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Analysis of GHG Emission from Cargo Vehicles in Megacities: The Case of the Metropolitan Zone of the Valley of Mexico

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Abstract: Cities consume most of the energy used worldwide and are the largest emitters of greenhouse gases (GHGs) that cause global warming, mainly from the road transport sector. In megacities, the light vehicle fleet is responsible for most of the emissions in the sector. Among this fleet, light commercial vehicles (CVs), which have grown to support instant delivery services demand, are also responsible for emissions and traffic congestion. Due to the urgency to reduce transport impacts, emission mitigation strategies are required. Aligned with this aim, this article evaluates GHG emissions along the entire process of energy production, called the operating trajectory, and also known as Well-To-Wheel (WTW), in four combinations of transportation modes for last-mile delivery services, using light CVs, such as electric or diesel vans, and electric cargo bikes (E-bikes). The analysis is firstly conducted in a local area of Mexico City and subsequently compared to other countries around the world. In this respect, the main result of this article shows that in the case study conducted in the Metropolitan Zone of the Valley of Mexico, the energy consumption of a given route for an electric van combined with E-bikes generates 24% less GHG emissions than a diesel van combined with E-bikes. Therefore, the achievement of effective mitigation strategies for GHG emissions reduction through vehicle electrification requires WTW emission analysis and quantification, optimal route design, a combination of sustainable transport modes and clean energy generation.

Keywords: GHG emissions; energy consumption; Well-To-Wheel; commercial transport; instant deliveries; megacities

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1. Introduction

The impact of anthropogenic greenhouse gases (GHGs) on global warming has been extensively documented in numerous studies worldwide, as, for instance, in [1–3]. The largest amount of GHG, of which the major component is carbon dioxide (CO_2), is generated from the combustion of fossil fuels to obtain energy used in diverse sectors [3–5]. Worldwide, GHG emissions from transportation are rising faster than in any other sector [6]. Nowadays, overall transport (road, air, rail and maritime) consumes more than 65% of oil fuels and 7% of natural gas and is the second largest emitter sector, responsible for releasing approximately 24% of global CO_2 emissions from fuel combustion [7]. In particular, road transportation accounts for 18% of global emissions, which represents above 74% of the entire transport sector emissions [6,7], due to internal combustion engine (ICE) vehicles. Besides CO_2 and other major GHGs, such as methane (CH_4) and nitrous oxide (N_2O), ICEs also generate other air pollutants harmful to the environment and human health [8–10]. Principally, in major and dense urban areas with large vehicle fleets, traffic congestion causes several negative impacts, such as high levels of emissions, long travel times, stress and noise, which affects health, quality of life, the local environment and also has an effect on global warming [9]. At present, road transport is one of the most significant emitters of GHG in most cities around the world [11,12]: it is estimated that between 33% [12,13] and 45% [14] of total urban GHG emissions in major cities are from road transport. Furthermore, cities are responsible for approximately 70% of global GHG emissions and other pollutants generated from the consumption of three-quarters of total energy [9,13,15,16]. Therefore, urban areas are considered major contributors to climate change, since cities are intensive emitting areas [17], where more than half of the global population lives [15].

Of the total emissions, approximately 98.0% are GHG and 58.4% come from transportation [18]. In particular, Mexico City has one of the highest levels of pollution nationwide; nevertheless, as the capital of the country, it plays an important role in the socioeconomic development of Mexico. The city contributes 15.3% of the total domestic GDP [19], which ranks it as the state with the highest economic participation. Additionally, Mexico City also ranks first in the national Gross Domestic Product (GDP) of primary activities (with 21.7% of the total), in which commerce is the sector of major state activity [19], which requires transportation of merchandise.

Similar to any other megacity with a high population density, the urban growth of Mexico City entails the development and implementation of diverse strategies in all sectors to guarantee quality of life for the population and, at the same time, provide sustainably all necessary services, including road transportation for people and goods. Although light passenger vehicles generate the most emissions, light commercial vehicles (CVs) also affect urban congestion and pollution by transporting goods and making mainly last-mile instant deliveries [20]. In Mexico City, physical contact restrictions and business closings imposed during the COVID-19 Pandemic led commercial establishments to respond efficiently to the need for fast-shipping service for goods via e-commerce promoting instant deliveries [21,22] by using bicycles, motorcycles and vehicles such as CVs and vans (a contraction of "caravans"). Since the Pandemic, e-commerce and instant deliveries have experienced a "boom", which is an efficient service of goods transport, payment and delivery that is expected to prevail in the future [21,22]. This implies an increase in vehicles used to merchandise deliveries and, consequently, an increase in fossil fuel consumption and emissions, which has led to the proposal and evaluation of sustainable alternatives to commercial transportation.

In large urban areas such as Mexico City, commercial transport logistics must be designed to be low-emission and contribute to reducing traffic congestion [20]. This logistics includes using electric vehicles, which are expected to contribute substantially to the reduction of emissions [16,23,24]. For instance, a combination of electric bicycles (E-bikes) and battery electric vehicles (BEVs) with zero direct emissions from the tailpipe might be beneficial. However, although no emissions are generated from BEVs, diverse assessments have also evaluated the emissions associated with other life-cycle stages of electric vehicles, including the electricity demanded from Well-To-Wheel (WTW) [23,25–29]. In this context, for any power train, these evaluations consist of a complete analysis of the fuel required to power a vehicle and the emissions it generates along its operating trajectory. This trajectory is known as WTW and ranges from the supply chain of the fuel (well) to the vehicle drive (wheel) [30]. Specifically, the analysis of WTW emissions is divided into two stages: Well-To-Tank (WTT) emissions, which are generated throughout the fuel supply chain (from the extraction of materials to produce the fuel to its delivery to the vehicle); and Tank-To-Wheel (TTW) emissions, which are released from the tailpipe due to the fuel consumption during the driving of the vehicle [30]. The WTW stages considered for this article in order to carry out a complete evaluation of the energy operating trajectory of vehicles are displayed in Figure 1. Emissions from maintenance operation and end-of-life (dismantling, decommissioning, disposal and recycling) are not included in this analysis.

