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Daily Real-time System for Assessing Urban Traffic Emissions Equilibrium Using IoT Data

Master's Thesis (30 ECTS)

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Abstract:

Global warming, driven by escalating greenhouse gas (GHG) emissions, is one of the most critical environmental issues facing the world today. One promising strategy for mitigating global warming and its associated impacts is the integration of green spaces within cities. This thesis aims to explore the critical relationship between street-level emissions and the presence of green areas in urban environments. By monitoring emissions at the street level and assessing the carbon sequestration potential of urban green spaces, we seek to understand how effectively green spaces can mitigate the impacts of urban pollution. The thesis underscores the necessity for real-time monitoring systems that provide actionable insights for urban planners and policymakers to optimize green infrastructure and reduce urban pollution impacts. The findings emphasize the role of urban greening in creating healthier cities better equipped to handle environmental challenges.

Keywords:
Global warming, street level emissions, monitor street level emission, carbon sink, tartu city

CERCS: P170, Computer science, numerical analysis, systems, control

Igapäevane reaalajas toimiv süsteem hindamiseks Linnaliikluse heitkoguste tasakaalustamine kasutades asjade interneti andmeid

Lühikokkuvõte:

Ülemaailmne soojenemine, mille põhjuseks on kasvuhoonegaaside (KHG) heitkoguste suurenemine, on üks kriitilisemaid keskkonnaprobleeme, millega maailm praegu silmitsi seisab. Üks paljulubav strateegia globaalse soojenemise ja sellega seotud mõjude leevendamiseks on haljasalade integreerimine linnadesse. Käesoleva doktoritöö eesmärk on uurida kriitilist seost tänavapõhiste heitkoguste ja haljasalade olemasolu vahel linnakeskkonnas. Jälgides heitkoguseid tänavate tasandil ja hinnates linna haljasalade süsinikdioksiidi sidumise potentsiaali, püüame mõista, kui tõhusalt saavad haljasalad leevendada linnasaaste mõju. Doktoritöö rõhutab vajadust reaalajas toimivate seiresüsteemide järele, mis annavad linnaplaneerijatele ja poliitikakujundajatele rakendatavaid teadmisi, et optimeerida rohelist infrastruktuuri ja vähendada linnasaaste mõju. Tulemused rõhutavad linnade haljastuse rolli tervislikumate linnade loomisel, mis on paremini valmis keskkonnaprobleemidega toime tulema.

Võtmesõnad:
Globaalne soojenemine, tänavatasandi heitkogused, tänavatasandi heitkoguste seire, süsiniku sidumine, tartu linna areng, tartu arukas linn

CERCS: P170, Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine (automaatjuhtimisteooria)

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Contents

1 Introduction

Global warming, driven by escalating greenhouse gas (GHG) emissions, is one of the most critical environmental issues facing the world today. The increasing concentration of carbon dioxide (CO_2) and other GHGs in the atmosphere leads to higher global temperatures, resulting in a host of detrimental effects on the environment and human health. As urbanization accelerates, cities become significant contributors to GHG emissions, primarily from transportation, industry, and energy use. Consequently, monitoring and controlling street-level emissions in urban areas is imperative for mitigating global warming and its associated impacts.

Street-level emissions, including carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM), originate from various sources such as vehicular traffic, industrial activities, and residential heating. These pollutants not only contribute to global warming but also pose serious health risks, including respiratory and cardiovascular diseases, which are exacerbated in densely populated urban areas. One promising strategy for mitigating urban emissions and enhancing environmental quality is the integration of green spaces within cities. Urban green areas, including parks, gardens and street trees, play a vital role in carbon sequestration, the process by which trees and plants absorb CO_2 from the atmosphere and store it as biomass. This natural mechanism helps offset a portion of the emissions generated in urban settings, providing both environmental and health benefits.

This thesis aims to explore the critical relationship between street-level emissions and the presence of green areas in urban environments. By monitoring emissions at the street level and assessing the carbon sequestration potential of urban green spaces, we seek to understand how effectively green areas can mitigate the impacts of urban pollution. Furthermore, the report will highlight the importance of urban planning and policy interventions in promoting green infrastructure to enhance carbon sequestration and improve air quality.

Through a comprehensive analysis of street-level emission data and the role of green spaces, this report will provide valuable insights into the benefits of urban greening as a tool for combating global warming. The findings will underscore the necessity of incorporating green areas in urban planning to create healthier and more sustainable cities that can better cope with the challenges posed by climate change.

1.1 Research goals

The objective is to develop and implement a real-time, IoT-based system that monitors and visualises urban traffic emissions, as well as evaluating the carbon sequestration potential of urban green spaces. The system's objective is to furnish actionable insights for urban planners and policymakers, enabling the optimisation of green infrastructure, enhancement of carbon sequestration, and reduction of the impact of urban pollution on climate change.

This objective places a premium on the integration of real-time data monitoring and visualisation, thus hoping to support urban planning and policy-making, while underscoring the significance of green spaces in the reduction of emissions and the combating of global warming.

- **RG1:** Understanding the importance of green space in urbanization.
- **RG2:** Identify effective ways to calculate carbon sequestration.

1.2 Road map

The road map of this thesis report is organised as follows:

- **Chapter 2: State of art.** This chapter offers an overview of existing research, work, and tools in order to provide context for the thesis research goals.
- **Chapter 3: Methodology.** This chapter chapter is the core of the thesis and gives detailed explanation about the system architecture and the data collection source. The subsection workflow gives a detailed explanation about how various modules work and are connected to each other.
- **Chapter 4: Results.** In this chapter, the results achieved in the previous chapter is analysed and discussed.

2 State of art

This thesis is comprised of two principal sections. The first section is concerned with the estimation of emissions from road traffic, while the second section is dedicated to an analysis of the relationship between photosynthesis and carbon sequestration in urban areas.

This chapter presents an overview of existing methodologies and tools for achieving this objective.

2.1 Emission monitoring tools

As mentioned in [MB01], traditionally, there are 4 categories of monitoring tools:

- Passive sampling
- Active sampling
- Automatic or continuous
- Remote sensing

Passive sampling employs diffusion tubes to quantify long-term pollution trends. The tubes are typically exposed for a period of one week or one month, after which the collected samples are subjected to laboratory analysis. [MB01]. In contrast, active sampling utilises sensors to quantify short-term pollution. This approach is frequently employed in studies that necessitate precise measurements of air quality over a defined time interval [MB01]. Continuous monitoring represents a more real-time approach, whereby sensors are automated. These systems are located at a fixed location and are capable of measuring multiple pollutants simultaneously [MB01]. Remote sensing technique uses optical methods to measure emissions from vehicles without direct contact. This category encompasses techniques such as laser-induced fluorescence and infrared spectroscopy, which can be employed to assess the concentration of pollutants in vehicle exhaust as it passes by [MB01].

The principal disadvantage of these conventional techniques for measuring traffic-related pollution is the infrastructure that is required. Furthermore, it is challenging to plan a city when the aforementioned systems cannot be modified in accordance with the desired outcomes and different scenarios can not be analysed.

Emission inventories are of paramount importance for the assessment and simulation of air quality, as well as for the evaluation of policy decisions in air quality management. The development of these inventories may be conducted manually or through the utilisation of computer-based vehicular emission models [ENBA14]. According to [ENBA14], the type of computer based models are Static model and Dynamic model.

Static models, also referred to as top-down or macroscale models, estimate emissions on a broad scale without the necessity for detailed data on specific sources. Such models generate emission rates and fuel consumption factors based on large-scale activities, such as transport productivity or vehicle-kilometres travelled (VKT). While these models are useful for large-scale projects and national inventories, they lack the detailed accuracy required for comparing different transportation scenarios. Dynamic models, also known as bottom-up or micro-scale models, utilise detailed micro-level data, including instantaneous vehicle and fuel combustion rates under a range of driving conditions. Such models offer superior accuracy and resolution, rendering them well-suited to the evaluation of dynamic traffic operations and urban-scale inventories. Some examples of dynamic emission models are PHEM and HBEFA. In contrast, static models are beneficial for comprehensive, large-scale planning and national inventories, whereas dynamic models provide precise, detailed emissions assessments for specific scenarios and urban environments [ENBA14].

