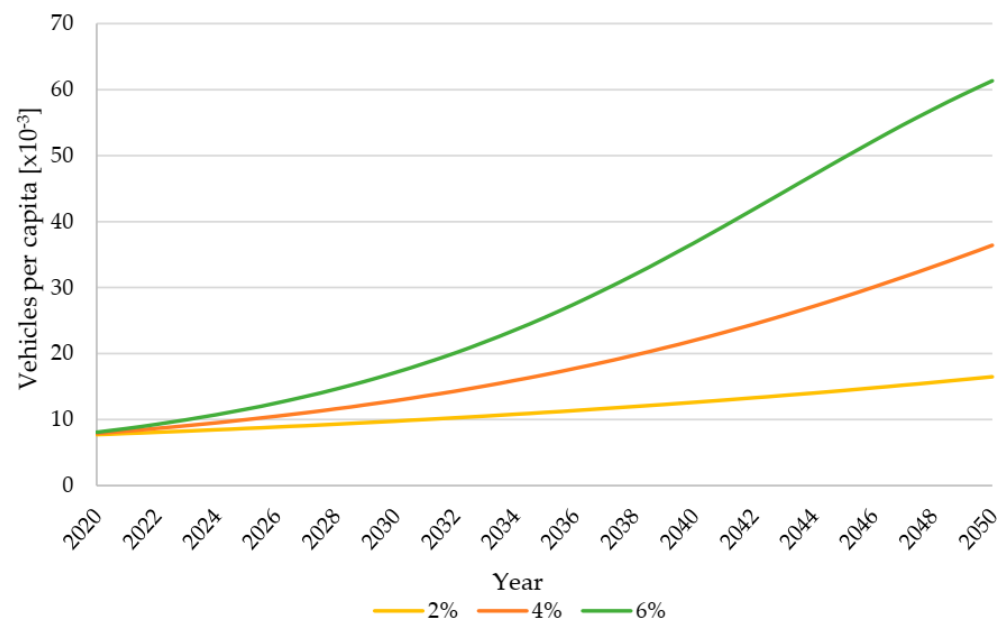


Figure 3. Motorization index by varying GDPc.

Moreover, in Figure 4, the quantity of emissions of CO₂, CO, NO_x, and PM_{2.5} per capita that would be generated by varying the GDPc is presented. In this figure, baseline scenario emissions with average growth percentages of the GDPc of 2%, 4%, and 6% are presented, observing a significant difference from the minimum to the maximum case. As can be observed, despite the reduction of the tons of emissions emitted due to the technological renewal of the fleet, CO, NO_x, and PM_{2.5} emissions reach a point of new increase. This shows that the reduction in emission factors is not enough to offset the total emissions of the number of vehicles. Additionally, a direct correlation between the GDPc and GHG and pollutant emissions has been identified. This is because a greater GDPc represents the greater purchasing power of the population to buy vehicles, which will induce an increase in the size of the fleet, thus, a higher level of emissions. This leads to the assessment that countries with greater levels of wealth should generate more rigorous strategies of decarbonization of heavy vehicles.

Additionally, Figure 5 shows how EC varies with different values of the GDPc. By the year 2050, there would be a total EC of 5.97 GJ per capita with a 2% annual growth of the GDPc, whereas the energy consumption would be 13.18 GJ per capita for a 4% annual growth. Finally, with a 6% annual average growth of the GDPc, there would be a total EC of 22.28 GJ per capita.

