



Classification of GPS Track Data Using AI Methods

A Case Study of Waste Collection Vehicles

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for obtaining the academic degree

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Dedication

Dedicated to my younger self, who found a fascination in writing software from a young age and decided to follow his dreams!

And to my parents, who wholeheartedly supported me throughout this journey.

Thank you.

Kurzreferat

Klassifizierung von GPS-Spurdaten mit Unterstützung von KI-Methoden am Beispiel von Abfallsammelfahrzeugen

In der Abfallwirtschaft ist die strategische Tourenplanung ein wichtiger Prozess, in dem durch optimale Gebietsaufteilung eine maximal effiziente Fuhrparkauslastung bei möglichst geringen Kosten ermittelt wird. Dies geschieht in Entsorgungsbetrieben sowohl für bestehende Auftragsgebiete, als auch bei der Kalkulation von neuen Ausschreibungen. Vor Allem bei Regionen, in denen keine Erfahrungswerte vorliegen müssen für eine robuste Tourenplanung zahlreiche unscharfe Annahmen getroffen und manchmal auch Schätzungen vorgenommen werden. Um diese Unsicherheiten durch die Analyse von geographischen Strukturen zur verringern soll eine Technologie in die bestehende Tourenplanungssoftware der Firma integriert werden, die folgende Aufgabenstellung automatisiert lösen kann: Anhand von bestehenden GPS-Aufzeichnungen sollen strukturelle Eigenschaften der jeweilige Sammelgebiete numerisch bewertet und klassifiziert werden. Gleichermaßen sollen anhand von geographischen (und möglichst frei verfügbaren Strukturdaten) aus noch unbekannten Gebieten erhoben werden können um diese auf die selbe Art und Weise klassifizieren zu können. Dadurch entsteht einerseits eine Referenzdatenmenge (von bestehenden Sammeltouren) und eine Vergleichsdatenmenge (aus den neuen Ausschreibungsgebieten). Dort wo die Klassifizierungsdaten übereinstimmen, kann davon ausgegangen werden, dass die planungsrelevanten Kennzahlen aus bestehenden Auftragsgebieten ohne gewagte Annahmen einfach übernommen werden können. Die Klassifizierung von GPS-Daten und geographischen Strukturdaten soll mit Hilfe von künstlicher Intelligenz automatisiert erstellt werden können. Auch die Überlegung, welche geographischen Strukturdaten denn überhaupt aussagekräftig sind um einen Vergleich anzustreben, sollen ggf. mit Hilfe von KI Technologien erfolgen.

Das Ziel der praktischen Arbeit ist es einen Sandbox-Service zu implementieren, der von der bestehenden Software der *infeo GmbH* aufgerufen und mit Daten gefüllt werden kann um so "auf Knopfdruck" Klassifizierungen und Vergleiche von GPS-Daten und Ausschreibungs-Strukturdaten zu erstellen. Die Anwender:innen haben dadurch die Möglichkeit für neue Ausschreibungen entsprechend passende Planungsparameter aus ihren bestehenden Auftragsgebieten zu berechnen und somit die Unsicherheiten bei der Ausschreibungskalkulation deutlich zu reduzieren.

GPS-Datenklassifizierung, Abfallwirtschaft, Künstliche Intelligenz, Geografische Datenanalyse, Maschinelles Lernen, Automatisierung

Abstract

Classification of GPS Track Data Using AI Methods: A Case Study of Waste Collection Vehicles

In waste management, strategic route planning is a crucial process where optimal fleet utilization is determined through the efficient division of service areas, with the goal of minimizing costs. This process is applied by waste disposal companies both for existing service areas and when calculating bids for new tenders. Especially in regions where there is no prior experience, numerous uncertain assumptions and estimates must be made for robust route planning. To reduce these uncertainties through the analysis of geographical structures, a technology will be integrated into the company's existing route planning software, which can automatically solve the following task: Based on existing GPS records, the structural characteristics of the respective collection areas should be numerically evaluated and classified. Additionally, geographical structural data (preferably from freely available sources) from unknown areas should be collected and classified in the same way. This approach will create both a reference data set (from existing collection routes) and a comparison data set (from new tender areas). Where the classification data match, it can be assumed that planning-relevant parameters from existing service areas can be applied to the new areas without risky assumptions. The classification of GPS data and geographical structural data should be automated using artificial intelligence. Furthermore, the consideration of which geographical structural data are meaningful for comparison should, if necessary, also be supported by AI technologies.

The practical goal of this work is to implement a sandbox service that can be called and populated with data by the existing software of *infeo GmbH*, enabling the creation of classifications and comparisons of GPS data and tender structural data "at the push of a button." This will provide users with the ability to calculate appropriate planning parameters from their existing service areas for new tenders, thereby significantly reducing uncertainties in bid calculations.

GPS Data Classification, Waste Management, Artificial Intelligence, Geographic Data Analysis, Machine Learning, Automation

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List of Abbreviations

GPS Global Positioning System

AI Artificial Intelligence

ML Machine Learning

API Application Programming Interface

CSV Comma-Separated Values

DACH Germany, Austria and Switzerland

DBSCAN Density-Based Algorithm for Discovering Clusters in Large
Spatial Databases with Noise

1 Introduction

“The world’s most valuable resource is no longer oil, but data” [1]

In today’s digital age, where electronic devices are a part of everyone’s daily lives, increasing amounts of data are being generated every day, and this trend shows no signs of slowing down. [2] With this increase in data, businesses ranging across all industries recognize the importance of leveraging it for decision-making and operational efficiency. This has led to a growing demand for technologies that can gather insights from data and integrate seamlessly into strategic processes.

