CETRA^{2024} 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

SIMULATING THE PROCESSES OF GOODS DELIVERING BY CARGO BICYCLES

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Abstract

Cargo bikes offer an attractive solution for eco-friendly deliveries in modern cities. By replacing conventional trucks, they can significantly reduce traffic congestion and reclaim public space. This translates to cleaner air, less noise pollution, and an overall improved quality of life for city residents. However, the benefits of cargo bikes may not be readily apparent to decision-makers who rely on traditional transportation methods. This paper proposes a novel, data-driven methodology to evaluate the clear advantages of cargo bike deliveries. We present a computer simulation model that assesses the effectiveness of cargo bikes compared to standard delivery practices. The model incorporates key factors such as a city's existing road network, the geographical distribution of delivery demands, and the operational capabilities of cargo bikes. To demonstrate the model's utility, we present a real-world case study simulating cargo deliveries within Dubrovnik's historic Old Town district. This Python-based model can be a powerful tool for decision-makers, allowing them to optimize cargo bike operations. Applications include identifying ideal locations for loading points and determining the optimal number of cargo bikes required for efficient deliveries within a specific urban environment. This approach provides a clear picture of the positive impact cargo bikes can have on urban deliveries, empowering decision-makers with the information they need to implement sustainable and efficient transportation solutions for their cities.

Keywords: cargo bike, freight delivery, simulation model

1 Introduction

Our world is rapidly urbanizing, with projections suggesting that by 2050, a staggering three-quarters of the global population will reside in dense city centers. This trend puts immense pressure on existing transportation systems, leading to a potential escalation of negative consequences. Traffic congestion, air pollution, and noise levels are all likely to rise dramatically. These challenges necessitate a proactive approach to sustainable urban development. Policymakers around the globe, particularly within the European Union, are actively seeking solutions. They recognize the need for a comprehensive legal framework that regulates and monitors the transportation sector, promoting efficiency and environmental responsibility. However, achieving significant results requires a collaborative effort encompassing all stakeholders – from policymakers to private businesses operating within the distribution network [1]. Sustainable innovations should prioritize social needs while fostering a healthy business environment.

DOI: https://doi.org/10.5592/CO/CETRA.2024.1714

Cargo bikes have emerged as a promising solution for urban deliveries, particularly well-suited for densely populated historic city centers [2-6]. These areas often have narrow streets, pedestrian zones, and high concentrations of commercial establishments that generate a significant demand for parcel deliveries. Additionally, one-way streets, time restrictions on motorized vehicles, and heavy pedestrian traffic can further hinder efficient deliveries by traditional methods [7-9]. While integrating cargo bikes into urban delivery systems offers undeniable benefits, a balanced perspective requires acknowledging potential drawbacks. Studies suggest that simply introducing cargo bikes may not yield significant advantages without additional measures like targeted campaigns to promote their use [10]. Additionally, electric cargo bikes face limitations related to battery range and potential equipment failures. Furthermore, the success of cargo bike implementation hinges on a supportive infrastructure – dedicated bicycle lanes, clear signage, designated parking areas, and a network of charging stations and transshipment points are crucial, but are often lacking [6, 11, 12].
Despite these challenges, simulation modeling offers a powerful tool to evaluate the feasibility and impact of integrating cargo bikes into urban delivery systems. By creating a virtual representation of this system, we can explore various delivery scenarios, and analyze the impact of fleet size, mobile hubs, and delivery time windows. This approach facilitates optimizing routes, scheduling deliveries, and strategically locating transshipment hubs, ultimately paving the way for a more sustainable and efficient urban delivery landscape.
This paper aims to describe the approach allowing researchers to simulate freight deliveries inside the selected city area. We use the Python implementation of this approach to show the potential of cargo bikes for sustainable deliveries within the historical center of Dubrovnik.

2 Mathematical model

Building a mathematical model of a transportation system involves identifying its key subsystems with each component characterized by a set of numerical attributes. Algorithms are then defined based on these parameters, using them as input data to perform calculations. The complete model, coded in a programming language, acts as a blueprint for implementing a computer simulation of the transportation system.