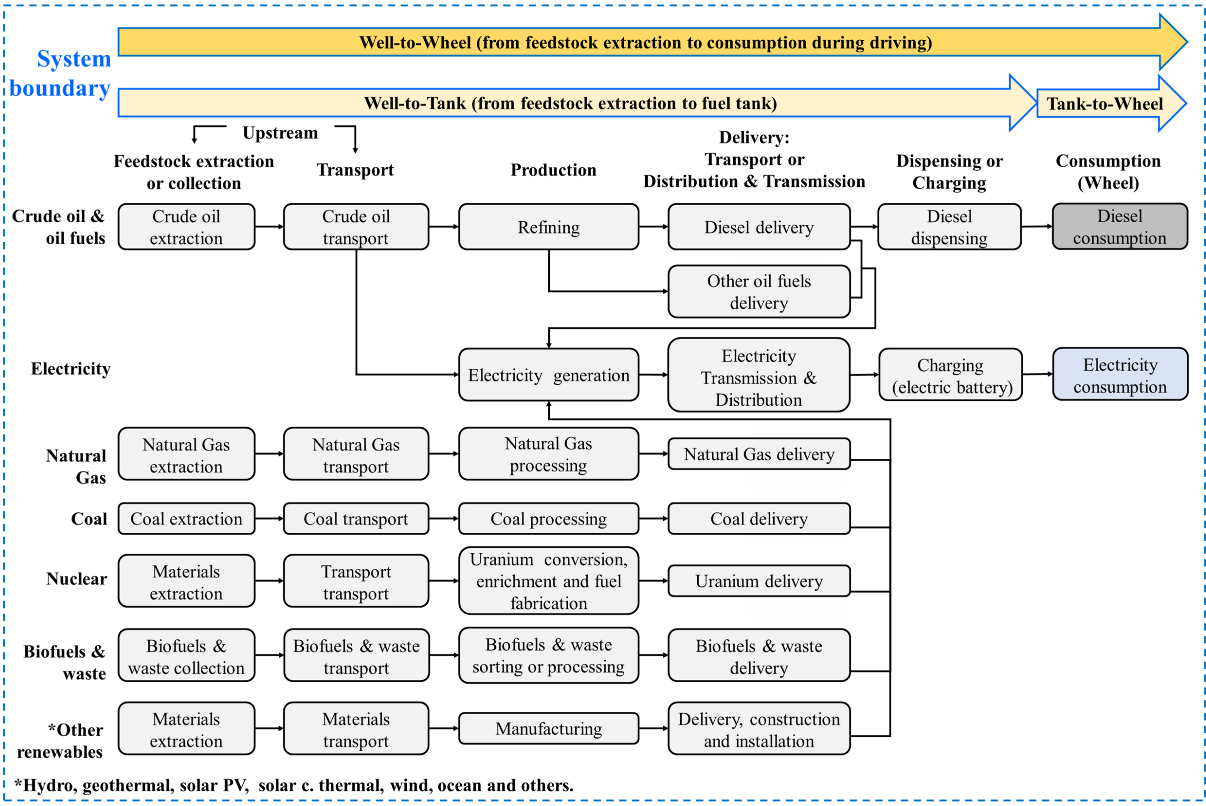

Figure 1. Well-To-Wheel GHG emissions from diesel and electricity diagram.

Recent studies have evaluated WTW emissions for diverse vehicle fleets. Gustaffson et al. [31] analyzed heavy-duty vehicles, whereas [32] focused on light-duty vehicles. On the fuel life-cycle, [33,34] analyzed the environmental impact and greenhouse gas emissions for several fossil fuels such as conventional gasoline, conventional diesel, liquefied petroleum gas, compressed natural gas, wheat-derived ethanol, corn-derived ethanol, cassava-derived ethanol, sugarcane-derived ethanol, rapeseed-derived biodiesel and soybean-derived biodiesel.

Furthermore, to improve the abatement of road transport emissions, it is also convenient to analyze possible routes that minimize energy consumption. In this context, various studies have been carried out regarding efficient instant delivery routing strategies, by considering a sustainable perspective and focusing on the reduction of emissions. Koç et al. [35] used a metaheuristic algorithm to examine the CO_2 emission fuel consumption and the operational cost of goods deliveries, depending on depot location, the composition of the fleet and the routing logistics. Kexin et al. [36] proposed an integrated and green logistics for an urban delivery service algorithm based on end-crowdsourcing service stations. This research evaluated the optimal location of terminal distribution nodes, discussed the use of vans and bicycles and assessed the environmental performance of green logistics by calculating carbon emissions.

One of the main approaches in the literature concerning routing strategies considering environmental issues is related to the Green Vehicle Routing Problem, a variant of the Vehicle Routing Problem. In [37], the authors proposed a model with a fleet of alternative fuel vehicles. The objective is to minimize the total distance traveled, taking into consideration the fuel tank capacity, so refueling stations are allowed on the route. Subsequently, different approaches have been proposed taking into consideration traffic conditions [38], refrigerated vehicles for perishable-product delivery [39], refueling stations and multiple depots [40], fleets with electric and regular vehicles with the aim of minimizing the cost of recharging and fuel consumption [41] and minimizing fuel consumption [42]. Paul et al. [43] used an algorithm to examine the routing problem by considering two-echelon along the transportation chain and heterogenous vehicles to minimize travel time, fuel consumption and overall carbon emissions. Xue [44] focused on a similar problem and evaluated delivery routes to calculate fuel and carbon emissions and costs, whereas the study by McLeod et al. [45] analyzed the last-mile delivery of diverse modes of transportation. The authors included the use of trolleys, vans, trucks, bikes and quadricycles to quantify and compare CO_2 and NO_X emissions and detailed operating costs.

The urgent need to address climate change requires comprehensive studies as decision-making tools, which include the evaluation of GHG emissions throughout the energy value chain to avoid burden shifting, the integration of sustainable modes of transport and the design of optimal routes. In response to this need, this article conducts an evaluation among vehicles of different fuel power trains regarding the energy consumption and GHG emissions generated from WTW, by comparing four combinations of transportation modes of CVs in a megacity. This assessment is intended to answer the following research questions: how do GHG emissions from TTW vary depending on the combinations of electric or diesel vans and E-bikes in an optimal route in Mexico City and how do emissions associated with electricity vary depending on the energy mix for power generation by country worldwide. The main contribution of this evaluation relies on a comparative analysis of the stages involved in the production and consumption of diesel and electricity over four modal transport options, which considered the environmental performance of different power train vans and E-bikes used for instant deliveries along optimal logistics routing based on the study by Galindo-Muro et al. [46].

This article provides several contributions to the state of the art: it provides data on the current situation of the GHG emissions in the area of Mexico City, further compared to other countries all around the world. Such data are, in general, accessible only with previous payments to online platforms. On the other hand, this proposal is based on data acquired from previous published studies and data given by public online platforms certified by other governmental authorities. Furthermore, the authors analyze the GHG emissions coming from the entire energy cycle, i.e., from the Well-To-Tank to Tank-To-Wheel transitions based on several strategies of energy production such as coal, oil, oil products and natural gas. The article also presents a case study in a high-density area of Mexico City and it includes the obtention of the WTW emission factors of each fuel, the energy and GHG emissions associated and a comparative analysis of electricity-related emissions in other countries which exemplify the diversification of energy mix for power generation (ranked by the amount of electricity generation in descending order): the People's Republic (P.R.) of China, the United States, India, the Russian Federation, Japan, Canada, Brazil, Korea, Germany, France, Saudi Arabia, Mexico, the United Kingdom, Turkiye, Indonesia, Italy, Australia, Spain, South Africa, Sweden, Poland, Norway, Argentina and the Netherlands.