One industry in which data-driven decision-making is becoming increasingly important is the waste management industry.

1.1 Motivation

“The Europe Waste Management Market size was valued at USD 116.21 billion in 2023, and is predicted to reach USD 169.37 billion by 2030, at a CAGR of 4.5% from 2024 to 2030.”[3]

This growth reflects the increasing need for efficient and sustainable waste management practices, in response to rising waste volumes across residential, commercial, and industrial sectors.

“The rapid population growth, urbanisation and economic development over the last decades has led to an increase in the generation of solid waste across the world. Providing high-quality waste management services is crucial to safeguard public health and protect the environment, but also to support resource efficiency, climate change mitigation and job creation.” [4]

The waste management sector is considered critical infrastructure and is under growing pressure to adapt to personnel shortages, blackouts, and rising costs. In many cases, the only viable solution is to optimize and automate operational processes. Digital transformation plays a key role in making day-to-day operations significantly more robust and efficient.[5]

This is the mission of *infeo GmbH*, the software company for which this thesis is being conducted:

“Die Abfallwirtschaft ist ein systemkritischer Wirtschaftsbereich und zählt zur kritischen Infrastruktur. Die Branche muss sich vor Personalausfällen, Blackouts und Kostensteigerungen schützen. Das gelingt oft nur durch Automatisierung und Optimierung von Prozessen, die das Tagesgeschäft maßgeblich robuster und effektiver machen.”[5]

This thesis supports the mission of *infeo GmbH* to revolutionize digital processes in the waste management sector by implementing AI-powered tools to automatically classify and compare GPS track data and geographical structural data. The resulting service enables waste management companies to efficiently gather planning-relevant parameters from existing service areas and apply them to new regions, reducing uncertainty, increasing planning accuracy, and accelerating decision-making.

1.2 Problem Statement

Companies operating in the waste collection business have trouble calculating accurate bids for new service areas when expanding their field of business. They often have to make assumptions and rough estimates on several parameters concerning the operation cost in new service areas. A data driven estimation can help create more accurate and less risky assessments for unknown collection locations. This can help reduce uncertainties and improve the accuracy of bid calculations.

1.3 Solution Approach and Goal

Therefore, the goal of this work is to reduce uncertainty for waste collection companies expanding their business to new service areas using existing GPS tracking data. The approach involves classifying the GPS tracking data from known service areas into four categories ranging from urban to rural. AI methods are then used to cluster the data into these categories and to train a classifier able to automate the categorization. Furthermore, algorithms and AI techniques to compare patterns found in the existing data with public geographic data from OpenStreetMap. This functionality is then bundled into a ready to use API service. The endgoal is to provide an API which suggests planning parameters for a given input geofence.

2 Background and Related Work

2.1 Technical Background

2.1.1 Feature Engineering for Geographic data

Geospatial data is not inherently suitable for machine learning algorithms, which is why the extraction of features for each tracking is crucial for a performant and accurate classifier. Extraction of features for GPS data points consisting of latitude, longitude and time

2.1.2 Clustering Algorithms

“Clustering is a useful tool in data science. It is a method for finding cluster structure in a data set that is characterized by the greatest similarity within the same cluster and the greatest dissimilarity between different clusters.”[6]

2.1.2.1 Density-Based Clustering with DBSCAN

DBSCAN (Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise) was introduced by Martin Ester, Hans-Peter Kriegel, Jörg Sander, and Xiowei Xu as an algorithm to identify clusters of arbitrary shape in spatial databases and distinguish noise. It relies on the notion of density-reachability among points based on a distance threshold *Eps* and a minimum number of points *MinPts*.[7]

Let D be a database of points and let $dist(p, q)$ be the distance between points p and q (typically Euclidean).

- The **Eps-neighborhood** of a point p is defined as:

$$N_{Eps}(p) = \{q \in D \mid dist(p, q) \leq Eps\}$$

- A point p is a **core point** if:

$$|N_{Eps}(p)| \geq MinPts$$

- A point q is **directly density-reachable** from p if:

$$q \in N_{Eps}(p) \text{ and } p \text{ is a core point}$$

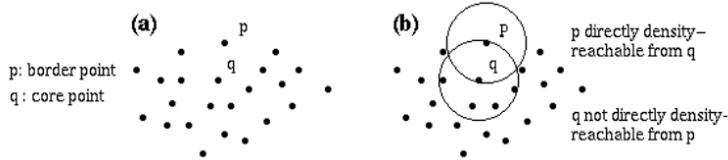


Figure 2.1: DBSCAN: Core points and border points [7]

- A point q is **density-reachable** from p if there is a chain of points p_1, p_2, \dots, p_n such that $p_1 = p$, $p_n = q$, and each p_{i+1} is directly density-reachable from p_i .
- Two points p and q are **density-connected** if there exists a point o such that both p and q are density-reachable from o .

