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Influence of Transport Demand Parameters on Environmental Pollution for Deliveries by Cargo Bikes in City Areas with Traffic Restrictions

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Abstract: In light of global environmental degradation, which is largely affected by the transport sector, increasing attention is paid to enhancing the quality of life in urban areas. Policymakers are taking steps to reduce transport-related pollution and accelerate the shift to sustainable city development. They introduce stricter requirements for fuel quality and transport emissions, impose fines for traffic congestion, increase parking fees, establish low-pollution zones, etc. The implementation of measures that may not be perceived positively requires careful planning and analysis. This involves using suitable techniques and software to evaluate and support planned strategies. We propose a comprehensive approach to assess the ecological effect of using a delivery fleet that incorporates cargo bikes, operating in conjunction with light vans within a restricted urban area. The presented methodology was implemented using Python programming language and includes simulation tools for the execution of alternative delivery scenarios and a model for determining emissions generated by the analyzed supply scheme. The developed approach was applied to selected areas of Krakow (Poland) and San Sebastian (Spain), and the obtained models were used to study the influence of transport demand on the decrease of transport-caused environmental pollution. Simulation results indicate a statistically significant influence of the mean consignment weight on the emission reduction obtained due to the use of cargo bikes.

Keywords: cargo bikes; transport demand modeling; vehicle emissions

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1. Introduction

The evolution of a modern city largely depends on the trends and directions of development of the transportation sector. Global processes such as urbanization and rising living standards lead to excessive consumerism and overproduction, which cause, among other things, an increase in the number of vehicles and the volume of freight transportation. Moreover, the recent rapid growth in technological innovations, as well as the COVID-19 pandemic, have contributed greatly to changing consumer behavior and given a strong impetus to the development of e-commerce and the CEP (Courier Express and Parcel) services, adding even more pressure to the already challenging last-mile delivery segment [1,2]. This final stage of the cargo journey is often recognized as one of the most difficult, costly, and polluting components of the shipping process [3–5]. Road transport activities in general, and the last-mile sector in particular, are usually associated with such aftermath as traffic jams, contamination of air, land and water by harmful substances, noise pollution, traffic accidents, reduction of urban public space, etc.—in other words, with a significant deterioration of living conditions in cities and damage to human health [6–8]. Moreover, transport to a great extent contributes to the acceleration of global warming, since the main product of the fuel combustion process that is released into the atmosphere is carbon dioxide CO_2, which is a primary greenhouse gas (GHG). Despite the widespread use of innovative technologies and alternative fuels, the transportation sector still relies heavily on non-renewable resources (gasoline and diesel) and is one of the largest producers of GHG in Europe—around 25% of global CO_2 emissions. Furthermore, road transportations were responsible for almost 80% of all European Union (EU) transport-caused environmental pollutions in 2020 [9].

Combating the negative consequences caused by transportation, European policymakers are introducing a wide range of regulations and initiatives aimed at reducing its environmental and socio-economic impact. The main environmental policies of the European Union, the Directives, set out the objectives that all member states must achieve by developing their own regulatory framework to meet the requirements and pursue common goals. In the field of environmental protection and sustainable development, key EU Directives establish acceptable levels of transport-related noise and pollutants (such as carbon dioxide CO_2, nitrogen oxides NO_x, particulate matter PM, and others), set fuel requirements and standards for the inclusion of green vehicles in the public fleet, etc. The most recent climate legislative package, the European Green Deal, and its extension, Fit for 55, declare the goal of reducing CO_2 emissions by 55% by 2030 and achieving carbon neutrality in the EU by 2050 [10]. To meet this ambitious target, the measures introduced for the automotive industry include tighter limits on CO_2 emissions, aiming to eliminate them completely in new cars and vans from 2035.

However, the introduction of emission-reducing technologies in the transportation sector alone is not enough to attain climate neutrality; even stricter rules limiting GHG emissions must be adopted, and the number of vehicles used must be radically reduced [11,12]. Such events can be initiated by implementing urban vehicle access restrictions [13], namely, by creating urban zones with low (LEZ) or zero emissions (ZEZ). Such areas are becoming increasingly popular and contribute greatly to changing travel behavior and moving away from motorized transport [14,15]. The main idea behind the establishment of restricted traffic areas is to reduce the harmful effects and inconveniences associated with road transport. Usually, the prohibition on entry to such zones applies to outdated and polluting vehicles (heavy-duty trucks, vehicles with Euro 3 and lower technology, etc.), which induces the use of public and more environmentally friendly transport and encourages walking and cycling. In special cases, completely traffic-free zones are created, where only pedestrian and bicycle traffic is allowed. At the same time, the adoption of sustainable regulations prompts logistics operators to modify their operational scenarios with the arrangement of transshipment centers near restricted access areas, to modernize the transport fleet and to involve in delivery activities green means of transport, such as electric vans and cargo bicycles. These solutions are often implemented on the territory of historical parts of European cities, such as Krakow [16], Rotterdam [17], Madrid [18], Paris [19], and others. Such central areas are characterized by a high building density, a concentration of commercial establishments, and narrow streets with one-way traffic and congestion, i.e., features that crucially complicate the processes of movement and delivery of goods. However, especially for such complex urban areas, the highest efficiency in terms of cost savings [20] and improved social and ecological conditions can be achieved with cargo bikes [21]. Therefore, to ensure the most effective functioning of the transportation network within an urban zone with access restrictions, a thorough analysis and a special approach to assessment and planning are required, which will consider the specifics of the road infrastructure, time and space limitations, composition of the transport fleet, as well as requirements for environmental protection.

This research aims to define the impact of the demand for pollution reduction based on real-world transportation networks, namely, the central parts of the cities of Krakow (Poland) and San Sebastian (Spain). The selected cities were partners of the CityChanger-CargoBike (CCCB) project implemented within the European Union's Horizon program. The simulations performed in the experimental part of this study are based on the approach developed by the authors and described in detail in papers [22,23].

The current paper is divided into several sections: after presenting the current situation in the field of environmental impact of road transport activities and reviewing the main scientific sources (Section 2), in Section 3 we illustrate the details of the developed travel demand model and present the software used for the simulations and calculations of transport emissions. Section 4 contains the results obtained by running the simulations of different delivery scenarios and the subsequent use of outputs in the emission calculation module. Next, in Section 5, we discuss our findings. The final conclusions are given in Section 6.

2. Literature Review

The application of an integrative approach (combining simulation modeling with models for calculating transport emissions) provides a toolkit for investigating the environmental consequences of adopting various alternative strategies and initiatives, understanding the relationship between delivery processes and sustainable development of the city, as well as facilitating informed decision making [22]. Simulation modeling to the greatest extent enables a detailed representation of the real-life components of the transportation network and their interaction, and can be implemented on different scales—from macro to micro simulation, with the help of ready-made software (for instance, SUMO [24], Paramix [25], MATSim [26], AnyLogic [27], Vissim [28], etc.) or by custom frameworks [16,17,23,29]. Further, information on transport activity (vehicle miles travelled, road category, fuel type, EURO standard, etc.) is provided to the vehicle emission model (such as COPERT [24,28], IVE [25], PHEM, MOVES, etc.), which allows researchers to estimate the amount of pollution generated by the analyzed transport system.