2. Methodology

The methodology proposed in this article is based on the evaluation from WTW and it is schematized in Figure 2 This methodology—the problem description and scope of which were discussed in the introduction—considers the energy associated with the energy that powers vehicles and is applied to a case study for Mexico City, centered on a densely populated area with high vehicular congestion and cycling infrastructure. However, it can be applied to other cities with similar characteristics.

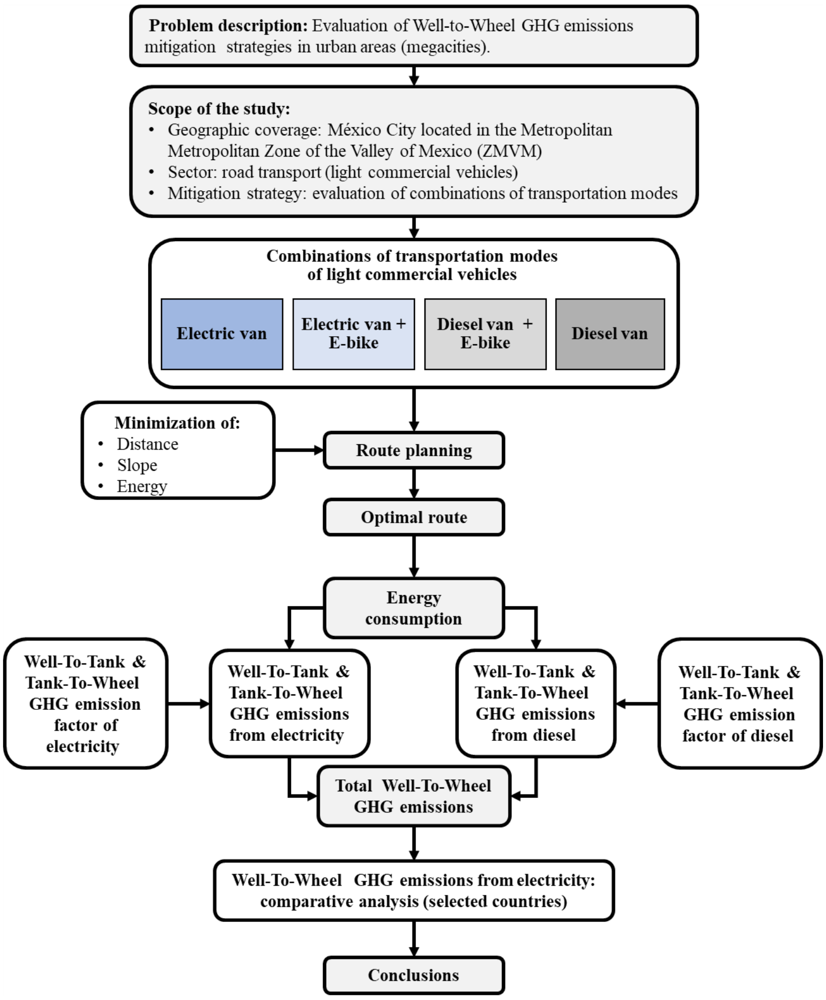

Figure 2. Methodology to evaluate GHG emissions from Well-To-Wheel in four combinations of transportation modes.

2.1. Optimal Logistic Combination and Energy Consumption of Modal Transport Options of CVs

For the specific case of CVs utilized for instant deliveries, this article evaluates and compares the environmental performance from WTW of different transportation modes in an optimal route. The transportation modes selected are the most commonly used in terms of instant deliveries, where small packages such as prepared meals and medicines are delivered. The route was obtained with a Vehicle Routing Problem formulation solved via Gurobi with Google Maps Api, according to the methodology reported in [46]. However, for the purpose of this research, the formulation is not discussed. The options contemplated involved a combination of a van and electric bicycles or the use of only a van for the entire route. The energy sources of the vehicles considering data availability for similar vehicles were diesel and electricity from the national public grid. These vehicles have comparable features: the driver seats, two passenger seats, rear wing doors and a payload of approximately 1 ton, according to commercial vehicles available on the market. The four combinations of transportation modes covering the optimal logistics route are the following (Figure 3):

- Combination 1. Electric van.
- Combination 2. Electric van combined with E-bikes.
- Combination 3. Efficient-engine diesel van combined with E-bikes.
- Combination 4. Efficient-engine diesel van.

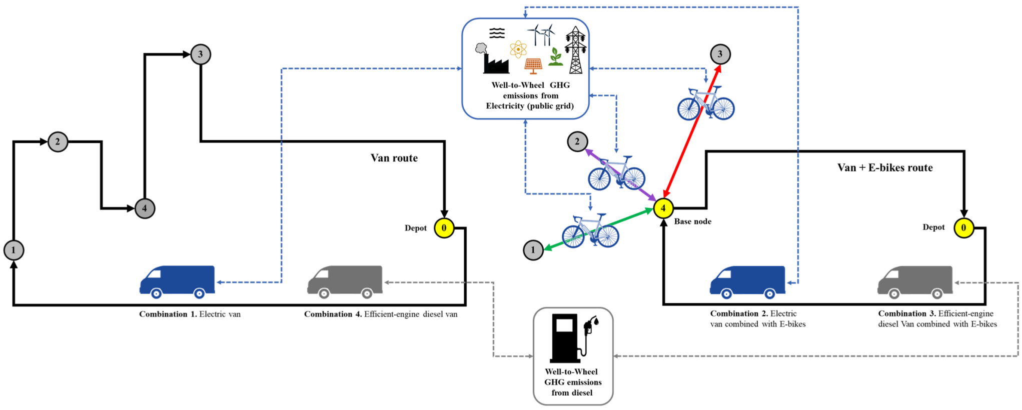

Figure 3. Four combinations of transportation modes depending on their energy sources and diagram of the optimal route using van or a combination of van and E-bikes.

The optimal logistic routing planning and the fuel consumed (fossil or electricity) for each option were based on the solution provided by the study developed by Galindo-Muro et al. [46], which considered the minimization of distance, slope and energy of the CVs as shown in Figure 3.

2.2. Calculation of Total GHG Emissions from Well-To-Wheel

To calculate the GHG emissions (CO_{2_e}, CH_4 and N_2O) from WTW of the combination of each transportation mode, it is required to evaluate the emissions of each fuel (electricity or diesel) separately, according to Figure 1. These emissions account for the total fuel consumed from WTW over the distance traveled by vehicles based on Equation (1) [47–49]:

$$E_{GHG,a} = [Fuel_a][EF_{GHG,a}] \tag{1}$$

where:
$E_{GHG,a}$ = Total GHG emissions per type of fuel (gCO_{2_e})
a = Type of fuel
$Fuel_a$ = Fuel consumed (kWh)
$EF_{GHG,a}$= GHG emission factor per type of fuel (gCO_{2_e}/kWh)

The emission factors are the amount of GHG (in gCO_{2_e}) produced per unit of energy (in kWh). For each fuel type, the WTW emission factors are obtained by summing the emission factors of the WTT and TTW stages. The procedures to obtain these emission factors for diesel and electricity are detailed in the following sub-sections. It is worth noting that, for the purposes of calculation in the next subsections, the data considered hereinafter can be found in [30,47–58].

