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Dynamics of Greenhouse Gas (GHG) Emissions in the Transportation Sector of Senegal

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Abstract: The transportation sector of Senegal is dominated by the road subsector, which relies on fossil fuels: gasoline and diesel. Their combustion generates substances such as carbon dioxide, methane, nitrous oxide, and many others responsible for climate change, which has negative impacts on the environment, human health, and activities. This study is based on data collected from Senegal's official reports on transport and energy, and Intergovernmental Panel on Climate Change (IPCC) greenhouse gases' analysis methods. In the period 2000–2013, growing emissions were experienced, reaching up to 2.38×10^6 tCO_2-eq in 2013. The aging vehicle fleet (~20 years old on average), made up of light-duty vehicles (around 85%), a fast-growing number of imported cars, and the predominance of diesel engines (around 59%) are the aggravating factors. Beyond climate change, other gaseous substances resulting from the combustion of fuels such as carbon monoxide (CO), sulfur oxide (SO_2), and particle matters (PMs) contribute to the deterioration of the outdoor air quality. Therefore, it is becoming urgent to monitor the evolution of these emissions and take appropriate measures to reduce their concentrations in the atmosphere. The Government of Senegal has taken a step forward through the modernization of transport infrastructure, and the creation of a center dedicated to the monitoring of outdoor air quality (Centre de Gestion de la Qualité de l'Air—CGQA) and a center in charge of the technical control of vehicles (Centre de Contrôle Technique des Véhicules Automobiles—CCTVA) in Dakar, but much remains to be done.

Keywords: greenhouse gas emission; fossil fuels; transportation sector; combustion; air quality

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1. Introduction

The transport sector is an important part of the economy, allowing the movement of goods and people over varying distances. Historically, people move for various reasons: search for food, need for trade, leaving for battle grounds, fleeing from a disaster, diplomacy, tourism, and so forth. Over time and thanks to technological, cultural, and political changes, the means of transport have been greatly modified, reaching today's sophisticated state with diverse means [1]. Therefore, mankind, who at a period of his history had only walking as means of transport, now has a range of choices: bicycle, motorcycle, automobile, train, aircraft, boat, and so forth. Modes of transport are usually grouped in categories: animal-powered transport, air transport (aircraft, airship, balloon, hang glider, helicopter), human-powered transport (cycling, walking), ship transport (boat, ship, submarine), rail transport (train, metro, tram), road transport (motorcycle, bus, car, truck, etc.), and others like lifts, escalators, and spaceships. Depending on its implementation and integration, the role of each mode is specific. Dostal and Adamec, for instance, studied the transport sector of the Czech Republic and showed the specific role and advantages of each mode [2]. New developments are modifying significantly the transport systems in the 21st century. Autonomous vehicles, drones, maglev trains, electric vehicles, and the hyperloop will change the transport of the present century. To be attractive, these means of transport must combine comfort, speed, robustness, and some luxury items, and require dedicated infrastructure.

The state of the transport infrastructure in Africa is linked to its recent history. Precolonial infrastructure was modified to serve the interests of colonial companies (i.e., transfer mineral and agricultural resources to Europe). Transport facilities were built, rail being predominant as it offers efficient and massive freight transport [3,4]. By 1960, most countries became independent, and first rulers had the ambition to bring prosperity to their populations. Most infrastructure in the modern Senegal are colonial heritage. In order to link various parts of the countries, roads were built and in some places car manufacturers installed assembly lines, like in Senegal [5]. Therefore, African nations, till the 1970s, enjoyed a relative era of prosperity, but the structural adjustment plans and other factors like low commodity prices (raw materials) and the Franc CFA currency devaluation (in 1994) led to severe economic crises (in Figure 1, the decline in the trade balance in Senegal from 1995), preventing them from investing in the development of infrastructure. This partly explains why Africa lags behind in transport development [6]. The state of the transportation sector was exposed in previous work, in which it is shown that African transport systems still need improvement [3,7].

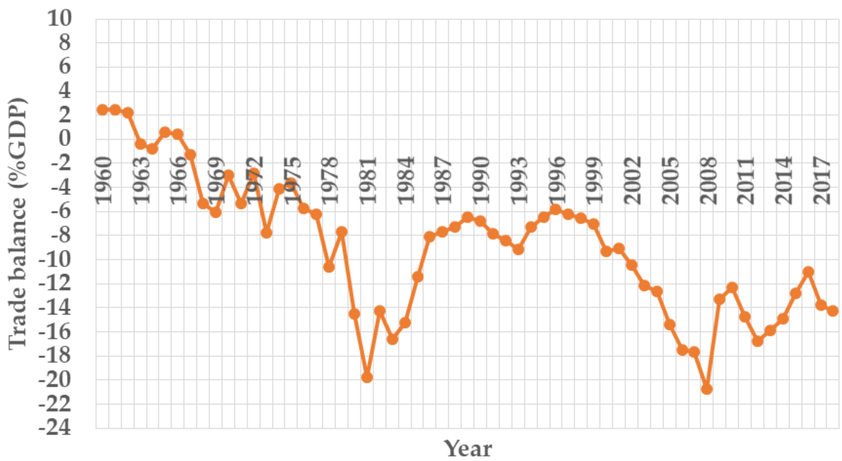

Figure 1. Time variation of the trade balance of Senegal (1960-2018), source: ref. [8].