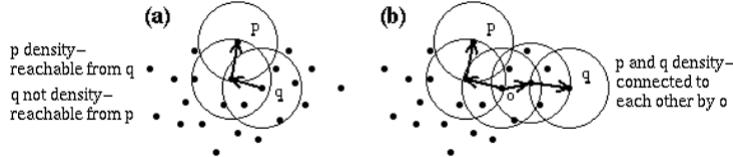


Figure 2.2: DBSCAN: (a) Density-reachability and (b) density-connectivity [7]

This concept allows DBSCAN to detect clusters without requiring the number of clusters as input, unlike other clustering algorithms such as K-Means and CLARANS, making it effective for outlier detection. [7]

2.1.2.2 k-means Clustering

K-Means is the first unsupervised algorithm used to cluster data in an euclidean space and is still widely used to partition a dataset $\{x_1, x_2, \dots, x_n\}$ of size n into $k \leq n$ sets $S = \{S_1, S_2, \dots, S_k\}$ [6]

The goal to minimize the within-cluster sum of squares (WCSS) can be shown with following function:

$$J = \sum_{i=1}^k \sum_{x_j \in S_i} \|x_j - \mu_i\|^2$$

The implementation of the algorithm uses an iterative refinement technique, also known as Lloyd's Algorithm. An initial set of k means is selected, randomly or are more sophisticatedly initialized in adaptations such as k-means++. Then the algorithm repeats the following two steps until the assignments do not change and k-means therefore converges:

1. **Assignment:** Assign each data point to the cluster with the least squared Euclidean distance (mean):

$$S_i = \{x_j : \|x_j - \mu_i\|^2 \leq \|x_j - \mu_l\|^2, \forall 1 \leq l \leq k\}$$

2. **Update:** Update the means of data points assigned to each cluster:

$$\mu_i = \frac{1}{|S_i|} \sum_{x_j \in S_i} x_j$$

2.1.2.3 Combining DBSCAN and k-means

DBSCAN can be used to identify anomalies by dividing the data set into two clusters. Cluster 0 with the valid data and cluster -1 with anomalies. Using the output of DBSCAN and removing the detected anomaly cluster -1 as the input for k-means, a more effective partitioning of the data into k number of groups can be achieved. Without DBSCAN, k-means clustering will likely assign one cluster to outliers of faulty data.

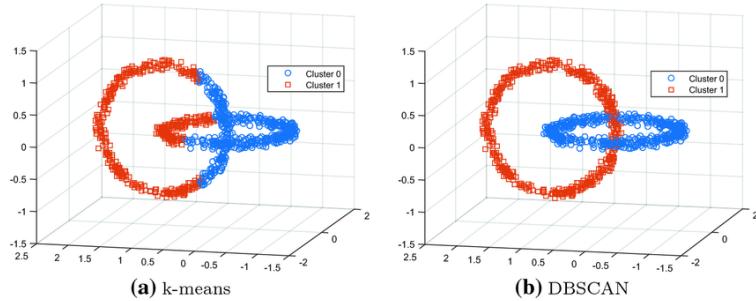


Figure 2.3: Comparison: k-means, DBSCAN clustering algorithms [8]

2.2 Related Work

GPS-Data analysis and classification has been studied in various studies and projects, such as identifying transportation modes or movement behavior. This section highlights related approaches to the classification and comparison of GPS data relevant to the problem of this thesis.

2.2.1 Transportation Mode Prediction with Feature Engineering

Etemad, Soared and Matwin [9] propose a five step framework to predict the underlying transportation mode from GPS traces. The steps of this framework include in order the preparation of data, point feature extraction (e.g., distance, speed, bearing rate and its derivatives), trajectory feature extraction (e.g., min, max, mean and std., percentiles), noise removal and normalization.

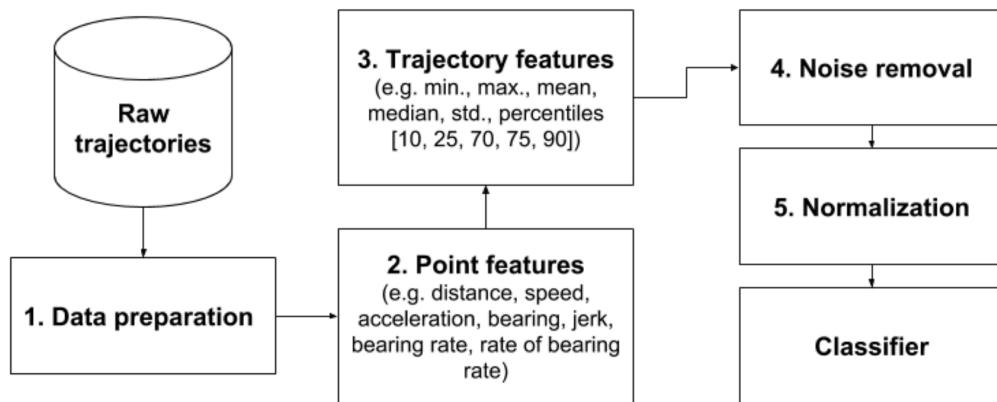


Figure 2.4: Steps of the framework for predicting of transportation modes proposed by Etemad et al. [9]

Their framework achieves competitive results with the classifier scoring 96.5% accuracy and a f1 score of 96.3%. The study shows the importance of noise reduction and feature engineering when working with GPS trace data. [9]

While their work focuses on the classification of transportation modes (e.g., walking, bike, car, etc.), the techniques used for extracting features and noise reduction, are also applicable for the structural classification of waste collection routes, which is the focus of this thesis.

2.2.2 Clustering of GPS Data using Distance-based Features

Koh et al. [10] present a framework to cluster users based on their movement patterns captured via an application on their mobile phones. The authors propose a new metric, *Daily Characteristic Distance (DCD)*, which is used to create a fair comparison between working and nonworking users on workdays and offdays and extract features in combination with *Origin-Destination (OD)* matrix features.

