Justifying the use of cargo bikes for last-mile deliveries: Case study for selected European cities

Abstract

Keywords: cargo bikes; transport modeling; CO2 evaluation; …

# 1. Introduction

**Introduction**: the importance of sustainable logistics (environmental pollution generated by transport, ways to reduce it), growth of last-mile deliveries (e-commerce, jams in cities), the use of alternative modes of transport to deliver goods in cities

Freight transportation is one of the most important levers of socio-economic progress, facilitating commerce as well as distribution and access to necessary goods and services. At the same time, the use of traditional transport leads to a significant deterioration of the environment and creates obstacles to sustainable development. Recently, the negative consequences of transport have become increasingly evident, including air pollution, noise, congestion, as well as health problems and poor quality of life in cities, requiring an immediate transition to more environmentally friendly means of mobility. In addition, the effects of climate crisis, which is also influenced by the motorized transport, are becoming more and more noticeable.

Ongoing global processes such as urbanization, rising living standards, technological advances and overconsumption are leading to rapid growth in e-commerce and demand for last-mile deliveries, placing additional burden on transportation systems.

ADD transport harm

In this context, the adoption of sustainable alternatives for last-mile segment has become an urgent necessity. Among the wide variety of innovative, emission-free alternatives, cargo bikes represent an effective competitive solution capable of solving a range of environmental, economic, and social problems.

Justifying the necessity of adopting cargo bikes for the last link of the supply chain requires a comprehensive approach, which includes an assessment of their advantages, limitations, and potential implications. In addition to environmental effects, such factors as economic efficiency and social benefits should also be considered. Furthermore, addressing potential barriers to bicycle adoption, such as business-as-usual private sector opposition, outdated regulations, and public reluctance, is critical to fostering widespread adoption and deployment of cargo bikes in urban delivery networks.

ADD Strategies – pilot programs, collaboration between academia, authorities, private sector, and society – evaluation of effects to highlight CB benefits, education, promotion…

Ways to justify the use of CB: assess environmental benefits (reduced emissions, air, and noise pollution); economic profits (lower operating costs, improved efficiency); operational advantages (reduced congestion, accessibility, and parking space); social consideration (livability, safety).

In this paper, we propose a comprehensive framework to justify the integration of cargo bikes into last-mile delivery operations, exploring their potential to improve the sustainability and efficiency of transportation system.

# 2. Literature review

**Literature review**: existing approaches to measure the efficiency of cargo bikes, the methodologies to measure the environmental effect of transport, known and described cases of successful use of cargo bikes (with numeric depiction of results achieved)

## 2.1. Sustainable transport in cities

## 2.2. Challenges for the last-mile deliveries

## 2.3. Existing approaches to measure the efficiency of cargo bikes

## 2.4. Methodologies to evaluate the environmental effect of transport

## 2.5. Examples of best practices of using cargo bikes

# 3. Model

**Proposed approach**: a structure of the simulation model (transport network, demand for deliveries, optimization modules?), in detail – an approach to simulate the demand for deliveries for the given city area, the proposed method to calculate the reduction of distance covered by traditional vehicles obtained due to the use of cargo bikes (with the corresponding CO2 reduction)

## 3.1. Transportation network model

We apply the elements of graph theory to model a freight transportation system. In this model, a delivery route becomes a sequence of points (nodes) and connections (links) on a graph that represents the road network. We represent the transportation network within a specific area as a graph called . The nodes represent all the possible locations, including customers, intersections, depots, and so on. The edges of the graph connect these locations, representing the paths between them. Finally, an additional element is included in the model to represent traffic analysis zones (regions) within the study area:

. (1)

To characterize each component of the graph, the sets of numeric, logical, and complex-type (but initially predefined) parameters were used.

The graph nodes is defined using the following variables:

, (2)

where – identification number of the of the -th node of the graph, such parameter has a unique value, ,

and – geographic coordinates of the -th node, respectively, latitude and longitude,

and – the collection of all links of the graph, for which the -th node is an inlet or outlet, respectively, ,

– a type of the -th node: road intersection, depot point (loading hub) or client,

– a reference to an object that represents the traffic analysis zone (this parameter is defined only for the node of type “client”),

– the graph node, that depicts the closest intersection to the -th node, ,

and – parameters of type Boolean, that set out the -th node as the inlet or the outlet for the study area and are defined only for the node of the “intersection” type,

– the overall number of the graph vertices.

