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Long-Term Forecast of Energy and Fuels Demand Towards a Sustainable Road Transport Sector in Ecuador (2016–2035): A LEAP Model Application

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Received: 16 November 2019; Accepted: 5 January 2020; Published: 8 January 2020



Abstract: The total energy demand in the transport sector represented 48.80% of the total consumption in Ecuador throughout 2016, where 89.87% corresponded to the road transport sector. Therefore, it is crucial to analyze the future behavior of this sector and assess the economic and environmental measures towards sustainable development. Consequently, this study analyzed: (1) the total energy demand for each vehicle class and fuel type; (2) the GHG (greenhouse gas) emissions and air pollutants NO_x and PM₁₀; and (3) the cost attributed to the fuel demand, between 2016 and 2035. For this, four alternative demand scenarios were designed: BAU: Business As Usual; EOM: Energy Optimization and Mitigation; AF: Alternative Fuels; and SM: Sustainable Mobility using Long-range Energy Alternatives Planning system. After analysis, the EOM, AF, and SM scenarios have advantages relative to BAU, where SM particularly stands out. The results show that SM compared to BAU, contributes with a 12.14% (141,226 kBOE) decrease of the total energy demand, and the economic savings for this fuel demand is of 14.22% (26,720 MUSD). Moreover, global NO_x and PM₁₀ emissions decreased by 14.91% and 13.78%, respectively. Additionally, accumulated GHG emissions decreased by 13.49% due to the improvement of the fuel quality for the vehicles that mainly consume liquefied petroleum gas, natural gas, and electricity.

Keywords: sustainable energy; alternative fuels; energy forecast; energy policies; road transport sector; Ecuador

1. Introduction

Over the last several years, the transport sector has gained particular relevance in the global energy context. During 2016, it represented around 27.8% of the total world energy demand [1], where oil remains its principal source with 96% [2]. It is estimated that the final consumption of liquid fuels worldwide in the transport sector has approximate participation of 55% by 2040. Thus, the final consumption share would remain constant from 2015 [3].

On the other hand, within the global energy consumption in this sector, liquid petroleum fuels would have a share that decreases from 95% in 2012 to 88% in 2040, due to the expansion of the consumption of alternative fuels [4]. Although natural gas and electricity still have deficient

consumption levels related to liquid fuels, they have a faster growth forecast of approximately three times between 2015 and 2040. For example, the consumption of natural gas for passenger and cargo transport would increase by almost 500% in the same period [5].

Between 2000 and 2012, in several Latin American countries, the energy demand in the road transport sector has been continuously increasing with high intensity every year; in Paraguay, it grew by 11%, in Panama and Bolivia by 5%, in Argentina and Costa Rica by 4% [6]. This trend has remained relatively constant, generating a significant increase in the vehicle fleet, with a 3.5% average each year, which is mainly composed of cars [7].

In 2012, in the countries of this same region, the transport sector had a total energy consumption share of 27% in the case of Nicaragua to 55% in the case of Ecuador. Inside this sector, road transport demanded around 85% of the total energy consumption, excluding Panama, where air transport continues to be very significant with 30% of the total energy consumption in the transport sector due to its geographical condition [8].

The high levels of liquid petroleum fuels consumption in road transport cause great concern at the global level but mainly in emerging market countries such as India, China, the United States of America, and large regions such as the European Union, Latin America, Southeast Asian, Eastern Europe, the Middle East, and Africa, which are the world's most energy demanded.

This concern is primarily related to the following reasons: (1) the localized polluting gases emissions within cities that reduce the quality of air which affects human and animal health [9,10]; (2) the increasing emissions of GHG that contribute to global warming, from 20 Gt CO₂e (billion metric tons) in 1990 to 37 Gt CO₂e in 2017, representing a 2.3% average increase per year. [11]; (3) the decrease of the non-renewable resources reserves due to their high demand; and (4) the limited energy generation alternative resources for worldwide consumption [12]. Consequently, most of the countries that signed the Paris Agreement study and promote initiatives to comply with Article 2 of the Agreement on Climate Change [13]. All this has influenced the development of numerous internationally relevant research studies related to (i) analysis of the reduction of polluting gases emissions, (ii) alternative fuels usage, and (iii) energy efficiency and optimization.

Among the most relevant and outstanding studies of some specific topics are the following: (a) energy for sustainable road transport and analysis of the energy demand consumption in road transport in China [9,14]; (b) fuels consumption in road transport in China and OECD countries [15]; (c) energy consumption and gases emission projection in Malaysia [16]; (d) atmospheric emissions from road transport and electric vehicles assessment in India [17,18]; (e) alternative fuels consumption in Japan and cleaner fuels in Europe [19,20]; (f) biofuels development for the automotive market in the UK and emission potential reduction for developing countries [21,22]; and (g) GHG reduction in the road transport sector in the U.S. and Korea [11,23].

These studies have different approaches and significant examples which show the need to know the energy implications and behavior of the road transport sector in the various countries and regions studied. Overall, they share similar aims to be analyzed on vehicular mobility: (i) estimate the energy demand and fuel type (fossil and alternative) for road transport; (ii) quantify positive and negative potential effects concerning polluting emissions; (iii) analyze the socio-economic benefits; and (iv) assess the impact of applying different policies in the road transport sector.

For all these reasons, it is crucial to develop and adopt, at a global level, firm and lasting policies that contribute to confronting these problems directly [24]. For example, the regional case of the sustainable urban mobility plan developed by the European Parliament [25], or local cases of urban mobility plans on all continents as in Madrid [26]; London [27]; New York City [28]; Abu Dhabi [29]; Bogotá [30]; Sydney [31]; Nairobi [32]; among others [33].

Therefore, following these trends, applied to Ecuador, the aims pursued by this research are the following: (1) estimate and analyze the total future energy demand for each vehicle type and fuel type consumed, within the road transport sector; (2) estimate the tank to wheel (TtW) total emissions of

the leading polluting gases, of the entire vehicle fleet; and (3) estimate the future total cost of energy demand of each fuel type consumed.

All these results are quantified and analyzed for the four alternative scenarios, which have been designed through the use of LEAP (Long-range Energy Alternatives Planning) system between 2016 and 2035, which will allow proposing the best scenario towards the sustainability road transport sector in Ecuador.

2. Review of the Road Transport Sector in Ecuador

Ecuador, with over 17 million inhabitants [34], is smaller than the 15 most populated cities worldwide [35], and it has around 2.1 million motorized vehicles [36], representing 120 vehicles per 1000 inhabitants. According to the “Transport statistics yearbook 2016” [37] published by the National Institute of Statistics and Census of Ecuador (INEC by its acronym in Spanish), 2,061,309 vehicles are registered in the national road transport sector, from heavy-duty vehicles to motorcycles. Table 1 shows the registered units corresponding to the vehicle classes, the fuel type, and the total energy consumed in the road transport sector in 2016.

Within this classification of vehicles, the most representative percentages are cars with 31.11%, motorcycles with 23.18%, followed by pick-up and off-road with 19.58% and 15.67%, respectively. Next, with smaller percentages are cargo trucks with 4.80%, cargo vans with 2%, and passenger vans and buses with 1.17% and 1.14%, respectively. Finally, dump truck with 0.57%, trailer truck with 0.47%, tanker truck with 0.11%, and other classes with 0.20%.

In 2016, according to the Association of Automotive Companies of Ecuador (AEADE by its acronym in Spanish), 137,768 motorized vehicles were sold, corresponding to 121,301 passenger vehicles and 16,467 cargo vehicles, distributed among different types [38].

According to the National Energy Balance 2017 based on the year 2016 [39], the transport sector has the highest energy demand, which in 2007 consumed 29,314 kBOE (thousand barrels of oil equivalent) (42.60%) and grew in 2016 to 44,284 kBOE representing 48.80% of the total demand energy. In that same year, the road transport sector had the highest consumption, with 89.87% of the total demand, 39,798.6 KBOE. Liquid petroleum fuels for these vehicles were the most demanded, gasoline with 19,670.11 kBOE and diesel oil with 20,066.12 kBOE, which represent 49.42% and 50.42%, respectively, both reach the 99.84% of the total fuels demand in 2016.

On the other hand, with a less significant demand are the LPG (liquefied petroleum gas) with 50.48 kBOE, bioethanol with 5.51 kBOE, and electricity with 6.18 kBOE, which together represent about 0.16% of the total. Within the fuel consumption sector, the vehicles with the highest demand are those of heavy-duty with 39.57%, followed by light vehicles with 26.44%, then light duty with 24.96%, passengers with 8.97% and other types with 0.06%.