An integral part of the transportation planning and decision-making process is the determination of travel demand, as this parameter is an indicator of the number and patterns of movement within a specified geographical area during a defined time. The traditional four-stage travel model is currently one of the most widely used approaches to determining travel demand due to its versatility and adaptability to the problem being addressed. In the classical sense, the model involves such successive steps as generation and distribution of traffic, modal choice, and traffic assignment. However, quite often the model is modified and adjusted for the needs of research by including additional steps, algorithms, assumptions, etc. [30–33]. The results of the demand assessment can be used for various purposes, such as determining infrastructure effectiveness, forecasting the supply volumes, managing and optimizing traffic flows, evaluating the efficiency of the transport network and its impact on the environment, etc. Freight demand modeling is a fundamental step in the development and implementation of efficient green urban practices, such as incorporating cargo bikes into logistics systems. Even though freight bicycles are a more sustainable means of transport, their adaption must consider their limited capacity, speed, and distance compared to traditional delivery vehicles.

Among the many benefits of using cargo bikes in urban deliveries, the following can be highlighted as the most important: cost savings (due to lower purchase, service, and operating costs); reduction of traffic jams and road casualties (due to the possibility of using bicycle lanes and sidewalks, ease of parking, and saving public space); reduction of transport emissions and noise, etc. [20,26,27,34–38]. However, for the successful implementation of cycles in transportation operations, their limitations and drawbacks must also be considered. The disadvantages of cargo bikes include restrictions on load and cargo volume, reduction of travel range, insufficient cycling infrastructure, and increased danger for cyclists (due to poor cycling etiquette, road accidents, the physicality of a cyclist, and difficult seasonal conditions) [16,17,38–41].

Numerous studies confirm the wide possibilities of using cycles in the highly popular on-demand and CEP services. The maximum weight of parcels handled by couriers does not exceed 30 kg [34] (some studies indicate an average package weight of 6 kg for most orders [35]), and the mean trip distance is often less than 10 km [42] (ranging from 5 to 16 km, while the average battery range is approximately 40 to 75 km [38]); such characteristics make it possible to transport small- and medium-sized freights by bicycles.

Research on technological processes that include cargo bicycles indicates their significant potential and competitiveness compared to traditional freight vehicles. Moreover, there are no other means of transportation that could match their ability to reduce traffic-related pollution. As demonstrated by the authors of paper [17], the simulation of delivery processes performed by cargo bicycles within the ZEZ showed a noteworthy reduction in emissions by up to 90%. However, the analysis of the effects of the implementation of urban consolidation centers together with the ZEZ indicated an increase in vehicle kilometers outside the zone [43]. Similarly, near-total elimination of CO_2 emissions (by 97% annually) was shown by a study of a delivery scheme that introduces electric cargo tricycles for CEP shipments, replacing diesel vehicles [34]. Moreover, the authors note a significant (by 31%) decrease in operating costs from the implementation of such a green scenario. The use of bicycles in the on-demand system instead of gasoline passenger cars and mopeds can lead to a reduction of CO_2 emissions by 5 and 11 times per order, respectively [36]. Designating cargo bicycles for the transportation of parcels weighing less than 30 kg, the authors of study [23] evaluate the environmental effect of implementing such an operational solution. Simulations of such scenarios showed a notable reduction in CO_2 emissions of around 60% in selected urban areas with restrictions.

In addition to analyzing the environmental and economic aspects of implementing alternative delivery options, an organization's business model is also investigated [35]. The authors focus on the last-mile urban delivery segment, where traditional modes of transport are combined with cycle logistics, and note the reduction in CO_2 emissions and shipping time as a result. Moreover, some researchers conduct a full life-cycle assessment of a mixed transport fleet, which includes electric cargo bicycles, to determine its ecological and operational impact, from production to disposal [44]. The authors emphasize that cargo bikes are a highly suitable, most advantageous, and economically viable solution for short-distance operations.

The use of cargo bikes for last-mile deliveries can significantly reduce transport-caused environmental pollution, especially in central city areas with a dense road network [22]. However, the positive ecologic effect of the cargo bikes largely depends on the total number of trips performed in the studied area while servicing the demand for deliveries, as well as on the part of trips performed by traditional vehicles where the conventional mode of transport could be replaced by cargo bikes.

3. Proposed Approach to Simulate Cargo Deliveries by Bikes

The methodology presented in the current research serves to assess the environmental effect of introducing zero-emission vehicles into urban freight logistics. Based on the input demand parameters, for the given transport network, the freight deliveries are simulated; by using the obtained simulation results (the number of vehicles, covered distances), the transport-caused emissions are calculated.

3.1. Simulation Model

The traditional approach to represent the general distribution of trips within the simulated area is the use of an origin–destination matrix (ODM). The rows and columns of the ODM correspond to the defined traffic analysis zones, whereas the internal zones may be expanded by slack zones that correspond to the areas outside the considered region. If inside the considered area, the N zones are defined *as* $R_1, R_2, \ldots, R_N$, and outside the area, the K auxiliary zones (not necessarily real, possibly, but generalized abstractions of bigger territories) are considered as $Z_1, Z_2, \ldots, Z_K$, then the following submatrices may be distinguished in the ODM (see Figure 1):

- The matrix of internal trips (rows $R_1, R_2, \ldots, R_N$, columns $R_1, R_2, \ldots, R_N$)—the matrix containing the numbers of trips performed inside the study area;

- The matrix of outgoing trips (rows R_1, R_2, …, R_N, columns Z_1, Z_2, …, Z_K)—the matrix containing the numbers of trips that started inside the study area in one of the zones and finished outside the area;
- The matrix of incoming trips (rows Z_1, Z_2, …, Z_K, columns R_1, R_2, …, R_N)—the matrix containing the numbers of trips that started outside the study area, entered the area from one of the slack zones, and finished in one of the internal traffic analysis zones;
- The through traffic matrix (rows Z_1, Z_2, …, Z_K, columns Z_1, Z_2, …, Z_K)—the matrix containing the numbers of trips that started outside the study area and finished outside the area, but the trip route partly lies inside the area.