Senegal, a country located in West Africa, shares borders with the Atlantic Ocean in the west, Mauritania to the north, Mali in the east, Guinea-Conakry and Guinea Bissau in the south. Some of the country's data are given here [9]:

- climate: hot tropical
- area: 196,722 km^2
- population: ~16.5 million inhabitants
- population growth rate: ~2.8%
- GDP (Gross Domestic Product) per capita (PPA): ~US $3349
- divisions: 14 regions
- capital city: Dakar
- HDI (Human Development Index): 0.51(2017)

The transport sector in Senegal represents around 10% of the GDP and consumes 33% of the total energy consumed in the country [10]. As in most African nations in sub-Sahara Africa, this sector is based on the utilization of fossil fuels which are a major source of greenhouse gases and atmospheric pollutants. These emissions have negative impacts on the climate and on the health quality. Studies have shown that the level of pollution in West Africa is vastly underestimated [11], and is constantly increasing with population growth and urbanization. According to the NGO Public Eye, pollution is partly due to the quality of the fuels found on the market [12]. They are imported from Europe where strict regulations do not allow their use. Countries in West Africa are inundated with poor-quality fuels without any control. Very little effort is made to reach a strict regulation in those countries where national agencies dedicated to quality control are weak or simply do not exist. These fuels, and more specifically the substances released in the atmosphere after their combustion, deteriorate the quality of the air and contribute to climate change with adverse consequences: frequent floods, seasonal irregularities, disappearance of flora and fauna, and so forth. Despite the critical situation observed, very little effort is being made to assess these emissions in sub-Saharan countries, as regions are severely hit and conflicts due to climate change have become frequent, especially in rural areas and Sahel regions. Combined with high rate of unemployment, poverty, corruption, and lack of sustainable development policy, climate change is fueling terrorism in Mali, Somalia, Sudan, Niger, Nigeria, Cameroon, and Burkina Faso. The present study assesses the dynamics of greenhouse gas emissions in Senegal. Thanks to the statistical data collected, these emissions are evaluated and analyzed. The paper is divided into several parts: first, the transport sector will be presented, then the greenhouse gases recalled as well as the factors that influence their concentration. Then, statistical data are analyzed and the methodology for calculating emissions presented. Results are finally presented and discussed before some conclusions are raised.

2. Materials and Methods

2.1. Description of the Transportation Sector of Senegal

The transport sector in Senegal is multimodal, divided into four modes: roadways, seaways, airways, and railways. Each mode has specific equipment and infrastructure. Transport modes need to be integrated, the objective being to ensure an easy move of people and goods within and outside the country.

2.1.1. Roadways Transportation

Roadways submodes are grouped into two main categories, depending on whether an engine is used or not. Walking, which involves the use of muscular energy, is very present for two main reasons: the low purchasing power of the populations and the lack of infrastructure. If walking is the means of choice in the countryside, it is clear that in cities also populations are forced to walk [13]. In urban areas, motor transport is expensive for the majority of populations. Bicycles are not popular, being used by very few people, and do not benefit from the existing infrastructure, which does not keep special lanes for cyclists. Animal carriages are popular among the underprivileged layers of the population [14]. In urban areas, it is used to transport people (as in Figure 2), goods, and municipal waste. It is very useful in rural areas where it appears to be the only means of transportation of large quantities of goods, and serves as an ambulance in some cases. Horse-drawn transport is an income-generating activity for craftsmen and donkey/horse breeders.

Figure 2. A horse carriage in the city of Thies (**left**) and a locally assembled car (**right**), “ndiaga ndiaye”.

For the motorcycle taxi, a rise in power has been witnessed in recent years, with more than 100,000 vehicles recorded, an ever-increasing number. At the beginning, it was used by unemployed young people, and it is gradually spreading to all those without lasting employment. The lack of regulation exposes motorcyclists to all kinds of risks, and particularly to accidents. They contribute to the economy by transporting people and goods, and also through the fuel they consume. Tricycles have recently made their appearance into the transport of goods, and are gradually supplanting carts. They are imported from China, and mounted locally. The automobile is a privileged means over long distances. Low purchasing power limits the development of individual transport and strengthens mass transport. Both inside and outside cities, there are buses, minibuses, taxis, and informal transport by very old vehicles operated without license (the so-called “clandos”), that carry people. Minibuses are of several types: Tata (assembled by the company SENBUS Industries), “car rapid”, and “ndiaga ndiaye” (see Figure 2). The latter are made in makeshift workshops by craftsmen with often insufficient technical skills. The government holds a public transport company, with two branches: “Senegal Dem Dikk” for intercity transport and “Dakar Dem Dikk” for urban transport in the capital city, Dakar. The vehicle fleet has more than 600,000 vehicles (more than 70% being in the Dakar region). These automotive vehicles are generally imported from other continents, with a small proportion assembled locally as minibuses. The road network was approximately 16,496 km long in 2016, and its modernization continued with the completion of several projects, including the construction of the Dakar-Diamniadio and Ila Touba highways. However, the density of the road network remains low as in most sub-Saharan African countries, and the percentage of paved roads is less than 40%.

2.1.2. Airways Transportation

Senegal has about ten airports; the most important is the Diamniadio airport inaugurated in 2018. Less important ones are Saint Louis, Cap Skiring, Ziguinchor, and Tambacounda. Records show that Senegal has had several airline companies in its history, but these often fizzled out. Senegal currently has a national company, Air Senegal, launched in 2018, and a private company, Transair.

2.1.3. Seaways Transportation

The country has four ports, the most important of which is in Dakar. Kaolack, Saint Louis, and Ziguinchor also hold port facilities. The country’s foreign trade takes place mainly through the port of Dakar, or 95% of trade. Maritime transport links Casamance to the capital, Dakar, and is critical for opening up this part of the country. On 26 September 2002, the “Joola”, the main ferry linking both parts of the country, sank one night due to poor meteorological conditions, poor maintenance, and overload, and close to 2000 lives were lost. In order to improve the connection, the maritime transport was reorganized, another ferry, “Aline Sitoe Diatta”, was bought, and the Farafeni’s bridge that crosses the Gambia was built. It is worth noting that fishing activities are important, involving populations living in the coastal regions and islands, where some craftsmen build local canoes with integrated gasoline engines.

2.1.4. Railways Transportation

Railways transportation began in Senegal in the 19th century during the colonial period and was intended for the exploitation of raw materials from the hinterlands and neighboring countries. After the independence in 1960, there has been a gradual decline in traffic, and poor management has led to the difficulties that plunged rail transport into a state of disrepair. The network is approximately 906 km long. A rehabilitation plan has been adopted by the government and investors are still expected. In an effort to modernize public transport in the overcrowded Dakar region, a 36 km long electric line, the “train express regional (TER)”, is being built and will help to smooth traffic between Dakar and its suburbs.

2.2. Greenhouse Gases and Transport

Greenhouse gases (GHGs) originate from natural sources and human activities (anthropogenic sources): transport and trade, industry, commercial and residential buildings [15].