The features derived from the DCD are combined with OD matrix features and are used in a k-means clustering algorithm to group the users into three behavior groups. The study analyses the resulting clusters with two newly proposed metrics: *User Commonality* (percentage of users that visited each point of interest (POI) category) and *Average Frequency* (average percentage of trips to each POI category). [10]

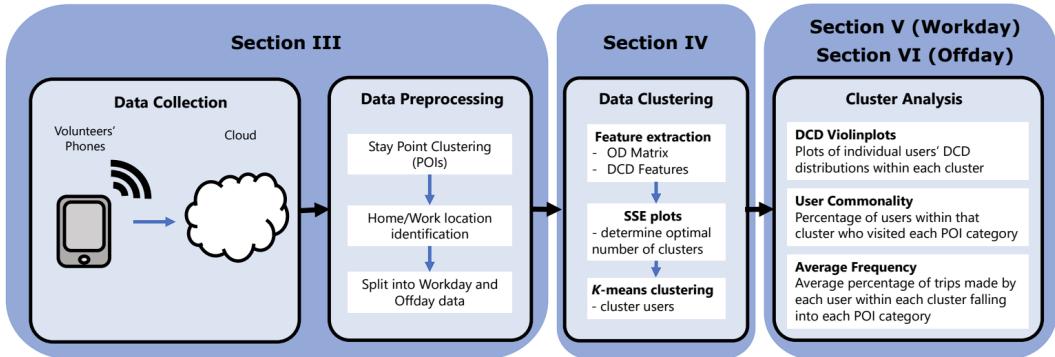


Figure 2.5: Steps of the framework proposed by Koh et al. [10]

The work of Koh et al. shows that meaningful patterns can be extracted from GPS data using unsupervised clustering methods. This approach is highly relevant for this thesis, as it demonstrates that structural characteristics can be derived from engineered features and effectively used for clustering and classification. Although the paper's focus is on GPS traces of individual people and captures data with mobile phones, the underlying methods can be applied for identifying patterns and similarities in GPS track data collected by waste collection vehicles.

3 Problem Definition and Solution Approach

3.1 Big Picture

GPS trackings are collected by waste collection vehicles during real-world operation in the DACH region. These raw trackings are compressed by *infeo GmbH* to reduce storage size while keeping necessary route information, and then saved in a centralized database. The data provided is a subset approved by *infeo GmbH* for analysis in this thesis.

The aim of this thesis is to develop a pipeline that can automatically classify GPS trackings to four categories (e.g., rural, town, suburban and urban).

The proposed solution follows a high-level workflow with the following steps:

1. **Data Preparation:** Data is cleaned and filtered to remove invalid or incomplete trackings.
2. **Feature Extraction:** Meaningful features such as point density and bounding box area are calculated for each tracking.
3. **Outlier Detection:** Secondary detection of invalid trackings and trackings that significantly deviate from expected patterns are removed using density-based clustering (DBSCAN).
4. **Clustering:** The cleaned tracking data is grouped into four clusters based on similarity using K-Means.
5. **Classification:** A Classifier is trained to generalize the clustering results and allow automated classification of new trackings.

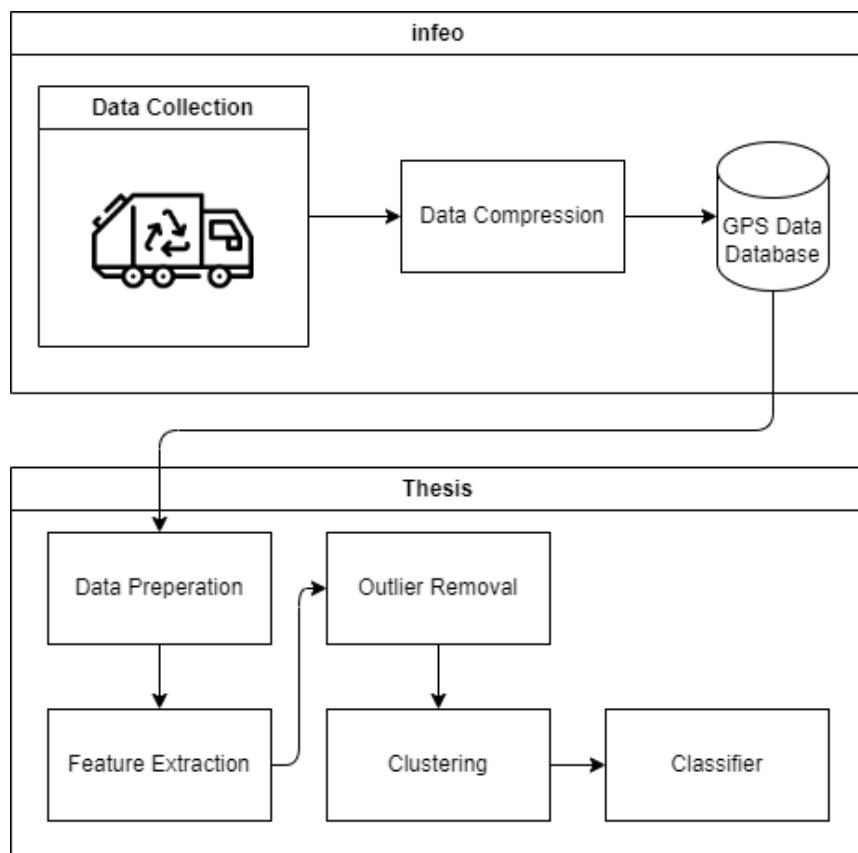


Figure 3.1: High-level overview of training the GPS track classifier

3.2 Description of the Dataset

Gaining an understanding of the provided data structure is crucial for identifying the available information and its limitations. This analysis enables the derivation of meaningful features and which types of information can be extracted from the dataset, and which cannot.