2.2 i-Tree tools

As outlined in [Now21], the i-Tree suite comprises a collection of software applications. These have been developed with the objective of assessing and valuing urban forest resources, understanding forest risks, and developing sustainable management plans. Below is an overview of the i-Tree tools, their functions, and their significance. i-Tree is a collaborative initiative that provides a range of tools to assist communities and organisations in the effective management of urban forests. The tools facilitate the quantification of the benefits provided by trees, including improvements in air quality, carbon sequestration, and energy savings. 4 of the key components of i-Tree tools are mentioned below:

- i-Tree Eco
- i-Tree Canopy
- i-Tree Landscape
- i-Tree Hydro

The Eco i-tree tool is a comprehensive assessment tool that evaluates the structural integrity and environmental benefits of urban trees. It quantifies the ecosystem services that trees provide, including the removal of air pollution, carbon storage, and energy conservation. The assessment is comprised of a number of key components, which are outlined below in reference to [Now21]. The tree inventory component enables the user to input data pertaining to individual trees or to undertake a comprehensive inventory of a specified area. The data typically comprises the identification of the species, the diameter at breast height, the height, and the dimensions of the crown. Furthermore, the composition of the forest is also considered. The tool analyses species diversity and composition, thereby providing insights into the overall health and resilience of the urban forest. The tool is capable of calculating a number of metrics, including species richness and the importance value of various species. Ecosystem Services: i-Tree Eco assesses the provision of ecosystem services by trees, including improvements to air quality, carbon sequestration, stormwater management, and energy savings. Moreover, the software estimates the monetary value of these services, which can be pivotal for urban planning and policy-making. Data Integration: The software integrates local meteorological and pollution data to enhance the accuracy of its assessments. This allows for a comprehensive analysis of how trees interact with their environment [Now21].

i-Tree Canopy [Now21] is a free, web-based application that enables users to readily and precisely ascertain land cover types, including tree canopy, impervious surfaces, and other cover classes, within a specified area. The tool employs the use of aerial imagery sourced from Google Maps to generate a random series of points over the specified area of interest. Subsequently, the user is required to assign each point to a pre-defined land cover category, such as "Tree" or "Grass/Herbaceous" [Now21]. As the number of classified points increases, the tool provides statistical estimates of the percentage of each cover type and the associated standard error. The data may be employed to establish canopy objectives, monitor progress over time, and estimate inputs for other i-Tree tools, such as i-Tree Hydro. i-Tree Canopy is particularly useful for communities seeking to assess their current tree canopy cover, set goals for increasing canopy, and monitor progress over time. It offers a cost-effective and efficient method for gathering land cover data, eliminating the need for extensive field surveys [Now21]. [Mal24] demonstrates a city-wide Urban Tree Cover (UTC) assessment conducted in Edirne using web-based online tools and high-resolution aerial photographs with a random sampling method. The analysis covered 445 ha and found that UTC in the 15 neighbourhoods of Merkez district decreased from 17.71% in 2005 to 13.41% in 2023, a decrease of 4.41%. Over the same period, impervious surfaces increased from 56.81% to 74.63%, an increase of 79.31 hectares [Mal24]. The study highlighted the effectiveness of using web-based GIS tools such as i-Tree Canopy and Google Earth Pro for cost-effective, rapid and reliable land cover and UTC assessments.

The i-Tree Landscape [Now21] tool facilitates the analysis and visualisation of tree canopy cover and other land cover types at a broader scale, encompassing neighbourhoods, municipalities, or entire regions. This tool integrates data from a variety of sources, including satellite imagery and local land use data, in order to provide a comprehensive understanding of urban forest resources [Now21]. The tool enables the assessment of a range of land cover types, including tree canopy, impervious surfaces, and grasslands.This facilitates comprehension of the distribution and extent of urban forests. Furthermore, the tool estimates the ecosystem services provided by tree cover, including carbon sequestration, air quality improvement, and stormwater management. Such quantification can prove invaluable for urban planning and policy-making [Now21]. Additionally, [Now21] also mentions that the tool is capable of incorporating a variety of datasets, including census data and environmental metrics, thereby facilitating a multi-faceted analysis of the impact of urban forestry on community health and well-being.

i-Tree Hydro is a flexible, stand-alone desktop application that simulates the impact of changes in urban tree cover and impervious surfaces on the hydrological cycle, including streamflow and water quality [Now21]. Developed by the USDA Forest Service [Now21], this tool is particularly valuable for urban planners and natural resource managers who seek to quantify the impact of vegetation on local hydrology.

The i-Tree tools are limited by the necessity for extensive data collection in order to achieve accurate assessments, which can prove challenging for some users. Furthermore, although the tools are user-friendly, they may still require a learning curve for those unfamiliar with ecological modelling. The effectiveness of these tools can also vary based on local conditions and species, necessitating localised adjustments in methodology. [Now21].

2.3 Carbon sequestration and urban green spaces

The process of urbanisation has a significant impact on greenhouse gas emissions, primarily due to increased energy consumption, transportation, and industrial activities. As urban areas expand, they become significant sources of carbon dioxide (CO_2) emissions, which contribute to the greenhouse effect and climate change. The process of urbanisation, which represents a pivotal aspect of societal development, is projected to exceed 60% globally by 2030 [Nat18]. This trend requires the implementation of effective strategies to reduce urban carbon emissions and enhance carbon sequestration [WFA23]. Carbon sequestration is the process of capturing and storing atmospheric (CO_2) in order to mitigate climate change. It plays a crucial role in reducing the amount of CO_2 in the atmosphere, which is a significant contributor to global warming.

There are two primary types of carbon sequestration: biological and geological. Biological carbon sequestration, also referred to as biosequestration, represents a natural phenomenon within the broader context of the carbon cycle. It encompasses the process of CO_2 absorption by plants, soils, and oceans. Whereas, the process of geological carbon sequestration entails the capture of CO_2 from industrial sources, including power plants and manufacturing facilities, and its subsequent injection into underground geological formations for long-term storage.

The role of urban vegetation, including forests and green spaces, in this process is of great importance. These areas act as carbon sinks through the process of photosynthesis, which sequesters and stores CO_2 [HYA11] [Lal12]. The efficacy of carbon sequestration in urban green spaces is dependent on a multitude of factors, including the structure of the plant community, the condition of the soil, and the implementation of management practices [WFA23]. The presence of dense vegetation and the maintenance of healthy soils are indispensable for the optimal enhancement of carbon storage capacity [WFA23]. Microbial activity within the soil is also a pivotal factor in carbon storage within urban green spaces [Bur24].

Despite the relatively modest extent of urban green spaces compared to the general urban area, they make a substantial contribution to the carbon balance at both the urban and global levels [ZSQ19] [WFA23].

2.4 Relationship between street emissions, carbon sequestration by nearby urban green spaces

It is imperative that urban planning incorporates the provision of essential infrastructure. However, in light of the alarming rates of global warming, it is of paramount importance to incorporate urban green spaces into urban planning in order to achieve a balance in greenhouse gas levels in the atmosphere [LFX24]. Street emissions, primarily from vehicles, contribute substantially to urban air pollution, including carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter (PM). The presence of urban green spaces, such as parks and tree-lined streets, has been demonstrated to mitigate pollutants through a range of mechanisms. These include carbon sequestration, whereby trees and plants absorb CO_2 during photosynthesis and store it as biomass and in the soil [FWH$^+$23], and pollutant filtration, whereby vegetation traps particulate matter on leaves and bark, thereby reducing airborne pollutant concentrations [LFX24].

There is currently no single, universally accepted mathematical model for calculating the absorption of CO_2 by urban green areas. In lieu of a unified methodology, a variety of approaches and models are employed, contingent upon the specific context and available data. In order to estimate carbon storage and annual sequestration rates by urban forests, tools such as i-Tree Eco are commonly employed, utilising detailed field data and local environmental conditions [SRD$^+$23]. Simplified models may employ factors such as the total area of green space and an average CO_2 absorption rate per unit area to provide approximate estimates as shown in equation 1 [BKKY22] [PMKD14] [ZCX$^+$23].

$$A_{\mathrm{g}} = AXR_{\mathrm{a}} \tag{1}$$

Where A_g is the CO_2 absorption by urban green areas, A is the total area of green space and R_a is the average CO_2 absorption rate per unit area of green space (grams of CO_2 per square meter per day).