Identified GHGs are [16]: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halogenated hydrocarbons (containing F, Cl, or Br). Carbon dioxide (CO_2) is derived from the combustion of fossil fuels and represents the bulk of anthropogenic emissions. Methane (CH_4) results from human activities such as farming, extraction of natural gas, pasture systems, and grass burning and from fermentation of organic matters. Nitrous oxide (N_2O) originates from crop farming, biomass combustion, and industrial activities. Halocarbons and other synthetic fluoro-compounds (HFC, PFC, and SF6) derive mainly from human activities.

Globally, the emissions counted come from the dominant subsector of road transport. International air transport and intercontinental maritime transport enjoy a legal vacuum as they contribute significantly to global warming, with planes and ships using large quantities of fuels. With regard to road transport, many factors influence emissions and are classified into four categories classified as follows [17]: vehicle characteristics (vehicle category, vehicle weight, type of fuel, age of the engines in the fleet, engine displacement, type of transmission, tire configuration, oil viscosity, aerodynamics, maintenance, etc.), the characteristics of the journey (load weight, distance of the trip, type of road, condition of the road, morphology of the road, character of the driver, use of embedded electronic devices, etc.), the characteristics of the trip (average speed, road congestion, etc.), and environmental characteristics (ambient temperature, wind speed, altitude, precipitation, humidity, use of the air conditioning system, engine temperature, etc.). The analysis of these characteristics shows from Senegal old and poorly maintained vehicles, low-quality fuels, tires in poor condition, weight and aerodynamics of vehicles often modified, and a lack of strict regulation. Trip analysis reveals overloaded vehicles (passenger and freight), unpaved or very poor roadways, frequent congestion, and careless and often unskilled drivers (without a driver's license or obtained fraudulently). The state of the transport sector as described here above explains the poor performance as obtained in previous work [5,18].

2.3. Statistical Data

Statistical data on the vehicle fleet can be obtained from several organizations [19–24]: the Ministry of Transport, the Ministry of Energy and Oil, and the National Agency for Statistics and Demography (ANSD). Challenges in data collection and lack of synergy between organizations make it difficult to obtain extensive, detailed, reliable, and consistent data. Data regarding the vehicle fleet and presented in this study are those of the ANSD and the Department of Road Transport (DTR) of the Ministry of Transport. Although these data differ, they display the same reality: an increasing number of imported vehicles. In Figure 3, it can be seen how fast the number of new vehicles has been growing since 2004. Before 2012, a vehicle of more than five years old could not be imported. But the newly elected government brought the limit to eight. However, pollution and congestion in the main roads of Dakar have prompted the government to elaborate a new regulation to prohibit import of used vehicles. According to the DTR, the vehicle fleet had about 290,977 vehicles by 2005, and 468,051 vehicles by 2015. By conjecture, Senegal's vehicle fleet would be around 600,000 vehicles in 2020.

In Senegal, automotive vehicles are classified into several categories: trucks, taxi cabs, buses, and minibuses, light duty, and so forth. The age of the car fleet is around 20 years, justified by the presence of very old vehicles on the roads. The oldest vehicles are found among taxi cabs, coaches, construction equipment, and trucks, with an average between 28 and 33 years of age [25]. Vehicles in good condition or relatively young are ambulances and vehicles belonging to tourism companies.

The number of seats in a vehicle varies and depends on its use. Light-duty vehicles have a limited number of seats, around five, and are used for urban trips, while vehicles intended for mass transport (buses and minibuses) have more seats, usually more than 10. Construction or freight vehicles only have seats for the driver and the assistant. According to the National Agency for Statistics and Demography (ANSD), the vehicle fleet in 2010 had a total of 326,000 vehicles, of which 278,258 were of less than five seats, representing 85% of the fleet (see Figure 4). Around 5% of the fleet is made up of public transport vehicles: minibuses (car rapid, ndiaga ndiaye, etc.), buses, and tourist vehicles.

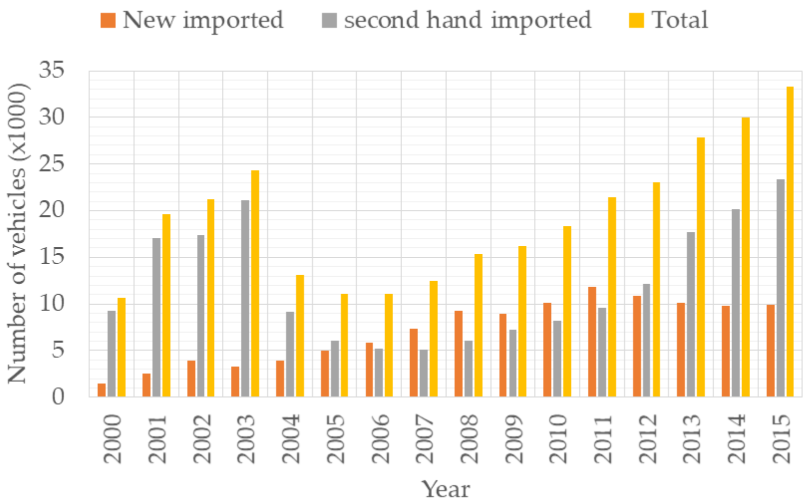

Figure 3. Increasing number of imported cars (source: DTR, 2015).

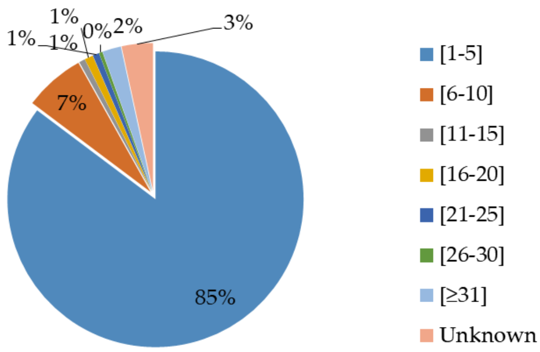

Figure 4. Distribution of the vehicle fleet by number of seats (Source: ANSD, 2010).