3.2.1 Overview

The dataset used is a collection of GPS tracking data collected by wastecollection vehicles from various wastecollection businesses and provided by *infeo GmbH*. It represents real-world data collected during regular wastecollection operation in the DACH region.

3.2.2 Source and Collection Method

The data was obtained by the onboard tracking systems installed by *infeo GmbH*, which collects GPS coordinates in regular intervals during regular operation. Each tracking represents a complete wastecollection route taken and includes metadata aswell as a list of GPS coordinates.

3.2.3 Structure of the Data

Each dataset entry represents a single recorded route refered to as *tracking* and contains metadata aswell as a time ordered list of gps coordinates.

Each tracking contains the following fields:

Table 3.1: Structure of a Tracking Entry

Field	Type	Description
<code>id</code>	Integer	Unique identifier of the tracking entry.
<code>name</code>	String	Name of the tracking (randomized for anonymization) identification.
<code>description</code>	String	Route metadata, often includes internal codes.
<code>recorded</code>	DateTime	Start date and time of the tracking.
<code>length</code>	Float	Total length of the route in kilometers.
<code>duration</code>	Integer	Total duration of the tracking.
<code>vehicleId</code>	Integer / Null	ID of the vehicle (nullified for anonymization).
<code>tourId</code>	Integer / Null	ID of the associated tour (nullified for anonymization).
<code>isExported</code>	Boolean	Flag indicating if the tracking was exported.
<code>editState</code>	Integer	Edit state used by the system.

Each GPS point contains the following fields:

Table 3.2: Structure of a GPS Point Entry

Field	Type	Description
<code>id</code>	Integer	Unique identifier of the GPS point.
<code>time</code>	DateTime	Timestamp of when the point was recorded.
<code>latitude</code>	Float	Latitude coordinate.
<code>longitude</code>	Float	Longitude coordinate.
<code>speed</code>	Float	Instantaneous speed at the time (in km/h).
<code>heading</code>	Float	Direction of movement in degrees.
<code>sequence</code>	Integer	Position of the point in the tracking sequence.
<code>metaTag</code>	Integer	Custom metadata tag.
<code>metaValue</code>	String	Value associated with the metadata tag.
<code>pointBaseType</code>	Integer	Internal point type used by the system.

3.2.4 Size and Coverage

The dataset consists of 101,353 individual trackings with a combined number of 123,785,460 waypoints. Trackings were recorded by waste collection vehicles operating in the DACH region.

3.2.5 Data compression

The dataset used in this thesis is pre-compressed internally by *infeo GmbH* while keeping essential route information [11]:

1. **Delete same waypoints:** Consecutive waypoints with identical GPS position are deleted.
2. **Delete waypoints with distance smaller than (x):** Delete all consecutive waypoints with a distance to each other of less than (x) meters.
3. **Delete waypoints with path curvature smaller than (x)^s:** For every group of three consecutive waypoints A , B , and C , the middle point B is deleted if all the following criteria are met:
 - a) The distance \overline{AB} is less than a specified threshold (e.g., 100 meters), or \overline{BC} is less than the threshold.
 - b) The distance \overline{AC} is less than a specified threshold (e.g., 1000 meters).
 - c) The change in heading α between segments \overline{AB} and \overline{BC} is smaller than a defined angle (e.g., 10°).

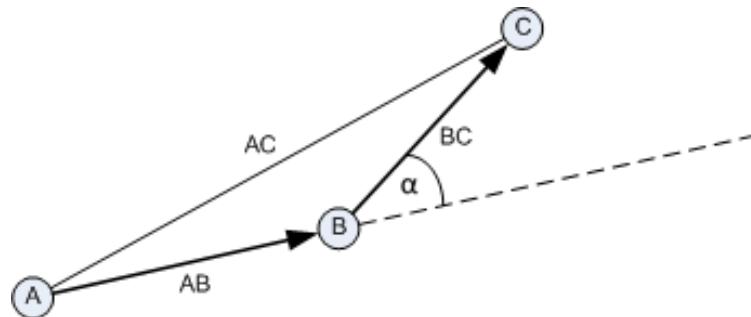


Figure 3.2: Waypoint curvature calculation used for compression by *infeo GmbH*
[11]

3.2.6 Limitations

A significant limitation of this study is due to the nature of the dataset. While the dataset is extensive, offering a large sum of trackings, many prove to be

irrelevant or misleading for analysis. According to discussion with *infeo GmbH* and manual visual inspection, the primary cause of these data issues is the manual operation of the tracking device in the waste collection vehicles.

The most common issues were:

- **Depot-only trackings:** Many trackings were exclusively recording the movement in the vehicle parking facility, capturing no real waste collection operation.
- **Non-operational trackings:** Tracking devices were left active for long periods of time, outside of operational hours, such as overnight, resulting in long trackings with little movement.
- **Large Signal gaps:** Some trackings suffered from significant gaps in the GPS track, resulting from signal loss of the tracker or possibly from the compression step introduced by *infeo GmbH*.