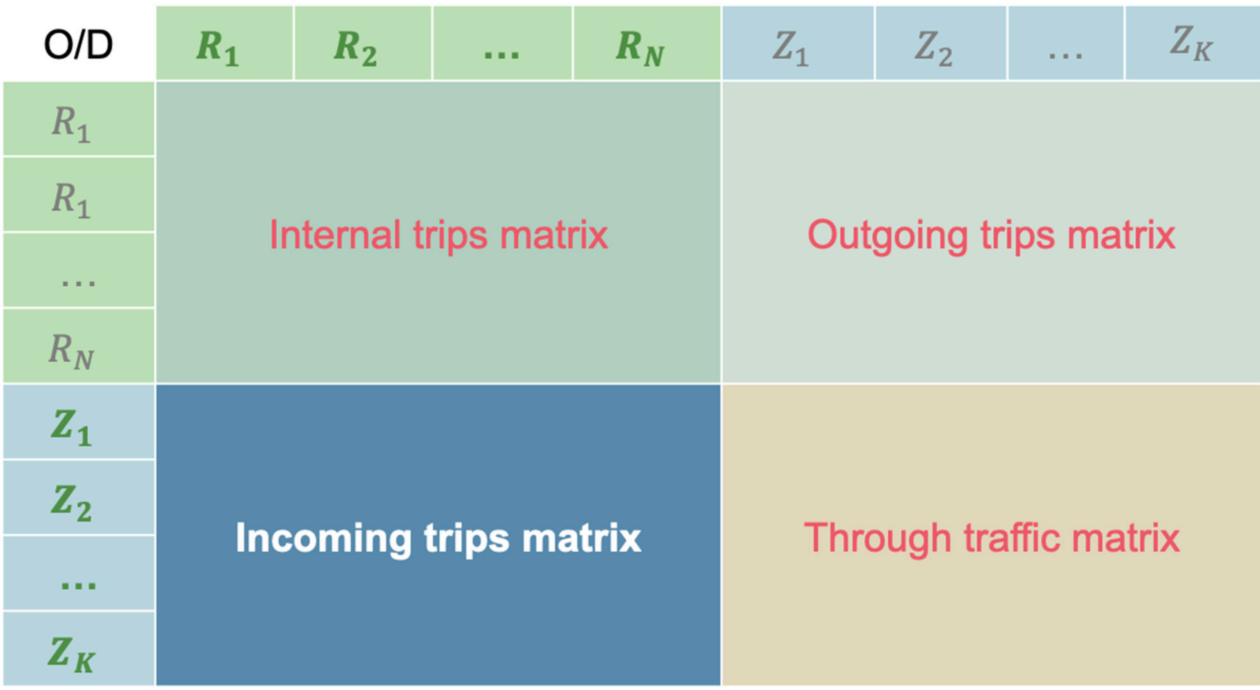

Figure 1. Submatrices of the travel matrix.

For the purposes of modeling transport demand inside small urban areas with restricted access to conventional vehicles, the elements of the matrix of internal trips are equal or close to zero, as inside such an area only the consignees are usually located. The same reasoning can be used for the matrix of outgoing trips: as the commercial objects inside the areas do not send consignments but receive them, the matrix elements will have values close to or equal to zero. The elements of the through traffic matrix should be insignificantly small, as there is no reason to travel through the area where the traffic is restricted, and the permitted vehicle speed is low. The only submatrix of the ODM that contains the non-zero elements representing traffic flows is the matrix of incoming trips (highlighted in Figure 1)—the trips from external zones to the study area.

The initial stage of the travel demand model, the generation of trips, is usually based on the socio-economic and land use analysis of the research area. It determines the mobility rates that are attracted to and produced by the TAZ. Since such an approach is the most appropriate and commonly used in macro- and mesoscopic traffic models, in the microscopic model, this stage is subject to the following enhancements:

- The study area's size allows for determining and identifying the type of all potential customers (declared on the maps as businesses) within the selected region;
- Given that the freight transportation demand is a stochastic process, a probability-based approach should be used for its characterization: namely, to assign the probability of the appearance of demand for deliveries depending on the client's type;

- Since most customers located in the historical parts of European cities (which are the object of the research) are commercial establishments, the presented model considers only business-to-business last-mile deliveries;
- Given the small size of the study area, it can be assumed that all traffic production will be generated at the entrances to this area—at transshipment points located along the perimeter of the area;
- Due to the small distances between the TAZs and the assumption that the trips are not performed between the area's zones, the traffic flows started in the internal zones should not be estimated by the demand model;
- Due to the speed limitations and the specifics of the road network, there will be no transit traffic through the studied urban area, and so the demand model does not determine the number of trips performed between external regions through the area.

As the study area is relatively small, the gravitation model, generalizing the trip distribution, may be replaced by a more straightforward approach—the inlet may be assigned by its random drawing. To implement this idea, the following modified approach to travel demand generation is proposed:

1. Generate a set of F requests considering the restriction:

$$F = \sum_{i=1}^{K} \xi_i, \tag{1}$$

   where ξ_i is the total number of vehicles entering the i-th entry (according to empirical research), (veh.); K is the number of entries (inlets) to the study area.
2. For each generated request, estimate the vector $\mathbf{p}_k$ of the probabilities of selecting corresponding inlets as the source of the trip:

$$p_{ki} = \frac{g_{ki}^{-2}}{\sum_{i=1}^{K} g_{ki}^{-2}}, \tag{2}$$

   where p_{ki} is the probability of selecting the i-th entry as the origin point for the k-th request; g_{ij} is the shortest distance according to the actual road network between the i-th inlet and the customer's location for the k-th request, (km).
3. Randomize the travel source for each request according to the values of elements in the $\mathbf{p}_k$ vector (e.g., by using the "roulette wheel" procedure).
4. Count the elements $\delta_{ij}^{(p)}$ of the travel matrix obtained as the result for the set of all generated requests with travel sources assigned at the previous stage.

Emissions are evaluated based on the distance covered by vehicles with the use of the methodology developed within the European Monitoring and Evaluation Program supported by the European Environment Agency (EMEP/EEA) [45].

The EMEP/EEA guidebook is the basis of one of Europe's most popular computer programs for assessing air pollution from road transport, the COPERT. This technique is used to produce annual national emission reports in EU countries but is also widely utilized for scientific, academic, and engineering purposes.

The general approach to transport emission evaluation provided by the EMEP/EEA methodology is to calculate the product of various traffic parameters (such as vehicle and road categories, fuel type and consumption, mileage, speed, etc.) with the corresponding emission factors. This methodology allows researchers to estimate the amount of transport emissions of different types, such as exhaust (hot- and cold-start emissions that appear as a result of the fuel combustion process) and non-exhaust (generated due to tyre, brake, and road surface wear, and evaporative emissions that formed due to fuel evaporation). Among the main pollutants whose quantities can be determined using the methodology are the following: carbon monoxide CO, nitrogen oxides NO_x, volatile organic compounds VOCs, greenhouse gases CO_2 and CH_4, particulate matter PM, and others. Moreover, depending on the available input data, the EMEP/EEA methodology makes it possible to estimate transport emissions at three levels of complexity, from Tier 1 to Tier 3, which allows researchers to perform calculations even with minimal information about the transport network. Thus, the Tier 3 technique requires data on vehicle mileage and average speed obtained for each vehicle type and technology, and the corresponding emission factors.

3.2. Software Implementation

By using the described approach to simulate the transportation demand, the comprehensive model for calculating vehicle emissions was implemented in Python programming language. The implemented model consists of two main parts: the first one represents a transportation system model for performing simulations of different freight delivery scenarios in the specified city area, and the second one uses the obtained information on traffic activity for the evaluation of transport emissions in this region. The developed software for simulations and the scripts with the experimental studies are available in open access in the GitHub repository: https://github.com/anniutina/TSM-EM (accessed on 1 September 2023).