2.4. Methods for the Evaluation of Greenhouse Gas Emissions

2.4.1. Energy Consumption in Transportation

Transport is an energy-intensive activity. Globally, it is second after the residential sector, and consumes nearly 29% of the total energy consumed globally [26]. Road transport is heavily dependent on fossil fuels, with gasoline and diesel covering almost all needs. The debate over whether heat engines (gasoline or diesel) should be phased out is going on, as hybrid and electric vehicles are progressively introduced in developed countries. Air transport is very dependent on hydrocarbons, aviation gasoline or kerosene jet fuel being used in most aircrafts. Small and single-person or remotely controlled electric planes (drones) are under development with good prospects. Maritime transport is also heavily dependent on fossil fuels: gasoline, heavy fuel oil, and light marine diesel (domestic fuel) are the fuels used. Railways transport is an exception and uses not only fossil fuels, diesel, and heavy fuel oil, but also electricity.

Types of energies by subsector in Senegal (in 2013) are as follows: kerosene for aviation, diesel fuel for railways (not taken into account in this study), gasoline for maritime transport, and gasoline and diesel for roadways. Fossil fuels undergo an exothermic chemical reaction (combustion) from which heat is released. The energy released is then used in various processes such as rotating the crankshaft, therefore converting heat into work. The quantity of heat released during the combustion process is given by Equation (1):

$$E = m\,\mathrm{LHV} \tag{1}$$

where m is the mass (in kg) of fuel, and LHV is the lower calorific value. Fuels are sold on the market in volume, and the mass is obtained by multiplying with the density. Fuels generally have different LHVs, and the more energetic they are, the higher the values will be. LHV values (in MJ/kg) are given in Table 1 for a number of fuels. As can be seen, fossil fuels (gasoline, diesel, fuel oil, etc.) are more energetic than those of biological origin, such as biogas. The total energy for a transport mode is deduced by summing the quantities of energies used in this subsector, and subsequently, the total energy consumed in the transportation sector is given by the sum of all quantities from all modes as given by (Equation (2)) where i refers to the fuel and j to the mode.

$$E_{ts} = \sum_{i,j} E_{i,j} \quad (2)$$

Table 1. LHV values for fuels.

Fuels	LHV (MJ/kg)	Density (kg/m^3)
Gasoline	44.80	750
Diesel	42.87	840
Aviation gasoline	44.80	704
Kerosene jet fuel	40.53	794
Marine gasoline	44.80	750

2.4.2. Calculation of Emissions of Carbon Dioxide, Methane, and Nitrous Oxide

Transport systems produce direct greenhouse gas emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from the combustion of fuels, and other pollutants such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulfur oxide (SO_2), particulate matter (PM), and nitrogen oxides (NOx). The quantity and the quality of the emitted substances depend on the type of fuels. The IPCC guidelines provide methods for the estimate of the gases emitted by all transport modes which will further be used in this study.

For the road subsector, carbon dioxide emissions are calculated on the basis of the type of fuel consumed and its quantity. The IPCC guidelines display two approaches (Tier 1 and Tier 2) for the estimation of the direct carbon dioxide emissions. The Tier 1 approach calculates carbon dioxide emissions by multiplying estimated fuel consumed with a default CO_2 emission factor. The Tier 2 approach is the same as Tier 1 except that a country-specific emission factor of the fuel consumed is used. Three approaches are available for the estimation of methane and nitrous oxide emissions. The Tier 1 approach uses fuel-based emission factors and is used when it is not possible to estimate the fuel consumption by vehicle type. Tier 2 uses fuel-based emission factors and vehicles' subcategories. The Tier 3 approach uses country-specific data, and emissions calculations are based on vehicle subcategory and activity level.

In this study, the default values as given by the IPCC were used. Although it is suitable to use values close to the reality, lack of reliable and consistent data is a challenge. The factors used might lead to the underestimation of the emissions. Investigations showed that the national fleet was old, above 20 years, and some vehicles may be functioning without catalytic converters. The improper operation or lack of catalytic converter increases methane emissions while lowering the nitrous oxide emissions. The engine loading is another factor which can increase methane and nitrous oxide emissions. Most cars are located in Dakar, which has a high traffic density. Moreover, buses and minibuses are usually overloaded. Fuel composition is an issue. Poor fuel quality and high sulfur content are said to be responsible for the poor air quality. Dakar is one of the most polluted cities in West Africa as medical doctors reported increased rate of respiratory diseases. Poor fuel quality adversely affects the engine efficiency and increases the emission rates.

The air transport is usually divided into four main categories: civil IFR and civil VFR flights, helicopters, and military flights. In general, two types of engines, reciprocating engines and gas turbines, are used in aircraft. Most aircraft run on kerosene jet fuel while small aircraft use aviation gasoline. Emissions depend on aircraft type, fuel type, engine type and load, and the flying altitude. The operation of an aircraft is divided into two main parts: the LTO (landing/takeoff) cycle and the cruise. LTO takes place below 1000 m, and includes taxi-in and -out, take-off, climb-out, and approaching-landing. Cruise takes place above 1000 m and includes climbing, cruising, and descending from cruise altitudes. All these phases have an impact on the fuel consumption and gas emissions. The IPCC guidelines provide three approaches for emissions estimates: Tier 1 based on fuel consumption, Tier 2 based on the number of LTOs and fuel use, and Tier 3 based on the data of individual aircraft. Although Tier 2 and 3 give more accurate results, Tier 1 will be used in this study as the only data available is regarding the fuel consumption. Moreover, the data obtained are related to the kerosene jet fuel sold in the country. Therefore, (Equation (3)) will be applied to determine the emissions of various gases along emissions factor default values provided by the IPCC guidelines.