As a consequence of these issues in the dataset, a comprehensive preprocessing and filtering was necessary to ensure the quality of the dataset used for analysis and classification. While the cleaning process was designed to be as robust as possible, it is possible that some faulty trackings persist in the filtered dataset and that some valid trackings were wrongfully discarded.

3.3 Dataset Analysis

Before a classification model can be developed, it is important to understand the underlying data it will be trained on. This section presents an exploratory data analysis of the cleaned dataset with the goal of identifying relationships of extracted features that help separate the four categories.

3.3.1 Sample Analysis

A small, manually selected sample of 8 tracking routes was selected for initial exploratory data analysis. Each route was inspected on the *AWM-Map-Tool* and then categorized into one of the four area type labels: URBAN, SUBURBAN, TOWN or RURAL. Each Label is represented by 2 tracking routes in the sample data to ensure a balanced representation.

Feature extraction was performed to calculate route-level metrics such as length, duration, bounding box area, point density, number of stops and average distance between points.

The goal of this sample is to explore patterns, validate assumptions, and identify features useful for future automatic classification.

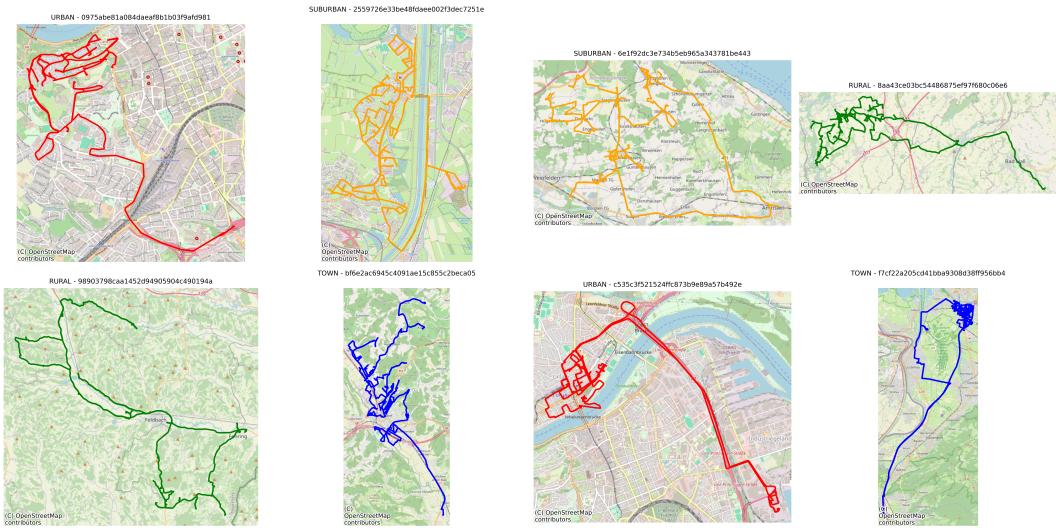


Figure 3.3: Mapgrid for selected sample trackings

The mapgrid shows spatial layout of each tracking route overlayed on a visual map. Each subplot corresponds to a single tracking and is colorcoded with the assigned lable (RURAL=Red, SUBURBAN=Orange, TOWN=Blue, URBAN=Green). This visual representation clearly shows the difference in route shapes and sizes between the four different area types.

Urban:

- Routes are geographically compact and highly localized.
- Movement appears dense with short travel distances between stops.
- Often confined to a small cluster of city blocks or neighborhoods.

Town:

- Coverage is slightly more dispersed than urban routes.
- Still relatively compact but less tightly packed.
- Serves a central area and nearby residential surroundings.

Suburban:

- Routes extend farther and cover wider areas than town routes.
- Show transitional behavior between urban and rural structures.
- Less dense stop distribution, indicating more spaced-out residential zones.

Rural:

- Routes are long and span large geographical areas.
- Stops are widely spaced, often connecting small, isolated settlements.
- The shape and path vary significantly, often following main roads between distant collection points.

