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# Pipeline for Modeling Urban Traffic Density as the Data Basis for Micrologistics and Autonomous Delivery Robots: Project MoVMi

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**Abstract.** This paper presents a framework for modeling urban traffic density to support micrologistics using automated guided vehicles (AGV), more specifically autonomous delivery robots (ADR). The project MoVMi integrates survey data, pedestrian simulations using SUMO, and AGV interaction modeling in CARLA to optimize last-mile delivery in urban environments. Our approach addresses challenges such as congestion and access restrictions, and balances routing efficiency with delivery time windows. The framework's adaptability allows application in various cities globally, enhancing urban freight transportation and sustainability. Future work will refine models with real-time data and extend applicability to diverse urban settings.

**Keywords.** Autonomous Vehicles, Last-mile Logistics, Simulation, delivery robots, Urban Freight Transportation

## 1. Introduction

Research in the field of automated delivery systems plays an important role in making our cities cleaner, more environmentally friendly and more livable. Further trends like the shortage of trained staff and the trend of urbanization play a key role [1]. Regardless of the recent employment of AGVs in urban areas this topic is considered under researched [2]. Regardless, numerous publications investigate several possibilities for autonomous delivery, such as mobile hubs [3] or the use of drones [4] or even the use of public transport in conjunction with AGVs [5]. As part of the presented project, a comprehensive analysis and modeling of

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urban traffic dynamics and delivery requirements was carried out. The aim of this project is to develop precise data and models that can serve as a basis for the optimization of micrologistics systems and the implementation of autonomous transport solutions. Urban freight bears a significant congestion cost borne by light commercial vehicles in an urban area [6] and further external costs of urban freight. Furthermore, urban areas have very specific requirements towards freight delivery. These include access restrictions to certain areas, which can be time-dependent, as well as complicated geographical conditions and traffic congestion, etc. [7]. The contradictory relationship between routing efficiency and fixed delivery time windows is particularly notable when it comes to deliveries to customers. Predefined time windows hinder efficient routing[8]. Customers want their deliveries to have a smaller ecological impact but also often do not want to bear the additional cost or wait time this implies [8]. To counter these constraints, automated delivery options are increasingly being investigated. The MoVMi project addresses this issue using Leipzig's city center as an example. The aim of the project is to gather, process and present data, models and simulations to evaluate the feasibility of the use of AGVs for micrologistic purposes in a city center.

In this article, we present a framework to model urban traffic and logistics demands to examine the efficacy of mobile autonomous robots in this environment. The paper is organized as follows. In the subsequent Section 2, we present the comprehensive framework developed for this study. This section details the architecture and pipeline of the modeling framework, including the survey design in Section 2.1, the pedestrian modeling in Section 2.2, and robot interaction modeling in Section 2.3. In Section 2.4, we describe the logistics simulation and how it integrates data from the previous models to optimize delivery routes. Section 3 discusses the results and the implications of our findings for urban logistics. Finally, Section 4 offers a conclusion and outlines future research directions, highlighting the potential applications of our framework in other urban environments.

## 2. Framework

In this Section, we present our modeling Framework, see Fig. 1. It mainly consists of a survey to determine the logistical demand, a pedestrian analysis for inner city traffic, and a pedestrian interaction assessment for the delivery robot. This data is utilized to generate a logistics simulation.

Our Survey identifies economic players who generate demand for freight transport in the city center and commercial customers of logistics service providers. It invites these potential stakeholders to participate in a survey. The questionnaire includes questions on current ordering and shipping behavior, delivery frequency, shipment size and company-specific questions.

The pedestrian modeling provides pedestrian densities via a simulation in which pedestrian flows are calculated on the basis of traffic count data and other boundary conditions. A movement speed model for the AGV is created in the context of pedestrian zones and footpaths by the robot interaction modeling. It can be flexibly adapted to different configurations of the AGV. The environment is scanned by different road widths and the calculated density of people. This