2.1 Transportation network model

Our model leverages graph theory to represent the freight transportation system. Within this framework, a delivery route is a sequence of nodes and links on a graph that depicts the road network. Formally, the transportation network within the study area can be represented as graph . Nodes () in this graph correspond to key locations such as potential customer locations, road intersections, and depot points. Links (), on the other hand, represent the roads between these locations. Finally, an additional element, , incorporates traffic analysis zones (TAZ) within the study area.

$$G = \{N, L, R\} \tag{1}$$

Each element within the graph is characterized by a set of predefined parameters. To define a specific node, denoted as (), we consider the following variables:

$$n_i = \{id_i, x_i, y_i, in_i, out_i, type_i, region_i, itsc_i, inlet_i, outlet_i\} \tag{2}$$

where is a unique identification number of the node; x_i and y_i are geographic coordinates (latitude and longitude) of the node; in_i and out_i, are lists of incoming and outgoing links connected to the node, respectively; $type_i$ is a classification of the node as a road intersection, depot (loading hub), or customer location; region$_i$, is a reference to the traffic analysis zone the node belongs to; itsc$_i$ is a reference to the graph node representing the closest intersection to this node (if applicable); inlet$_i$ and outlet$_i$ are Boolean flags indicating if the node is an entry point (inlet) or exit point (outlet) for the study area; is the total number of the graph nodes. Each l$_j$ (j = 1, .., N$_L$) in the graph is defined by a set of three parameters:

$$l_j = \left\{ n_j^{out},\ n_j^{in},\ weight_j \right\} \tag{3}$$

where n_j^{out} and n_j^{in} denote the outlet and inlet nodes, respectively; weight$_j$ is the numeric parameter associated with the graph edge; N$_L$ represents the total number of links within the graph.
The urban area is segmented into a set of traffic analysis zones R$_k$ (k = 1, .., N$_R$):

$$R_k = \{id_k, x_k, y_k, nodes_k\} \tag{4}$$

Where id$_k$ denotes the unique identifier of the -th zone; x$_k$ and y$_k$ represent the geographic coordinates of the i-th zone's centroid; nodes$_k$ is the collection of nodes within the k-th zone of the model N$_R$ represents the total number of TAZs.

2.2 Travel demand model

Travel demand in transportation systems is typically linked to social activity patterns within a defined geographic area and timeframe. However, acquiring all real-world delivery request data can be challenging. Therefore, travel demand modeling aims to utilize mathematical tools to replicate real-world processes with the highest possible accuracy. A common approach for representing trip distribution within a simulated area is the origin-destination matrix (ODM). Each row and column in the ODM correspond to a designated TAZ. The ODM can be further broken down into submatrices: internal trips (the submatrix shows the number of trips occurring entirely within the study area), outgoing trips (the submatrix represents trips originating within the study area but ending outside), incoming trips (the submatrix captures trips originating outside the study area, entering through a TAZ, and ending within the area), and through traffic (the submatrix shows trips that originate and terminate outside the study area, but with a route passing partially within).
When modeling small urban areas with restricted access for conventional vehicles, the internal trips and outgoing trips submatrices are likely to have minimal or zero values. This is because such areas typically house consignees (receivers) rather than senders of goods. Similarly, elements within the through traffic matrix might be negligible due to the limited appeal of traveling through a restricted zone with low permitted speeds. Consequently, the primary focus for modeling delivery traffic in these areas becomes the incoming trips submatrix, representing deliveries from external zones to consignees within the study area.
Traditionally, travel demand modeling for freight deliveries within a restricted traffic zone often employs a 4-step approach that incorporates a gravity model. However, due to the relatively small size of the study area, the complexity of a gravity model for trip distribution may not be necessary. In this paper, we propose a simpler and more direct approach. Trip origins (inlets) can be assigned randomly, weighted by a probability that considers the actual distance to each potential inlet. This revised approach streamlines the modeling process while maintaining accuracy:
1. Generate a set of F requests for deliveries considering the restriction:

$$F = \sum_{i=1}^{K} \xi_i \tag{5}$$

Where ξ_i is the total number of vehicles entering the i-th entry (according to observed traffic), [veh.]; K is the number of entries (inlets) to the study area.

2. For each request, calculate the vector p_k containing the probabilities of selecting the available inlets as the source of the trip:

$$p_{ki} = \frac{g_{ki}^{-2}}{\sum_{i=1}^{K} g_{ki}^{-2}} \tag{6}$$

Where p_{ki} is the probability of selecting the i-th entry as the origin point for the k-th trip; g_{ij} is the shortest distance according to the road network between the i-th inlet and the customer's location, [km].

3. Employ a stochastic sampling technique, like the roulette wheel selection, to randomly select a source for each request. This selection is weighted based on the corresponding probabilities in the vector, ensuring locations closer to the destination or adhering to constraints have a higher chance of being chosen.

For transparent and reproducible research, the software developed for these simulations and the scripts used in the experimental studies are openly accessible on GitHub: https://github.com/anniutina/TSM-EM.