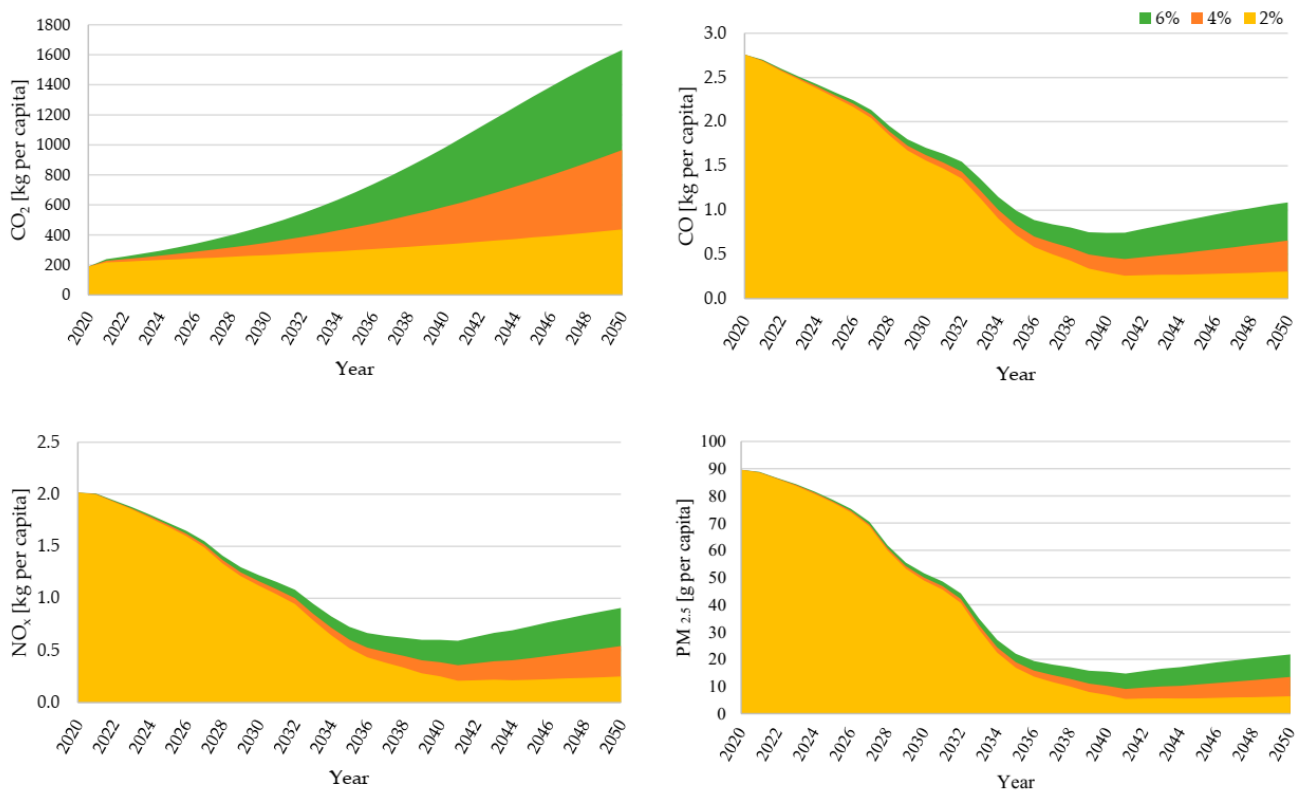


Figure 4. Total emissions per capita by varying GDPc.

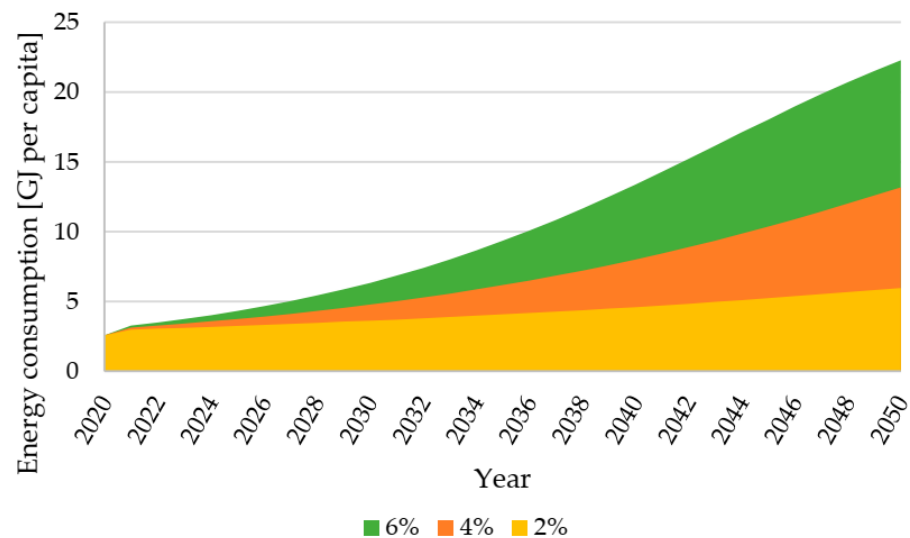


Figure 5. Energy consumption by varying GDPc.