The graph links are described using a set of parameters:

, (3)

where and – respectively, outlet and inlet nodes for the -th link in the graph, ,

– the numeric characteristic of the -th link (for instance, delivery cost, the link length, or other),

*NL* – the overall number of the graph links.

The specified-th traffic analysis zone :

, (4)

where – an identification number of the of the *k*-th analysis zone of the demand model, ,

and – geographic coordinates of the -th zone centroid,

– the collection of nodes located in the -th zone of the model,

– the total number of traffic analysis zones into which the simulated area is divided.

The travel demand model can be determined as an ordered collection of elements, that represent the requests occurred during the defined period within the specified urban area with the restricted traffic:

, (5)

where is the -th element in a sequence of requests for the delivery services, when , – the time of appearance of the -th request.

In detail, each given request can be expressed using such characteristics:

, (6)

where are the nodes that are the entry to the analyzed zone of the city and a customer location, respectively (origin and destination points for the -th request),

– the probability of the appearance of the -th request for the delivery of cargo, which is determined for a specific type of customer who produces the request,

– the weight of the consignment, [kg],

– the total number of requests in the flow.

As a result of solving the routing problem, a collection of delivery routes is obtained, where each -th element, a route , includes the ordered set of requests (consequently, the ordered nodes of the graph represent the delivery route). Each -th route can be characterized by the following parameters:

, (7)

where – a collection of the shipment requests performed during the -th route,

– the length of the -th route (total distance covered by vehicle on the route),

– the total weight of the consignment, that was shipped during the -th route [kg],

– the number of delivery routes that is calculated by solving the vehicle routing problem.

Traditionally, the optimal route is the shortest (or closest to the shortest) route completed by the vehicle when servicing the set of orders , where the definition of the shortest can be applied to the covered distance or to the total delivery time. However, more complex indicators are oftentimes used as the objective function in the routing procedures: e.g., the total transport work (in ton-kilometers of vehicle-kilometers), the total delivery costs, or a profit obtained by a transport company as the result of servicing the orders.

All serviced requests for delivery of freights performed by the given means of transport, that reach their destinations by covering the shortest route, can be used as the alternative representation of the demand :

. (8)

Parameters obtained as the result of traffic simulations allow the evaluation of the performance of the transportation system, and the comparison of simulation results with real-world data or with other operational scenarios allows identifying areas for improvement and further correction. Besides, such output could be used for the further analysis of the sustainability of the delivery chain, and most importantly – for the assessment of environmental indicators of the system.

## 3.2. Travel demand model

Travel Demand Modeling (TDM) plays a vital role in transportation planning practices. It offers a comprehensive framework encompassing various methodologies to analyze hypothetical scenarios. TDM facilitates a deeper understanding of the factors influencing freight delivery demand and enables the forecasting of future needs.

When applied to freight deliveries, TDM sheds light on the volume and characteristics of freight movement within a defined geographical region and timeframe. The specific metrics employed (e.g., total freight weight, number of shipments) can be tailored to the research objectives and available data. This approach proves instrumental in identifying the dominant freight flows within the study area, essentially pinpointing the key routes for cargo movement.

The determination of travel demand in a relatively small urban area with imposed traffic restrictions could be performed using the traditional four-step model applied to the matrix of incoming trips.

The first step of the model, trip generation, traditionally relies on socio-economic and land-use analyses of the study area. This analysis focuses on the quantity and category of goods produced or consumed within the defined region. It establishes the attraction and production rates of mobility associated with each Traffic Analysis Zone (TAZ). While this approach remains the most suitable and widely used in macro- and mesoscopic traffic models, the proposed model for microscopic applications incorporates the following enhancements:

* **Customer Identification:** Given the smaller study area size, the model explicitly identifies all potential customer types within the chosen region. This identification leverages business listings from maps.
* **Stochastic Demand Characterization:** Recognizing the inherent randomness of freight transportation demand, the model employs a probability-based approach. This involves assigning a probability of delivery demand for each customer type.
* **Focus on B2B Deliveries:** Given the prevalent commercial nature of businesses located in historical European city centers (the research focus), the model concentrates solely on business-to-business last-mile deliveries.
* **Traffic Production at Entrances:** Due to the limited study area size, all traffic generation is assumed to occur at designated transshipment points situated along the area's perimeter.
* **Internal Trip Omission:** The short distances between TAZs, coupled with the assumption of no internal zone-to-zone trips, allow the model to exclude internal trip estimations from the demand analysis.
* **Exclusion of Transit Traffic:** Speed limitations and the specific road network configuration within the urban area preclude transit traffic. Consequently, the demand model does not calculate the number of trips originating from and ending in external regions that merely pass through the study area.

The trip generation stage produces a matrix containing the expected number of **externally originated** and **internally attracted** trips within the study area. This matrix serves as a crucial input for subsequent stages of the demand-modeling algorithm.

The second step, trip distribution, leverages the outputs from the first stage – including trip volume, trip length, and travel times. This information is used to predict the spatial distribution of transportation flows, essentially the origin-destination patterns. Additionally, the trip distribution model incorporates the road network represented as a graph as an input parameter. Finally, an Origin-Destination Matrix (ODM) is calculated using an adjusted gravity model, quantifying the trip flows between each entry point (transshipment point) and each zone within the study area.

The assessment of ODMs is usually performed by the conventional gravity model. Such approach assumes that the flow of freights between the origins and destinations has directly proportional relationship with the number of trip attractions occurred in the destination zone, and inversely proportional relationship to distance or travel time (so called “friction factor”) between the pairs of zones.

Using the gravity model, each element of the ODM can be estimated based on the set of generated requests as follows:

, (9)

where – freight flow (the expected number of trips) originated in the -th zone and attracted to the -th zone,

– total production at the -th zone,

– total attraction of trips at the -th zone,

– the number of traffic analysis zones,

– generalized adjustment factor for transportation between zones,

– friction or travel time factor, the indicator that is related to the distance between the zones and can be determined by calibration process:

, (10)

where – the travel time from the -th to the -th zone (if the travel speed does not vary significantly for the trips, the travel distance can be used instead of the travel time),

*c* – the model parameter, predefined or defined based on the available empirical data.

Although the effectiveness and universality of the gravity model are confirmed by its popularity, adaptability, and long-term use, for this research, the problem of trip distribution will be solved by the adjusted gravity model with the use of the probability-based approach.

At the **third step**, the mode choice, the alternative means of mobility (namely, cargo bikes) are introduced for a certain share of trips, which is usually defined based on ton-kilometers parameter for freight deliveries.

The choice of transportation mode is determined by various factors and could be predicted by different methods. The simplest and one of the most popular approaches to mode choice modeling is the use of the logit models (binary or multinomial) (1). In such models, the choice is made based on the preferences, associated with the utility of each given mode of transportation. The value of the utility and disutility (cost) parameters can be affected by such explanatory variables as travel and waiting time between the points; speed; the cost of travel and parking; emissions; convenience and usability indicators, etc. Further, the probability of each mode is calculated and applied to O-D pairs. Since intra-zonal and inter-zonal trips are not considered when modeling demand for deliveries to the urban area with restricted traffic, there is no need to use such models.

The CEP industry (which includes Courier, Express, and Parcel services) is increasingly involved in the introduction of cargo bicycles in urban freight operations of the last mile, as well as in the cooperation with city officials regarding the placement of transshipment points (2). Being a segment of the logistics and transportation realm, the CEP branch is aimed at fast and efficient transportation of various consignments with comparatively low weight and volume (individual shipment weight maintained by the CEP rarely exceeds 30 kg) (3). Besides, EU regulations limit the parcel weight, that can be handled by a single average person to 31.5 kg (4). Whereas the scientific literature provides rather contradictory and heterogeneous information regarding the parameters of cargo suitable for transportation by freight bicycles (cargo weight and size), as well as considering the specificity of the investigated closed urban area with implemented restrictions, the transportation with bicycles should be carried out under conditions when the following assumptions are fulfilled:

* consideration of the average loading capacity of the cargo bicycles leads to the limitation of the maximum weight of freights intended for transportation by the single cargo bike by the parameter ,
* the weight of a single consignment is a deterministic value in real life, therefore considering the ability to lift a single load by a person, the cargo weight parameter can be limited by the parameter ,
* as most customers have no data on the weight and size of the cargo they receive, for the flow of requests the consignment weight parameter was established as a collection of random variables, generated from the normal distribution,
* the carrying capacity of vehicles operating in the study area is limited to 3.5 tons,
* speed restriction in the urban residential area for EU countries is 20…30 km/h (5) (whereas the average speed for cargo bikes is 20…25 km/h),
* consideration of the allowed timeframe for the possibility of carrying out delivery operations in the analysis zone,
* the spatial distribution of requests that appear in the study area can be defined based on the assumption of the rational behavior of freight carriers, who aim to minimize the delivery distance by arriving to the destination customer locations through the nearest entry paths.

Assigning cargo bicycles to deliver freights whose weight does not exceed the value of the parameter , the mode choice model analyzes two alternative operating schemes:

* the basic variant describes a delivery scheme in which only light delivery vehicles (LDVs) are involved in serving customers in a specified urban area in a defined period,
* the mixed-fleet option implements the following delivery scheme: LDVs reach transshipment points located near the restricted area, in which light loads (weighing less than ) are reloaded onto cargo bikes, which deliver these cargoes to customers inside the study area; heavier loads (weighing more than ) remain delivered by LDVs.

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 according to the probability that considers the actual distance to that inlet. To implement this idea, we propose the following modified approach to model the travel demand:

**1.** Generate a set of requests for the delivery of goods in the study area under consideration of the following restriction:

, (12)

where – the total number of vehicles entering the -th entry (according to empirical research), [veh.];

– the number of entries (inlets) to the study area.

**2**. For each generated request, estimate the vector of the probabilities of selecting corresponding inlets as the source of the trip:

, (15)

where – the probability of selecting the -th entry as the origin point for the -th request,

– the shortest distance according to the actual road network between the -th inlet and the customer’s location for the -th request, [km].

**3**. Randomize the travel source for each request according to the values of elements in the vector (e.g., by using the “roulette wheel” procedure).

**4**. Count the elements of the travel matrix obtained as the result for the set of all generated requests with travel sources assigned at the previous stage.

## 3.3. Vehicle emission estimation

The methodology EMEP/EEA for calculating exhaust gases provides a possibility to determine the amount of such pollutants as CO, NOx, VOCs, CH4, CO2, N2O, NH3, SOx, PM, PAHs, POPs, and others, which are divided into four groups depending on the availability of calculation characteristics. Group 1 includes pollutants, that could be calculated using a detailed approach: CO, NOx, VOCs, which takes into account specific emission factors, road category and engine type; group 2 defines emissions based on fuel consumption and uses the ‘bulk’ emission factors for pollutants: NH3, SO2, Pb, CO2, N2O, and CH4; group 3 includes pollutants, that could be calculated by the simplified method and the 4th group estimates pollutants as a share of total NMVOC emissions (6).

Therefore, the most advanced Tier 3 approach of the EMEP/EEA methodology for total vehicle exhaust emission evaluation proposes to summarize such types of emissions:

, (16)

where – emissions from the engine of a vehicle in motion, [g],

– emissions during vehicle start-up, [g].

In addition to being dependent on the type of fuel and the conditions in which the vehicle engine operates, emission factors are influenced by the road situation in which the vehicle is being exploited. This means, that in urban conditions vehicles most frequently produce cold-start emissions, and on the highways, traffic almost does not perform starts and stops and consequently, in such conditions, more hot emissions are produced. Therefore, depending on the situation on the road, total emissions for every pollutant could be assessed as:

, (17)

where – emissions for urban, rural or highway type of roadway, [g].

Since the presented research involves estimating road transport emissions only on city roads, Equation (17) transforms to:

. (18)

The calculation of hot exhaust emissions of the -th pollutant, [g], associated by a vehicle with the -th technology operating on the roads of the -th category, is performed as follows:

, (19)

where – number of operating vehicles with the -th technology, [veh],

– the distance travelled by vehicle with the -th technology on roads of the -th category, [km/veh.],

– the emission factor determined for the -th pollutant, the vehicle of the -th category, and the -th road type, [g/km].