3 Case study of Dubrovnik Old Town

The CityChangerCargoBike (CCCB) project, funded by the European Union's Horizon 2020 program, investigated the effectiveness of cargo bikes for urban deliveries. Through case studies conducted in select areas of participating cities, the project explored various cargo bike logistics systems. These case studies served a dual purpose: validating the functionality of our newly developed simulation model and quantifying the potential emission reductions achievable by implementing cargo bike delivery schemes. Dubrovnik, a city in southern Dalmatia, Croatia, served as one of the partner cities within the CCCB project.

Following standardized guidelines, partner cities collected traffic data for a single period only. In Dubrovnik, this data collection occurred between September 9th and 15th, 2021, specifically during the 9:00 AM to 10:00 AM timeframe. The results of the traffic flow measurements for light commercial vehicles (LCV) and private cars (PC) are presented in Table 1.

Table 1 Traffic counts observed on the inlet to the study area of Dubrovnik

Vehicle type	09.09.2021	10.09.2021	13.09.2021	14.09.2021	15.09.2021
LCV	15	11	16	12	15
PC	1	1	1	3	1

To simulate the demand for transportation services within the designated study area, a custom module was developed to extract relevant parameters of commercial establishments from OpenStreetMap (OSM). This module retrieved data including the establishment's name, geographic coordinates, address, and business type. The retrieved data was then processed to classify potential customers into distinct groups. The classification relied on the object categories (represented by map feature tags) stored within the OSM database. This resulted in the following customer segments: grocery stores (6 objects), food and dining establishments (101 objects), lodging businesses (98 objects), various shops (20 objects), and other businesses (57 objects).

An examination of Fig. 1 (the graph of Dubrovnik's central region) and customer data reveals a distinct characteristic of business establishments within the Old Town. The tourist-oriented nature, architectural style, and geographical layout of the area significantly influence the location and composition of businesses. Two primary customer segments emerge with nearly equal representation: "food and dining" and "lodging businesses", each accounting for 36% and 35% of all establishments, respectively. The next sizable group, "other establishments," encompasses entertainment, cultural institutions, and others, constituting 20% of businesses in the Old Town. Finally, "other stores" represent the least prevalent category, making up only 10% of establishments.

Dubrovnik's Old Town presents unique challenges for vehicle access, hindering traditional delivery methods. Encircled by historic fortress walls, the area has only one main entry point accessible by car. Furthermore, the southern sector is entirely pedestrian-only due to its staircases, further restricting vehicle movement within the Old Town.

To show the potential of the developed model, we estimated the possible savings in distance covered by traditional vehicles inside the urban area for the scenario when conventional commercial vehicles are partly replaced by cargo bikes.