2.2.1. Calculation of the Total GHG Emission Factor of Diesel from Well-To-Wheel (WTW)

The diesel emission factor from WTW is obtained by adding the WTT and the TTW emission factors. In particular, the WTT emission factor refers to the diesel supply chain and it is obtained by considering all the values of the inner stages of WTT (upstream, production (diesel refining), delivery to the diesel charging stations and dispensing) [30,59]:

- Upstream. This upstream emission factor of diesel includes crude oil exploration, drilling, development, extraction, processing and transport to the refinery gate [50]. This factor depends on the location of the crude oil reserve, the extraction methods and the modes of transportation to the refinery gate; however, this article adopts the average value from Masnadi [50]: 10.3 CO_{2e}/MJ for global average, 11.27 CO_{2e}/MJ for the United States and 9.86 CO_{2e}/MJ for Mexico.
- Refining. Each type of crude oil has different characteristics and is refined relying on diverse processes and quality specifications depending on the demand of the

destination markets [30,51]. However, on average, the refining process to produce oil fuels is the third largest source of stationary GHG emissions worldwide [51]. The refining average values are adopted from Elowainy et al. [52].

- Delivery and dispensing. These values are assumed to represent 5% and 0.1% of WTT and 0.91% and 0.02% of WTW, respectively [30].

Finally, the TTW emission factor is obtained from the combustion of diesel, which is consumed by the vehicle. The *default value of diesel combustion* is obtained from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for GHG Inventories [47–49]: $EF_{Diesel} = 74.1$ gCO_{2e}/MJ, equivalent to 266.8 gCO_{2e}/kWh.

2.2.2. Calculation of the Total GHG Emission Factor of Electricity from Well-To-Wheel (WTW)

The WTW electricity emission factor is also obtained by adding the WTT and TTW emission factors. Therefore, it is the sum of the values of the inner stages of WTT: upstream, production (electricity generation), delivery (T&D losses through the grid) and electric vehicle-charging stations. It is important to indicate that the emission factor of electricity comprises the contribution of each technology associated with its generation in each WTW inner stage [30,59,60]:

- Upstream. For the upstream GHG emission factors of electricity and due to the unavailability of specific data for individual processes and information for all countries, this article adopts the values from Moro and Lonza, Prussi et al. and Scarlat et al. and [54–56] for coal, oil, oil products, natural gas, biofuels and waste to generate electricity. The upstream of these fuels includes materials extraction and transport, refining or processing and delivery to the electricity or CHP plants [54–57,59]. The upstream values for utility-scale electricity generation from nuclear, hydropower, wind, solar photovoltaics, concentrating solar thermal, geothermal and ocean energy vary according to the specific characteristics of technologies per energy source. However, the emission factors considered in this article are adopted from the harmonized values of the National Renewable Energy Laboratory (NREL) [57], also due to the unavailability of specific data. The GHG upstream emission factor of these sources comprises resource extraction, material manufacturing, component manufacturing and construction.
- Generation. The GHG emission factor of the electricity generation stage is based on the overall fossil fuels (coal, oil, oil products and natural gas) consumed in the electricity and CHP plants, divided by the total electricity generated from all fossil and non-fossil energy sources [60]. The calculation of this emission factor is determined using Equation (2), in accordance with the methodology proposed by the International Energy Agency (IEA) [60]; and the energy input data are obtained from the Energy Statistics of the IEA by 2020 [58].

$$EF_{Electricity} = \frac{\sum_{Fuels}\left[\left(Input_{\mathrm{EP}}+\left(Input_{\mathrm{CHP\ plants}}-\frac{\mathrm{Heat\ output}}{\eta_{Heat}}\right)+OwnUse_{\mathrm{Plants/Ele}}\right)EF_{Fuel}\right]}{Ele_{Inlad}} \quad (2)$$

where:
$EF_{Electricity}$ = Emission factor of electricity
$\sum_{Fuels}$ = Sum of fuels from emitting sources consumed to generate electricity
$Input_{\mathrm{EP}}$ = Fuel input into electricity plants (kWh)
$Heatoutput$ = Total heat generated in the combined heat and power (CHP) plants (kWh)
η_{Heat} = Efficiency of heat generation in the CHP plants (assumed to be 90%)
$OwnUse_{\mathrm{Plants/Ele}}$ = Electricity self-consumption in electricity and CHP plants (kWh)
EF_{Fuel} = Default GHG emission factors of fossil fuels from the IPCC Guidelines for GHG inventories (gCO_{2e}/kWh) [47,49]
Ele_{Inland} = electricity generation from all sources, including the non-emitting sources (kWh)

The emission factor values for the fossil fuels are obtained from the default GHG emission factors of fossil fuels according to the IPCC Guidelines for GHG inventories (gCO_{2e}/kWh) [47,49] and, for the specific case of coal and oil products consumed to generate electricity, the contribution of each individual fuel is considered.

- Delivery. The delivery emission factor of electricity includes transmission and distribution, including losses. The emissions generated in this stage vary, on average, from 3% to 13%, according to the IEA [30]. In particular, the emission factor regarding electricity losses during transmission and distribution (T&D losses) through the grid (from the generation point to the consumption point) is calculated according to Equation (3) [60]:

$$EF_{Loss} = EF_{Electricity}\left(\frac{Losses}{TotalGrid}\right) \quad (3)$$

where:
EF_{Loss} = Emission factor electricity losses
$EF_{Electricity}$ = Emission factor of electricity
$Losses$ = Total grid T&D losses (kWh)
$Totalgrid$ = Total electricity transiting through the national electricity grid, which corresponds to the gross electricity production plus imports minus own use in electricity and CHP plants (kWh)

- Charging. The emission factor of the vehicle charging phase represented 5.5%. This last percentage is assumed in this article as an average between slow and ultrafast charring [30].

The TTW emission factor of electricity is zero because no emissions are emitted directly from the tailpipe. In terms of energy consumption, while the emissions generated from the tailpipe of an internal combustion vehicle depend on the type of oil fuel used, the emissions generated directly from a BEV are considered to be null.

2.2.3. Calculation of Total GHG Emissions from Well-To-Wheel for Each Combination of Transportation Modes

The total GHG emission factors from WTW of diesel and electricity are used in Equation (1) to calculate the emission of each of the four combinations of transportation modes. Finally, the optimal combination powered by diesel (average world value) is compared with the optimal combination powered by the electric grid of the selected sample of countries.