Marine transport covers all water-borne transport from recreational boats to cargo ships (ferries, tankers, carriers, container vessels, etc.) and includes ocean-going, in-port, and inland waterway activities. Marine and inland vessels use mainly steam, diesel, and gasoline (2/4 stroke) heat engines. Electricity, hydrogen, and fuel cells are yet to be adapted in water transport. The combustion of the utilized fossil fuels (coal, gasoline, diesel, and bunker or distillate) generates greenhouse gases and pollutants as well. The emissions could be also evaluated based on the IPCC guidelines which provides two approaches (Tier 1 and Tier 2). The Tier 1 approach is based solely on the fuel consumption. The Tier 2 approach emphasizes the fuel type and engine type. In this study, the Tier 1 approach is used, thus applying (Equation (3)) for all gases. Moreover, the statistical data available take only into account the fishing activities along the coastal areas and the rivers in the country. Fishing activities are carried out by small groups of fishermen who use gasoline engines. It is assumed here they are two-stroke type engines similar to those found in European inland waterways. The default emission factors used are displayed in Table 2.

Railway transport uses diesel and electric locomotives. Diesel locomotives tend to be more popular and are grouped into three main categories: railcars and yard and haul locomotives. Electric locomotives are powered by stationary power plants. The estimate of the emissions in this subsector depends on the quality, quantity, and consistency of the available data. Unfortunately, for this mode, it was not possible to get any data despite the long history of the railway in Senegal. It should be recalled that the railway reached Senegal during the colonial period (19th century), but was progressively abandoned after the 1960s.

Emissions of the main greenhouse gases (carbon dioxide (ε_{CO_2}), methane (ε_{CH_4}) and nitrous oxide (ε_{N_2O})) can be evaluated using Equation (3) [27]. Emission of a specific gas is obtained by multiplying the energy of each fuel k, E_k (in TJ) by the emission factor of the gas, f_k^{GHG} (in kg/TJ) contained in Table 2 as given by the IPCC [28].

$$\varepsilon_{GHG} = \sum_k E_k . f_k^{GHG} \tag{3}$$

Emissions can be further converted into CO_2 equivalent, taking into account their global warming potential (GWP). With carbon dioxide as the reference, Table 3 gives the global warming potential of several substances, including nitrous oxide and methane, which tend to be higher than that of the carbon dioxide. Nevertheless, the concentration of the carbon dioxide is much higher as the product of the combustion in the atmosphere. Total amount of carbon dioxide (i.e., the global effect of all three greenhouse gases) is therefore given using Equation (4) (as CO_2-eq) in which i refers to the fuel, k to the gas, and α_{GHG} is the global warming potential of the gas.

$$\varepsilon_{CO_2-eq} = \sum_i \sum_k E_i.\alpha_{GHG,k}.f_i^{GHG;k} \quad (4)$$

Table 2. Emission factors for greenhouse gases, source: Ref. [28].

Fuels	Emission Factors		
	CO_2 (kg/TJ)	CH_4 (kg/TJ)	N_2O (kg/TJ)
Gasoline/road	69,300	33	3.2
Diesel/road	74,100	3.9	3.9
Gasoline/water *	71,000	110	0.4
Jet kerosene/air	71,500	0.5	2

* IPCC default emission factors for European ships and boats on inland waterways (two-stroke engine).

Table 3. GHGs and Global Warming Potentials (GWP), source: Refs [29,30].

Substances	Chemical Formula	GWP (Over 100 Years)	Sources
Carbon dioxide	CO_2	1	Combustion processes
Methane	CH_4	25	Landfills, coal mining, wastewater treatment, biomass combustion
Nitrous oxide	N_2O	298	Agricultural soils and nitric acid production

3. Results

3.1. Energy Consumption

Details on fuel consumption in the period 2000–2013 are given in Table 4, by transport mode and by fuel type. Energy consumption analysis shows the dominance of road transport (see Figure 5). It is seen that in the period 2000–2013, the share of the road transport has been increasing over the years, to reach up to 95% in 2013. Trips using motorized vehicles take place most often on roads. This is a characteristic found in developing nations, where transport facilities are not well established. For the specific case of Senegal, road transport appears as the most affordable means of transport, but the reality on the ground is complex. In this subsector, diesel is the most used fuel (Figure 6), and this is justified by its price, lower than that of gasoline. The country's vehicle fleet is made up of 59% diesel engines which consume 81% of total energy (see Figure 6). This is partly explained by the fact that most diesel vehicles are used for public transport. Transport businesses see them as more profitable. Railways transport (not taken into account in the study) is in poor condition, and data on this mode are rather scarce. Nevertheless, efforts are being made to rehabilitate the existing infrastructure. Internal passenger transport with tram and metro is yet to be developed. Maritime transport is limited to the Atlantic coast, to passenger transport between the regions of Dakar and Casamance and to fishing activities. Air transport, which was a dynamic subsector before 2006, is declining due to the bankruptcy of successive companies. From 39%, its share in the energy consumption came down to almost 0%. A new airport was inaugurated in 2018 and a new company, Air Senegal, was created in 2019 to bring more activities in this subsector. However, air transport, less popular than road, will continue to serve a minority of privileged people with high income.

Table 4. Fuel consumption (2000–2013), source: Refs [29,30].

Year	Road				Aviation		Water		Total
	Gasoline		Diesel		Kerosene		Gasoline		
	PJ	%	PJ	%	PJ	%	PJ	%	PJ
2000	2.54	9.55	12.08	45.49	10.41	39.20	1.53	5.76	26.56
2001	2.67	10.65	11.82	47.21	8.92	35.65	1.62	6.48	25.03
2002	2.89	11.70	12.99	52.51	7.17	28.98	1.68	6.81	24.73
2003	3.06	10.71	14.58	51.02	9.20	32.19	1.73	6.07	28.57
2004	3.13	10.08	16.13	51.94	10.23	32.94	1.56	5.03	31.06
2005	3.07	10.10	15.50	50.95	10.45	34.33	1.40	4.62	30.43
2006	2.96	9.05	17.12	52.34	11.29	34.52	1.34	4.09	32.70
2007	3.26	11.93	21.59	78.87	1.26	4.60	1.26	4.61	27.37
2008	3.19	12.71	19.63	78.32	0.99	3.94	1.26	5.04	25.06
2009	3.65	13.55	21.61	80.22	0.08	0.28	1.61	5.96	26.94
2010	3.84	13.66	22.83	81.29	0.15	0.55	1.26	4.49	28.09
2011	3.92	13.06	24.36	81.24	0.45	1.49	1.26	4.21	29.99
2012	3.99	13.91	23.33	81.38	0.03	0.12	1.32	4.59	28.67
2013	4.51	14.17	25.71	80.76	0.01	0.03	1.61	5.04	31.83