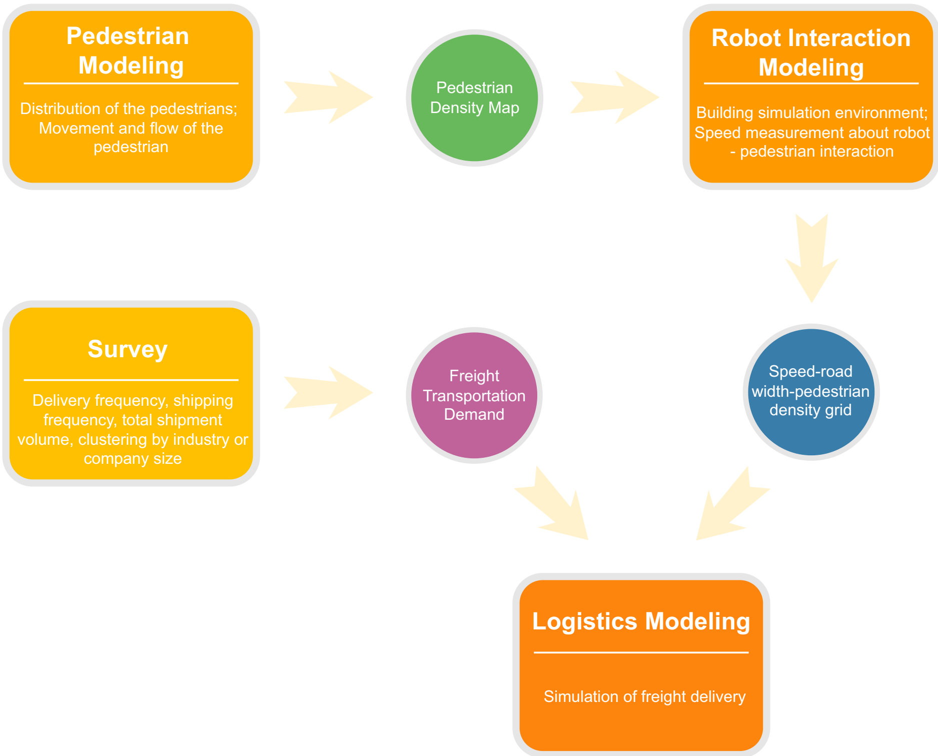



**Figure 1.** The pedestrian simulation in SUMO generates a density map of pedestrians. This is used by the CARLA simulation to calculate the speed-road width-pedestrian density grid. From this and the survey, an overall logistics simulation is created. Finally, the feasibility and need for micro-depots and logistics robots can be calculated.

results in a predicted average speed for the driverless transport system that is dependent on the boundary conditions. Based on the aforementioned traffic and time-dependent predicted average speed, the driverless transport system's route planning is carried out using the logistics demand data from our survey. How the tools of the Framework interact is illustrated in Fig. 2a.

### *2.1. Survey and demand modeling*

The survey is designed to capture the ordering and shipping behaviors of businesses, aiming to provide a detailed inventory analysis of freight transport activities. By identifying current behaviors and challenges, the survey enables the tailoring of micrologistics and autonomous transport systems to meet the actual needs of businesses, thereby enhancing efficiency and sustainability. These data-driven insights are critical for developing simulation models and innovative solutions to address these challenges effectively.

The survey employs a combination of quantitative and qualitative methods to gain a comprehensive understanding of freight transport issues. Quantitative data is collected through an online questionnaire, while qualitative data is obtained from interviews. This mixed-method approach ensures a broad and representative database, captures specific information necessary for developing tailored solutions, and strengthens data validity. Active involvement from the local business community is emphasized to ensure the practicality and relevance of the solutions developed.

Implemented using SoSci Survey [9], the data collection adheres to strict data protection regulations, ensuring anonymity and confidentiality. After careful data cleaning, 135 usable responses were obtained. The evaluation of this data is conducted using R Studio, providing descriptive analysis and visualization of key parameters. The survey includes sections on delivery and shipping frequency, types and volumes of shipments, logistics providers used, transport methods, delivery challenges, and future perspectives on autonomous and alternative delivery systems, ensuring comprehensive data collection for effective urban logistics solutions. The questionnaire and results will be made available on Mobilithek [10].

In addition to the quantitative surveys, qualitative data is gathered through interviews with representatives from logistics companies like DHL, Hermes, and UPS. These interviews focus on delivery traffic challenges, alternative delivery methods, and the future perspectives of autonomous delivery systems.

The findings of the survey provide a solid basis for understanding the current state and challenges of urban freight transport, in this case for the city centre of Leipzig. Building upon the comprehensive data gathered from the survey, the next step involves addressing the modeling of pedestrian behavior within the same urban landscape. Understanding pedestrian traffic is equally crucial for optimizing urban logistics, as it directly influences the movement of AGVs and the overall flow of goods and people.