Additionally, exhaust emissions are highly affected by the vehicle speed, which varies depending on different modes of movement and can be included in emission assessment through the several approaches:

* choosing the average speed introduced for different types of road conditions (“urban” – 20 km/h, “rural” – 60 km/h, and “highway” – 100 km/h) and application of the corresponding emission factor,
* determination of the mean speed distribution curves and further integration over the emission curves:

, (20)

where – the vehicle speed defined for different road categories, [km/h],

– the speed-dependency expression of ,

– the best fit curve equation, that depicts the frequency distribution of average speeds, depending on the way the vehicle is driven on different categories of roads.

The advanced Tier 3 approach could be applied for assessment of the hot-start exhaust emissions with selection of the fixed average speed since the roads in the research area belong to urban ‘residential’ category, and additionally speed limits (of up to 20 km/h) should be introduced for the vehicles inside the study area (creating so called “limited traffic zone”).

Moreover, the developed model assumes that cargo bikes are capable to replace:

* medium-sized passenger cars (PC) from the segment M1 (vehicles serving for passenger transportations with less than 8 seats except the driver's) with gasoline engine and technology port fuel injected (PFI) or diesel engine and technology diesel particulate filter (DPF), with Euro standard from Euro 3 to Euro 6d,
* light commercial vehicles LCV from the segment of the type N1-I (vehicles with maximum mass less than 3.5 tones for the transportation of goods) with diesel engines and technology DPF standardized from Euro 3 to Euro 6d.

According to the accepted methodology, the speed-dependent emission factors for the corresponding vehicle of the -th technology and the specified -th pollutant should be evaluated using the following formula:

, (21)

where – the average speed of vehicles, [km/h],

, , , , , , – calculation coefficients, provided by the EEA methodology (7).

The quantity of cold-start emissions can be determined as the additional quantity of emissions over the hot-start emissions as the fraction of the completed route, which the vehicle performed with a cold engine. Cold-start emissions of the -th pollutant for the relevant period could be calculated for the vehicle with the technology as follows:

, (22)

where – a fraction of the distance travelled with the cold engine by the vehicles with the -th technology for the -th pollutant. Such parameter depends on the average monthly temperature and the manner of using the vehicle (namely, the simplified average route lengths, , which is established as 12.4 km for European countries [19]),

– number of operating vehicles with the -th technology, [veh.],

– the distance travelled by vehicles with the -th technology, [km/veh.],

– the hot emission factor determined for the -th pollutant and the vehicles of the  
-th category, [g/km],

– the cold to hot ratio for the -th pollutant and vehicles of the -th category; that parameter depends on the examined pollutant and the ambient temperature , and could be evaluated using the equation:

. (23)

Depending on the type of pollutant, during the cold-start process, the additional emissions of the CO and VOCs are occurred due to the fuel enrichment, which increases the engine efficiency. On the other hand, the NOx does not depend on the fuel enrichment, but is very sensitive to temperature. Moreover, it is considered that the effect of cold start does not occur at an external temperature higher than 25°C for CO and 30°C for VOCs.

The approach suggests accepting for the calculations of the ratio mean ambient annual temperature, the average trip speed and vehicle category. The higher the category of the vehicle (from Euro 3 to 6), the less time it takes for its catalytic systems to get to the shutdown temperature and, consequently, the less emissions are produced.

A fraction of the distance travelled during the cold-start phase is evaluated by means of the equation:

. (24)

It should be noted, that for diesel vehicles the cold-start emission excess indicator has a low value compared to gasoline ones, therefore diesel vehicles are not differentiated.

Since CO2 emissions are generated from different sources (from the combustion of fuel and lubricating oil in the engine and through carbon-containing additives in the exhaust), the determination of this component is performed for each case.

Such approach is based on the ratio of hydrogen to carbon as well the ratio of oxygen to carbon atoms which depict the chemical formula CxHyOz:

, , (2.25)

. (26)

To calculate evaporative emissions the simplified Tier 1 methodology was applied, which suggests using such generalized formula:

, (27)

where – the total number of vehicles that belong to the -th category,

– the average emission factor for the VOC pollutant and the vehicle of the -th category (such data is only available for passenger cars, light commercial and two-wheeled vehicles); these emission factors depend on the daily temperature variations and could be defined for such intervals: 20…35°C, 10…25°C, 0…5°C and –10…5°C.