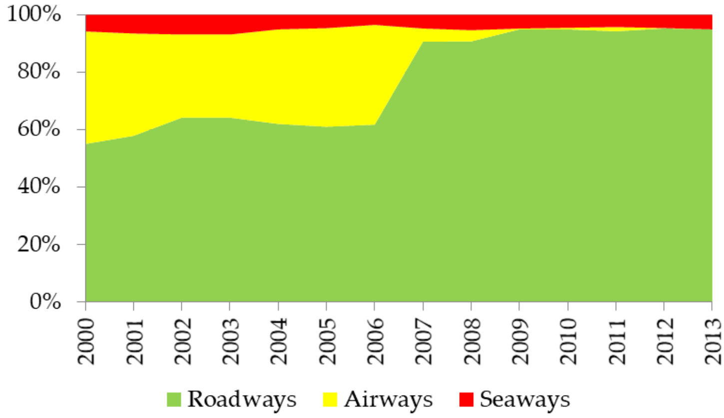

Figure 5. Distribution of the energy consumed by mode in the period 2000–2013 (source: adapted from data given by the Ministry of Energy and Petroleum).

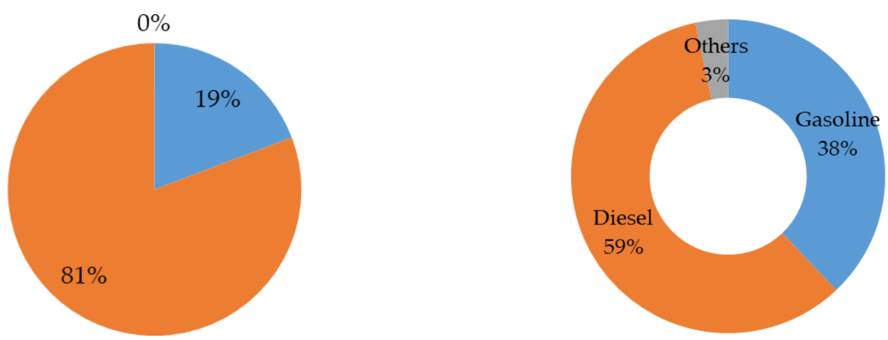

Figure 6. Energy consumption distribution by fuel (left) and distribution of car fleet by type of motor (source: ANSD, 2013).

3.2. Greenhouse Gas Emissions

Data from Table 4 were used to draw the evolution of different gases emitted after combustion in fossil-fuel-driven engines. Figures 7–11 show the evolution of the main greenhouse gases. Direct carbon dioxide emissions come from all transport subsectors (road, aviation, and maritime transport), except rail transport, which is not taken into account. Figure 7 shows the evolution of this gas in the period 2000–2013. As it can be seen, the carbon dioxide from the road is steadily increasing, reaching 2.21 million tons in 2013, 86% coming from the combustion of diesel oil. The contribution of aviation was between 28 and 43%, peaked at 43% in 2004, before it fell below 4% after 2005. Air transport played a significant role in the period 2000–2006, but has always been a difficult business in Senegal. In 1961, 11 countries including Senegal set up Air Afrique and by 2002, it closed down. Senegal had a public company, Air Senegal, founded in 1971, which in 2000 went bankrupt. Later on, the government joined with Royal Air Maroc, a Moroccan company, to create Air Senegal International (ASI) in 2001. Mismanagement and disagreements among partners led to a progressive decline from 2006, and to its closure in 2009. Local entrepreneurs with the support of the government founded Senegal Airlines in 2011, which was dissolved in 2015. In 2019, the government launched another company, Air Senegal. This brief historical review justifies the variations observed in carbon dioxide emissions from air transport. The contribution of maritime transport is between 4 and 7% and was 114,000 tons in 2013. It is worth noting that only gasoline used by fishermen was taken into account in this study. Road transport provides a significant amount of carbon dioxide due to the growing vehicle fleet, diesel fuel, economic activities, and other factors like climate. Road represents 52–96% of direct carbon emissions.

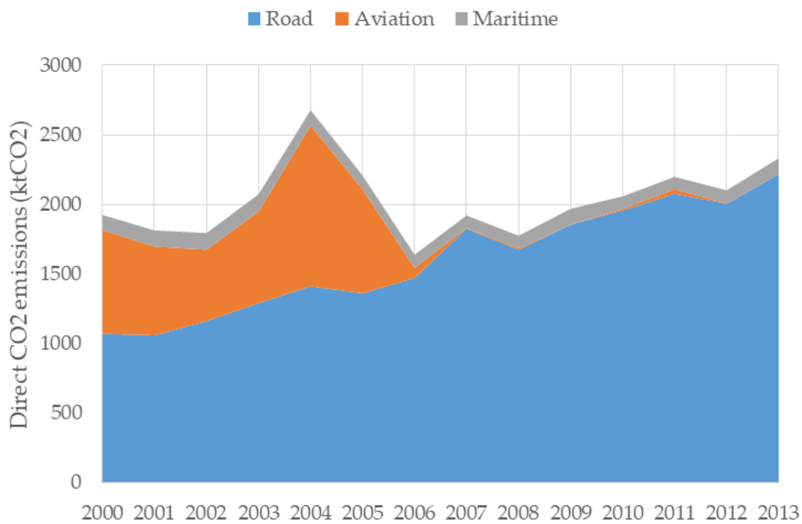

Figure 7. Dynamics of the direct carbon dioxide emissions (2000–2013).