In this context, the most demanded fuels for the road transport sector are diesel and gasoline. In a much smaller amount, they are the LPG, bioethanol (E5), and electricity. Therefore, the primary fuels that would be sought to introduce a more significant measure in the automotive sector are bioethanol (E10), biodiesel (B10), LNG (liquefied natural gas), CNG (compressed natural gas), LPG, and electricity [40]. These fuels were successfully implemented several years ago in Ecuador’s neighboring countries; as in the cases of Brazil, Chile, and Colombia with biofuels, Argentina, Peru, Brazil, and Colombia with vehicular natural gas, and almost all Latin American countries with the recent increase of hybrid and electric vehicles sales [8].

Table 1. Vehicle classes and fuel consumption in the road transport sector in Ecuador in 2016 [37].

Class	Registered Vehicles (Units)						Fuel Consumption (kBOE)					
	Diesel	Gasoline	Hybrid	Electric	LPG	Total	Diesel	Gasoline	Bioethanol	Electricity	LPG	Total
Passenger												
Car	1774	631,349	2993	46	5134	641,296	17.29	6060.39	2.26	0.07	49.18	6129.19
Off-road	7325	313,112	2451	54	56	322,998	82.61	3566.92	3.44	0.10	0.29	3653.36
Bus	23,056	380	-	96	-	23,532	2701.01	42.04	-	5.78	-	2748.83
Van	645	23,388	1	1	6	24,041	18.49	804.50	-	0.01	0.09	823.09
Motorcycle	115	477,733	4	21	45	477,918	0.16	736.54	-	0.01	0.05	736.76
Cargo												
Pick-up	83,016	320,331	115	13	65	403,540	1651.89	7293.40	-	0.06	0.63	8945.98
Van	20,284	20,976	1	3	4	41,268	442.10	545.45	-	0.02	0.04	987.61
Trailer truck	9694	54	-	1	-	9749	892.21	5.01	-	0.03	-	897.25
Cargo truck	94,822	4078	-	2	4	98,906	13,042.10	588.61	-	0.10	0.20	13,631.01
Dump truck	11,500	220	-	-	-	11,720	937.32	18.68	-	-	-	956.00
Tanker truck	2178	50	-	-	-	2228	259.04	5.75	-	-	-	264.79
Other class												
Other class	3649	464	-	-	-	4113	21.90	2.82	-	-	-	24.72
	258,058	1,792,135	5565	237	5314	2,061,309	20,066.12	19,670.11	5.70	6.18	50.48	39,798.59

In this way, the Ecuadorian Republic's Government would work to comply with Articles 15 and 413 of their Constitution [41], about the use of environmentally clean technologies, alternative energies, and energy efficiency. Articles 15 and 413 promote two main axes: (i) energy efficiency, and (ii) fuels supply model change that stimulates the demand diversification. Additionally, the road transport sector would contribute to achieving the signed objective in the Nationally Determined Contributions (NDC) about the Paris Agreement [13], in which Ecuador is committed to reducing 9% of CO₂e estimated emissions until 2025 [42]. However, the country still lacks a clear green fiscal reform, and it suffers from expensive energy subsidies, where gasoline and diesel are the most inefficient subsidies [43].

Therefore, there is a need to develop studies and promote initiatives by public institutions in the country related to sustainable mobility, which includes the following: (a) strategic lines of demand towards energy resources development [44]; (b) assessment and energy efficiency opportunities inland transport in Ecuador [45,46]; (c) strategic action lines in the transport sector for climate change mitigation in Ecuador [47,48]; (d) identification of energy efficiency needs in transport [49], and (e) impact evaluation methodology on energy consumption due to electric vehicle integration [50].

In particular, almost all cited studies above contain measures of sustainable mobility. However, the problem is that they are not inclusive for each other and show isolated independent results. In this way, this study has identified the most significant results of these national initiatives to integrate them with the most relevant international trends regarding energy policies applied to sustainable mobility, and which are potentially viable in Ecuador.

Finally, it is relevant to indicate that the current government is in the study phase for a proposal related with the construction of a high conversion refinery that would have 300 thousand barrels of oil per day processing capacity [51], which will be added to the 110 thousand barrels current capacity [52]. Hence, it is expected that the most demanded fuels, diesel and gasoline, will be of national production, reducing Ecuador's dependence on foreign petroleum liquid fuels, since the current refiner capacity does not meet domestic demand according to the "Hydrocarbons Statistics Report 2016" of the Hydrocarbons Regulation and Control Agency (ARCH by its acronym in Spanish) [53].

3. Methodology

3.1. Road Transport in the LEAP Model

LEAP (Long-range Energy Alternatives Planning System) is an integrated software tool used to perform long term energy policy studies, environmental assessments, and cost analyses based on scenarios that represent different cases of energy production and consumption from different sources that need to cover the demand of all sectors of the economy [54].

Inside of the LEAP system design configuration, the parameters for the base year (Scenario: Current Accounts) were defined in a hierarchical tree structure method for the two following designed modules:

- (1) Key Assumptions module, where the socioeconomic variables data are entered.
- (2) Demand module, where the final energy demand data of each sub-sector are entered with their corresponding branches. In this case, vehicular classes with their particular technologies and fuels consumed.

In this way, the hierarchical tree has been designed into its different branches with the available data for the base year [55].

The LEAP model hierarchical structure applied to the vehicle fleet of Ecuador is grouped according to the following (see Figure 1):

- (a) socio-economic statistics,
- (b) passenger and cargo vehicles groups with their corresponding classes,
- (c) energy policies applied to different scenarios, and
- (d) energy source type that the vehicle consumes.

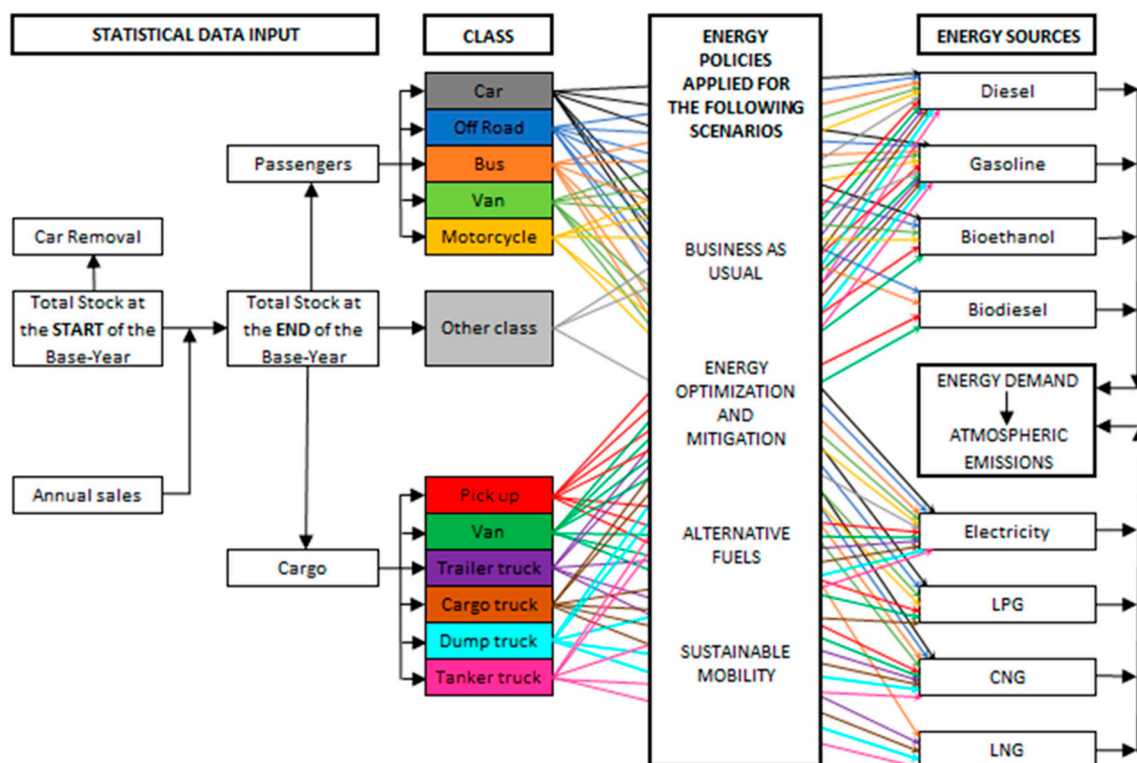


Figure 1. Road transport structure for Ecuador LEAP model.

Regarding the data input, two national statistical reports of road transport in Ecuador have been compiled. The first report is the “Transport Statistics Yearbook 2016” [37], published by the National Institute of Statistics and Census of Ecuador. The second report is the “The automotive sector 2016” [56], published by the Association of Automotive Companies of Ecuador (AEADE by its acronym in Spanish). These documents include part of the necessary statistical data that has been used in LEAP to establish all scenarios with 2016 as the base year.