Figure 6 shows the influence of the GDPc in total emissions per capita in different periods in natural gas inclusion scenarios. As can be observed, CO₂ emissions are most affected by the GDPc, generating increases of up to 375% by the year 2050. Likewise, as evidenced, independent of the GDPc, there is an initial reduction in CO and NO_x emissions; however, an increase in these pollutants is generated by the year 2050. The tendency that the greater the GDPc, the greater the generation of these emissions, has been identified. It was also identified that, for PM_{2.5} emissions, independent of the GDPc, the inclusion of natural gas technologies generates a significant reduction of the emission of this material.

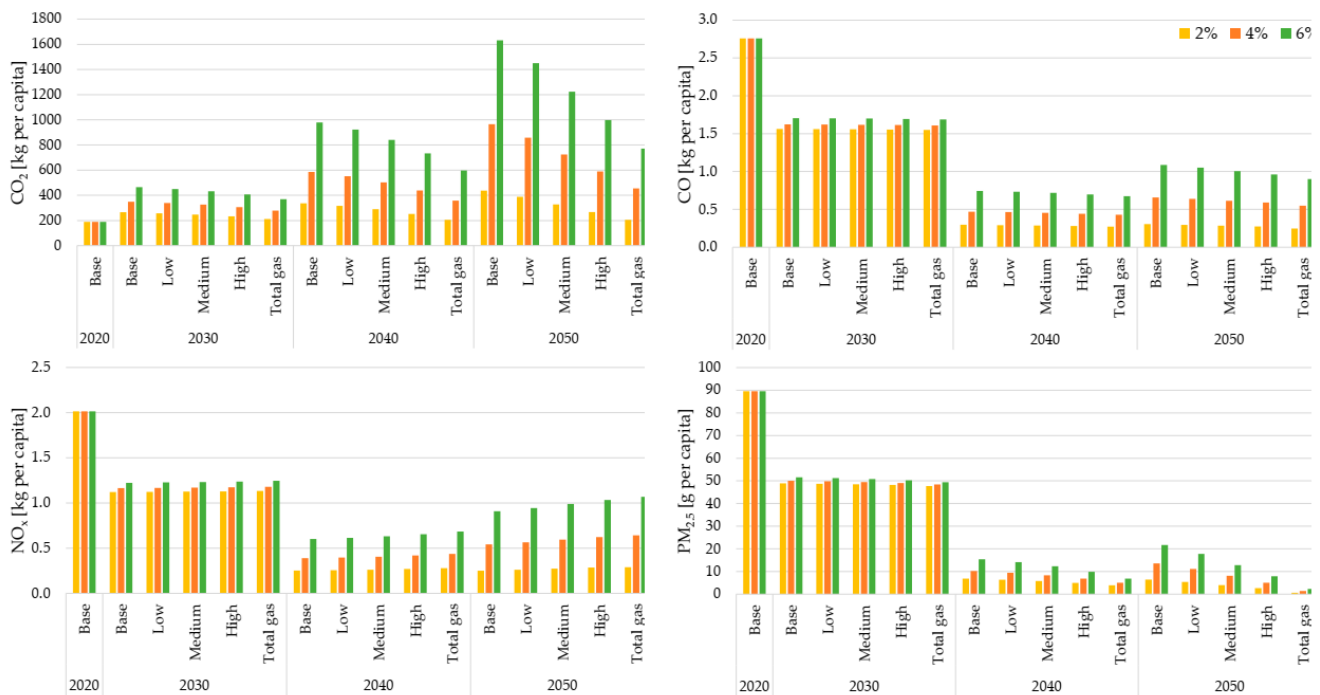


Figure 6. Sensitivity analysis—total emissions per capita.

5. Conclusions

In this article, an evaluation of the inclusion of natural gas as a transition fuel to reduce the use of diesel and gasoline in heavy-duty passenger (HDPV) and freight vehicles (HDFV) has been executed. Taking into consideration their operating conditions, the use of compressed natural gas (CNG) in HDPV and liquified natural gas (LNG) in HDFV are considered.

Four substitution scenarios were proposed considering different natural gas penetration rates. For the evaluation, a baseline of vehicles in Colombia was used as a case study. Vehicle projections were made based on the socioeconomic criteria of the population, annual vehicle kilometers traveled (VKT), fuel economy, and vehicle emission standards.

Based on the results, we can conclude that the inclusion of natural gas in heavy transport road vehicles significantly reduces CO and PM_{2.5} emissions per capita. By 2050, potential reductions of around 82% and 77% of these pollutants, respectively, are identified in HDPV. On the other hand, a reduction of PM_{2.5} emissions of the order of 90% can be expected by 2050 in HDFV, compared to the baseline scenario. The results show that the use of natural gas in HDV can generate relevant environmental benefits in the medium and long term. However, it is necessary to promote the renewal of the fleet.