### *2.2. Pedestrian modeling*

Due to the limited availability of empirical data on pedestrian traffic within the modeling area, the distribution of pedestrians must be estimated. This distribution per street is subsequently employed to calculate the occupancy, which is then used to determine the movement speed of the AGV in Section 2.3.

To model the movement and flow of the pedestrian traffic inside the inner city boundaries the simulation software SUMO is used [11]. SUMO is a microscopic traffic simulator that enables the simulation of pedestrian flows in a simplified manner [12]. In order to simulate pedestrians adequately, several preconditions apply to the used map and simulation environment.

The process of setting up a map for simulation involves several steps to ensure accuracy and realism. Initially, the map is generated using SUMOs Export Wizard for OpenStreetMap (OSM) [13], which provides a foundational layout. This exported map was then edited to meet specific preconditions. This includes the removal of unnecessary infrastructure such as rail lines, public transport stops, and footpaths that traverse buildings. Street widths are adjusted to reflect real-world dimensions. Additionally, connections between streets are edited and adjusted to create a coherent and navigable network. Traffic rules were modified to align with real-world regulations.

Finally, trip definitions for pedestrian traffic are set up, allowing for the simulation of pedestrian movement and behavior within the map. These are compared to the data provided by the cities traffic counting infrastructure available on hystreet [14] and adjusted. The resulting flows make the pedestrian traffic spread over the city in a random matter, ensuring that all streets are populated by pedestrians. The resulting simulations output is the pedestrian occupancy on every street section over time. This gets forwarded to the Robot interaction model.

### 2.3. Robot interaction modeling

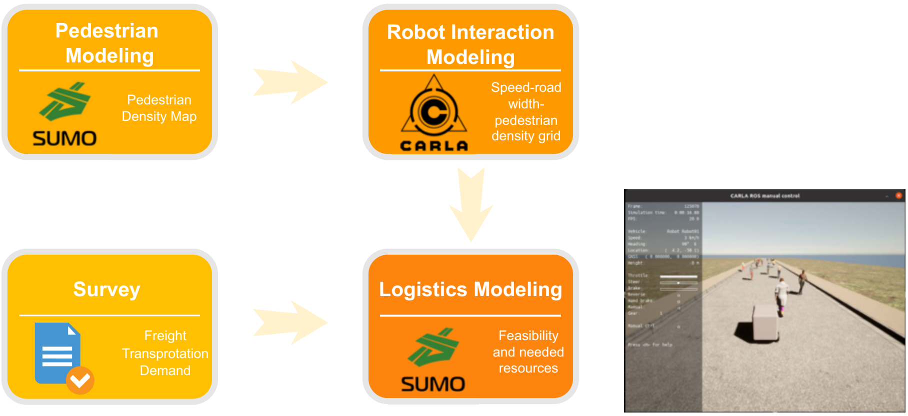
The interaction of an AGV with pedestrians in a realistic simulation environment is modeled using CARLA [15] as a simulation platform. CARLA enables the detailed analysis of driving behavior under specific environmental conditions and supports the development, training and validation of autonomous driving algorithms. The platform offers enhanced functions for modeling specialized sensor configurations, dynamic adaptation of environmental conditions, control of static and dynamic actuators, and integration of new maps and vehicle models. CARLA also incorporates autonomous driving functions that can be utilized directly in simulations, rendering it particularly suitable for precisely simulating interactions between AGV and pedestrians. Another technical advantage is the seamless integration with Robot Operating Sytem 2 (ROS2) [16] via the CARLA-ROS Bridge, which facilitates the expansion of simulation scenarios to accommodate specific requirements. The primary objective of pedestrian robot simulation is to generate a speed profile that depicts the relationship between road width and pedestrian density. In order to achieve this objective, it is necessary to create maps with varying road widths and to integrate a new vehicle model that corresponds to the specific dimensions of a AGV [17].

#### 2.3.1. Setting up the simulation and customizing the frameworks

The AGV is modeled using Blender and imported into CARLA, with dimensions of $1\,\mathrm{m} \times 1\,\mathrm{m} \times 1.2\,\mathrm{m}$. This allows the robot sufficient space for multiple packages. The simulation is conducted at a maximum speed of $8\,\mathrm{km\,h^{-1}}$. This configuration is adaptable to different sizes and configurations of AGV.

Roadrunner [18] is used to create the simulation maps. Roadrunner enables the precise definition of road networks, the adjustment of road widths, the modeling of elevation differences and other topographical features. It also allows the import of OSM data and the conversion to OpenDrive formats. A total of 18 different maps are created, each with a road width ranging from 2 m to 8.5 m and comprising approximately 150 m of straight road.