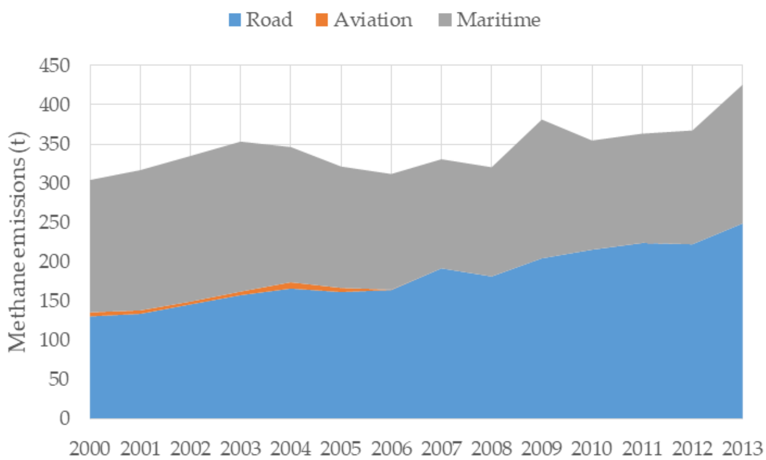

Figure 8. Dynamics and origin of methane emissions (2000–2013).

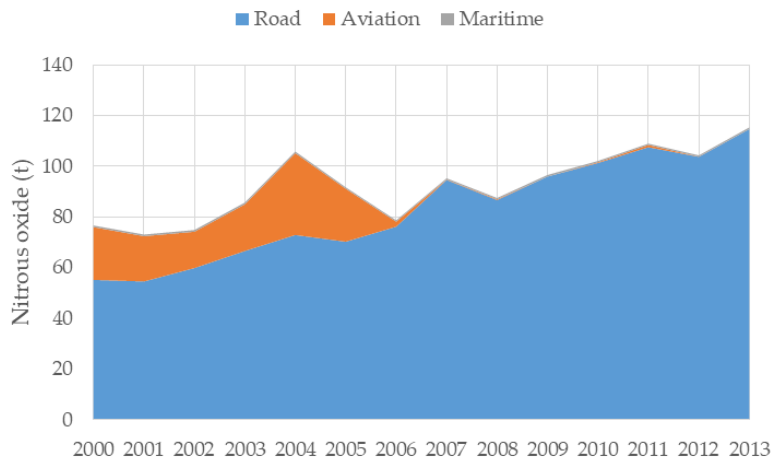

Figure 9. Dynamics and origin of nitrous oxide emissions (2000–2013).

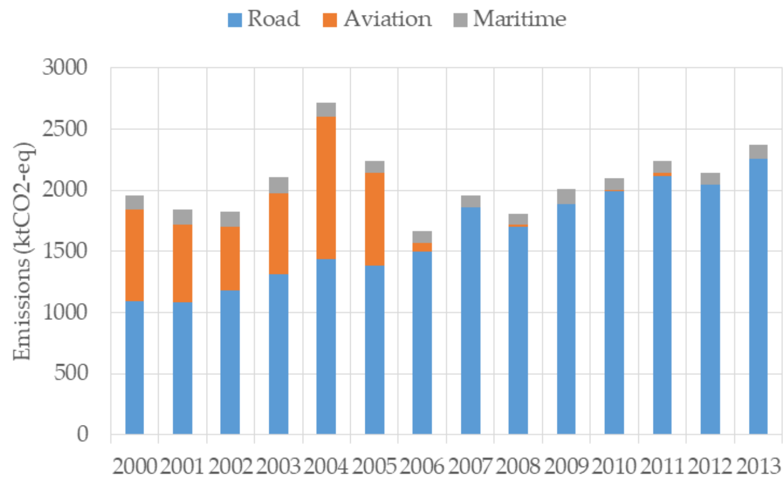

Figure 10. Total emissions from the transport sector in the period 2000–2013.

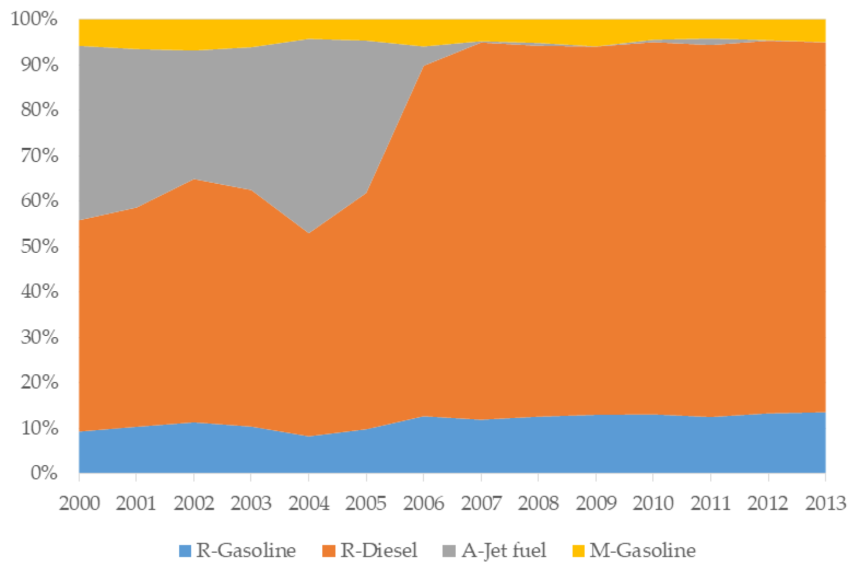

Figure 11. Evolution of the impact (CO_2-eq) of each fuel (2000–2013).

Methane is a gas emitted by natural sources and as well by combustion of fossil fuels. Figure 8 shows that on the roads, the quantity of methane emitted is steadily increasing;

from 130 tons in 2000, it reached 249 tons in 2013. Its share is between 42 and 61%. Maritime transport is the second contributor, with a share between 40 and 57%. Aviation has a very small impact, with nearly zero tons in 2013. In the period 2000–2013, aviation emitted less than 6 tons of methane per year.

Nitrous oxide, as seen in Figure 9, is mostly emitted on roads. It is seen that its amount is constantly increasing. From 55.25 tons in 2000, it reached 114.59 in 2013. Its share was also increased from 72% up to 99%. Aviation emitted between 19 and 31%, and decreased drastically below 1% because of the low level of activity in this subsector. Maritime transport emits less than 1 ton/year while its share remains below 1%.