Moreover, as support by the data input for the base year, a study related to the estimation of fuel consumption of the road transport in Ecuador that only presents results for 2012 was considered [57]. For the demand methodological analysis, the stock-turnover model has been used, where the energy consumption in the road transport sector for each vehicle class is defined by Equation (1):

$$EC = \sum TSV_i(t) \times VKT_i(t) \times FE_{ij}(t) \quad (1)$$

where TSV is the total stock of vehicles of class i , VKT is the average annual vehicle kilometer traveled (mileage) of the class i , and FE is the average fuel economy of class i of the fuel type j (vehicle kilometer/liter), in the time t in years. Then, the results of each class are added together, and the total energy consumption of the sector is obtained [58].

Due to the lack of information in the country regarding the fuel economy for each vehicle class, average values that correspond to the same vehicle technology that circulates and that are sold currently in Ecuador have been used. These values were taken from the document “Fuel Economy Guide 2018” [59] published by the U.S. Department of Energy and from the document “2018 Fuel Consumption Guide” [60] published by the Government of Canada.

In the case of atmospheric polluting emissions, the emission per consumed energy unit is the used method for each vehicle type and fuel source, where environmental effects, the category, and its measurement unit, are based on the Technology and Environmental Database (TED). TED includes emission factors proposed by the Intergovernmental Panel on Climate Change (IPCC) [23], and presents,

by default, a large number of multiple effects in a hierarchical way, according to the energy demand for the road transport sector [54,61]. The emission forecast has been estimated using Equation (2):

$$EP = \sum EC_j(t) \times EF_{jk}(t) \quad (2)$$

where EC is the energy consumption of the fuel type j and EF is the emission factor of pollutant type k under fuel type j , with time t in years.

Finally, the lifecycle profiles have been included. These describe the vehicle's main characteristics that change over time, from the technological degradation behavior and the aging of the current stock. For any profile designed, their values can be entered in two ways: (1) data points curve (dp curve), where the known historical values have been introduced directly; and (2) exponential curve (exp curve), where the positive or negative constant value of the exponential curve has been specified, to each designed profile [54]. The profiles are designed using Equation (3):

$$V = V(t-1) \times Exp(t \times \pm c) \quad (3)$$

where V is the value in % with time t in years, $V(t-1)$ is the initial value of the variable, and $Exp(t \times \pm c)$ represents an exponential curve with a constant c in year t [62]. Among the included profiles are the following: (a) antiquity of the vehicular stock park (dp curve); (b) vehicles survival (exp curve); (c) average traveled distance degradation (exp curve); (d) fuel economy degradation (exp curve); and (e) emissions degradation (exp curve). In this way, Table 2 describes the main variables for all scenarios in the base year 2016.

Table 2. Vehicle classes and fuel consumption in the road transport sector in Ecuador in 2016 [37].

Variables	Passenger					Cargo							
	Car	Off-Road	Bus	Van	Motorcycle	Pick-Up	Van	Trailer Truck	Cargo Truck	Dump Truck	Tanker Truck	Other Class	
Total vehicles ^a (2,061,309)	641,296	322,998	23,532	24,041	477,918	403,540	41,268	9749	98,906	11,720	2228	4113	
Fuel share ^b (%)													
type	Diesel	0.28	2.27	97.97	2.68	0.02	20.57	49.15	99.44	95.87	98.12	97.76	88.72
	Gasoline	80.51	79.57	1.61	97.29	99.97	79.41	50.83	0.55	4.12	1.88	2.24	11.28
	Ethanol	18.41	18.13	-	-	-	-	-	-	-	-	-	-
	Electricity	0.01	0.01	0.42	0.01	-	-	0.01	0.01	0.01	-	-	-
	LPG	0.80	0.02	-	0.02	0.01	0.02	0.01	-	-	-	-	-
Average Mileage ^c (km)	16,000	14,000	70,000	40,000	8300	25,000	28,000	45,000	85,000	50,000	53,000	4000	
Average Fuel Economy ^d (MJ/100 km)													
type	Diesel	376.97	493.83	1017.82	447.55	94.24	501.37	486.29	1281.70	1014.05	1021.59	1406.10	942.43
	Gasoline	377.27	513.86	961.41	537.06	102.77	573.53	580.16	1292.93	1064.18	1064.18	1359.23	762.50
	Hybrid (Gasoline)	238.69	364.67	-	364.67	66.30	414.40	414.40	-	-	-	-	663.04
	Electricity	64.00	82.80	423.00	108.00	18.00	126.00	126.00	432.00	360.00	360	432	144
	LPG	182.48	222.15	-	232.25	72.99	243.31	232.25	-	-	-	-	-
	E5	373.23	506.17	-	-	-	559.74	-	-	-	-	-	-
	CNG	103.95	157.41	367.29	220.38	-	183.65	220.37	1101.88	668.67	668.67	1101.88	-
	Bi-Fuel	279.88	368.01	-	-	-	405.11	207.69	-	-	-	-	-
	E10	269.20	498.48	-	524.45	100.54	560.87	566.63	-	-	-	-	-
	B10	-	496.47	1022.91	-	-	504.01	488.55	1296.78	1025.74	1033.65	1423.82	-
LNG	-	-	382.86	-	-	-	-	1093.13	713.65	713.65	1069.78	-	

Source: ^a: [37]; ^b: [37,56]; ^c: [57,63,64]; ^d: [57,59,60].

3.2. Design of Scenarios

Through the LEAP system, in the research of this energy prospective, the hierarchical relationships were established between the following four alternative scenarios: Business As Usual (BAU), which will present a similar trend behavior to its last 10 years; Energy Optimization and Mitigation (EOM) and Alternative Fuels (AF), which will implement particular characteristics for each scenario starting from the BAU scenario; Sustainable Mobility (SM), which inherits data from the BAU, EOM, and AF scenarios, in addition to its particular characteristics (see Figure 2). In this way, the scenario's hierarchical structure has been designed in the LEAP system for road transport in Ecuador.

According to the particularity of each scenario design, plenty of different measures and initiatives of energy efficiency [6,65,66], alternative fuels [18,67–70], atmospheric emissions [71,72], and sustainable mobility [9,73–75], trends have been applied and integrated. National and international research institutions and researchers have developed these initiatives, who have studied the road transport sector [76].

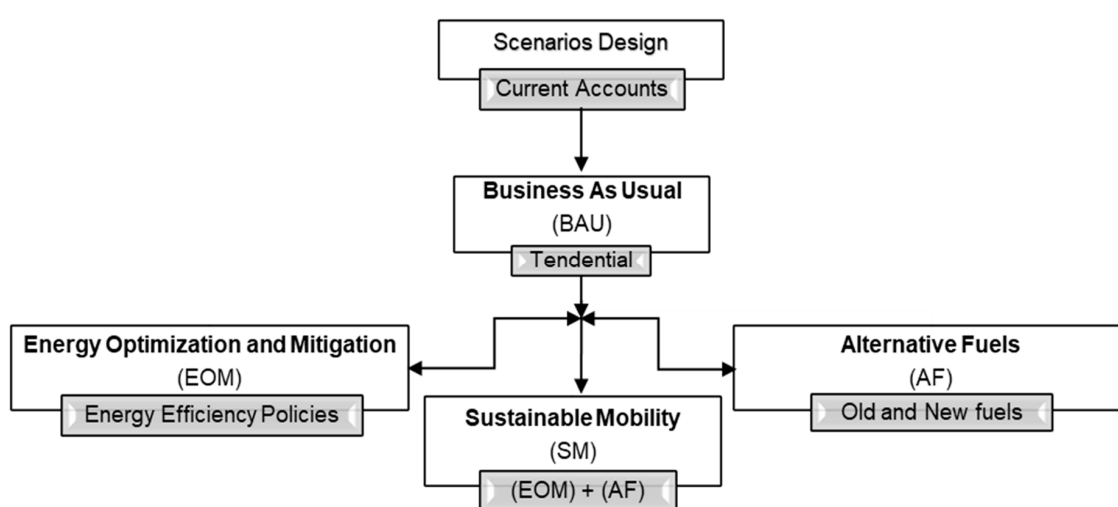


Figure 2. Scenarios design in the LEAP model for the road transport sector in Ecuador.

3.2.1. Business as Usual (BAU) Scenario

The main characteristics of this scenario are focused on projecting historical annual growth trends of the vehicle fleet for each class and fuel type that it consumes, which grew 6.8% average between 2008 and 2016 each year [37]. At the same time, a slight growth of hybrid and electric vehicles sales forecast reported by AEADE have been included [77]. The Energy Efficiency Organic Law influences this new sales growth [78], which promotes the efficient, rational, and sustainable use of all energy sources.