2.3. Worldwide Comparison of GHG Emissions from the Well-To-Wheel

The same methodology applied to obtain Mexican emission factors of electricity was considered to obtain those of other countries, based on the input data of the Energy Statistics of the IEA 2020 [58]. These nations exemplify the energy mix for power generation in 2020 around the world, which is displayed in Figure 4. This figure shows the diversification of power generation technologies and the contribution of each of them to the total output. Depending on the country, the power sector can use fossil fuels (coal, oil, oil products and natural gas), nuclear energy, biofuels and waste and clean renewable energies (wind, hydropower, geothermal, solar photovoltaics, concentrating solar thermal and ocean), which condition the generation of emissions.

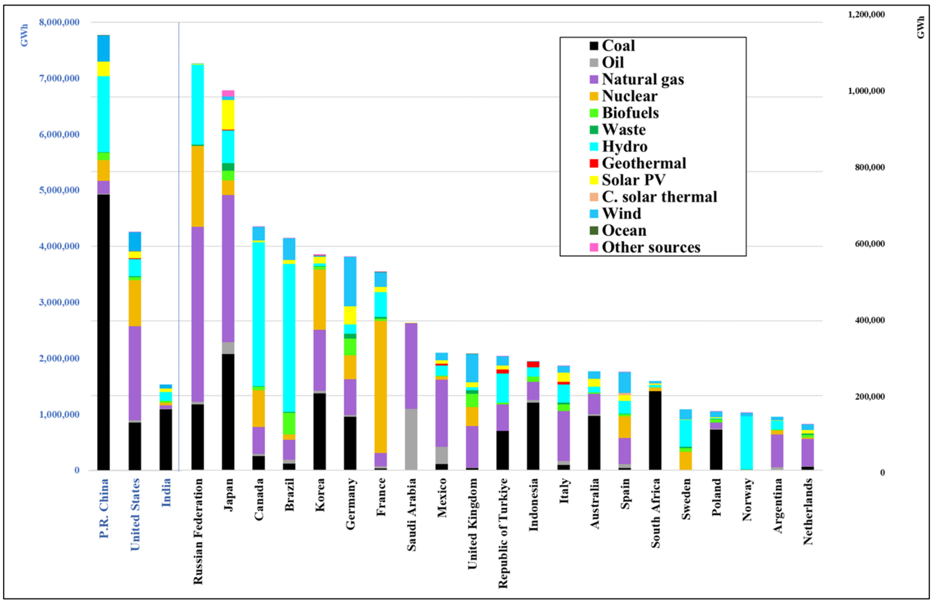

Figure 4. Electricity generation by energy source in selected countries in 2020.

3. Results

3.1. Combinations of Transportation Modes of CVs

Today, the use of multiple vehicle types in delivery operations should be adapted to the new taxonomy of cities. For this reason, the design of an optimal routing must explore different alternatives in order to execute all deliveries on time and satisfy the demands of the population. In this case study, the aforementioned methodology given in Section 2 is here applied in the context of the *instant deliveries* problem. The following scenario is selected according to the results presented in [46] for the optimal arrival destination of an electric van carrying E-bikes on board, in which energy consumption is minimized. It is important to indicate that the energy consumption is sensitive to urban characteristics.

In the scenario of using only the van, the CV leaves the depot (node 0), travels to dispatch the merchandise at each of the delivery nodes (1, 2, 4 and 3) and returns to the depot. On the other hand, starting from the depot (node 0), the van travels directly to a base node (node 4) and unloads the electric bicycles. The E-bikes deliver the merchandise to three other nodes (1, 2 and 3) in a round trip and are then loaded back onto the van and the van returns to the depot. It is worth noting that the version that combines VAN and E-bikes would require at least two additional workers which would increase the overall costs. In this work, however, the authors do not take in consideration cost analysis derived from human work force.

3.2. Total GHG Emissions from Well-To-Wheel

3.2.1. Total GHG Emission Factor of Diesel from Well-To-Wheel

The results of the diesel emission factor of each fuel from WTW are presented in Table 1. For the specific case of Mexico, this article considered that 70% of diesel (average percentage from 2018 to 2021) is produced in the United States and 30% in Mexico [53].

Table 1. GHG emission factor of diesel from Well-To-Wheel.

Diesel	Units	Well-To-Tank					Tank-To-Wheel	Total WTW
		Upstream	Production (Diesel Refining)	Delivery	Dispensing	Total (WTT)	Consumption (Fuel Combustion)	
World average	$gCO_{2e/kWh}$	37.08	17.40	2.87	0.06	57.41	266.80	324.21
USA	$gCO_{2e/kWh}$	40.58	17.64	3.07	0.06	61.34	266.80	328.14
Mexico	$gCO_{2e/kWh}$	35.49	17.40	2.79	0.06	55.74	266.80	322.53
70%USA/30%MX	$gCO_{2e/kWh}$	39.05	17.57	2.98	0.06	59.66	266.80	326.46
Share from WTT	%	65.5%	29.4%	5.0%	0.1%	10%		
Share from WTW	%					18.3%	81.7%	100%

As can be observed in Table 1, the GHG emission factor from WTW associated with diesel accounted for 326.46 gCO_{2e}/kWh, of which 18.3% corresponded to WTT and 81.7% for the fuel combustion (TTW) in the vehicles.

3.2.2. Total GHG Emission Factor of Electricity from Well-To-Wheel

The results of the electricity emission factor of each fuel from WTW are presented in Table 2.

Table 2. GHG emission factor of electricity in Mexico from Well-To-Wheel in 2020.

Electricity	Units	Well-To-Tank					Tank-To-Wheel	Total WTW
		Upstream	Production (Electricity Generation)	Delivery	Charging	Total (WTT)	Consumption (Fuel Combustion)	
Mexico	$gCO_{2e/kWh}$	43.08	419.94	51.21	29.93	544.16	0.00	544.16
Share from WTT	%	7.8%	77.3%	9.4%	5.5%	100%		
Share from WTW	%					100.0%	0%	100%

In 2020, the electricity produced in Mexico was generated from fossil fuels (coal, petroleum coke, liquefied natural gas (LPG), natural gas, diesel and fuel oil), nuclear energy, biofuels and waste (biogas and sugarcane bagasse) and clean renewables (hydropower, geothermal, solar photovoltaic and wind) [53]. These results indicate that, according to this energy mix, the GHG upstream emission factor represented 7.8% of WTT and WTW in 2020, and the emission factor from generation accounted for 77.3% of WTT and WTW. Meanwhile, the delivery (transmission and distribution, including losses) emission factor of electricity accounted for 9.4% of WTT and WTW by 2020, based on the Energy Statistics of the IEA 2020 [58]. As indicated by the IEA, electricity losses vary from approximately 2% in small and high-income economies to 30% in large and middle- and low-income countries [30]. The total GHG emission factor of electricity from WTW in Mexico by 2020 accounted for 544.16 CO_{2e}/kWh, of which 100% corresponded to WTT.