The developed travel demand model is based on the tools that allow obtaining objects from the OpenStreetMap (OSM) database. This open-source project is intended for the public to accumulate and maintain map data about buildings, roads, landmarks, and other features. Owing to its open-content license, OSM is widely used by researchers, authorities, individuals, and businesses for various tasks, such as urban planning, navigation and routing, analysis, education, etc.

For the incorporation of OSM features into the travel demand model, the extraction of the OSM map elements, located inside the selected area (closed polygon), was performed using OSM Overpass API and the Python library *overpass*. This instrument allows researchers to query the specified OSM elements (with the help of the Overpass Query Language) into the JSON object. Further, the data are processed and written into a csv- or txt-file.

The calculation of emissions based on the EMEP/EEA methodology is implemented in the corresponding modules of the developed software:

- *exhaust*—allows calculating of hot and cold exhaust emissions; the main method of the module, *calc_exhaust_emissions*, returns the dictionary where the keys represent the exhaust emission factors (CO, NO_x, VOC), and the values, i.e. the collections of the corresponding emissions' values for private cars with gasoline engines, private cars with diesel engines, and light commercial vehicles with diesel engines; additionally, the module contains auxiliary methods that load the data from the EMEP database;
- *wear*—allows the estimation of wear emissions based on the total delivery distance covered by the vehicles inside the study area; the *calc_wear_total* method returns the dictionary with the keys representing wear emission factors (TSP, PM10, PM2.5, PM1.0, PM0.1) and the values representing the corresponding results of calculations;
- *co2*—provides the method *calc_co2* that returns the estimated values of CO_2 emissions from fuel, lubricant combustion, and additives;
- *evaporative*—allows the calculation of the evaporative VOC emissions based on the total number of vehicles operating inside the study area; the method *e_voc* returns the estimated value of the VOC emissions.

For running the simulations based on the developed tools, it is necessary to obtain input data (the transport network parameters and empirical values of incoming traffic flows) and perform the following steps:

- Prepare the files containing parameters of potential customers located inside the study area: outline the polygon along the perimeter of the analyzed zone and determine the geographic coordinates of all its vertices (such tools as OSM or Google Maps could be used for these purposes, and the developed library contains the methods allowing the automatization of data collection from the OSM database);

- Prepare the data on the road network (the method *load_from_file* of the *Net* class allows the reading of the network data from the files) and incoming traffic flows (should be provided as the dictionary with the entry nodes as keys and traffic flows as values);
- Define the probability of occurrence of a delivery request from the defined types of customers (should be provided in the form of a dictionary with the types of clients as keys and the probabilities as values);
- Instantiate the object of the *Net* class, and read the network data;
- Generate the set of requests providing the input flows and the probabilities of the request appearance as the arguments of the *gen_demand* method;
- Run the method *simulate* on the created net object providing the generated requests, the collection of outlets, and the collection of the loading hubs as the arguments.

The described routine allows researchers to obtain the results of simulation as a tuple that contains two collections: the list of distances covered for the traditional technology of servicing and the list of distances covered by conventional vehicles when cargo bikes are used as the alternative mode of transport. By providing these data to the methods for the emissions' estimation, the corresponding values for different types of pollutants can be obtained. The difference between the emissions for traditional technology and the option of servicing with cargo bicycles will show a reduction in emissions due to the use of cargo bikes.

4. Results of Simulations

The experimental studies within this research were carried out based on the cases of the Old Town of Krakow (Poland) and the Old City District in San Sebastian (Spain). Both studied areas have restrictions for conventional vehicles to enter the district. The streets in the studied areas are mostly narrow and represent medieval urban planning.

The models of the transport systems for the city areas were developed based on the data obtained during the field studies performed in the CCCB project. The corresponding traffic counts were organized to estimate the incoming and outgoing traffic flows. The calculations were performed manually by the participants located at defined points near the boundaries of the selected city zone, by filling in the survey form with the number of vehicles divided by the modes of transport and the type of vehicles.

4.1. Models of Transport Systems

To perform simulations of the demand for transport services, in addition to the results of traffic counts, the developed module for retrieving GIS data from the OpenStreetMap tool was used to obtain parameters of commercial objects located inside the study area. These data include the object's name, geographic coordinates, address, and type. Further, this collection of potential customers was divided into the following groups (Table 1):

- Food and dining establishments, such as cafes, bars, restaurants, etc.;
- Lodging businesses, including hotels, hostels, and apartments;
- Grocery stores and supermarkets;
- Various shops, such as computers, convenience, bookstores, etc.;
- Other customers, such as universities, museums, libraries, banks, etc.

Table 1. The collection of potential customers obtained from the OpenStreetMap tool for the chosen study regions of the selected cities.

Customer Groups	Krakow	San Sebastian
Grocery stores	28	20
Food and dining	380	148
Lodging businesses	108	22
Various shops	184	85
Others	256	28
Total number	954	303

The parameter probability of the appearance of a request for delivery services was determined based on the expert survey study, conducted within the framework of the CCCB project. The division of potential customers on types was performed according to the categories of objects (map feature tags) stored in the OSM database.

To estimate the reduction of emissions for the studied city area, multiple runs of the developed simulation model are needed to obtain statistically significant results. The samples containing simulation results should be analyzed; the normal distribution of the obtained parameters should be confirmed and the sample size that ensures the statistical significance for the given confidence level should be estimated.

For each of the cities, the corresponding simulation model was launched 300 times with the parameters accepted according to the following assumptions:

- The simulation period was expanded to the width of the time window when vehicles could enter the studied city area (the incoming traffic flows were calculated based on the average value per hour obtained from the conducted traffic counts);
- The normal distribution was used to generate the random variable of the consignment weight; the average consignment weight was accepted based on the estimations of the experts (the corresponding survey was held at the first stage of the CCCB project among the experts representing partner cities); to guarantee the variability of the packages' weight starting from the smallest possible values, the standard deviation of the consignment weight was accepted at the level 0.3;
- The elements in the vector of probabilities of the requests' appearance for different types of potential clients were accepted as constant values.

In each model launch, for the generated demand for deliveries, two alternative servicing technologies were applied: deliveries of goods by conventional vehicles directly to the clients, and shipments of loads to the hubs with their further deliveries to the clients by cargo bicycles. The difference between the total distance covered by conventional vehicles for the traditional and cargo-bike-based technologies was used as the resulting parameter to estimate the statistical significance of the conducted simulations.

The main statistical characteristics (bounds, average, and variation parameters) of the samples of the distance reduction obtained for the study areas of the CCCB partner cities as the result of simulations are shown in Table 2.

Table 2. Characteristics of the stochastic variable of the saved distance obtained based on the results of conducted simulations.