More complex models incorporate additional variables, such as tree species, age, size (measured by diameter at breast height), and specific local environmental conditions, in order to enhance the accuracy of the results [LL12]. [MBB17] shows leaf level gas

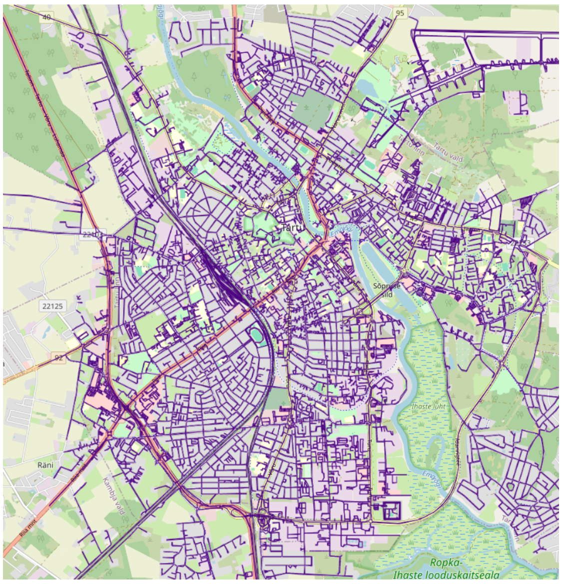


Figure 1. Tartu Road Network

exchange model. The equation to calculate CO_2 absorption rate (μmol m^{-2} s^{-1}) can be seen below:

$$A_{\mathrm{n}} = g_{\mathrm{c}}(C_{\mathrm{a}} - C_{\mathrm{i}}) \tag{2}$$

Where A_n is biochemical model of photosynthesis, g_c is the stomatal conductance, C_a is the CO_2 around the leaf and C_i is the CO_2 inside the leaf.

Ongoing research aims to develop more precise and comprehensive models that account for different types of vegetation and urban conditions [ZSG^+22]. Additionally, some researchers are focusing on optimisation models to determine the ideal amount and configuration of green spaces required to effectively absorb CO_2 emissions in urban areas [ZCX^+23].

3 Methodology

3.1 System Architecture

This chapter sets out the detailed methodology adopted in pursuit of the thesis's stated goal. Our work is built as an extension to that set out in [KPH$^+$22]. It is therefore important to provide some background to system and architecture of the project before setting out the current methodology.

3.1.1 Background

[KPH$^+$22] presents a real-time system for estimating daily modal split and generating origin-destination (OD) matrices using Internet of Things (IoT) data in the city of Tartu, Estonia. The research employs an integrated, data-driven approach to model trip-based mobility within the urban environment.

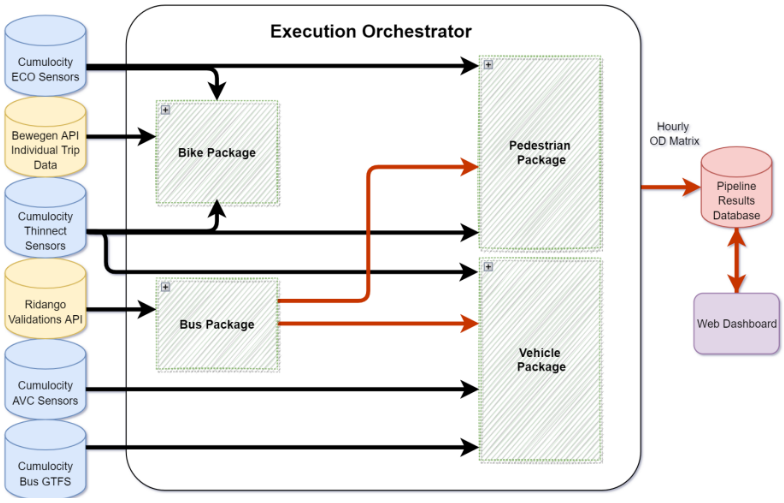


Figure 2. Real-Time System for Daily Modal Split Estimation and OD Matrices Generation Using IoT Data: System architecture [KPH$^+$22]

The system estimates the modal split for different transportation modes in Tartu, including bicycles, buses, vehicles, and pedestrians. The researchers compared their modal split estimation results with field counts, revealing some variations. With regard to bicycles, the field count was 1.2% compared to an estimated 1.1%. In the case of pedestrians, the field count was 23.6% versus an estimated 38.9%. With respect to vehicles, the field count was 75.1% compared to an estimated 59.9%. The real-time system provides daily updates on modal split and OD matrices, offering timely insights into urban mobility patterns. Figure 2 shows the system architecture of their platform. It consists of two primary components: The data analysis pipeline and the web dashboard.

The data analysis pipeline extracts detailed data from various modality-specific sources such as the bus ticket validation information system, Cumulocity ECO sensors, thinnect etc. This raw data is then analyzed to generate hourly and district-level trip estimates for the entire city, presented as an OD matrix for each of the four transport modes within one-hour intervals.

The web dashboard presents a graphical representation of the results within the context of a web application, facilitating interactive visualisation and browsing. Furthermore, the dashboard provides additional aggregation functionalities, such as the presentation of results from a 24-hour period based on the hourly pipeline outputs.

The two blocks are linked by persistent storage to an SQL database for post-evaluation and troubleshooting. The pipeline is scheduled to execute automatically once every 24 h to analyse the previous day's information and store the results into the SQL database, thus making them available to the web dashboard. The system's pipeline involves four packages for each transport modality and an execution orchestrator. The orchestrator ensures the execution of individual packages in a specified order and manages the re-execution of packages that produce failures. If a package's input relies on the output of another package (for instance, the vehicle package depending on the bus package's results), the execution orchestrator makes sure the required packages are completed beforehand.

Vehicle package: Cities use traffic counters to monitor traffic volumes, but these only sample the overall traffic dynamics. To accurately estimate vehicle movements, the Simulation of Urban Mobility (SUMO) is used. SUMO is an open-source traffic simulator that bridges the gap between limited sensor data and real traffic flow. By calibrating with real counts, SUMO provides realistic traffic simulations. In Tartu, AVC sensors at the city limits and Thinnect sensors within the city help to collect comprehensive traffic data. The process involves using Open Street Map data for regional mapping and initialising simulations with a 24-hour trip set. Inputs include bus trip data and AVC sensor data calibrated using the Cadyts dynamic traffic assignment tool.The architecture of the vehicle package in [KPH$^+$22] can be seen in figure 3.

In this thesis we use the same system architecture and use the data generated by [KPH$^+$22] and extend as shown in Figure 4 it to include emission monitoring and find the effect of green areas in the city of Tartu on street level emissions. The green boxes in Figure 4 indicates that those are the modules those were updated in the process of adding the new features.

3.2 Data sources

The data sources can be categorized into 2 types: Dynamic and static. In this context, "dynamic sources" represent stream data that are fetched on-demand from sensors each

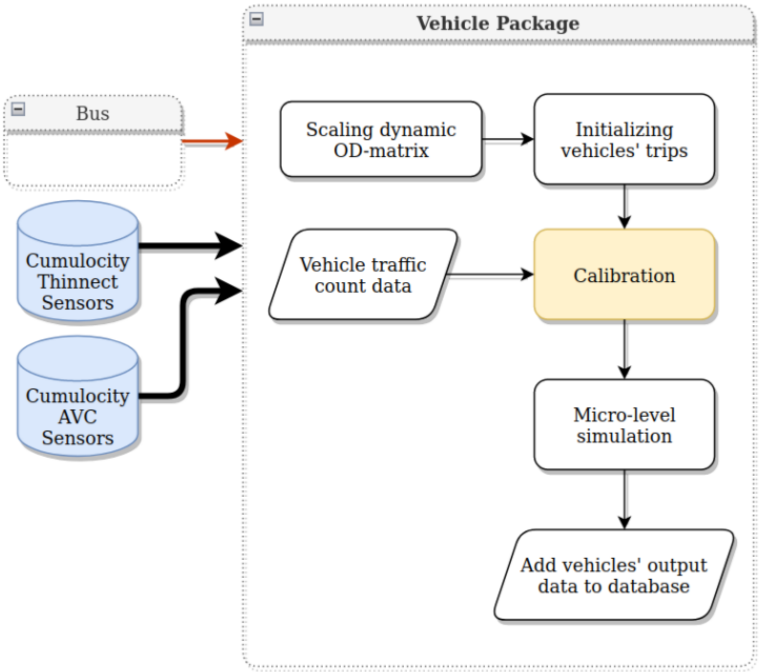


Figure 3. Real-Time System for Daily Modal Split Estimation and OD Matrices Generation Using IoT Data: Vehicle Package [KPH+22]

time the pipeline is run. In contrast, "static data" refers to data that are expected to change infrequently; examples of this would include the geodata regarding the green areas in the Tartu city.

3.2.1 Dynamic source

A dynamic source is something that is not static and requires to be fetched more often. In our case a dynamic data can be the data coming from thinnect and AVC sensors. This data is which is used to calibrate our simulation to generate the real world scenario and therefore is required to be collected everyday.

3.2.2 Static source

Our system design utilizes two sets of static data. The first set is a file that represents the geographic shapes and borders of the districts, which is used to identify the origin and destination of trips within each district, and includes an assigned identifier code for each district. The second set consists of a mapping of City Bike stations to the respective districts.