With this statistical data for all vehicle types of the national fleet, the total passenger and cargo sale of units has been projected, which will be the same for the EOM and AF scenarios up to the year 2035. However, future sales percentage varies for each new vehicle class depending on the design of each scenario, where the new fuel types incorporation is not expected beyond those that currently exist (see Table 3).

Table 3. Cont.

Demand		Passenger						Cargo				
Variables	Car	Off-Road	Bus	Van	Motorcycle	Pick-Up	Van	Trailer Truck	Cargo Truck	Dump Truck	Tanker Truck	Other Class
Sales Share for AF and SM scenarios (%)^d												
type	Diesel	0	0	0	0	0	0	27	30	30	27	58.50
	Gasoline	0	0	0	0	35	0	0	0	0	0	11.50
	Hybrid	25	30	-	30	25	15	30	-	-	-	20
	Electricity	18	15	-	15	15	12	15	8	10	10	10
	LPG	17	10	0	12	-	10	15	-	-	-	-
	E5	0	0	-	-	-	5	-	-	-	-	-
	CNG	10	15	25	12	-	10	7.5	15	15	15	-
	Bi-Fuel	3	10	-	-	-	10	7.5	-	-	-	-
	E10	27	17	-	31	25	18	10	-	-	-	-
	B10	-	3	36	-	-	20	15	30	30	30	30
LNG	-	-	25	-	-	-	-	20	15	15	20	

Source: ^a: [77]; ^b: [56]; ^c: [40]; ^d: [45,47,79].

3.2.2. Energy Optimization and Mitigation (EOM) Scenario

In this scenario, relevant energy efficiency studies and initiatives have been applied, which have been considered for their potential importance in public policies for road transport in Ecuador, supported by Energy Efficiency Organic Law [78].

Considering the energy efficiency and optimization initiatives, the average goal percentage of energy demand reduction for passenger vehicles would be 5% to 2025, 15% to 2030, and 20% to 2035 [45,79–81]. For the cargo vehicles, it would be 5% to 2025, 10% to 2030, and 15% to 2035 [82–85]. Among the most important initiatives that have been incorporated, the following can be cited:

- Scrapping through “Plan RENOVA” with tax incentives for the renewal of older vehicles that completed their life cycle [48].
- The improvement of fuel quality and the use of more efficient engines that achieve savings of up to 10% in 2035 [40].
- The improvement of the urban, interurban, and interregional public transport quality [86,87].
- Improvement of the efficiency in the passengers interurban transportation BRT (Bus Rapid Transfer Systems), mainly for the largest cities in the country [88].
- The income of massive and sustainable urban public transport (The Quito Metro, Cuenca tram), and the implementation of cargo and passenger electric trains between Quito and Guayaquil [89].
- Campaign for improving driving conditions and vehicular traffic flow (eco-driving initiatives) [90], together with smart traffic lights and urban planning [81].

3.2.3. Alternative Fuels (AF) Scenario

In this scenario, through a public policy strategy related to the energy matrix change of Ecuador [91], the Energy Efficiency Organic Law [78], and the Productive Development Law [92], the increased usage of several alternative fuels [18,20,93–99] is encouraged, for the vehicular market in the road transport sector in Ecuador. In this sector, through tax incentives, the state promotes the removal of VAT on hybrid and electric vehicle imports for private use, passengers transport, and cargo transport [92].

Thus, for this scenario design, it follows the same vehicle demand growth in future sales as the BAU and EOM scenarios. However, in this case, the alternative fuels and new vehicular technologies have been introduced to the fuels market, compatible with the current and new fuels. The new alternative fuels will be bioethanol (E10) [57,72,100], biodiesel (B10) [16,22,57,79], liquefied natural gas (LNG), compressed natural gas (CNG) [91], liquefied petroleum gas (LPG) [57], and of another type like electricity. The new vehicle technologies that enter in this scenario are Bi-Fuel, different models of Hybrid; Full Hybrid (HEV) and Plug-in Hybrid (PHEV) vehicles; Battery Electric Vehicles (BEVs); and those compatible engines with LPG, LNG, and CNG consumption [50] to reduce air pollution, GHG emissions, and noise pollution in cities [101].

3.2.4. Sustainable Mobility (SM) Scenario

For the design of this scenario, all characteristics of energy efficiency and mitigation, and alternative fuel scenarios have been inherited through a hierarchical structure in the LEAP model. In addition, a new trend group and sustainable mobility projects have been included [8,9,47,70,88,102,103]. Globally, some of these initiatives have already been incorporated, and it is expected that, in the next years, they will be adopted by developing countries [104]. Among the main additional initiatives to be integrated are the following:

- Energy-saving and emission reduction as a result of the decrease of the vehicle fleet due to car-sharing and moto-sharing projects [105,106].
- The massive use of electric bike-sharing for improving the sustainability of integrated transportation system [107] through public and private rental companies [75,87,108].
- Use of electric scooter, electric segway, electric hoverboard in urban areas [71].

All these new projects still present uncertainty of the real impact in the future, but what is indisputable is that they are becoming increasingly important in road transport, and are present in cities these days. In this context, for the design of this scenario, it has been considered that future vehicle sales have a slight and gradual decrease, where fewer passenger private vehicles are sold each year for urban transport towards 2035. In this case, this scenario differs from the previous three, where BAU, EOM, and AF have the same global sales demand but have different percentage configurations for each vehicle's class and fuel type that consume (see Table 3).

4. Results and Discussion

4.1. Energy Demand Forecasting

The analysis indicates that the energy demand for the scenarios has a difference in growth due to the fuel type that the vehicles of the Ecuadorian road transport sector consume. Figure 3 shows the energy demand growth trend in road transport for each scenario between 2016 and 2035. The differences in demand between scenarios began to be seen from 2025. For the BAU scenario, the energy demand trend is maintained, with a growth of 181.49% between 2016 and 2035. For the EOM scenario, the estimate shows a growth of 158.41%, for the AF scenario, a growth of 124.69%, and in the case of the SM scenario, a growth of 113.89%. The most significant difference in demand is among the BAU scenarios (higher) and SM (smaller) having a difference of 26,902 kBOE, which would indicate an energy demand reduction of 31.60% in 2035. Thus, the estimates show that in the whole analysis period, the average energy demand would be 97,358.50 kBOE.

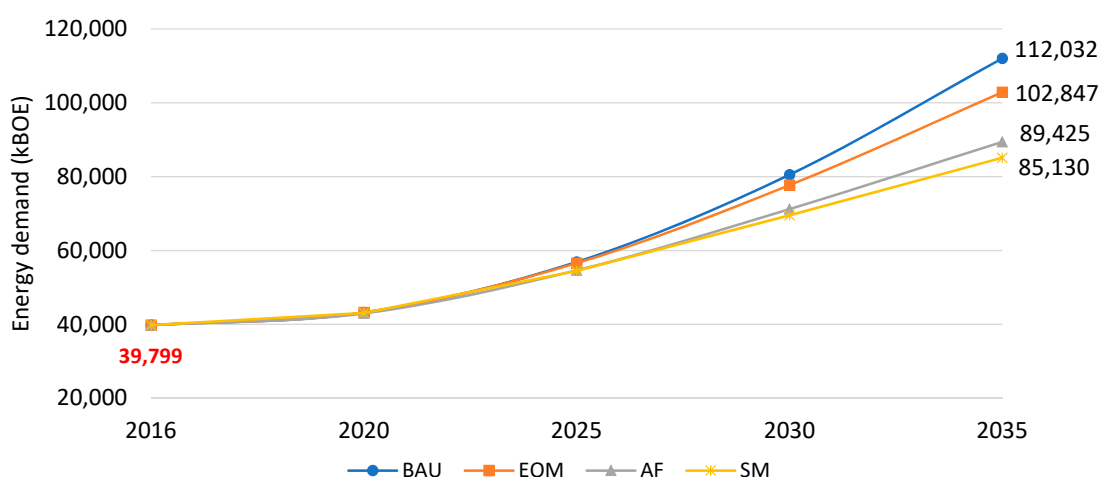


Figure 3. Total energy demand forecasting of road transport for each scenario from 2016 to 2035.

4.2. Fuels Demand Projections

The fuel demand forecast for each scenario shows that BAU maintains its trend, and there are no significant changes regarding historical behavior (see Figure 4). In this scenario, gasoline with 49.42% in 2016, decreases to 47.15% in 2035. In the case of diesel, its contribution was 50.42% in 2016, and it grows slightly to 51.92% by 2035. In contrast, although the electricity demand grows 137 times, and goes from 6.18 kBOE in 2016 to 853.52 kBOE in 2035, its global contribution is barely 0.76%. For the other fuels in this scenario, LPG and bioethanol, their demand is not significant, where they barely reach 0.2% in 2035. Therefore, it is unquestionable that diesel and gasoline continue to be the principal energy sources, concentrating 99.07% of the total in 2035.