Parameter	Krakow	San Sebastian
Minimum, [km]	71.595	80.088
Maximum, [km]	112.99	100.431
Average, [km]	95.464	89.547
Standard deviation, [km]	7.347	3.742
Variation coefficient, [-]	0.077	0.042

For the obtained samples, the histograms characterizing the variables of the saved distance for each case are shown in Figures 2 and 3; the number of bins at the histograms is evaluated based on Sturge's rule. In the presented graphics, the red curve shows the density function for the normal distribution with the parameters (mean and standard deviation from Table 2) evaluated based on the corresponding empirical values.

As it follows from the graphics in Figures 2 and 3, the shape of the distribution for the obtained samples is close to the theoretical normal distribution for each of the study areas, which means that it is valid to make the hypothesis about the normal distribution of the saved distance obtained from simulations. This hypothesis was checked with the chi-square Pearson's test.

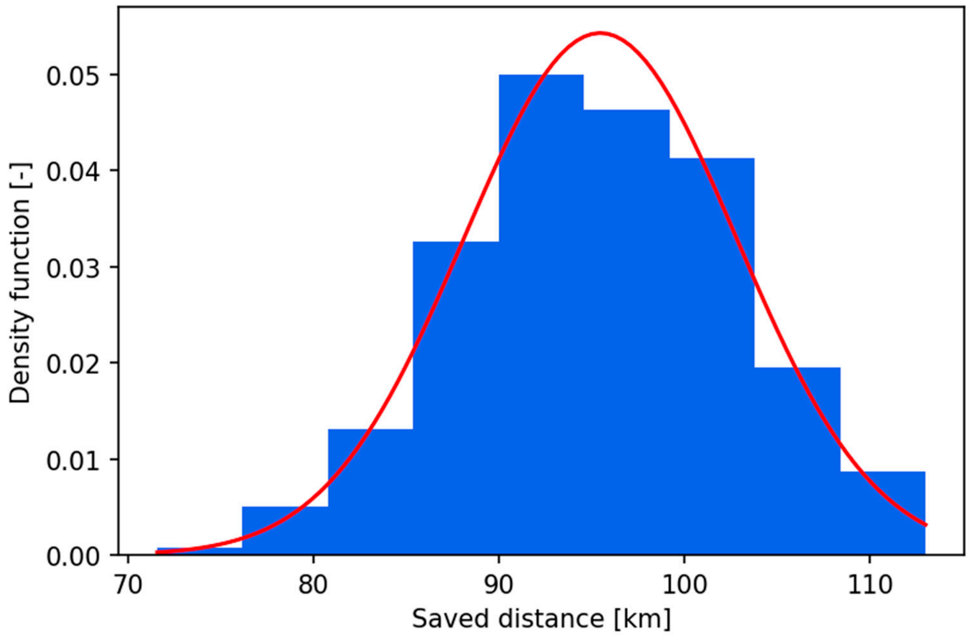

Figure 2. Distribution of the saved distance based on the simulations for Krakow.

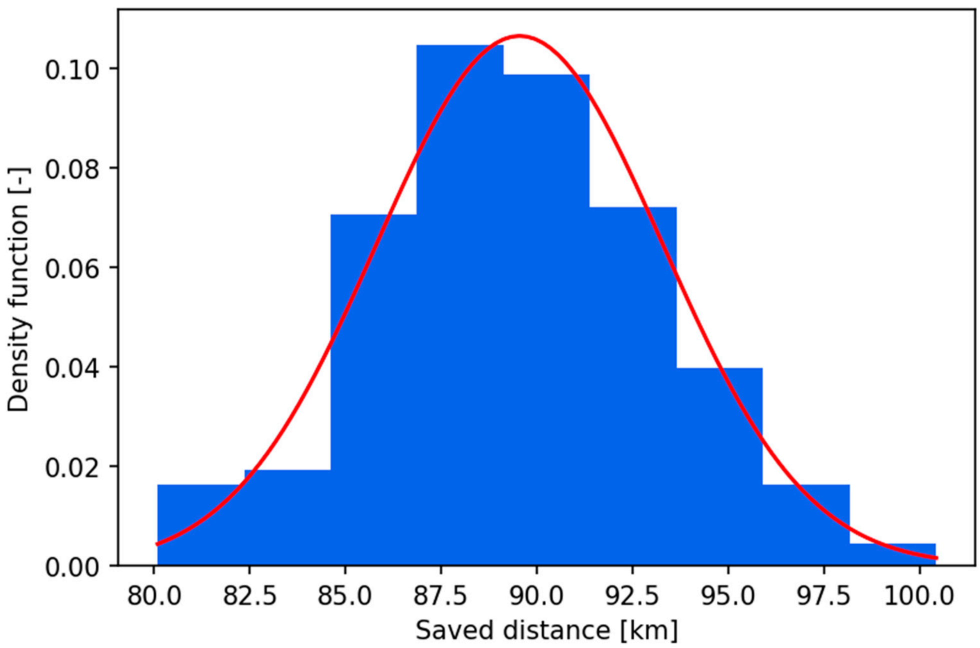

Figure 3. Distribution of the saved distance based on the simulations for San Sebastian.

Based on the obtained simulation results, the estimation of emissions produced by conventional vehicles inside the study areas may be performed. For this purpose, the modules *exhaust*, *wear*, and *co2* from the developed library were used. As input arguments of the corresponding methods for the emissions' estimation, the number of vehicles and the distances covered by the vehicles were provided.

The numeric results of the emissions' reduction are shown in Table 3 for exhaust pollutants and in Table 4 for wear pollutants. The presented data were scaled to year based on the simulations' results under the assumption that the obtained daily reduction of emissions represents the average over the days in a year.

Table 3. Reduction of exhaust emissions due to the use of cargo bikes.

City	CO, [kg/Year]	NO_x, [kg/Year]	VOC, [kg/Year]	CO_2, [Tons/Year]
Krakow	20.522	40.921	3.100	8.405
San Sebastian	19.249	38.385	2.908	7.884

Table 4. Reduction of wear emissions due to the use of cargo bikes.

City	TSP, [kg/Year]	PM10, [kg/Year]	PM2.5, [kg/Year]	PM1.0, [kg/Year]	PM0.1, [kg/Year]
Krakow	1.961	1.394	0.724	0.115	0.092
San Sebastian	1.840	1.308	0.679	0.108	0.086

It should be noted that the presented results for the emissions' reduction were obtained based on the set of assumptions as the result of simulations and the obtained values may differ insignificantly if a similar experiment is conducted; however, the results are very sensitive to changes of the key input data, such as the average consignment weight and the bicycles' load capacity.

4.2. Impact of the Consignment Weight on the Simulation Results

To study the impact of the consignment weight on the reduction of transport-caused emissions, a series of simulations were conducted for a range of weight from 10 kg to 500 kg. Similar to the experiment described in the previous chapter, the smaller values were studied with more detail; values in the range up to 150 kg were considered with the step of 10 kg, whereas the values bigger than 150 kg were varied with the step of 50 kg. The loading capacity of the bikes was accepted as being equal to 150 kg in the experiment series. The impact of the consignment weight was studied for three levels of incoming traffic—the smallest observed, the biggest ones, and the average. In each series, 50 launches of the simulation model were completed to ensure the statistical significance of the obtained results.