3.2.3. Total GHG Emissions from Well-To-Wheel for Each Combination of Transportation Modes

In accordance with the results, traveling the entire delivery route by using only the diesel van releases 1.3 times more GHG emissions from WTW than the electric van, 5 times more that its combination with E-bikes and 6.5 times more than the electric van combined with E-bikes (Figure 5).

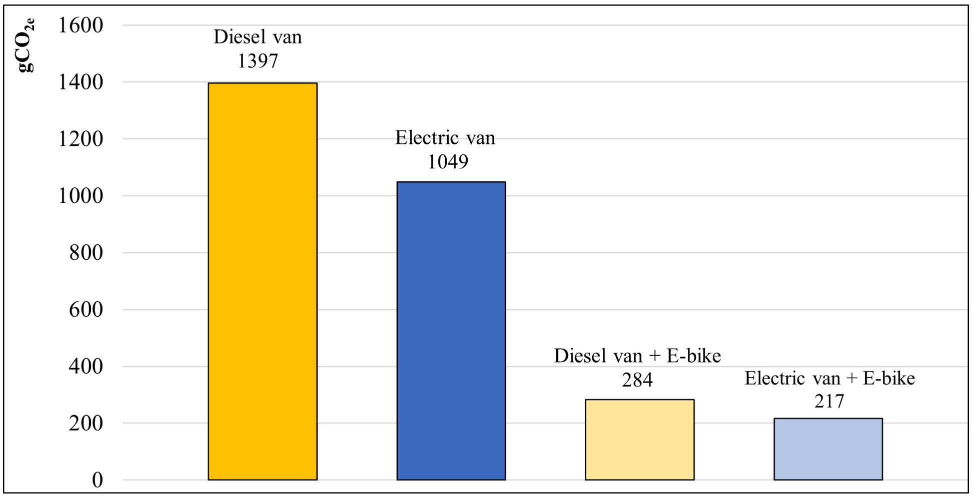

Figure 5. Diagram of Well-To-Wheel GHG emissions of the optimal route for each combination of transportation modes in Mexico by 2020.

Table 3 presents energy consumption and GHG emission generation from WTW, depending on whether an electric or diesel van is used and whether it is used in combination with E-bikes.

Table 3. Well-To-Wheel energy consumption and GHG emissions of the optimal logistics route (Mexico in 2020).

Combination	Nodes Delivery Sequence	Energy Consumption	GHG Emissions	Energy Consumption	GHG Emissions
		kWh	gCO_{2e}	kWh	gCO_{2e}
		Electric van		Diesel van	
Van	0 to 1	1.640	892.423	3.640	1188.388
Van	1 to 2	0.028	15.182	0.062	20.217
Van	2 to 4	0.088	47.668	0.194	63.477
Van	4 to 3	0.072	39.343	0.160	52.391
Van	3 to 0	0.100	54.146	0.222	72.463
TOTAL		1.928	1049.032	4.279	1396.936
		Electric van + E-bike		Diesel van + E-bike	
Van	0 to 4	0.271	147.429	0.601	196.323
E-bike	4 to 1 to 4	0.011	5.882	0.011	5.882
E-bike	4 to 2 to 4	0.008	4.333	0.008	4.333
E-bike	4 to 3 to 4	0.008	4.118	0.008	4.118
Van	4 to 0	0.101	54.879	0.224	73.079
TOTAL		0.398	216.614	0.852	283.735

In the case study applied in Mexico, the benefit of using electric bicycles is significant, in terms of reducing energy consumption and emission production. Like other megacities around the world, the Government of Mexico City has developed policies and programs that promote the use of bicycles as a sustainable mode of transportation. According to the Ministry of Mobility (SEMOVI), since 2004 the city has progressively implemented and strengthened a safe cycling infrastructure with 393 km (with expansion plans of 600 km by 2024), 10 bicycle parking facilities and 687 public bicycle stations, which position it as the city with the highest kilometer length for bicycles in the country. This cycling infrastructure network includes bus–bike lanes, bicycle priority lanes (lanes shared with cars), cycle lanes (exclusively for bikes), cycle tracks (exclusive lanes physically separated from motor traffic), recreational cycle tracks, shared paths (bicycles and pedestrians) and Sunday routes. This infrastructure can be leveraged to improve mobility in the city. As illustrated, in Mexico the emissions generated by the combination of an electric van and E-bikes is lower than the diesel counterpart. This is since 77% of the energy mix for electricity generation is composed of fossil fuels. However, three-quarters of the fossil fuels used are dry gas, which has a lower emission factor than coal, oil or oil products. In the country, decreasing or increasing the electricity emission factor depends on the public policies implemented to generate electricity. In this sense, Mexico could follow the example of countries that generate cleaner electricity or those nations that generate electricity with a high percentage of coal. Consequently, a comparative analysis is conducted to exemplify the performance of different countries with different energy mixes in electricity generation.

3.3. *Comparison of GHG Emissions from the Well-To-Wheel in Selected Countries*

The GHG emission factor of electricity from WTW according to the desegregated energy mix in Figure 4 in diverse countries is displayed in Figure 6. It is important to mention that the results obtained in this article may differ from nationally reported emission factors due to different criteria and assumptions, statistical variations between supply and demand, adoption of average values for upstream stages and the use of other data and information sources in 2020. In that year, high-income economies were among the three countries with the lowest GHG emission factors, significantly lower than the factors of the countries at the top of the list. For instance, the GHG emission factor of Sweden was 80 times lower than the emission factor of South Africa.

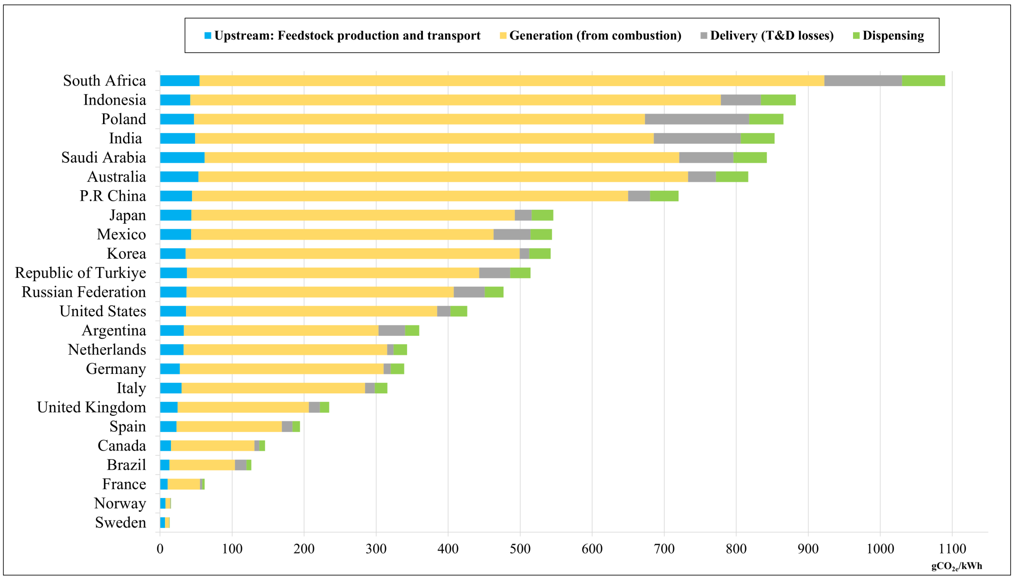

Figure 6. Well-To-Wheel GHG emission factor of electricity by country in 2020.