In the EOM scenario (see Figure 5), the percentages of energy demand are very similar to BAU. The gasoline has a contribution of 46.97% and diesel 52.09% by 2035. However, between 2016 and 2035, the total fuel demand for EOM relative to BAU decreases by 39,688 kBOE, close to the total demand

of 2016 (39,799 kBOE). This very significant result confirms that through the application of energy efficiency policies, a considerable saving in energy demand could be guaranteed.

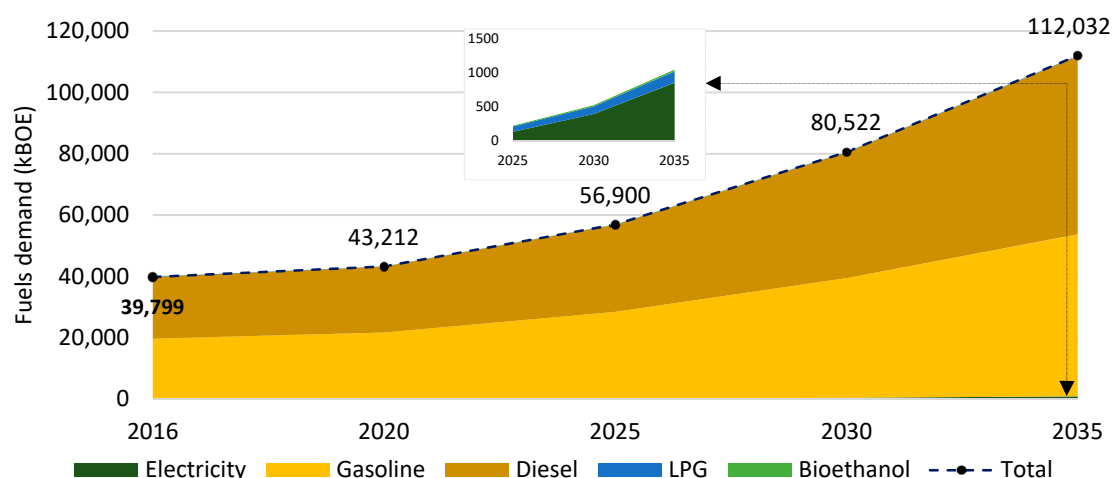


Figure 4. Fuels demand by sources in the BAU scenario from 2016 to 2035.

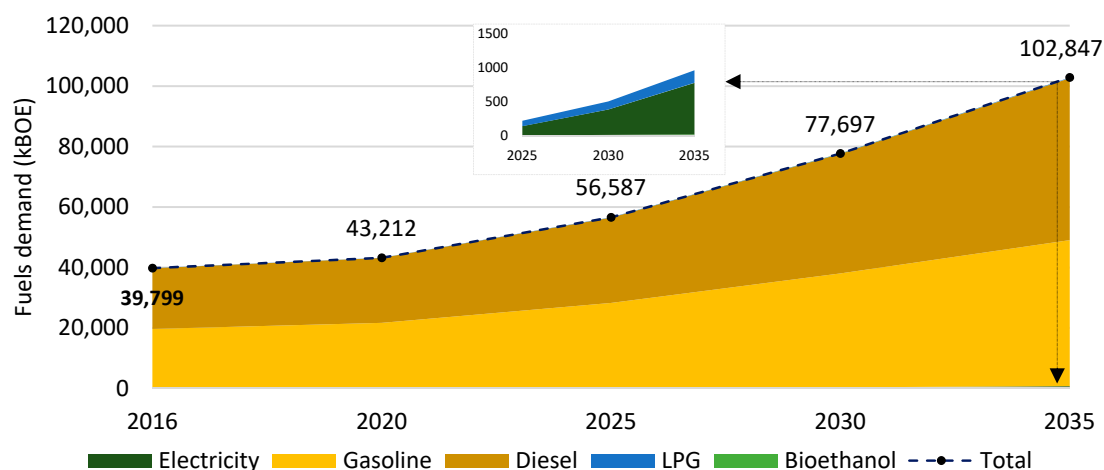


Figure 5. Fuels demand by sources in EOM scenario from 2016 to 2035.

For the BAU and EOM scenarios, the results show that the combined energy demand for electricity, bioethanol, and LPG do not reach 1%, which is practically insignificant; this is an effect of the design of these scenarios due to there is not a significant inclusion of vehicles that consume alternative fuels.

In the AF scenario (see Figure 6), the global demand for energy grew by 124.69% towards 2035. However, due to the implementation and promotion of policies that promote vehicles that consume fuels from alternative energy sources for road transport. The accumulated energy demand decreased 120,944 kBOE, relative to BAU in the 2016–2035 period, that is, the approximate equivalent to the total energy consumption of 2016, 2017, and 2018 altogether.

According to the fuels demand for the AF scenario, slight changes appear in the alternative fuels demand after 2025, but this demand continues to be low with 2.87% for that year. However, this demand continues to grow up to 15.57% (CNG 5.01%, LNG 3.88%, LPG 3.22%, electricity 2.99%, bioethanol 0.32%, and biodiesel 0.15%), from which 8.89% would be powered by natural gas in 2035. This means 9.5 times more compared to BAU.

In conclusion, the total share of accumulated alternative fuels demand of AF would be 75,256 kBOE between 2016 and 2035 (CNG 22,042 kBOE, LNG 16,975 kBOE, LPG 18,121 kBOE, electricity 15,395 kBOE, bioethanol 2175 kBOE, and biodiesel 548 kBOE), which would represent almost the total energy demand of the road transport sector (74,717 kBOE) in 2031.

For the SM scenario, more significant and optimistic changes are shown for the energy demands in all scenarios. First, the accumulated total difference in energy demand is 141,227 kBOE less compared to the BAU scenario until the year 2035. Next, the inclusion of alternative fuels happens to have a relevant share of 17.77% (CNG 6.16%, LNG 5.03%, LPG 3.25%, electricity 2.89%, bioethanol 0.28%, and biodiesel 0.16%), reaching 15,131 kBOE in 2035 (see Figure 7).

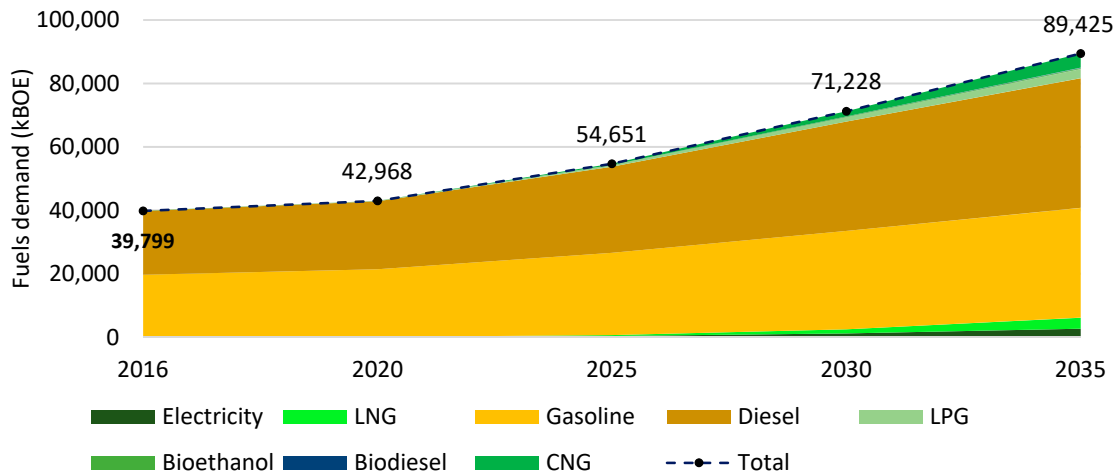


Figure 6. Fuels demand by sources in AF scenario from 2016 to 2035.

At the same time, the accumulated total demand for gasoline shows a decrease of 133,922 kBOE, and in the case of diesel, a fall of 79,324 kBOE relative to BAU. These values are samples of significant energy savings for the country, because nowadays, these fuels continue to be imported in large amounts, and everything suggests that this will not change in the near future. As recent as in 2016, Ecuador imported 57.86% of diesel of the total national consumption [109].

Finally, the most relevant result is that the total energy demand in the SM scenario decreases by 30.43% relative to BAU in 2035. However, the total share of diesel and gasoline continues to be essential in the whole energy mix of the road transport sector with 47.39% and 34.84%, respectively.