The number of conventional vehicles servicing the clients inside the study areas corresponds to the value of the sum of incoming traffic flows. The number of traditional vehicles remains the same for both considered technologies of the clients' servicing, regardless of whthere the cargo bikes were used or not. However, for the cargo-bike-based option of servicing, some of the conventional vehicles do deliver loads directly to clients; the shipment is transported by van to the loading hub, where cargo bikes pick it up and perform the delivery inside the area with restricted traffic. If the loading hubs are located at the entrances to the area (as in the case of the Old City of San Sebastian), the conventional vehicles do not enter the zone, and the corresponding transport-based emissions could be considered as eliminated in such a case. However, if the location of the loading hubs is stipulated inside the area with restricted traffic, the traditional vehicles would enter the area and make a trip to the hub and then from the hub to leave the zone. In this case, the total distance covered by conventional vehicles would decrease compared with the option of direct deliveries to clients. The number of traditional vehicles delivering the loads directly to the clients depends on the consignment weight: if the consignment is too big to be delivered by cargo bikes, it should be delivered directly. Such dependencies obtained as the result of the simulation experiment for the cargo-bike-based technology of servicing are shown in Figures 4 and 5.

As expected, the number of direct deliveries increases when the mean consignment weight grows. When the weight of shipments is small enough, the direct deliveries would be eliminated, as the packages could be delivered by cargo bicycles. And contrariwise, if the weight of consignments is too big to be serviced by bikes, the part of direct deliveries would go up to 100%. As it may be observed from the results presented in Figures 4 and 5, if the average consignment weight is equal to the loading capacity of the cargo bicycles, nearly half of the requests could be serviced by bikes.

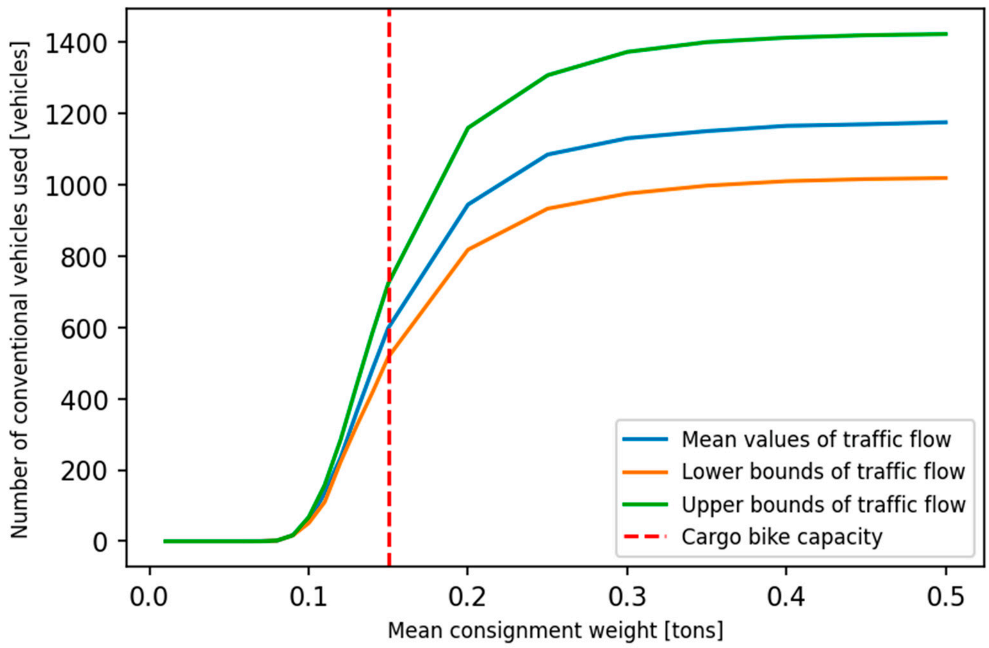

Figure 4. The number of conventional vehicles that deliver loads directly to clients for the study area of Krakow.

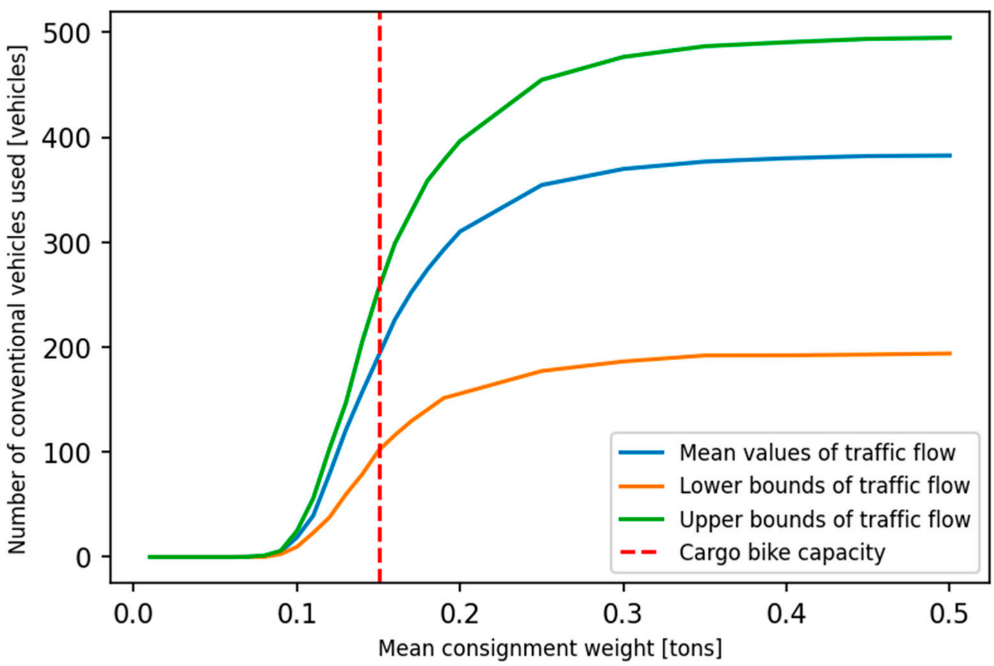

Figure 5. The number of conventional vehicles that deliver loads directly to clients for the study area of San Sebastian.

5. Discussion

According to the EMEP/EEA methodology, the quantities of different types of pollutants are calculated primally based on the number of vehicles and the corresponding mileage performed during the studied period. As the equations used to calculate emissions are linear regarding the number of vehicles and the covered distances, the values for the different types of transport-caused emissions change proportionally. Carbon dioxide is used as the representative pollutant to show the influence of the consignment weight on the reduction in emissions obtained due to the servicing of part of the requests by bikes.

The average values of the CO_2 reduction for the study areas of Krakow and San Sebastian calculated for the samples in each of the experiment series and scaled to the period of a year are presented in Figures 6 and 7.