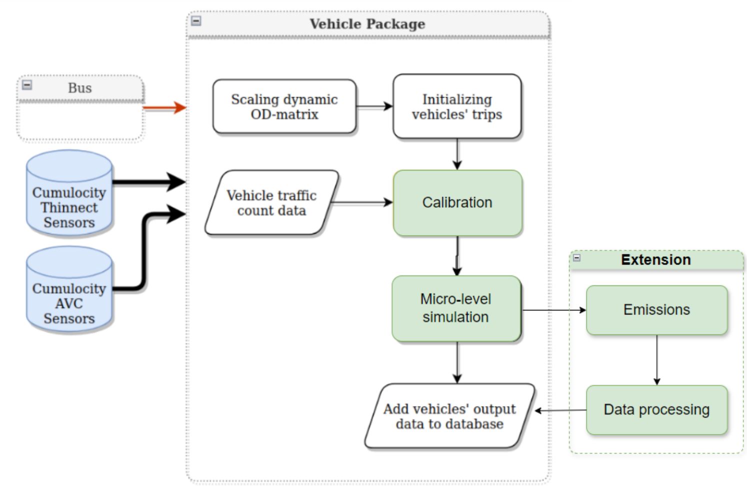


Figure 4. Architecture: Vehicle package extension

3.3 Workflow

This thesis presents an extension to the vehicles package, which includes the calibration step for estimating emissions for each trip and the recording of edge-wise fuel consumption and emissions of CO_2, NO_x, PMx and CO. In the context of a model street network, an edge represents a road segment. The recorded value represents the average for that road segment in a specific simulation step. Following the recording of emissions and fuel consumption, the output is cleaned and converted into JSON format for storage in the DB, where it can be accessed by the front end for visualisation purposes. The JSON format of the output contains a mapping of road segment and total hourly emission for the entire simulation. The simulation generates data for a full 24-hour period.The web dashboard has been extended with a further tab for the purpose of visualising street-level emissions and gaining an understanding of the street-level hourly emissions. It utilises the recorded data from the database.

Subsequently, the next phase of the project will commence. In this phase, the focus is on the green space surrounding the network, and the potential impact of this green area on road-level emissions. The initial objective was to extract all green areas and categorise them according to their type, such as forest, shrubs, grass, and so forth. Subsequently, the surrounding area affected by these green areas was identified. To ascertain the impact of green areas on nearby street-level emissions, the primary task was to determine the affected road segments.

3.3.1 Vehicle package extension

The vehicle package of [KPH$^+$22] runs calibrated simulation, as introduced in section 3.1.1. To establish SUMO for the purpose of traffic simulation, we initiated the process by creating or importing the road network and defining the traffic demand. This entailed the specification of routes, vehicle types, and traffic volumes. Subsequently, Cadyts was employed to calibrate the SUMO simulation. This involved importing real-world traffic data, collected by Cumulocity thinnect sensors and AVC sensors, into Cadyts and running iterative calibration to adjust the simulation parameters. This process was undertaken in order to ensure that the simulated traffic flows closely matched the observed data.

The vehicle package is extended futher to record the trip emissions. In order to incorporate emissions modelling into SUMO, it is necessary to select an appropriate emissions model from the pre-existing options. These include the Passenger Car and Heavy-Duty Emission Model (PHEMlight) and the Handbook Emission Factors for Road Transport (HBEFA) model. In the course of our research, we employed the default emissions model, designated HBEFA3/PC_G_EU4. This model represents a gasoline-powered Euro norm 4 passenger car, constructed using the HBEFA3-based model.

The SUMO simulation is conducted in discrete steps, with each step representing one second in the real world. Cadyts provide an output for each aggregation period, with the default period set at 900 steps. The generated data is in XML format. The XML output comprises two types: firstly, there is the general average edge data, including density, waiting time, and so forth; secondly, there is the eco data, which contains all the total and average emissions output for each edge. This report is recorded for each aggregation period. The final iteration of calibration is taken because that signifies the most converged towards equilibrium. Hence, the output of the final iteration is taken for further processing.

Data processing Given the rawness of the data, it is of the utmost importance to ensure that the data processing is carried out effectively. As previously stated, the data is aggregated for each period. The initial stage of the data processing procedure is to extract the hourly total emissions for each edge or road segment by grouping the data in an appropriate manner. The data was grouped by edge and interval, with one interval representing 900 steps. As one step in simulation indicates one second in the real world, an interval of 900 steps represents 900 seconds in the real world. This means that four intervals represent one hour. To obtain hourly emissions, the end interval was considered as the time of data recording and converted into hours.

Furthermore, a linear colour map was created to assign a distinct colour to each edge based on the total emission for each emission type. The final output of data processing is a dictionary in which each edge represents a key and the respective value is an object comprising all data related to that edge, including geometry, hourly emissions, the name of the street, and so forth.

3.3.2 Emissions and green area

The next part of the thesis is to build a naive model to determine the carbon absorption by the urban green area in the city of Tartu. Urban area comprises of variety of green areas such as parks, gardens, scrubs, etc. Tartu, Estonia's second-largest city, effectively integrates diverse green spaces, including extensive parks, urban forests, riverside areas, and green infrastructure, into its urban landscape, proving it to be the best fit to analyse the effect of different types green area on carbon dioxide removal.

Carbon dioxide is a critical greenhouse gas that significantly contributes to global warming. It traps heat in the Earth's atmosphere, leading to the greenhouse effect, which causes the planet's average temperature to rise. Human activities, particularly the burning of fossil fuels in vehicles, power plants, and industries, have dramatically increased CO2 levels in the atmosphere. This accumulation of CO2 is the primary driver of climate change, making it essential to manage and reduce emissions. Green areas in urban cities are crucial in this effort, as they act as natural carbon sinks, absorbing CO2 from the atmosphere and mitigating the impact of vehicle emissions and other urban sources of pollution. By integrating green spaces into city planning, urban areas can play a significant role in combating global warming while improving air quality and overall environmental health.

The SUMO simulation in the previous step of workflow generates the emissions for each aggregated interval and in this module, we combine that data and carbon aborption rate for a green area to get the net emissions at that area. As seen in figure 5, the process commences with the extraction of green areas within Tartu City utilising OpenStreetMap data. This is followed by the calculation of the area of each green space in square metres (m^2). Subsequently, an hourly CO_2 absorption rate per square metre is assigned to each green area based on its type. This rate is then multiplied by the area to calculate the hourly carbon absorption. Thereafter, nearby road segments for each green area are identified, and total CO_2 emissions from these roads are calculated. Ultimately, net emissions are determined by subtracting the total carbon absorption from the total CO_2 emissions. Hourly calculations are aggregated to calculate the total values.

3.3.2.1 CO_2 absorption rate

The absorption rate is determined considering various factors like the green space type, what type of vegetation grow at that place, how old is a tree, etc. And example of detailed calculation of annual carbon sequestration by park can be seen in [SAH$^+$22]. [WCL21] suggests that choosing plant species with high carbon sequestration potential is crucial. This involves selecting species that are not only effective at storing carbon but also suitable for the local climate and soil conditions. Therefore, finding correct absorption

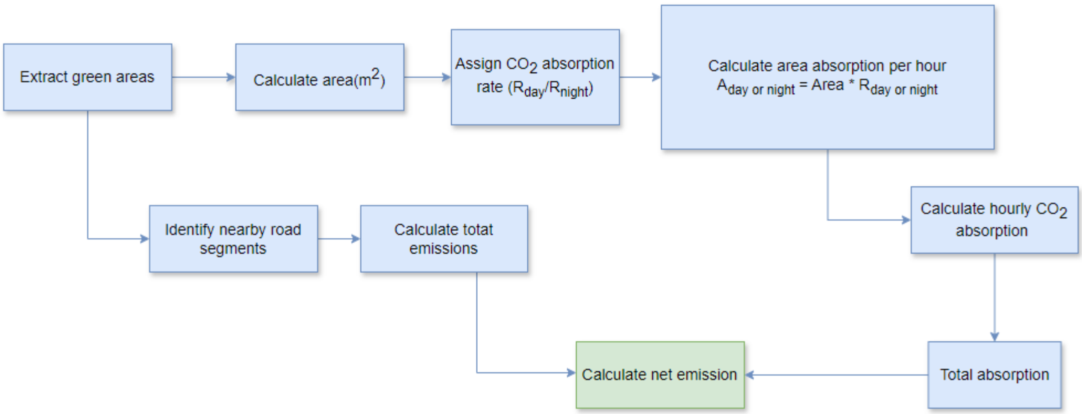


Figure 5. Emissions flow diagram

rate for a green space in a geographical area requires much higher knowledge about plant species, stomatal conductance, leaf level carbon storage capacity etc. In our study we didn't go so deep and concentrated in general average carbon absorption rate in mg m$_{-2}$ hour$_{-1}$ based on the green space type. Therefore, we combined various sources of research done on different countries to form the results shown in Figure 1.