For the research purposes, for the EU cities, the emission factor can be assumed for the average temperature in range 0…15°C, which is equal to 5.7 g/vehicle/day.

Worth noting that methodology for evaporative emissions calculations (that appear from the fuel evaporation from the fuel tank) should be applied in the cases when the vehicle is not operating and the engine is turned off, when the vehicle is parked or during the driving. Additionally, the fuel evaporates during the refueling process.

The use of the corresponding tier of the EMEP/EEA methodology largely depend on the availability of the input data characterizing both the technological process of deliveries (the number of vehicles, the distances covered by vehicles) and the climate conditions in the studied region.

# 4. Case studies

Case studies were conducted for selected areas of the following cities-participants of the CCCB project to explore different logistics systems that use cargo bikes in delivery processes, test the developed simulation model, and evaluate the emission reductions achieved by implementing a delivery scheme that includes cargo bikes:

* Krakow – the second-largest Polish city, which is situated in Lesser Poland Voivodeship in the southern part of Poland,
* Mechelen – a city and municipality in the province of Antwerp in the Flemish Region of Belgium,
* Vitoria-Gasteiz – the capital of the province of Alava and the capital of the Spanish autonomous community of the Basque Country, Northern Spain,
* San Sebastian – the city and municipality in the Spanish Autonomous Community of the Basque Country, Northern Spain,
* Rimini – the city in the Emilia-Romagna region of Northern Italy.

The summarized characteristics of the chosen cities and the study districts are presented in Table 1 and are relevant for 2021 and 2022 year (8).

Tab. 1. The population characteristics, total city area, and the size of the analyzed region

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| City, country | Area, km2 | Population | Density, inh./km2 | Study area, km2 |
| Krakow, Poland | 326.9 | 802,653 | 2456 | 0.68 |
| Mechelen, Belgium | 65.2 | 86,996 | 1334 | 0.62 |
| Vitoria-Gasteiz, Spain | 276.8 | 253,996 | 918 | 0.19 |
| San Sebastian, Spain | 60.9 | 187,892 | 3086 | 0.17 |
| Rimini, Italy | 135.79 | 148,688 | 1100 | \*\*\* |

The architectural attributes of the historical centers of selected cities stem from their formation in the Middle Ages, affect the current way of life, and can be characterized by the following common typical features:

* compact layout and oftentimes the presence of defensive walls,
* high density and size of the population,
* a high share of economic activity,
* high administrative status,
* narrow streets and often the presence of one-way streets, pedestrian districts, etc.

Such characteristics frequently lead to the emergence of negative conditions in these areas (such as the appearance of congestion, air and noise pollution, inconveniences to pedestrians, etc.), but on the other hand, these features can greatly contribute to the development of efficient cycle logistics for deliveries of the last mile. Therefore, the following criteria were outlined, which should be met by potential urban areas for simulations and further analysis:

* The selected zone must be located inside the city center, which has introduced traffic restrictions (such as limited or prohibited assess for motorized vehicles, exclusion of heavy and highly polluting transport, etc.),
* The presence inside the area of many businesses (such as grocery stores, restaurants, hotels, etc.), which make up potential customers for LSP,
* The availability of a sufficient number of participants in the experiment: persons performing traffic calculations must be simultaneously located at all entries and exits along the perimeter of the investigated area.

All cities participating in the experiment meet the defined criteria: the research areas have restrictions imposed on motorized vehicle entry, the number and coordinates of the objects located inside the area can be determined, and sufficient human resources can be allocated to perform the traffic calculations. The common feature for each research area – is a time-defined permit for traffic entry.

To gain insight into traffic activity and the spatial distribution of travel demand, after defining the research areas and the locations of origins and destinations, the next step – is performing measurements of traffic volumes over a specified period. Traffic flow measurements are essential for demand analysis providing necessary information for understanding travel behavior and estimating transportation needs. Traffic counts help to evaluate the number of trips between origins and destinations allowing to determine the main routes and travel schemes; they give information about the usage of different transport modes allowing to perform the modal split; they could be used for travel time analysis and efficiency of the transportation network, for demand forecasting and besides for evaluation of the effectiveness of transportation policies.