The emission factor of diesel is very similar around the world. However, the emission factor of electricity can be very different across nations, which can influence the suitability of using a diesel CV with an efficient engine or an electric CV. Therefore, in this study, the GHG emissions of electricity from WTW for 23 countries worldwide have been compared, using the optimal route of the vans in combination with E-bikes, as an example. The results of this comparative analysis are schematized in Figure 7, which ranks the countries in descending order according to GHG emissions.

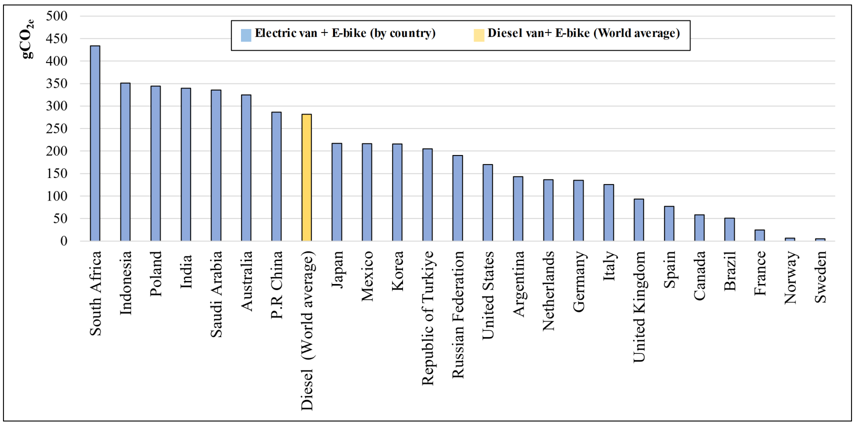

Figure 7. Total Well-To-Wheel GHG emissions in selected countries.

The figure highlights that a modal transport combination using a diesel vehicle (with a world average diesel emission factor) with E-bikes can generate between 98% and 91% more GHG emissions from WTW than its electric counterpart in Sweden, Norway or France. However, in countries with a very high electric emission factor, such as South Africa, Indonesia or Poland, the modal combination using the electric van generates between 35% and 18% more than a diesel CV with an efficient engine, which can be observed in Table 4.

Table 4. Contribution of major energy categories of electricity generation, Well-To-Wheel electricity emission factor and emissions of the full-electric optimal route by country in 2020.

Country	Electricity Generation			Well-To-Wheel Electricity Emission Factor	Electric van and E-bikes Emissions (Optimal Route)
	Fossil %	Nuclear %	Renewable %	gCO_{2e}/kWh	gCO_{2e}
South Africa	88.5%	4.1%	7.3%	1090.19	434.03
India	76.0%	2.8%	21.2%	853.12	339.64
Poland	81.2%	0.0%	18.7%	865.65	344.63
Indonesia	81.2%	0.0%	18.8%	882.63	351.39
Saudi Arabia	99.8%	0.0%	0.2%	842.44	335.39
Australia	77.4%	0.0%	22.6%	816.71	325.15
P.R China	66.6%	4.7%	28.7%	719.98	286.64
Japan	72.5%	3.8%	22.1%	545.88	217.33
Mexico	77.3%	2.6%	20.1%	544.16	216.64
Korea	65.1%	27.7%	6.6%	542.32	215.91
Republic of Turkiye	57.7%	0.0%	41.9%	514.45	204.81
Russian Federation	59.9%	19.8%	20.3%	476.96	189.89
United States	60.4%	19.3%	20.2%	426.51	169.80
Argentina	66.6%	7.5%	26.0%	359.97	143.31
Netherlands	68.1%	3.3%	28.2%	343.04	136.57
Germany	42.5%	11.2%	46.0%	338.91	134.93
Italy	56.6%	0.0%	43.2%	315.53	125.62
United Kingdom	38.3%	16.2%	45.6%	234.67	93.43
Spain	32.9%	22.1%	44.9%	194.36	77.38
Canada	17.8%	15.1%	67.1%	145.62	57.97
Brazil	13.2%	2.3%	84.5%	126.80	50.48
France	8.6%	66.5%	24.7%	61.88	24.64
Norway	1.3%	0.0%	98.5%	15.28	6.08
Sweden	0.5%	30.0%	69.4%	13.19	5.25
Diesel (world average)				326.46	283.71

These results are attributed to the high proportion of fossil fuels consumed in the electricity generation mix, which produce a significant amount of GHG emissions [59], as can be seen in Figure 8.

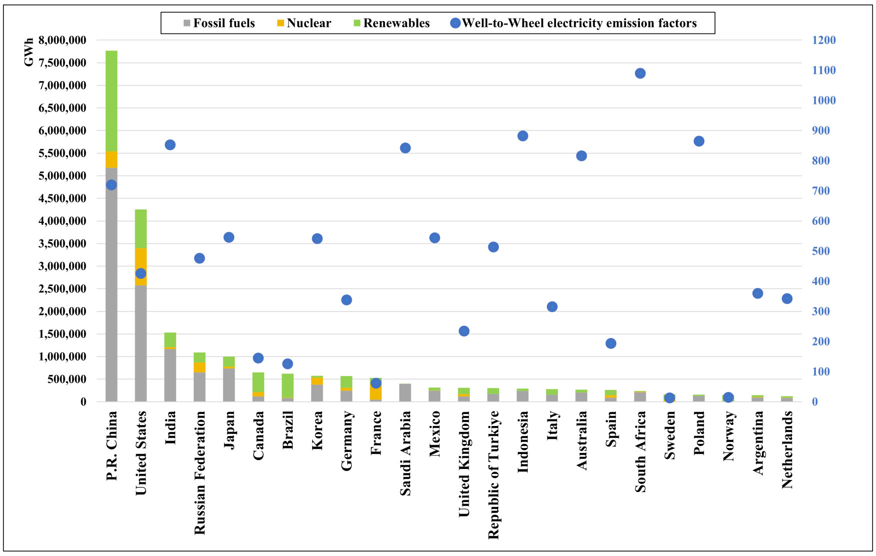

Figure 8. Electricity generation by source in selected countries.