Forests and wooded areas exhibit the highest CO_2 absorption rates among green spaces, ranging from 5 to 20 $\mu molm^{-2}s^{-1}$. This efficiency is attributed to the large trees with extensive leaf areas that facilitate photosynthesis. These areas are crucial for carbon sequestration due to their ability to absorb significant amounts of CO_2 [AOH+21] [Bea23] [HXC+23] [LSZ20].

Grasslands and meadows have moderate CO_2 absorption rates, typically between 1 to 5 $\mu molm^{-2}s^{-1}$ [TOB+24] [HXC+23] [LSZ20]. Although lower than forests, these areas are reliable carbon sinks over the long term, as they are resilient to environmental stresses such as droughts and fires. Their ability to maintain carbon sequestration under varying conditions makes them valuable in the context of climate change mitigation.

Urban parks and gardens show variable CO_2 absorption rates, generally ranging from 1 to 10 $\mu molm^{-2}s^{-1}$ [ANM+12] [HE08]. The absorption rate in these areas depends on plant types, maintenance practices, and overall green coverage. However, highly maintained parks with extensive lawns may have lower net sequestration due to emissions from maintenance activities [HE08] [HXC+23]. Cemeteries, which often include a mix of trees, shrubs, and grass, generally have CO_2 absorption rates similar to parks and gardens, ranging from 1 to 5 $\mu molm^{-2}s^{-1}$. While not as efficient as forests, they still contribute to urban carbon sequestration efforts. Overall, the CO2 absorption capabilities of these green spaces vary based on local conditions, vegetation types, and management practices, highlighting the importance of tailored strategies for maximizing their carbon sequestration potential [HXC+23] [LSZ20].

Farmlands typically absorb CO_2 at rates of 1 to 5 $\mu molm^{-2}s^{-1}$. These rates can fluctuate based on factors such as crop type, soil management practices, and seasonal changes. Effective agricultural practices can enhance the CO2 absorption capacity of farmland, contributing to overall carbon management strategies [Bea23] [HXC+23] [LSZ20].

Scrublands have relatively low CO_2 absorption rates, ranging from 0.5 to 2 $\mu molm^{-2}s^{-1}$ [Bea23]. In contrast, wetlands can absorb CO2 at higher rates, between 1 to 10 $\mu molm^{-2}s^{-1}$, due to complex interactions between plants and microbes that enhance carbon sequestration [LSZ20]. These ecosystems play a significant role in maintaining ecological balance and supporting biodiversity [Bea23] [HXC+23].

The process of photosynthesis requires the input of sunlight in order to facilitate the absorption of carbon dioxide and the generation of oxygen. Respiration occurs in a plant or tree in parallel with the processes occurring in other organisms. During the diurnal period, the rate of CO_2 absorption is significantly higher than the rate of CO_2 release as a by-product of respiration. Conversely, during nocturnal hours, the only flux present is that of CO_2 release, as evidenced by reference [VRT+13]. The precise rate of release varies according to the specific type of vegetation, local environmental conditions, and other factors. Forests and wetlands tend to exhibit a relatively lower net night-time CO_2 release compared to grasslands and urban green spaces. Nevertheless, they still contribute to night-time CO_2 emissions. As our analysis is limited to emissions from vehicles generated by simulations in the preceding step, we can effectively avoid the emissions generated by green areas at night. Therefore, the carbon absorption rate taken at night is 0 for all green space types.

Green space type	CO_2 Absorption Rate ($\mu molm^{-2}s^{-1}$)
Forest	5-20
Grassland	1-5
Meadow	1-5
Park	1-10
Garden	1-10
Farmland	1-5
Wood	5-20
Scrub	0.5-2
Wetland	1-10
Cemetery	1-5

Table 1. CO_2 absorption rates for every green space types identified in Tartu

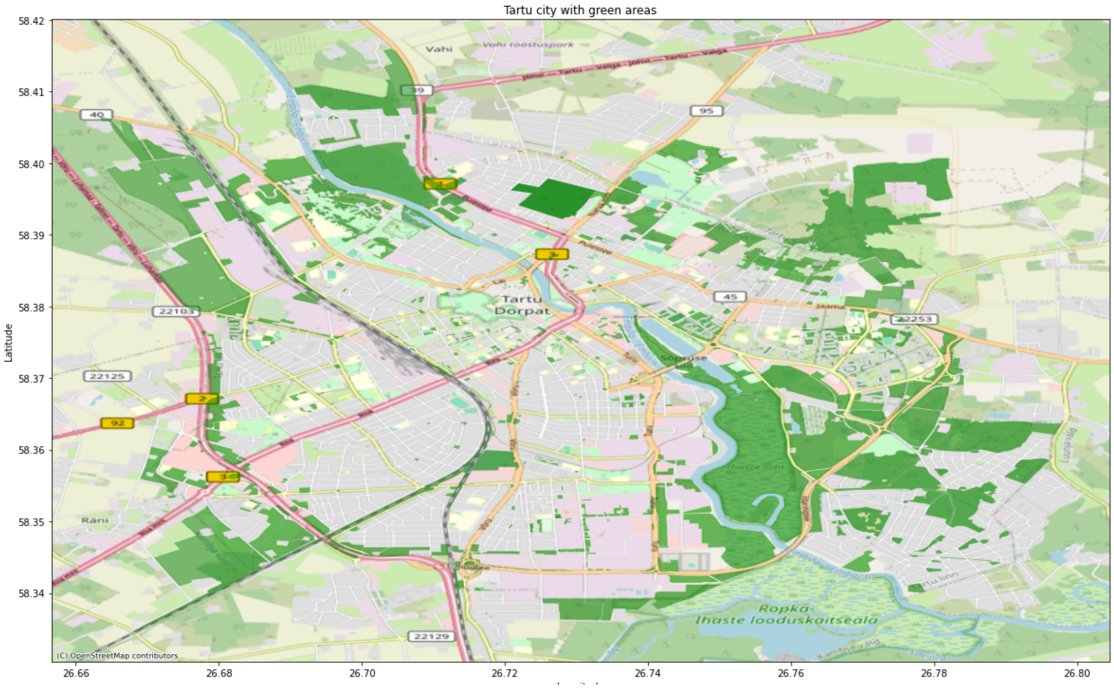


Figure 6. Urban green areas - Tartu

3.3.2.2 Identify nearby road segments

To calculate the total emissions, a green space was dealing with, it was important to identify the neighboring streets. The emissions from these streets are combined to get the total emission on which we want to observe the effect of respective green space carbon sink. According to [DM21], the impact of green areas on the environment can be considered at two distinct scales: a local scale, which encompasses an area of approximately 10 to 500 metres, and a regional scale, which extends over wider geographical areas. The latter is of particular relevance in urban contexts.

The green areas of Tartu city were extracted using OpenDtreetMap, as illustrated in Figure 6. Subsequently, the geometries of the aforementioned green areas were expanded in order to extract the neighbouring street. The expansion was conducted to encompass streets situated within an approximate 20-metre radius of the respective green space. Figure 7 illustrates the expanded area, which will henceforth be referred to as the "area of interest" (AOI). Subsequently, a straightforward intersection was employed to ascertain the nearest roads from the Tartu network data. The resulting visualisation is presented in Figure 8.