The calculations of transport, involved in commercial activities inside the defined study areas, were carried out within the framework of the CCCB project. Participants from partner cities followed such recommendations for conducting the field experiment:

Performing calculations manually by participants located at defined points near the boundaries of the city zone with restrictions, filling in the number of vehicles divided by the following types into the forms:

* heavy-duty vehicles, HDV (with a payload of more than 3.5 tons),
* light commercial vehicles, LCVs (with a payload of less than 3.5 tons),
* taxis,
* private passenger cars,
* special purpose vehicles, SPVs (such as garbage trucks, ambulances, firetrucks, etc.),
* cargo bicycles.

Since the entrance of motorized transport to the analysis zones has time limits, traffic measurements were carried out during the morning rush hour, when the entry for commercial vehicles is allowed for operations before the beginning of a workday.

The number of study participants was equal to the number of entries and exits from the analyzed area to ensure a representative outcome.

In addition to inlets and outlets, measurements were carried out on several internal streets of the zone (3 – 5 points with the highest intensity) for further model validation.

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. This data includes the object’s name, geographic coordinates, address, and type. Further, this collection of potential customers was divided into the following groups (Table 2):

* food and dining establishments, such as cafes, bars, restaurants, etc.,
* lodging business, 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.

Tab. 2. The collection of potential customers obtained from the OpenStreetMap tool for the chosen study regions of the selected cities

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Customer groups | City | | | | | |
| Kraków | Mechelen | Vitoria-Gasteiz | San Sebastian | Rimini |
| Grocery stores | 28 | 13 | 10 | 20 |  |
| Food and dining | 380 | 126 | 51 | 148 |  |
| Lodging business | 108 | 7 | 6 | 22 |  |
| Various shops | 184 | 187 | 110 | 85 |  |
| Others | 256 | 56 | 61 | 28 |  |
| Total number | 954 | 389 | 238 | 303 |  |

![A picture containing kite, flying, outdoor, map

Description automatically generated]()

Figure 1. Transportation network with nodes, that represent potential customers inside the analysis area of the Old Town of Krakow

A screen shot of a computer screen

Description automatically generated

Figure 2. Transportation network with nodes, that represent potential customers inside the analysis area of Mechelen

Chart, scatter chart

Description automatically generated

Figure 3. Transportation network with nodes, that represent potential customers inside the analysis area of Vitoria-Gasteiz

A picture containing star, night, outdoor object, night sky

Description automatically generated

Figure 4. Transportation network with nodes, that represent potential customers inside the analysis area of San Sebastian

To estimate the reduction of emissions for the study areas of the CCCB partner cities, multiple runs of the developed simulation models 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:

* simulations period was expanded to the size 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 from the CCCB partner cities (the corresponding survey was held at the first stage of the CCCB project among the experts representing partner cities), whereas the standard deviation of the consignment weight was accepted at the level 0.3 (to guarantee the variability of the packages’ weight starting from the smallest values),
* the elements in the vector of probabilities of the requests’ appearance for different types of potential clients were accepted equal to 1.0 (as the experimental studies presented in Section 4.4 have shown, the values of these probabilities do not influence the results of simulations significantly).

In each model launch, for the generated demand for deliveries inside the study area, 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 3.

Tab. 3. Characteristics of the stochastic variable of the saved distance obtained based on the results of conducted simulations

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | City | | | | |
| Kraków | San Sebastian | Vitoria-Gasteiz | Mechelen | Rimini |
| Minimum, [km] | 71.595 | 80.088 | 9.761 | 6.647 |  |
| Maximum, [km] | 112.99 | 100.431 | 25.147 | 26.128 |  |
| Average, [km] | 95.464 | 89.547 | 17.321 | 16.908 |  |
| Standard deviation, [km] | 7.347 | 3.742 | 2.886 | 3.630 |  |
| Variation coefficient, [-] | 0.077 | 0.042 | 0.167 | 0.215 |  |

# 5. Discussion

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