The fundamental functions of CARLA are modified in order to meet the specific requirements of the interaction between AGV and pedestrians. In the original version of CARLA, pedestrians are observed to navigate primarily on footpaths and only cross roads at designated crossings. Vehicles, on the other hand, avoid footpaths. To generate a realistic speed profile for pedestrian zones that reflects the navigation of AGV through dense crowds, the ability to navigate pedestrians across the entire road surface is incorporated. The collision avoidance capabilities of CARLA's autonomous driving functions have been enhanced and adjusted to align with the new conditions.




(a) Interaction between the survey, Carla and Sumo components

(b) Robot-Pedestrian Simulation in Carla

**Figure 2.** The figures show the interaction of the individual tools and presents a scene in CARLA.

Another essential part to determine the speed profile is the implementation of a fixed pedestrian density. This is achieved in CARLA by enabling the creation of specific navigation zones through the definition of polygons, within which the density of pedestrians can be precisely specified and maintained at a constant level. The number of pedestrians within these zones is calculated based on the density and the area of the zone. The pedestrians navigate to randomly selected destinations within the defined areas and are monitored. Upon exiting the area, they are removed from the simulation and replaced by new pedestrians to maintain a constant footfall density. An example can be seen in Fig. 2b.

The CARLA pedestrian model is characterized by a high degree of realism, including a range of pedestrian attributes and behaviors, including individuals running, as well as different age groups and movement patterns. Pedestrians navigate along direct routes to their destinations, but are able to circumvent obstacles and other road users when necessary. In order to ensure that the AGV does not operate on pavements, the defined navigation areas must be designed in such a way that they do not include pavements. This allows for a realistic simulation of the interaction between AGV and pedestrians.

During each simulation run, the AGV navigates through the defined area at a constant pedestrian density. After leaving this area, the average speed of the AGV is calculated.

### *2.3.2. Creation of the characteristic grid*

The creation of a statistical predicted average speed profile necessitates the execution of multiple simulation runs. To this end, an automated simulation pipeline is implemented, which relies on the use of a scenario file. This file contains the specifications pertaining to the map to be utilized, the definition of pedestrian zones, the starting and ending positions of the AGV, and the parameters to be simulated for pedestrian densities. Furthermore, the minimum and maximum pedestrian densities, as well as the step size, are specified. Additionally, the scenario specifies the number of iterations to be conducted for each combination of density and map. The scenario file is loaded, and the corresponding simulations are initiated automatically. Upon reaching the target point, the simulation terminates the current iteration and initiates the next. The calculated mean speeds for this specific simulation run are stored alongside the respective pedestrian densities and street widths in a comma-separated values file.

### *2.3.3. Preparation of data for further use*

The aggregate of the individual simulation outcomes serves as the foundation for the calculation of the actual mean speeds in real-world operations. The data derived from the pedestrian simulation are employed in this calculation through the use of SUMO. In order to interpolate the speed values for pedestrians with densities and road widths that were not directly simulated, a Radial Basis Function (RBF) interpolation with a Gaussian kernel was applied, complemented by a smoothing of the data. Given a set of data points $(x_i, y_i)$, where $x_i \in \mathbb{R}^d$ are the input points and $y_i \in \mathbb{R}$ are the corresponding values, the RBF interpolator seeks a function $s(x)$ such that $s(x_i) = y_i,\ \forall i$. The interpolation can be described by

$$s(x) = \sum_{i=1}^{N} w_i \Phi(\|x - x_i\|) \tag{1}$$

with

$$\Phi(r) = \exp\left(-\left(\frac{r}{\varepsilon}\right)^2\right).$$

The parameter $\varepsilon$ is a shape parameter that controls the width of the Gaussian kernel and the term $\|x - x_i\|$ is the euclidean distance between the input point $x$ and the date point $x_i$.

The calculated mean speeds are stored together with the corresponding road ID. Once this has been completed, a graph can be constructed over the simulated road network, which serves as the basis for the logistics simulation.

### *2.4. Logistics modeling*

The logistics simulation is set up in a number of critical steps in order to ensure accurate modeling of AGV operations. Firstly, for each street on the map, the calculated mean velocity of the AGV is updated based on the pedestrian occupancy and width of the specific street. This reflects different occupancy levels occurring during the day. The freight demand is characterized by the number of parcels, categorized by size and destination. This demand is mapped to approximately 150 locations evenly distributed across the city, each described by geographic coordinates. These locations represent their surrounding areas on the assumption that delivery time discrepancies within these areas are negligible. A nearest neighbor search is conducted on the geographic coordinates of each location to find a corresponding map element (street section, i.e., "edge") that the AGV can travel through, establishing the destinations for the routing algorithm.