This figure displays the share of the three major categories of energy for electricity generation (fossil fuels, nuclear energy and renewable sources) to generate electricity in different countries, as well as its corresponding emission factor from WTW. Regardless of the amount of energy generated, the emission factor depends mainly on the amount of fossil fuels consumed in the power and CHP plants since it is the production stage that generates the most emissions. Specifically, the countries that use the highest percentages of coal to generate electricity are those with the highest emission factors, with the exception of Saudi Arabia, which had a high emission factor because 99.8% of its electricity was generated with natural gas, crude oil and oil products. In contrast, countries such as Norway, Brazil and Canada generate between 67% and 99% of their electricity from renewable sources. In the case of Sweden (69% and 30%) and France (25% and 67%), the use of renewable and nuclear energy has made their electricity systems have a low WTW emission factor.

4. Discussion

In the case under study in Mexico, the delivery route obtained using the combination of electric van and E-bikes implies an 80% reduction in GHG emissions in contrast with the case of traveling only in the diesel van without the use of E-bikes, whereas the electric van and the E-bikes emits 24% less GHG emissions than diesel van and E-bikes, which is also a favorable result for this study. Therefore, strategies such as the one of combining vans and E-bikes could help reduce emissions mainly if vehicles are cleaner throughout their energy supply chain; that is the underlying reason for which the country requires the alignment of public policies between the energy generation and transportation sectors in the context of atmospheric decarbonization targets.

At the global level, even given the impact of urban areas on global emissions, cities also have a significant emission-reduction potential to address climate change mitigation [12,14,16,61,62], by implementing emission-mitigation strategies, such as the one proposed in this article. The evaluation of the four modal transport options and the comparative analysis of the electricity emission from WTW in diverse countries reveals that an optimal route of an electric van combined with E-bikes can reduce the consumption of energy and the generation of GHG emissions significantly. Even though they are more expensive and sales remain low [19], electric vehicles are expected to contribute to global mitigation by not releasing direct tailpipe emissions [63]. Furthermore, in addition to consuming less energy and having zero emissions, E-bikes face traffic congestion. In this sense, a sustainable option for short distances is the bicycle, which is an efficient, affordable, operational low-cost and clean mode of urban transportation that contributes to improving mobility [64,65].

Therefore, the promotion and appropriate use of cycling infrastructure, along with the use of electric vehicles and the design of optimal routes to undertake a growing economic activity, such as instant deliveries, can be beneficial for large cities in terms of mitigating emissions. However, for this strategy to be successful, the composition of the energy mix for electricity generation is critical. Although EVs do not generate emissions directly from the tailpipe (TTW), from the WTT, the electricity that powers the vehicles could be associated with a certain amount of GHG. The electricity consumption of electric vehicles entails a rise in the load factor of power plants [23,66] and a potential increase in GHG emissions in this sector [29,59,67,68]. In this sense, the additional emissions from the power system linked to the vehicle fleet electrification [67] cause a burden shift from the transport sector to the electricity sector [28,29,66,68,69].

It is important to highlight that high-income countries are mainly those that have the economic resources to invest in the implementation of new clean technologies and charging infrastructure; these nations have also a population with a higher income and thus able to afford electric vehicles. In countries with electric emission factors from WTW higher than fossil fuel emission factors, the use of electric vehicles generates more GHG emissions than an internal combustion vehicle with an efficient engine. In this regard, diverse improvements are being deployed to reduce emissions in the transport sector, which include improving the efficiency of ICEs and establishing emissions performance standards [63]. CVs with these characteristics continue to be the best sellers in countries similar to Mexico, mainly because they are still more affordable and more models are available [19,63]. In addition, vehicle selection is highly influenced by urban infrastructure and the national economy. In order to achieve an actually effective reduction in WTW emissions to address the global climate agenda, experts worldwide suggest preferably the use of renewable energies for electricity generation [23,24,26,67,70,71]. In the long term, it is expected that the largest percentage of electricity would be produced from clean renewable sources, as suggested in the Net Zero Emissions (NZE) Scenario proposed by the IEA [24]; for instance, 68% of the global generation in this scenario would be from solar and wind energy by 2050. Future research work could address life-cycle emissions from energy carriers, including operation and maintenance and downstream stages; and life-cycle emissions from vehicle manufacturing. Furthermore, there is also a need to estimate operative costs of instant delivery services and country-specific emission factors for each stage and for each specific technology, because the values vary depending on several factors, as mentioned in Sections 2.2.1 and 2.2.2.

It is worth mentioning that data utilized for the emission identification of the WTT process, in the case study, are taken from a national average since for the Mexican case, finding accurate data divided by city represents a hard task, so far. This may add a bit of uncertainty to the obtained results that are discussed under the assumption that for the WTT process, data are homogeneous over the entire country.

5. Conclusions

Cities play a crucial role in the development and implementation of innovative planning strategies in high-polluting sectors, including road transport. In the particular case of a fast-growing economic activity, such as instant deliveries, where CVs also affect urban congestion and produce GHG emissions, the design and evaluation of suitable strategies can help to mitigate these impacts. However, it is required to consider the overall emissions linked to the energy consumed by the vehicles, in order to avoid burden shift. Therefore, this study proposes an analysis from WTW of different modal transport options, which considers the use of electric and diesel vans with similar characteristics, traveling independently or in combination with E-bikes. The analysis includes the energy consumption of an electric- and a diesel-powered train and a comparison of electric grids of diverse countries.

The results indicate that, in an optimal route, a combination of a BEV with E-bikes generates fewer emissions from WTW than the diesel counterpart in Mexico. However, in countries with a high electrical emission factor due to the consumption of fossil fuels for power generation, electric vehicles might pollute more than an ICE. Therefore, it is critical that it be mandatory that power generation of energy be clean, in order to address the challenges of climate change through the vehicle fleet-electrification strategy. In addition, designing optimal commercial transportation routes in a megacity, along with the use of more sustainable modes of transportation, such as E-bikes, is beneficial in terms of emissions and reduced traffic congestion. Furthermore, the importance of the road transport sector and the impacts it generates rely not only on energy consumption and emission generation but also on the quality of life of the population. This implies that adequate sustainable planning for the future that promotes clean, efficient, affordable and multimodal transport is required.

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Abbreviations

CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CHP	Combined heat and power
CVs	Commercial vehicles
E-bike	Cargo electric bicycles
BEVs	Battery electric vehicles
GHG	Greenhouse gases
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
CH_4	Methane
NZE	Net Zero Emissions
N_2O	Nitrous oxide
PM	Particulate matter
SEMOVI	Ministry of Mobility (acronym in Spanish of Secretaría de Movilidad)
TTW	Tank-To-Wheel
T&D	Transmission and Distribution
WTT	Well-To-Tank
WTW	Well-To-Wheel
ZMVM	Metropolitan Zone of the Valley of Mexico

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