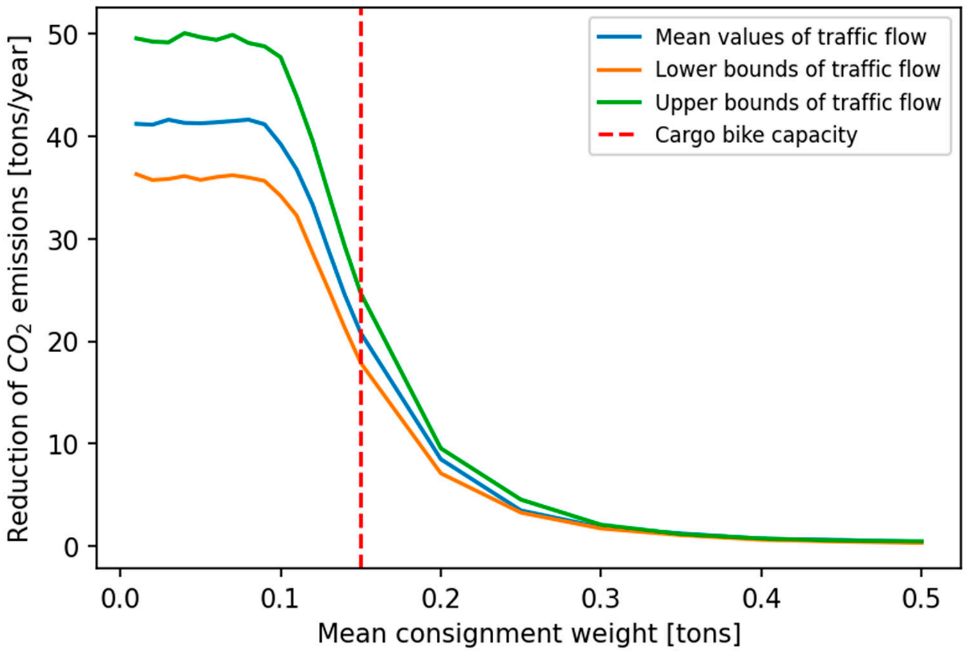

Figure 6. Dependence of CO_2 reduction on the consignment weight in Krakow.

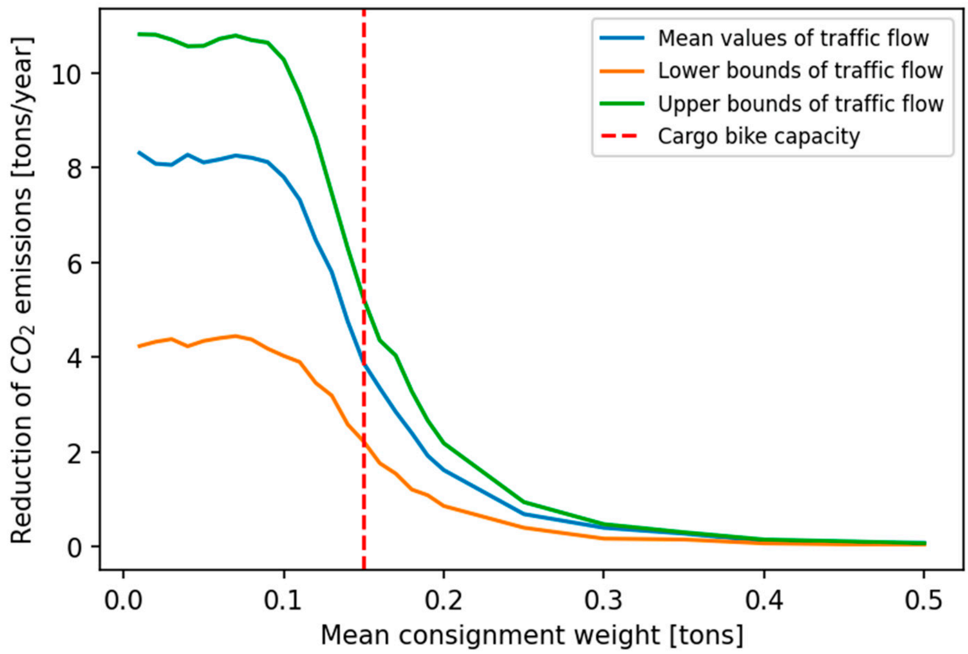

Figure 7. Dependence of CO_2 reduction on the consignment weight in San Sebastian.

The presented results show that the emission reduction decreases with the mean consignment weight rising. The obtained dependencies are not linear, and special attention should be given to the threshold located on the left part of the graph: for the average values of the consignment weight up to 100 kg, the use of cargo bikes is characterized by the highest efficiency in terms of emission reduction. This effect is explained by the corresponding biggest values of the distance saved due to the use of bikes observed in that range, which in turn is the result of the replacement of conventional vehicles with cargo bicycles for the major part of the requests.

As the loading capacity of cargo bicycles directly influences the part of the requests that could be serviced by bikes inside the area with restricted traffic (given the assumption that the requests with a load weight lesser than the bike capacity could be serviced by a bike), the corresponding experimental studies aiming to determine that impact numerically were conducted.

The simulation experiment was performed for the study areas of Krakow and San Sebastian for the average values of incoming traffic flows (obtained as the result of traffic counts within the field studies completed in the CCCB project). The values of the mean weight of consignments ranged from 10 kg to 500 kg and were studied in a more detailed way for the values between 10 kg and 200 kg (with the step of 10 kg), and with the step of 50 kg in the range of values over 200 kg.

As the alternative capacities of cargo bikes (accepted as being the same for all bikes used for the clients' servicing—under the assumption of a homogeneous fleet of bicycles), the range of values from 100 kg to 300 kg with the step of 50 kg were studied. In each of the experiment series, 50 launches of the simulation model were performed to calculate the average reduction of CO_2 obtained due to the use of cargo bikes.

The average quantities of carbon dioxide reduction inside the study areas of Krakow and San Sebastian obtained as the result of the conducted simulation experiment are shown in Figures 8 and 9. Only the results for bike capacities of 100 kg, 200 kg, and 300 kg are presented to make the graphics clearer; the graphs for the capacities of 150 kg and 250 kg look identical and would be located between the curves representing the capacities of 100 kg and 200 kg and the capacities of 200 kg and 300 kg, respectively.

An obvious regularity can be observed from the presented graphs: the greater the loading capacity of bikes, the more to the right the curve of the dependence of CO_2 reduction on the consignment weight is shifted. However, from a practical point of view, another result is more important—the threshold of the maximum efficiency of the cargo-bike-based technology of servicing shifts to the right proportionally to the increased capacity of cargo bikes.