For each destination, a route is then calculated using the Dijkstra algorithm [19], which is suitable for routing in time-dependent environments [20]. This ensures efficient navigation and delivery by the AGVs. The calculated Routes are then analyzed.

## 3. Discussion

The MoVMi project has created a robust data base by integrating survey results, synthetically generated data and logistics simulations. The survey, combined with the visualization of logistics demand based on these results - taking into account delivery windows and package sizes - provides a solid basis for further analysis. These visualizations, rendered as OSM overlays, significantly enhance the understanding of traffic dynamics in Leipzig's city center.

The next steps are to conduct a comprehensive logistics simulation for Leipzig city center, taking into account the dynamic interactions within the urban delivery network. A key objective is to develop a framework that uses OSM maps, traffic count data and Building Information Modelling (BIM) data on lane widths to automatically generate a map of average traffic speeds. This framework will ultimately assess the feasibility of automated deliveries using logistics robots. Future research should also focus on continuous improvement of route planning through real-time data and practical testing to further increase the efficiency and accuracy of simulations.

Although significant progress was made, the project encountered several challenges. The survey, which was limited to commercial traffic, had a lower than expected participation rate, but still provided a solid data base. Conducting logistics demand surveys becomes essential in this context to provide accurate input data. The use of publicly available data, while beneficial, presents several challenges in creating a comprehensive and accurate simulation. Noteworthy is the sub-optimal quality of the OSM maps, particularly in terms of pedestrian path delineation, which required significant adjustments. While machine-readable maps like those from OSM are a valuable resource, they often contain inaccuracies in mapping, traffic rules, and transportation allowances. This necessitates additional efforts to make such data useful. The accuracy of pedestrian distribution models is limited by the availability of real-time data, and simulation environments may not capture all the nuances of real-world interactions. Although pedestrian occupancy on specific streets can be determined, the distribution of pedestrians across the city remains problematic, complicating the validation of resulting traffic flows. In addition, modifications to CARLA are required to allow pedestrians and robots to navigate freely in the streets. The modeling of pedestrian movement presents its own set of challenges; while tools like SUMO are not ideal, alternatives such as INCONTROL Pedestrian Dynamics [21] have also proven inadequate for complex geographies. The integration of JuPedSim [22] into SUMO provides more realistic pedestrian dynamics but also has limitations regarding the geographies and is considered for future development. Simplified interaction modeling further limits the accuracy of the simulation. Despite these challenges, the project made significant progress in creating a reliable framework for urban traffic and logistics modeling.

## 4. Conclusion and Outlook

In conclusion, this study presents a robust framework for modeling urban traffic and logistics demands to facilitate the deployment of autonomous delivery robots in urban environments. By integrating survey results, pedestrian simulations, and AGV interaction modeling, we have developed a comprehensive approach that addresses the unique challenges of last-mile delivery in city centers.Through this incorporation of real world data, the presented framework allows for more realistic simulation of AGVs in a micrologistics role. With minor modifications the processing of a variety of classical problems, namely the Vehicle Routing Problem, can be achieved. Despite the significant progress, several challenges remain. However, the potential for future research and application is substantial. Our framework can be adapted and applied to other cities worldwide that share similar urban structures and logistical challenges. Cities with extensive pedestrian zones and high delivery demands, such as Freiburg, Hanover, Heidelberg, Ulm, Mainz, Magdeburg, Stuttgart, Bonn, and Düsseldorf in Germany, as well as international cities could benefit from our models and simulation software. Future work should focus on enhancing data accuracy by incorporating more real-world data and refining simulation parameters. Collaborations with industry and policymakers will be essential to ensure the practical applicability of our framework. Continued development of real-time data integration and practical testing will further improve the efficiency and reliability of autonomous delivery systems. The next steps involve a detailed analysis of survey results and comprehensive simulations to fine-tune our models. The ultimate goal is to create a scalable and adaptable framework that addresses the logistics challenges of urban environments worldwide, contributing to cleaner, more efficient, and more livable cities. Accurate data and models are critical to overcoming the challenges of urban freight transportation. Our study lays the groundwork for future research and practical implementations, paving the way for advanced micrologistics systems in urban settings.

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