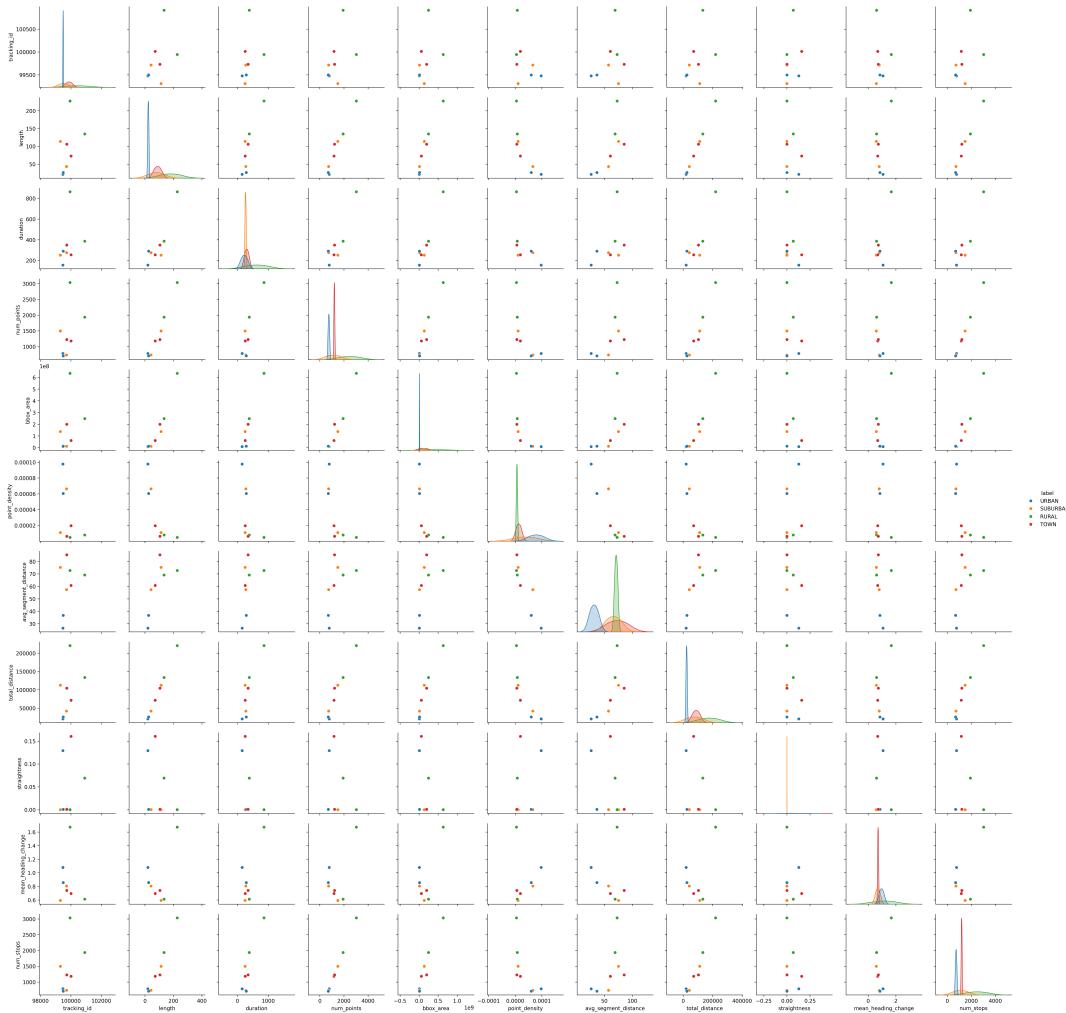


Figure 3.4: Pairplot of selected GPS route features grouped by area label

The pairplot compares the relationships between the extracted features (eg., length, duration, number of points, bounding box area, point density, average segment distance and number of stops). Rural and urban trackings show a

clear difference in multiple features. Point density and average segment distance are especially good discriminators. Suburban and town trackings show more variance and occasionally overlap with eachother, giving a not so clear distinction.

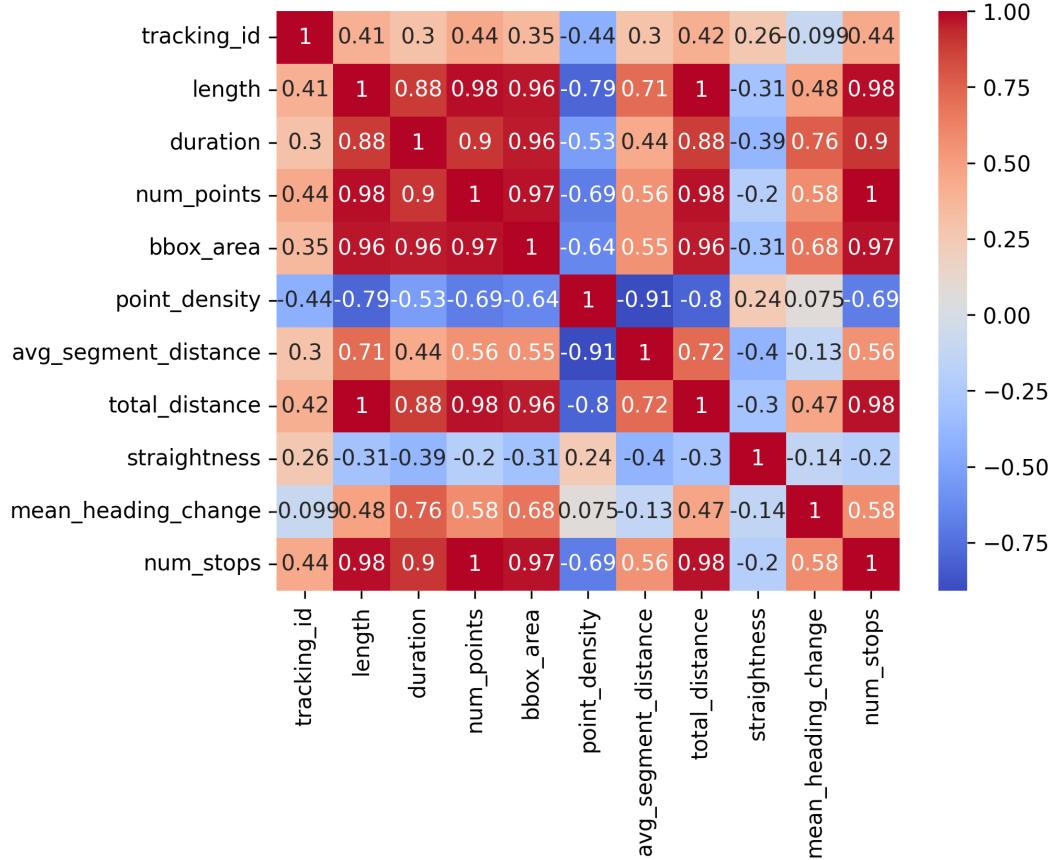


Figure 3.5: Correlation Matrix of selected GPS route features grouped by area label

The Correlation Matrix highlights the strong correlations between features in the selected sample. A high positive correlation between length, duration and number of points can be observed. Additionally the point density has a strong negative correlation with the tracking length, number of points and average segment distance.