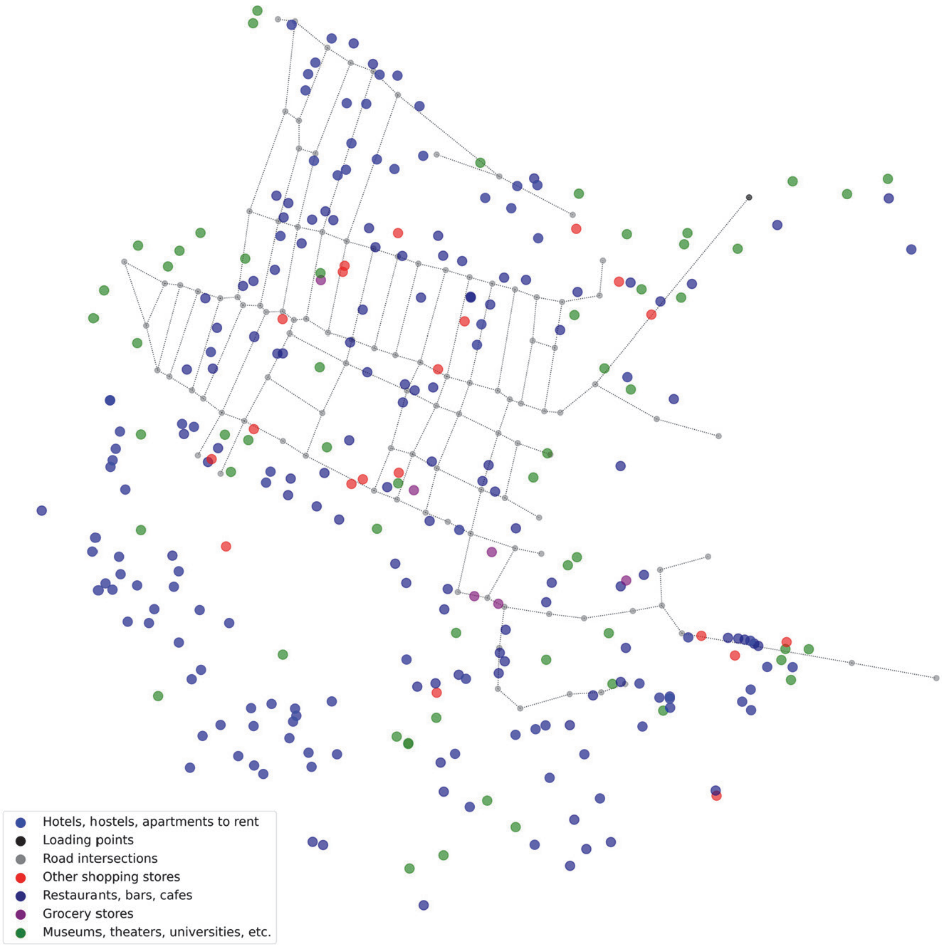

Figure 1 Transportation network with nodes representing potential customers

To quantify the reduction in distance covered by traditional vehicles within the Dubrovnik study area, the simulation model necessitates multiple runs to achieve statistically significant results. Obtained simulation results must undergo statistical analysis to confirm their normality. Additionally, a sample size sufficient to ensure statistical significance at a given confidence level needs to be determined. The simulation model was executed 300 times, with parameters established based on the following assumptions:

- expanded simulation period: the simulation period was extended to encompass the entire timeframe during which vehicles could enter the study area. Incoming traffic flows were calculated using hourly averages derived from the conducted traffic counts;
- randomized consignment weight: a normal distribution was employed to generate a random variable representing consignment weight; the average weight was adopted based on expert estimations from the CCCB partner cities (obtained through a survey conducted at the project's initial stage); a standard deviation of 0.3 was used to introduce variability in package weight, incorporating a range of values from the smallest sizes.

The histogram in Fig. 2 illustrates the distribution of potential distance savings observed in the simulation experiments.

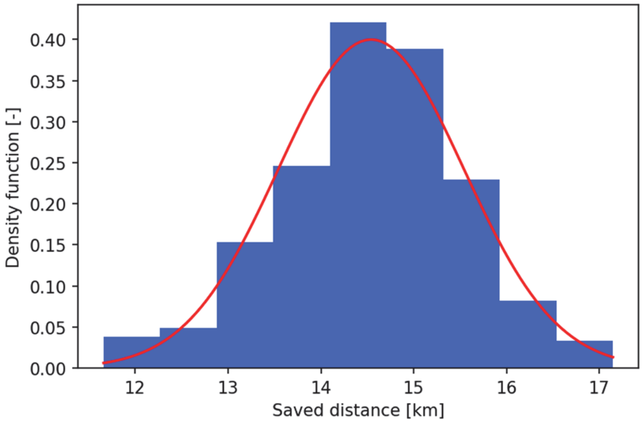

Figure 2 Distribution of the saved distance based on the simulations

Our findings for Dubrovnik are particularly promising when considering distance reduction relative to traditional delivery methods (assuming all deliveries are currently made by conventional vehicles). The study area's unique layout allows for all deliveries to be completed using cargo bikes. This is achievable because a single loading hub can be strategically placed near the Old City Gates, the sole entry point for deliveries within the studied area. Consequently, traditional delivery vehicles can be entirely excluded, leading to significant distance reductions.

4 Conclusions

The parameters obtained from the transport system simulations offer valuable insights into transportation system performance. Comparing these results with real-world data or alternative scenarios allows for targeted identification of areas for improvement and model refinement. Furthermore, simulation outputs obtained based on the proposed method can be leveraged to estimate emissions generated by the transportation system and their atmospheric dispersion.

It is crucial to acknowledge the limitations of the proposed methodology in the aspects of real-world variability (the demand model may not fully capture the unpredictable nature of urban environments) and data accuracy (the simulation's adequacy relies heavily on the accuracy of input data). Despite these limitations, the proposed simulation methodology remains a valuable tool for planning and optimizing cargo bike deliveries. By acknowledging these limitations and incorporating real-world data collection alongside the simulation model, we can gain a more comprehensive understanding of the feasibility and effectiveness of cargo bicycles in urban logistics.

The proposed methodology and its Python implementation are designed for ongoing development within the scientific community. To facilitate collaboration, the developed Python code, prepared input data, and completed simulation experiment results are publicly available. This open-source approach encourages further research and refinement, ultimately accelerating the integration of cargo bikes into sustainable urban transportation systems.

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