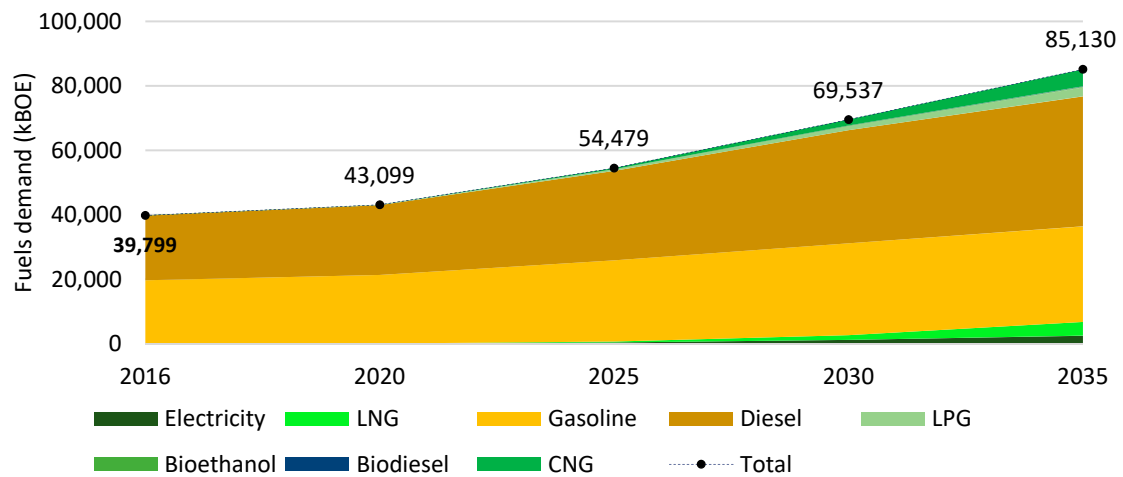


Figure 7. Fuels demand by sources in the SM scenario from 2016 to 2035.

4.3. Forecast of the Total Stock of Vehicles

The forecast of the total stock of vehicles presents an identical growth for the BAU, EOM, and AF scenarios, and different from SM, which grows slightly less (see Figure 8). This result is a consequence of the SM design, where the reduction of the vehicle fleet through car-sharing and moto-sharing, the

extensive use of electric bikes is promoted, and through the addition of electric scooter, electric Segway, and electric hoverboard for urban areas.

The total growth of the stock of vehicles for BAU, EOM, and AF is 313%, growing from 2,061,309 to 8,513,600 units, while for SM, it represents a growth of 294.44%, reaching 8,130,686 units, between 2016 and 2035. This means that SM would have an accumulated decrease in 2,287,935 vehicles compared to the other three scenarios in the same period (1,923,166 passenger vehicles and 364,769 cargo vehicles), which is comparable to the total stock of vehicles in 2017 (2,312,197 vehicles).

In the assessment of passenger vehicles of SM regarding the other three scenarios, the accumulated stock of cars decreases 1,507,069 units and of off-roads decreases 1,335,084 units. Together, as it is a scenario where sustainable mobility policies are promoted, the accumulated buses stock increases in 227,564 units, passenger vans in 106,858 units, and motorcycles in 584,585 units, this is outstanding since motorcycles represent 48.73% of the total sold units in SM until 2035.

In the case of SM cargo vehicles, there is an accumulated decrease in the pick-up stock in 445,185 units. Consequently, as a result of the applied policies for this scenario, the accumulated stock of cargo vans increases in 39,344 units, cargo trucks in 29,322 units, trailer trucks in 7347 units, tanker trucks in 3253 units, and dump trucks in 1149 units.

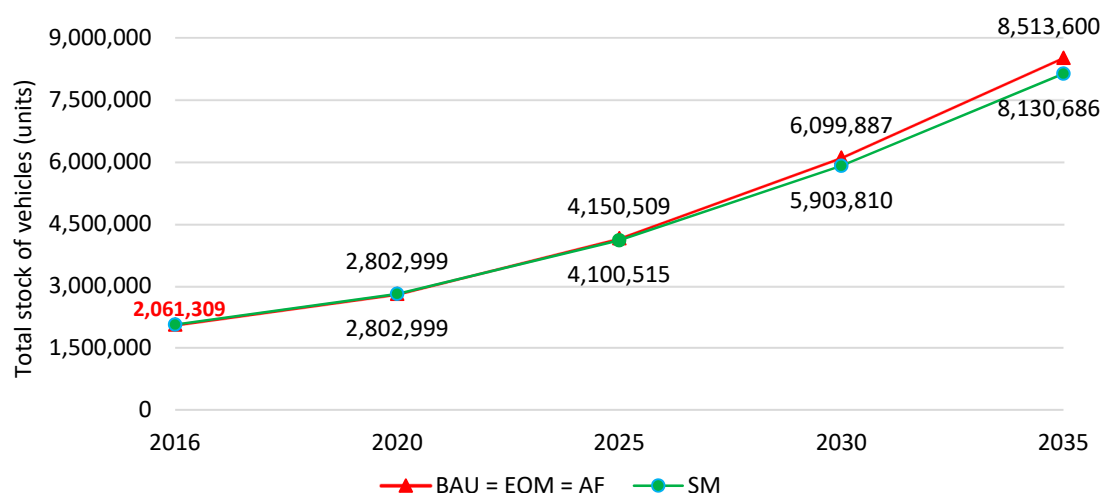


Figure 8. Annual total stock of the vehicles for each scenario from 2016 to 2035.

4.4. Forecast of Emissions

As a consequence of the combustion of the fuel, between 2016 and 2035, a different quantity of atmospheric pollution emissions take place according to each demand scenario in the road transport sector. Consequently, this section has been divided into two parts to be analyzed: (1) results of the GHG emissions that contribute to global warming, (2) the results of pollutant gas emissions that degrade the air quality. In this particular case, the nitrogen oxides emissions are represented by NO_x and the emissions of particulate matter are represented by PM_{10} .

4.4.1. Greenhouse Gas (GHG) Emissions

The estimates of GHG emissions are measured in CO_2 equivalent (CO_2e) units, which are presented for all scenarios in Figure 9. For EOM relative to BAU, the total of accumulated GHG emissions fall by 3.12% between 2016 and 2035, which represents a reduction of 16.46 Mt CO_2e (million metric tons) emissions into the atmosphere, due to lower demand for diesel and gasoline.

Likewise, it is interesting that for AF and SM scenarios, where sustainable mobility policies have been integrated and alternative fuels introduced, the expected happens. In AF related to BAU, the accumulated GHG emissions decreased by 11.70%, the equivalent to 56.96 Mt CO_2e , due to the emissions reduction caused by the lower average fuel demand of diesel and gasoline per vehicle.

For SM relative to BAU, something similar to AF happens, where the accumulated GHG emissions decrease to 13.49%, which represents 64.65 Mt CO₂e, in the same study period. This is a consequence caused by the decreased cumulative emissions by the combustion of LPG, CNG, and LNG until 2035. However, it is noteworthy to highlight that the accumulated GHG emissions caused by gasoline and diesel consumption decrease by 54.41 and 34.16 Mt CO₂e, respectively.

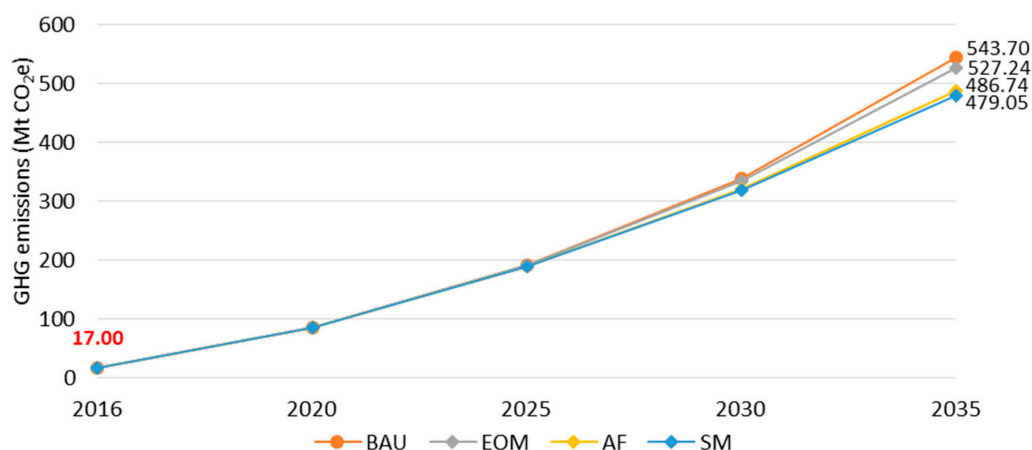


Figure 9. Accumulated GHG emissions for each scenario from 2016 to 2035.