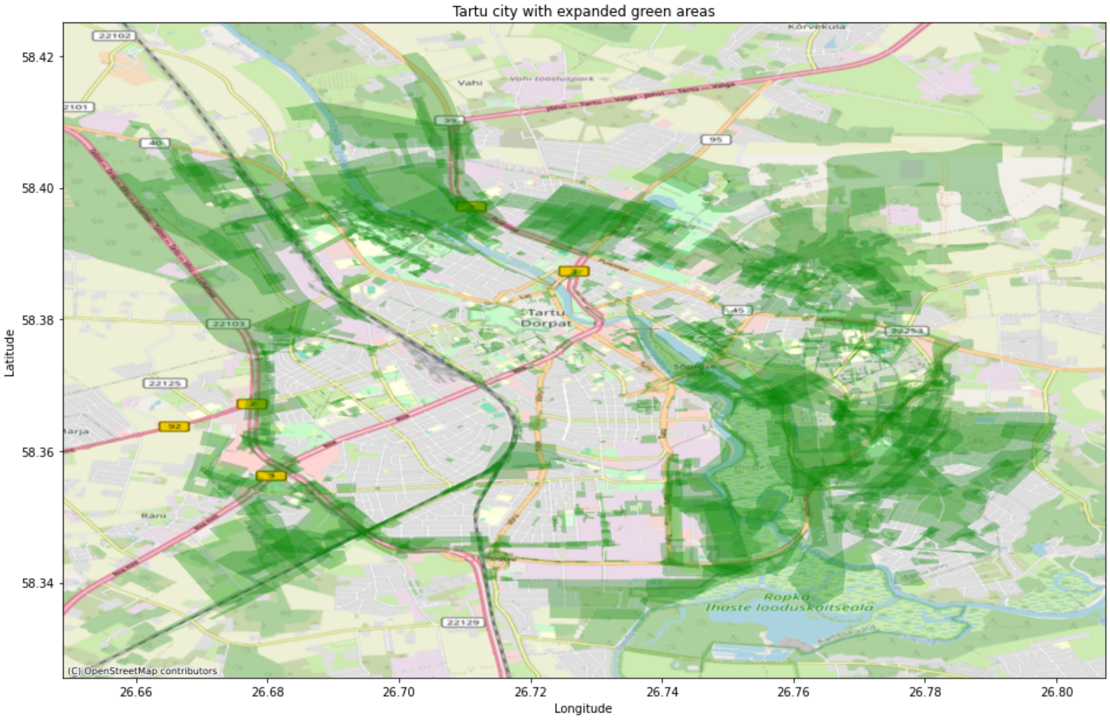


Figure 7. Tartu green areas expanded

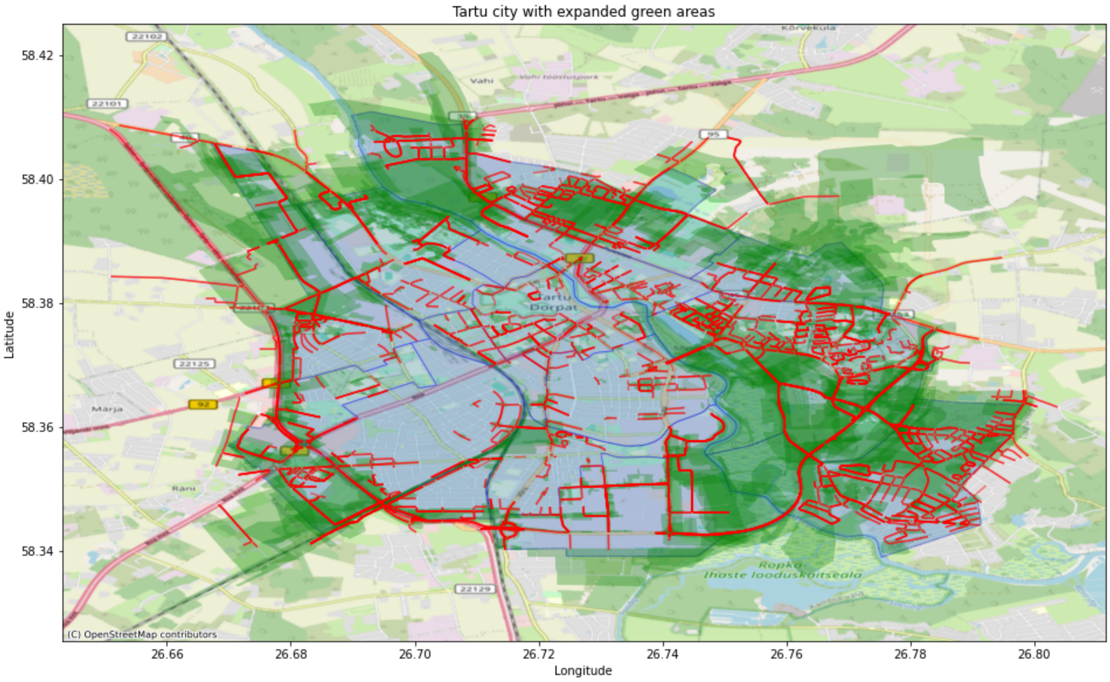


Figure 8. Roads near the green areas

3.3.2.3 Carbon sink calculation

Once the nearby roads had been identified and categorised according to their corresponding green space, the subsequent step was to calculate the total emissions. The emissions from all roads are then aggregated to obtain the total emissions for an AOI. Similarly, the total hourly emissions for an AOI are calculated by combining the hourly emissions from all road segments.

Subsequently, the carbon absorption rate, ascribed to each area of concern in the preceding steps, is utilised to calculate the hourly absorption for each area, in accordance with the equation referenced in section 2.4. For the purpose of calculating hourly absorption, the hours between 6 and 18 were assumed to correspond to daytime hours, while the remaining hours were considered to be hours with no sunlight. Equation 3 and 4 gives a clear picture of how the algorithm works.

$$A(h) = \begin{cases} \mathrm{A}_{\mathrm{day}} & : \mathrm{h} \geq 6, \mathrm{h} \leq 18 \\ \mathrm{A}_{\mathrm{night}} & : \mathrm{h} \leq 6, \mathrm{h} \geq 18 \end{cases} \tag{3}$$

where, A(h) is the hourly absorption. A_{day} is calculated the daytime hourly absorption for an area and A_{night} is the same for night.

$$A_{\mathrm{T}} = \sum_{h=0}^{23} A(h) \tag{4}$$

where, A_T is the total CO_2 absorption.

The next step is to calculate the net emissions. The net emission provides insight into the quantity of CO_2 that remains after all absorption processes have occurred. It is calculated by subtracting the calculated CO_2 absorption from the total emission associated with a given AOI. Equation 5 offers a representation of how aggregated net emission is calculated.

$$E_{\mathrm{net}} = \sum_{i=1}^{n} E_{\mathrm{n}} - A_{\mathrm{T}} \tag{5}$$

where, n is the number of nearby road segments around the AOI and E_n is the emission for each of those road segments.

3.3.3 Web dashboard

The web dashboard is a Node.js-based web application that provides a visual representation of the data that has been processed in the preceding steps. The system adheres to a three-tier architectural model, comprising a data layer, a back-end and a front-end. The SQL database serves as the data layer, storing all the cleaned and processed data, which is accessed by the back-end of the project. The back-end, or application layer,

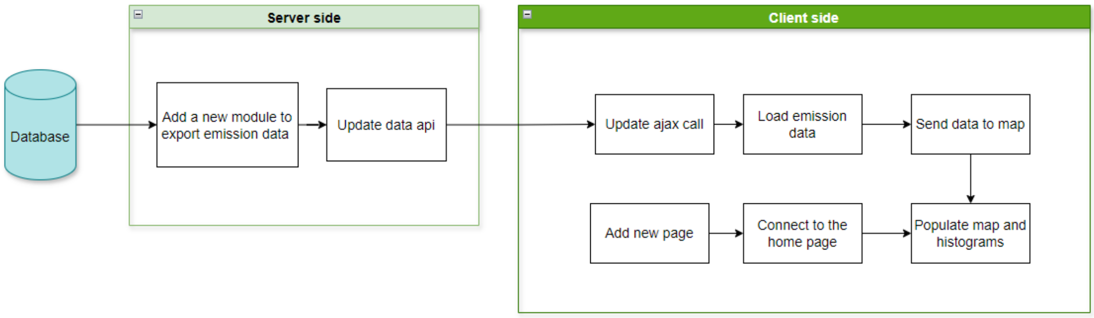


Figure 9. Updates done in Web dashboard project of [KPH$^+$22]

defines the business logic and provides endpoints to make data available for the front-end, or presentation layer. The presentation layer ultimately utilises the data and provides visualisation.

As aforementioned, my work is built as an extension of [KPH$^+$22], the web dashboard was also extended to add the emissions visualization as well. The updates on the Web dashboard project of [KPH$^+$22] can be seen in figure 9. The visualizations are analysed and discussed in the results section.

4 Results

4.1 Study Area

Tartu is the second-largest city in Estonia, covering a land area of 39 km² and a population of 97,435 as of 2023. The city is renowned for its verdant parks and extensive green spaces, with the Emajõgi River traversing Tartu and offering picturesque vistas and avenues for leisure pursuits. Our methodology was implemented in Tartu, with each green area considered a distinct spatial unit in our study.

The road network in Tartu is well developed, facilitating efficient transportation within the city and connecting it to other parts of Estonia and neighbouring countries. Figure 1 illustrates the road network of the city of Tartu.

Tartu is a city at the forefront of innovation and committed to smart city initiatives. It has deployed several IoT sensors throughout the city to collect and manage various traffic-related information. Our approach is grounded in a rigorous examination of vehicular traffic patterns and the analysis of street-level emissions. This methodology is detailed in the following sections.