The effects of all greenhouse gases can be evaluated, taking the action of carbon dioxide as reference, thus using the global warming potential. Figure 10 shows the origin and the evolution of carbon dioxide emissions, which increase over time, from 1.96 up to 2.38 million tons in 2013. Road transport is the most important emitter, and sees its share increasing from 55% up to 95%. In the period 2000–2005, aviation emitted about 28–43% of total emissions before its contribution decreased down to almost 0%. Maritime transport emits an average of 108 ktCO2-eq/year, and its share is less than 7% and decreases over the years. At this point, one can conclude that the greenhouse gases in the transport sector in Senegal are mainly due to road transport.

Figure 11 shows the impact of different fuels over time. The impact of the road gasoline is almost stable, with an average of 11.50%, and that of the maritime gasoline as well (5.28%). The impact of the aviation jet fuel, as high as 35% in the period 2000–2006, is less than 5% from 2006 and after. The negative impact of the diesel fuel has been growing over the studied period, from 46.59 in 2000 up to 81.50%. Therefore, the emissions produced by the transport sector is due to road transport, and more specifically, diesel oil has a key role.

Fuel consumption is followed by the emission of harmful substances, and the more energy is consumed, the higher will be the emissions. Nevertheless, the link between fuel consumption, greenhouse gas emissions, and economic growth should also be mentioned. Figure 12 shows the correlation between the GDP (gross domestic product) and the emissions in the transportation sector of Senegal. Data related to the GDP were extracted from Ref. [8]. The GDP per capita has been increasing since 1990, from 1447 up to US$ 3430 in 2018 [8]. In the periods 2000–2004 and 2006–2013, it is seen that the GDP correlates with the greenhouse gas emissions increasing; the GDP/capita increases with the carbon dioxide emissions. This confirms that at some point, the emissions in the transport sector are strongly correlated with economic growth.

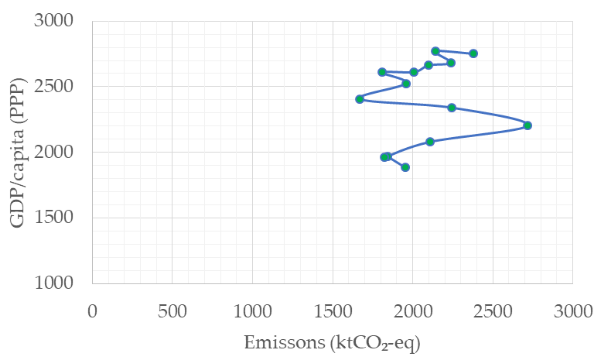

Figure 12. Correlation between emissions (ktCO_2-eq) and GDP per capita in the period 2000–2013.

4. Discussion

Carbon dioxide emissions as seen in the previous section are mainly due to diesel oil, which at the same time produces pollutants like sulfur dioxide, particle matter, carbon dioxide, and carbon monoxide, responsible for several diseases (asthma, lung cancer, cardiovascular attacks, etc.). It is worth noting that this fuel will be banned in the upcoming years in some countries across the world, while in African nations, no debate has been organized around the adverse effects of this fuel. Public Eye, a Swiss NGO (non-governmental organization) conducted a study which showed poor fuels (with high level of sulfur and other pollutants like benzene) produced in Europe were dumped in Africa [12]. The World Health Organization (WHO) has urged African nations to put strict regulations on fuels and invest in establishing clean processes in local refineries to improve the quality of local products. A policy aiming at protecting the environment and reducing the negative impact of fossil fuels, and in particular, diesel, should be considered in Senegal. The first step will be to eliminate the use of diesel in light vehicles, but this is a huge challenge. In 2009, it was decided to establish a center dedicated to the monitoring of outdoor air quality (Centre de Gestion de la Qualité de l'Air—CGQA) and a center in charge of the technical control of vehicles (Centre de Contrôle Technique des Véhicules Automobiles—CCTVA) in Dakar. Both centers are active, but operate only in the capital city. The extension to other major cities (Thies, Saint Louis, or Touba) is still awaited.

Beyond the fuel, actions in the direction of improving infrastructure and reducing the number of old vehicles with low efficiency should be taken. The government is about to introduce a new regulation to reduce the import of used vehicles, even though very old vehicles will still be found on roads. Another regulation on recycling of old vehicles would be more effective, but this approach is yet to be studied. Improvements of the road network are underway, but the maintenance of existing infrastructure is a huge challenge. In the Dakar region, a bus rapid transit (BRT) is under construction to reduce traffic congestion on main highways. The electric railway line (TER) will smooth the transport between Dakar, the Diamniadio airport, and its suburbs. Renewal of part of the vehicle fleet has been recorded and the introduction of a new and stricter driving license is in preparation. Substantial efforts remain to be made in the quality control of fuels, the introduction of electric motors, and the organization of less emitting means of transportation such as the bicycle. On the other hand, the automotive value chain is not fully mastered. The country does not have an automobile industry, and almost all vehicles in the fleet come from abroad in used condition. Special emphasis must be placed on training and mastery of the value chain including recycling. The idea of producing electricity in solar photovoltaic plants to power electric vehicles is not incongruous and deserves in-depth investigations.

Transport research is important as well as data collection. Reliable data should be available from different stakeholders and agencies so as to allow researchers to get insight into transport systems. Moreover, research in dedicated labs is important, and curricula should be made available on different aspects of transport: engineering, economics, sociology, logistics, and so forth.

5. Conclusions

The transportation sector of Senegal is multimodal with a dominant roadways subsector. Fossil fuel consumption is dominated by diesel oil, which generates the bulk of emissions. These emissions are increasing over the years, as seen in the period 2000–2013, and are favored by several factors, including the poor condition of the roads, the aging vehicle fleet, and so forth. The government is developing important projects like highways, airport, electric railway, and BRT construction, and installation of an air quality monitoring system, but a lot remains to be done. A sustainable transport policy should be established that would include a focus on light-duty diesel vehicles and their renewal, and in particular, light-duty vehicles, taxi cabs, and coaches with an average age of approximately 30 years. The modernization of transport infrastructure, with facilities in all parts of the country, must be a priority. The government would benefit from setting up a policy for the automotive sector, ranging from manufacturing to recycling, and whose benefits are numerous: protection of the environment, preservation of the health of populations, rebalancing of the trade balance, and job creation.

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