4.4.2. NO_x and PM₁₀ Emissions

As a result of the fossil fuel combustion, several pollutants are produced in different concentrations that affect air quality. In this investigation, two of the most common pollutant compounds that affect human health have been considered for their estimation; the nitrogen oxides, NO_x, and particulate matter, PM₁₀, which corresponds to the particulate fraction of the Total Suspended Particles (TSP), with a diameter less than 10 microns [110].

For NO_x emissions, the accumulated emissions of SM, AF, and EOM decrease, relative to BAU, by 684.24 kt (thousand metric tons), 591.32 kt, and 166.21 kt until 2035, respectively (see Figure 10).

Moreover, NO_x emissions have been significantly reduced per vehicle unit between 2016 and 2035. In 2016, for BAU, the NO_x average emissions were 0.077 t/vehicle (metric ton per vehicle), while the average emission for BAU, EOM, AF, and SM are 0.054, 0.050, 0.041, and 0.040 t/vehicle in 2035, respectively. In this way, the integration of new energy efficiency and mitigation measures is justified because there is a direct relationship between fuel consumption and atmospheric pollution.

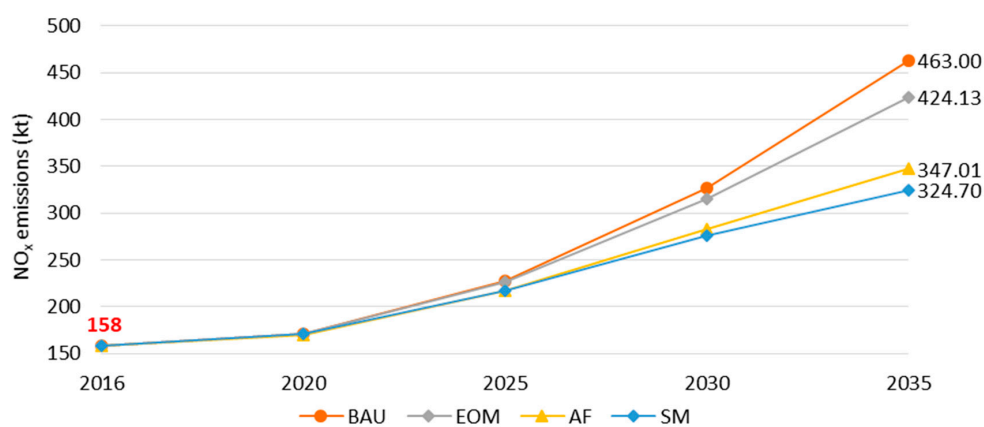


Figure 10. Annual NO_x emissions for each scenario from 2016 to 2035.

Regarding the annual emissions of the particulate matter PM₁₀, these present a behavior similar to the NO_x emissions. That is to say, while the consumption of fossil fuels increases, the PM₁₀ emissions

increase too. Specifically, in BAU, the PM₁₀ emissions are tripled, while in SM they are doubled from the base year until 2035 (see Figure 11). Nevertheless, it should be considered that for the two scenarios, the stock of vehicles has almost quadrupled (see Figure 8).

Regarding the accumulated PM₁₀ emissions, between 2016 and 2035, the SM, AF, and EOM scenarios show a reduction of 13.78%, 9.53%, and 4.4%, relative to BAU, respectively. At that time, diesel continues to be the primary emissions responsible for this pollutant each year, with an average of 86.36% in SM, 91.58% in AF, 92.93% in EOM, and 92.67% in BAU.

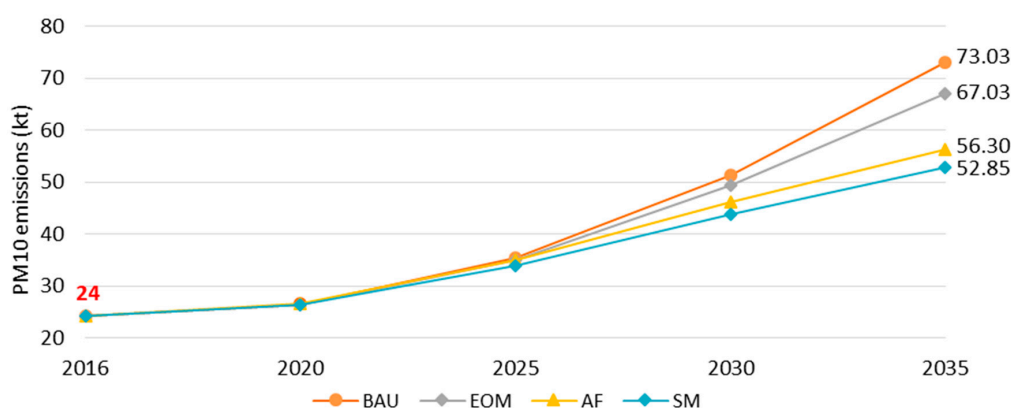


Figure 11. Annual PM₁₀ emissions for each scenario from 2016 to 2035.

4.5. Forecast of the Total Fuel Cost Savings

Considering the estimation of international fuel prices for the transport sector up to 2050, carried out by the U.S. Energy Information Administration in its report “Annual Energy Outlook 2019” [111], Figure 12 shows the estimate of the accumulated economic cost due to the fuel consumption for each scenario until 2035. Between the SM, AF, and EOM scenarios, the accumulated savings, relative to BAU, are 14.22%, 12.24%, and 3.86% until 2035, respectively. This confirms that by applying energy efficiency and sustainable mobility policies, the benefits of energy savings and economic savings would be present. The estimated global savings for fuel consumption would be around 26,720 MUSD (million US dollars), between SM and BAU, an approximate of 25% country’s total gross domestic product in 2018 [112].

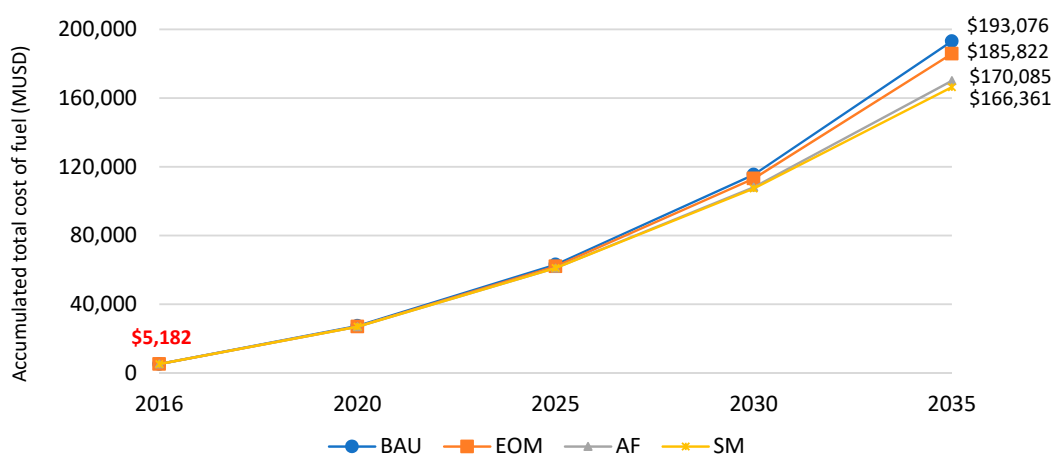


Figure 12. Accumulated total cost of fuel for each scenario from 2016 to 2035.

4.6. Summary and Analysis of the Main Results

In summary, Table 4 shows the main results for defined years between 2016 and 2035 every five years. Among the most relevant results are the following.

Table 4. Summary of the main results for the alternative scenarios in specific years.

Description		2016	2020	2025	2030	2035
Total Stock of Vehicles (Units)						
Scenarios	BAU—EOM—AF	2,061,309	2,802,999	4,150,509	6,099,887	8,513,600
	SM	2,061,309	2,802,999	4,100,515	5,903,810	8,130,686
Total Energy Demand (kBOE)						
Scenarios	BAU	39,799	43,212	56,900	80,522	112,032
	EOM	39,799	43,212	56,587	77,697	102,847
	AF	39,799	42,968	54,651	71,228	89,425
	SM	39,799	43,099	54,479	69,537	85,130
Total Fuels Demand (kBOE)						
Business As Usual						
type	Diesel	20,066	21,473	28,409	40,962	58,164
	Gasoline	19,670	21,650	28,269	39,037	52,825
	Electricity	6	27	135	393	854
	LPG	50	57	77	113	164
	Bioethanol	6	7	10	16	25
Energy Optimization and Mitigation						
type	Diesel	20,066	21,473	28,249	39,534	53,576
	Gasoline	19,670	21,650	28,118	37,659	48,312
	Electricity	6	27	133	371	754
	LPG	50	57	78	118	183
	Bioethanol	6	7	10	16	23
Alternative Fuels						
type	Diesel	20,066	21,438	27,155	34,489	40,877
	Gasoline	19,670	21,332	25,928	31,001	34,618
	Electricity	6	51	377	1196	2672
	LPG	50	123	512	1388	2877
	Bioethanol	6	22	70	171	290
	LNG	-	-	265	1278	3472
	CNG	-	-	344	1669	4481
	Biodiesel	-	-	-	35	138
Sustainable Mobility						
type	Diesel	20,066	21,640	27,738	35,088	40,340
	Gasoline	19,670	21,262	25,180	28,508	29,659
	Electricity	6	52	378	1157	2463
	LPG	50	123	479	1294	2770
	Bioethanol	6	22	65	151	239
	LNG	-	-	283	1469	4283
	CNG	-	-	356	1835	5243
	Biodiesel	-	-	-	35	133

Table 4. Cont.