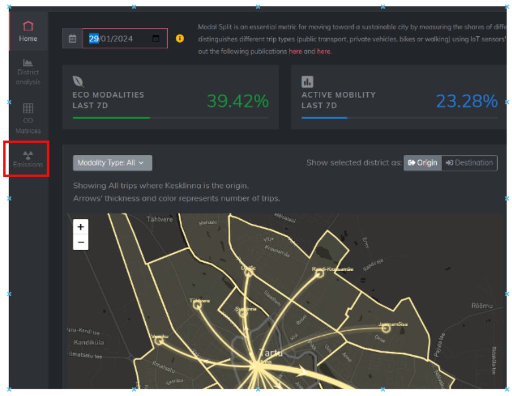
4.2 Assumptions

The carbon sequestration is a very complicated process and to simulate it fully, we need extra domain knowledge about properties of green house gases in atmosphere, content of troposphere, specie level knowledge about how Carbon dioxide is stored and the list is very big. Since, such things were out of our scope and we are interested in only a naive approach, we made assumptions. The assumptions are listed below:

- Only CO_2 emitted by the vehicles as a result of traffic simulation is considered to be the only source of CO_2 in the environment. The pre-existing atmospheric CO_2 and any other sources are ignored.
- The calculation of atmospheric CO_2 circulation from the troposphere to other layers, including the stratosphere, requires an understanding of air mass movement and the transport mechanisms that govern CO distribution. In our work, we considered an optimistic CO_2 dispersion scenario, in which CO_2 is assumed to be completely removed from the atmosphere every hour.

4.3 Monitoring emissions data

A new page has been incorporated into the [KPH$^+$22] project. Figure 10 shows a clear view of how the new page can be accessed from the existing dashboard.



29/01/2024

Modal Split is an essential metric for moving toward a sustainable city by measuring the shares of diffe
distinguishes different trip types (public transport, private vehicles, bikes or walking) using IoT sensors'
out the following publications here and here.

ECO MODALITIES LAST 7D 39.42%

ACTIVE MOBILITY LAST 7D 23.28%

Showing All trips where Kesklinna is the origin.
Arrows' thickness and color represents number of trips.

Figure 10. Entry point of new page from [KPH+22] dashboard

The data generated in the vehicle extension package is used as input here to create a dashboard to monitor it regularly. Figure 11 illustrates hoe the new emissions monitoring page looks like. The map on the left illustrates the average distribution of emissions in the road network of Tartu. The dropdown menu located in the top left corner of the interface allows the user to modify the emission types. On the botton-left of the graph we can see the legend with range of emissions in milligram(mg).

The hitograms on the right side of the dashboard show the hourly distribution of emission. The first histogram depicts emissions throughout the day at the city level, while the second graph presents an hourly image of emissions at the street level.

The dashboard presents visualisations of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PMx). Upon selection of a specific pollutant, the map and graphs are updated accordingly.

4.4 Carbon sink model result and analysis

The carbon sink model is where we used equations 3, 4 and 5, to calculate the net emission for respective AOI Tartu city. Using all the required data, the results were generated and plotted in various ways.

Figure 12 illustrates the carbon absorption, calculated in accordance with equation 1, for each area of vegetation type. The figure shows how the various areas absorb CO_2 in an hour. The green areas were classified and narrowed down into four categories based on their absorption rate. A comparison between the various vegetation types and their respective CO_2 absorption rates per hour can be made on the basis of the data presented in Figure 13.

A visual inspection of the figure reveals that the park has the highest capacity for carbon dioxide absorption. However, our previous study indicated that forests have the

Displays the street level emissions.
Arrows' thickness and color represents number of trips.