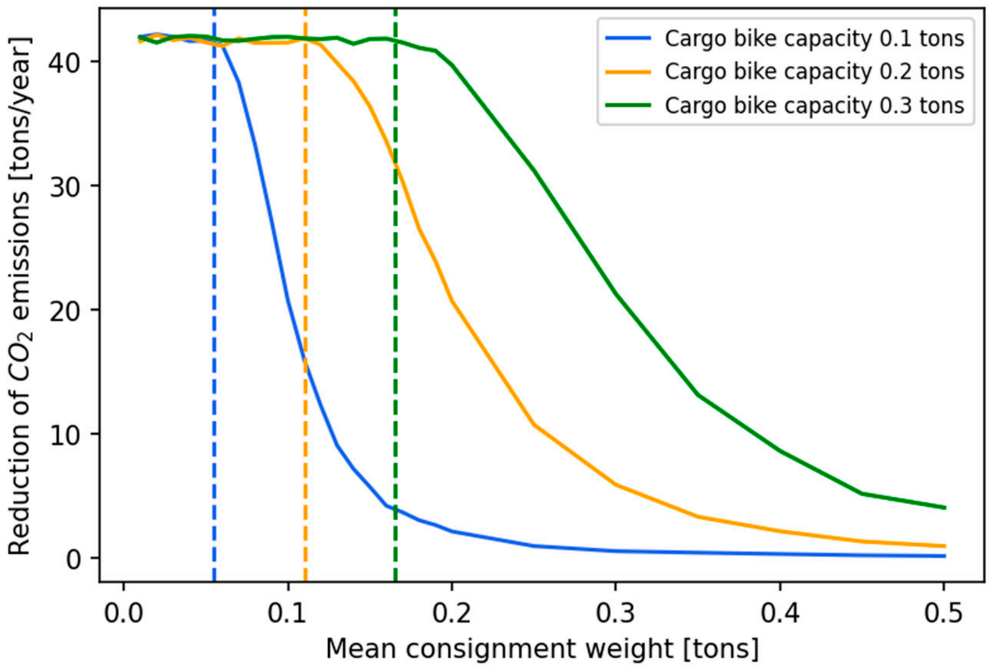

Figure 8. Dependence of CO_2 reduction on the consignment weight for different capacities of cargo bikes for the study area in Krakow.

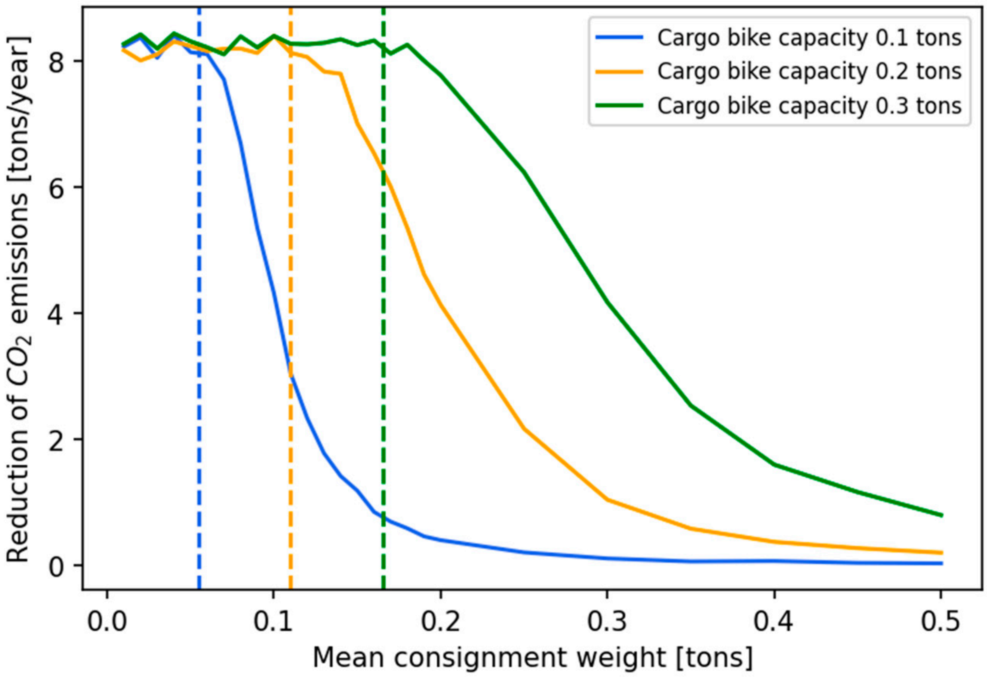

Figure 9. Dependence of CO_2 reduction on the consignment weight for different capacities of cargo bikes for the study area in San Sebastian.

To evaluate the threshold of the most efficient use of cargo bikes (the biggest value of the mean consignment weight for which the maximum environmental effect of cargo bikes does not decrease), the following subroutine was proposed:

- The difference between current and previous values of CO_2 reduction is estimated for each of the mean consignment weight values considered in the experiment;
- For each of the weight values, starting from the third element in the sequence, the fulfillment of the following conditions is checked:
- Two previous values of differences in CO_2 reduction in the sequence are negative;
- All the following values of CO_2 reduction in the sequence are smaller than the current one.
- If both conditions are fulfilled, the current value of the mean consignment weight represents the threshold.

The depicted subroutine was applied to the obtained experiment data, and the thresholds were evaluated for each of the considered capacities for the cases of Krakow and San Sebastian. The results are shown in Figures 8 and 9 as dashed vertical lines with the colors corresponding to the colors that represent alternative loading capacities.

In all considered cases, the threshold of the most efficient use of cargo bikes equals around 55% of the bike loading capacity. This empirically obtained result could be used in practice for the justification of the capacity of bikes dedicated to servicing the requests inside the urban area; after the mean consignment weight is evaluated, the least loading capacity could be estimated as roughly 180% of the consignment weight—in this case, the maximum environmental effect of cargo bikes will be ensured.

6. Conclusions

The studies conducted based on the considered areas of Krakow and San Sebastian contribute to the justification of the adequacy of the proposed approach and to its use in practice to ground the parameters of the cargo-bike-based delivery systems.

The impact of the mean consignment weight and the loading capacity of cargo bikes on the reduction in transport-caused emissions was investigated within the experimental studies. The obtained numeric results allowed the detection of the threshold of the most efficient use of the cargo-bike-based technology, which in practice contributes to the justification of the loading capacity for the bikes used for freight deliveries in the urban area.

The obtained results, however, should be treated considering the assumptions made within the proposed approach to simulate the transport demand and the technological process. The model assumptions that restrict its use for the estimations of the environmental effect of cargo bikes include the following: (a) the servicing process is considered within city areas with limited traffic (e.g., historical or commercial areas); (b) it is possible to locate in the selected city area a loading hub for transshipments of loads from commercial vehicles to cargo bikes; and (c) the size of packages to be delivered by cargo bikes allows the safe transportation of loads by bikes.

As the directions of future research, the following problems may be distinguished:

- The developed methodology for modeling the system of cargo deliveries with the use of bicycles assumes simulations of the service process in the areas of cities with limited traffic (modeling only external–internal travels). The developed model can be supplemented with modules for internal, internal–external, and transit trips.
- The modeling of the size of shipments in this study was based on a normal distribution (due to the lack of access to empirical data). An important direction of further research is a detailed empirical study of the random variable of the consignment weight separated for different types of potential clients.

The proposed methodology and its software implementation are subject to further development within the scientific community, as the developed Python code, the prepared input data, and the results of the completed simulation experiments are available for public access.

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