Description		2016	2020	2025	2030	2035
Total GHG Emissions (kt CO₂e)						
Scenarios	BAU	17,004	18,052	23,742	33,539	46,566
	EOM	17,004	18,052	23,612	32,365	42,762
	AF	17,004	17,933	22,660	29,158	35,967
	SM	17,004	17,991	22,609	28,513	34,305
Total Fuel Cost (Million US dollars)						
Scenarios	BAU	5181.94	6042.19	8077.99	12,304.90	17,842.52
	EOM	5181.94	5859.70	8033.58	11,872.46	16,376.58
	AF	5181.94	5824.61	7716.16	10,649.30	13,537.67
	SM	5181.94	5841.96	7687.33	10,359.40	12,706.02

The estimation of the total stock of vehicles used in cities and on roads between the BAU, EOM, and AF scenarios regarding the SM, is higher by 382,914 units in 2035. Though the most significant fact is that, between 2016 and 2035, there will be a total of 2,287,935 fewer vehicles circulating in SM than in the other three scenarios; this is a consequence of the application of sustainable mobility policies such as the Ecuadorian Energy Efficiency Organic Law [78], where priority is given to the inclusion of passenger transport such as buses and vans, which generate a lower demand for private vehicles such as cars and off-road, and which generally carry very few passengers. At the same time, in cargo vehicles, the use of heavy cargo transport is promoted, and the use of pick-up vehicles decreases, which are often underutilized.

The total energy demand in each of the scenarios continues to grow progressively every year between 2016 and 2035. While for BAU, the demand increases by 181.49%, for SM, it increases by 113.89%. This represents 26,902 kBOE less energy only in 2035, which is equivalent to almost half of the total energy demand for SM in 2025. It is also comparable to the total diesel demand (27,155 kBOE) or gasoline (25,928 kBOE) in AF in 2025. Consequently, the SM is the most optimal scenario regarding global energy demand point of view.

Therefore, in the case of fuel demand for all scenarios, the gasoline and diesel, two of the most critical products due to their higher demand, are significantly reduced. In the diesel case, this fuel grows from 20,066 kBOE in the base year for all scenarios to 58,164 kBOE in BAU, to 53,576 kBOE in EOM, to 40,877 kBOE in AF, and 40,340 kBOE in SM, in 2035; this means a fall in diesel demand of 30.64% between SM and BAU.

Something similar happens in the case of gasoline. The demand for this fuel in the base year was 19,670 kBOE. By 2035, the demand forecast for this fuel decreases for all scenarios. For SM to 43.85%, to 34.47% in AF, and 8.54% in EOM, relative to the BAU scenario, respectively. For other energy sources, such as LPG, LNG, CNG, and electricity, it is essential to perceive that they begin to have discrete participation in 2025, which significantly reflects the goals of changing the current fuel demand model.

Then, the GHG emissions were a total of 17,004 kt CO₂e in 2016. Hence the average ratio was 8.24 t CO₂e per vehicle for each scenario in 2016. At the end of the study period, for BAU, EOM, AF, and SM, this ratio changes to 5.47, 5.02, 4.22, and 4.22 t CO₂e per vehicle in 2035, respectively. Therefore, these results for this particular case show that with the increased use of alternative fuels, mainly LPG, LNG, and CNG, the GHG emissions decrease in SM and AF relative to BAU, also due to the emissions caused by the average decrease of diesel and gasoline consumption.

Finally, regarding fuel cost analysis, it is noteworthy that with the increased use of alternative fuels and the integration of energy efficiency and optimization policies, the annual average fuel consumption cost per vehicle is progressively reduced for all years. In 2016, the average cost was 2513.91 USD, and

this cost changes to 2095.77 USD in BAU, 1923.58 USD in EOM, 1590.12 USD in AF, and 1562.72 USD in SM, in 2035.

5. Conclusions

This paper detailed the high energy demand of the road transport sector, and especially petroleum fuels consumption in Ecuador. This study has analyzed the total energy demand for each fuel type, the total motor vehicle stock, the GHG emissions, the emissions of two main air pollutants (NO_x and PM_{10}), and the total fuels cost, within the road transport sector, for each of the four energy policy alternative scenarios (BAU, EOM, AF, and SM), between 2016 and 2035.

According to the estimated results, diesel and gasoline very possibly continue to be the principal energy sources for the automotive sector in the country for all scenarios. This implies that not only should it be necessary to take measures to direct the system towards a sustainable mobility scenario, it also seems an urgent task that to plan and develop the essential infrastructure to reduce the dependence of petroleum fuels importation, which would have a positive effect for reducing costs. Initially, as a support of an energy transition stage, it is essential to start-up operations as soon as possible to promote projects for national petroleum fuels production to cover the future petroleum products demand for the automotive sector, such as the tender procedure of the study for the construction of a refinery that has already started, which would process 300 kBOE/day approximately. At the same time, the new infrastructure should be developed to increase the use of new fuels such as LPG, CNG, LNG, electricity, and biofuels in the automotive sector.

Moreover, a possible “sustainable transport policy” might be that of pursuing a modal share towards transport systems which have less impact on local pollution and global emissions; according to local needs, these might result in automated undergrounds, or in less expensive and with more moderate hourly-capacity automated people movers (APM), as those cable-driven adopted in cities for micro-mobility.

Overall, the main results for the AF and SM scenarios have been a significant decrease in the global energy demand of 120,944 kBOE and 141,226 kBOE relative to BAU in 2035, respectively. Together, the global cost has decreased by 26,720 MUSD due to the change in fuels demand, and PM_{10} has decreased by 20 kt between SM and BAU by 2035. Likewise, when alternative fuels are used significantly more (electricity, biofuels, LPG, CNG, and LNG), accumulated GHG emissions decrease by 11.70% for AF and 13.49% for SM, relative to BAU, up until 2035. Nevertheless, through an overall balance of all the results in the analyzed scenarios, it is concluded that SM would be the most optimal scenario for the automotive sector in the country.

Therefore, it is essential to develop a model that preserves the equilibrium of energy demand for each fuel type, while reducing the global emissions impact of air pollution and climate change and, subsequently, due to the applied mobility policies, a significant fuels cost-saving in the country is produced, moving towards a comprehensive sustainable mobility system.

Finally, this study has served to identify specific challenges and opportunities, in time and form, and it is concluded that there is an urgent need to establish state policies on energy efficiency, consumption of alternative fuels, and sustainable mobility, for both medium and long terms, and progressively implement them. Consequently, the energy sources peculiarities of the country, the implications of environmental impact related to air pollution and global warming, and socio-economic benefits must always be taken into account.

This research placed in Ecuador provides a useful LEAP model that can be used to study global processes. The same methodology and approach used in this work could be applied mainly for developing countries that share common demographics and macroeconomic characteristics with Ecuador.

Author Contributions: Conceptualization; L.R.-G., D.B. and L.F.M.; writing—review and editing, L.R.-G., D.B., S.N.-S., and K.E.-S.; methodology, L.R.-G., S.N.-S., and K.E.-S.; Formal analysis, L.R.-G., D.B., L.F.M., S.N.-S., and K.E.-S.; Supervision, D.B. and L.F.M. All authors reviewed together this paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Secretaría Nacional de Ciencia y Tecnología (SENESCYT) and the Instituto de Fomento al Talento Humano (IFTH) of Ecuador [grant number 2013-AR2Q1374].

Acknowledgments: We thank the Energy and Fuels Department of the Technical School of Mining of the Universidad Politécnica de Madrid (UPM), Transversal Unit of Road Scope Management of the Universidad Politécnica de Catalunya (UPC), and Escuela Superior Politécnica del Litoral (ESPOL) for the total support.

Conflicts of Interest: The authors declared no conflict of interest.

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