Figure 11. New dashboard for monitoring emissions

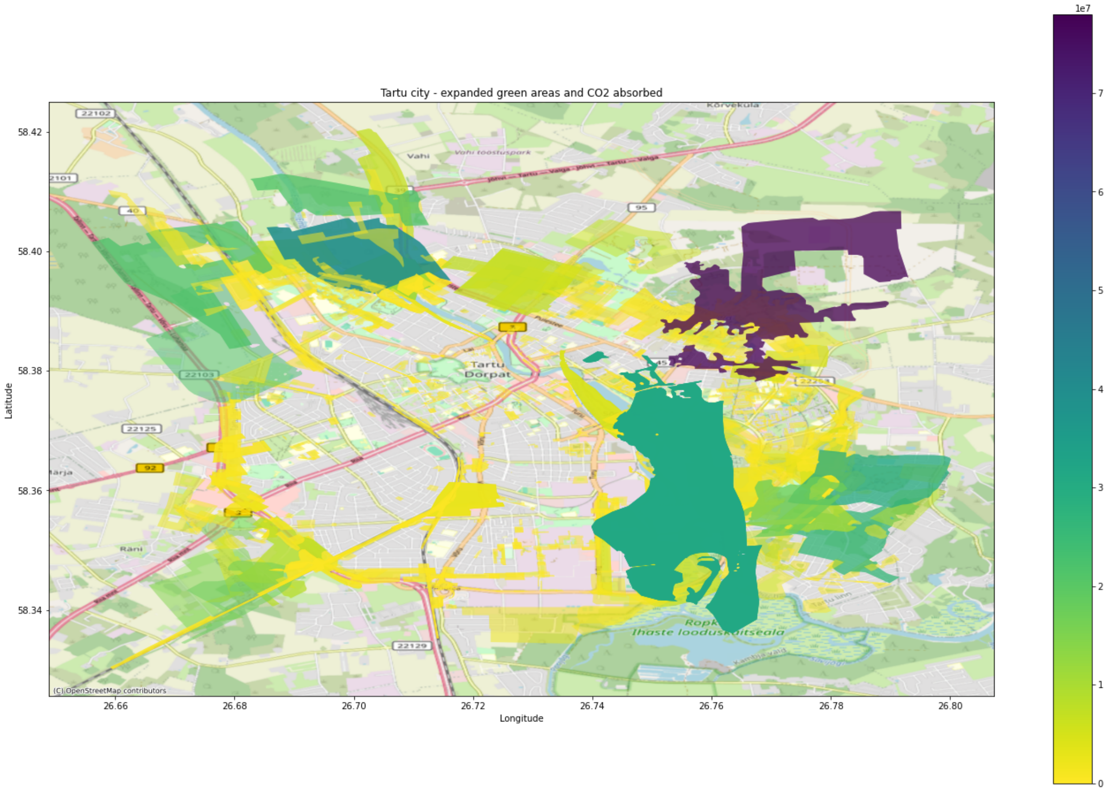


Figure 12. Tartu city: Total carbon absorption

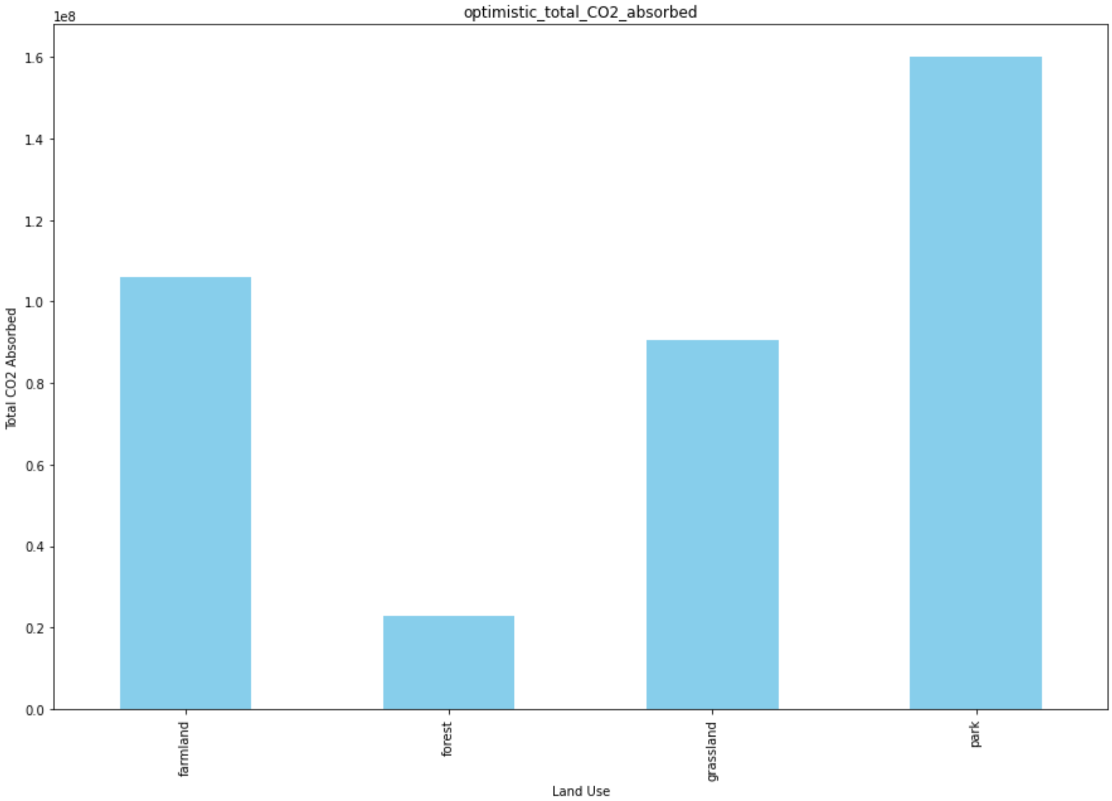


Figure 13. Carbon absorption per vegetation class

highest absorption rate. In an urban environment, forested areas are typically limited in extent. It is therefore reasonable to conclude that the absorption by forest within the city of Tartu is less than that occurring in parks and grasses. A review of Figure 14, reveals that the majority of green spaces in the city are parks, which may have higher absorption rates than other types of green areas. In this study, cemeteries, gardens, and grasslands have been included in the park category. This suggests that urban planners must consider the importance of selecting appropriate plants and trees when designing parks.

The net emissions calculated using the proposed carbon sink model were also plotted and can be seen in Figure 15. From the figure, it can be observed that the emissions are on the order of 10^{10}, whereas in the aforementioned graph 13, we saw that the absorption was only on the order of 10^8. It is evident that the impact of the carbon sink is inconsequential. This could be attributed to either the presence of significant errors in the model or the generation of implausibly elevated emissions through the SUMO simulation. Further investigation is necessary to ascertain the underlying cause. However, a crucial step would be a comparison with the actual, real-world data.

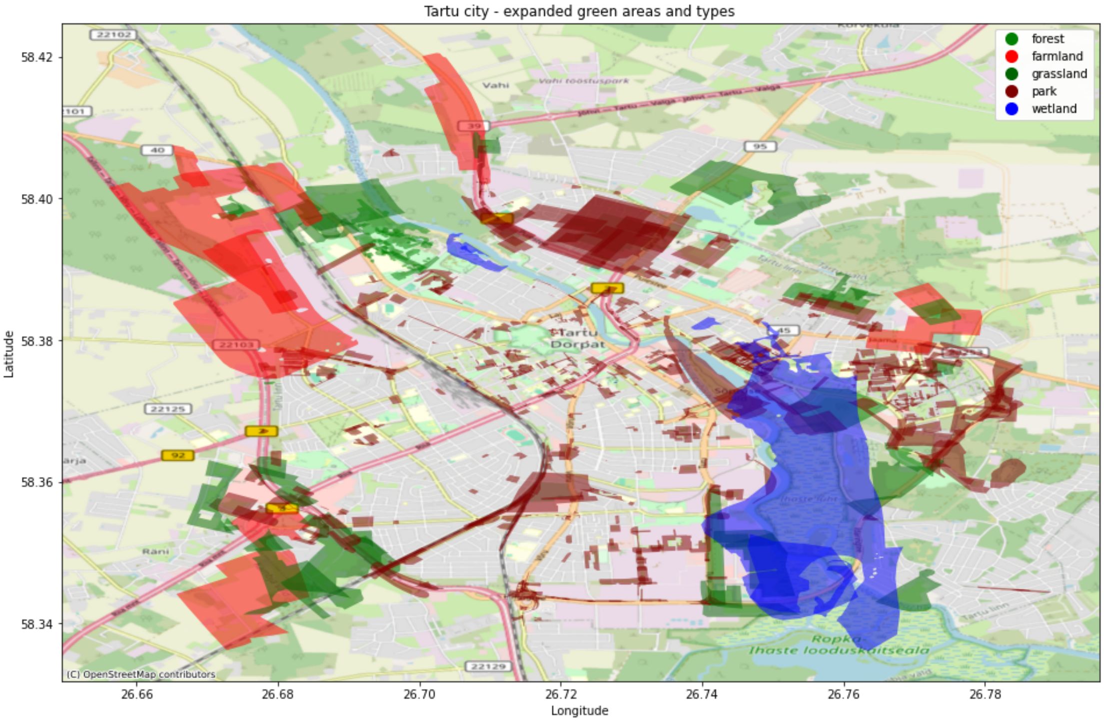


Figure 14. Vegetation type in Tartu city

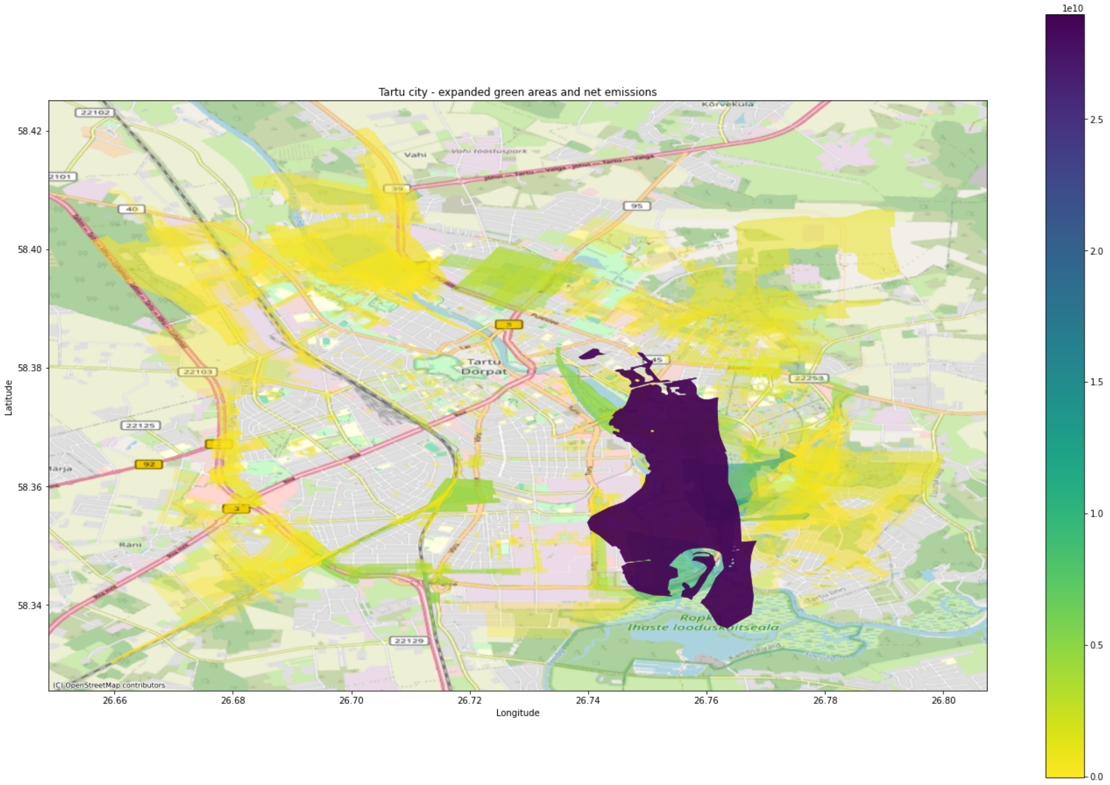


Figure 15. Tartu: Net emissions

5 Conclusion

In this work, the sensor data was successfully used to calibrate the simulation model to generate traffic data. This traffic data helped to estimate the street level emissions using the Handbook Emission Factors for Road Transport (HBEFA) model. A temporal and spatial visualization was created as an extension of existing traffic monitoring dashboard provided by [KPH$^+$22].

Extensive research on various sources to determine the average absorption rate for four classes of green space which are farmland, forest, grassland and park. A naive model is proposed to estimate total hourly absorption of carbon dioxide by different types of urban green spaces and subsequently used it to estimate the carbon sink. The results showed that parks have most influence in neutralising pollutants from urban areas. This makes it crucial to have well designated areas for parks while planning urban cities. In addition to this, it is essential to choose right type of species for plantation. The model gives a good insight towards carbon sink measurement. However, this may not be the most effective way and requires further collaboration with domain experts to validate its outcomes.

The findings of this thesis provide a more comprehensive understanding of the distribution of street emissions in Tartu city. This tool can be employed for the purpose of urban planning, with the objective of enhancing the city's sustainability and mitigating the adverse effects of pollution on public health.

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