In the case of HDFV, there is evidence of a significant reduction in CO, NO_x, and PM_{2.5} emissions until 2035. Nevertheless, from this year, a net increase in the generation of these pollutants is identified. This is a product of the significant rise in the number of vehicles in operation. Thus, the inclusion of LNG in the HDFV fleet generates environmental benefits medium-term; however, long-term benefits will require more ambitious and complementary strategies of the decarbonization of the vehicles.

Based on the results of the period from 2034–2036 (medium-term), strategies should be developed to reduce pollutant emissions in the future. This said, addressing challenges in transport requires an integral approach that implements greater actions to diversify energy sources in the transport sector. Long-term, the most important action would be a transition to electric vehicles (EV), which provide a more viable road to clean transportation with zero emissions.

A sensitivity analysis of evaluated indicators concerning the GDPc was performed. It was identified that with a higher GDPc, there is a higher purchasing power of vehicles, which induces growth in the vehicle fleet in operation. Thus, this triggers a significant increase in GHG and pollutant emissions. This tells us that greater wealth—a greater GDPc—demands the deployment of more ambitious energy and environmental policies in the transport sector.

Several authors disagree on the effects of the use of natural gas in HDV since some studies reveal that CO₂ emissions and energy consumption are reduced, others report increases on these parameters. This is because results are closely linked to the characteristics of the vehicle fleet under analysis and its operational conditions. The results showed in this article are based on the historical data and information of the HDFV and HDPV fleet of Colombia and the energy demand reported on local studies. Nevertheless, the projected behavior of pollutant emissions, such as NO_x is aligned to the results reported in other studies, where the increase in the emissions of this pollutant is reported when LNG is used in HDV.

The results presented in this study are based on limited information on the actual operation and technological characteristics of the HDV fleet in Colombia. Thus, to generate technical inputs closed to the reality of the country is required for supporting the enforcement of policies to reduce energy consumption and pollutant emissions on HDV. Thence, the existing gaps between real and reported data on pollutant emissions, fuel consumption, and the VKT of HDPV and HDFV need to be closed. In addition, modeling the impact of geographical conditions and the age of the vehicles on fuel consumption and pollutant emissions will allow us to perform more reliable projections. Finally, to compare natural gas-powered vehicles with electric and hybrid technologies is necessary to establish a whole roadmap to move the HDV fleet towards sustainability.

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Appendix A

Table A1. Emission factors for HDPV and HDFV [45–47].

HDPV				
Fuel	Euro Standard	CO [g/km]	NO _x [g/km]	PM _{2.5} [g/km]
Gasoline	Euro I	73.903	5.710	0.125
	Euro II	97.398	5.220	0.035
	Euro III	70.932	4.600	0.031
	Euro IV	24.356	3.430	0.010
	Euro V	6.213	1.180	0.007
	Euro VI	6.213	0.230	0.0003
Diesel	Euro I	6.753	24.826	0.653
	Euro II	6.753	20.140	0.409
	Euro III	6.753	18.022	0.275
	Euro IV	4.740	10.446	0.227
	Euro V	0.318	1.937	0.021
	Euro VI	0.318	0.374	0.001
CNG	Euro I	1.148	17.626	0.144
	Euro II	1.148	14.299	0.090
	Euro III	1.148	12.796	0.0605
	Euro IV	0.806	7.417	0.050
	Euro V	0.054	1.375	0.005
	Euro VI	0.054	0.266	0.0002
HDFV				
Fuel	Euro Standard	CO [g/km]	NO _x [g/km]	PM _{2.5} [g/km]
Gasoline	Euro I	44.009	3.741	0.056
	Euro II	18.980	2.489	0.019
	Euro III	11.563	1.349	0.016
	Euro IV	5.006	0.343	0.006
	Euro V	1.437	0.055	0.003
	Euro VI	1.437	0.055	0.003
Diesel	Euro I	21.56	5.543	0.310
	Euro II	9.425	5.187	0.477
	Euro III	6.012	4.175	0.221
	Euro IV	2.194	1.461	0.085
	Euro V	0.502	0.377	0.012
	Euro VI	0.502	0.377	0.012
LNG	-	0.487	0.513	0.0015

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