This correlation is to be expected and confirms the consistency of the data, since the points (GPS coordinates) are recorded in uniform intervals. This plot also indicates the possible redundancy of features such as number of points and number of stops.

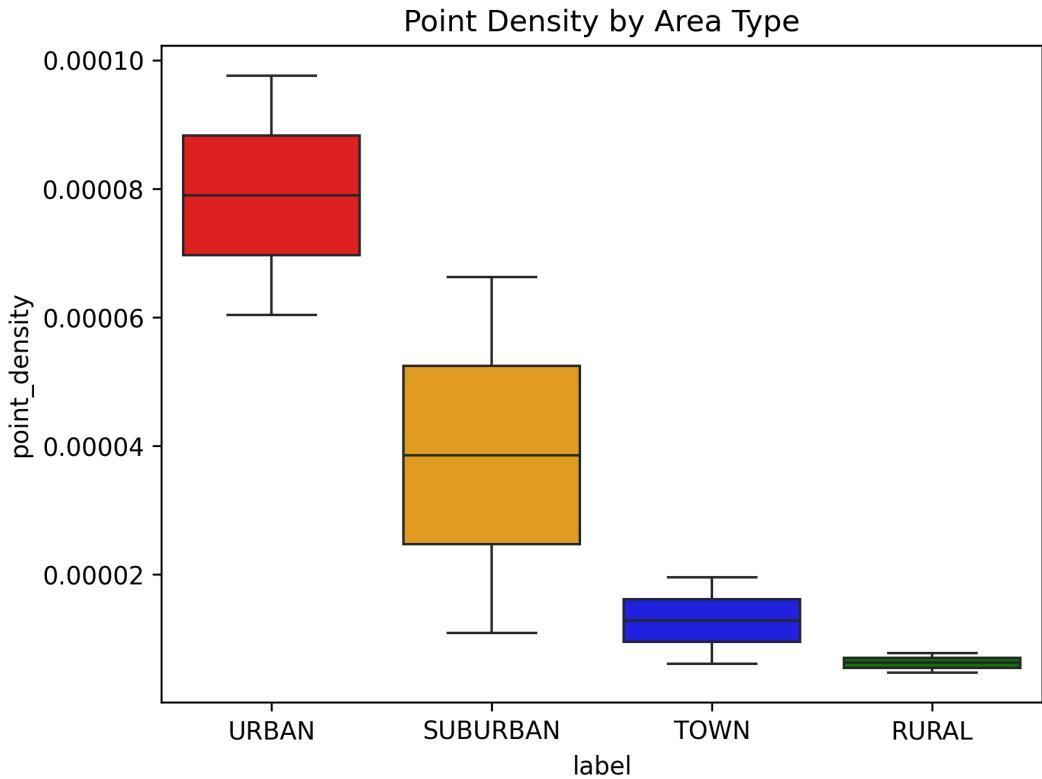


Figure 3.6: Boxplot of point density grouped by area label

The point density boxplots for each label shows a clear difference between the labels. Urban trackings appear to have the highest density and rural trackings the lowest, with suburban and town trackings falling in the middle with a wider variability.

This validates that the point density is a strong feature for classifying trackings to the four labels.

3.4 Solution Approach

This chapter outlines the methods used to analyse and classify the GPS tracking data collected by waste collection vehicles. The approach is structured in multiple stages, beginning with exploratory data analysis, proceeding with feature extraction, data cleaning, outlier detection, clustering and finally training a classifier. The goal is to identify tracking patterns that allow for structural classification of trackings into four categories: Urban, Suburban, Town and Rural.

3.4.1 Exploratory Data Analysis

The foundation of this thesis is the dataset provided by *infeo GmbH*. It contains anonymized GPS track data collected by waste collection vehicles during real world operation. Due to its large size of more than 100.000 GPS tracks and its anonymization, a clear picture of the data needed to be established as the first step. With visual examination of different random trackings a sample of eight manually labeled trackings was gathered. The selected trackings were labeled to four categories, two trackings per category.

- Urban (Dense building structures, complex road networks, and minimal spacing between stops)
- Suburban (Moderately spaced residential areas with organized street layouts)
- Town (Smaller clustered settlements with simpler road structures)
- Rural (Sparse housing, long roads, large distances between collection points)

With the manually selected trackings varying in geographical structure, a exploratory data analysis helped transfer the visual distinction to clear differences found in the data of each tracking category.

3.4.2 Feature Extraction from Sample Dataset

To enable the use of machine learning algorithms, each tracking originally represented by a consecutive list of GPS waypoints with latitude and longitude must be transformed into feature vectors. Feature extraction methods were applied to derive representative metrics for each tracking.

This approach is well established and used in similar studies such as the classification of transportation modes by Etemad et al. [9] and clustering of GPS data using distance-based features by Koh et al. [10]

3.4.2.1 Features Available in Trackings

1. **Length:** Total distance of the tracking, in kilometers as recorded in the database.
2. **Duration:** Total time duration for the tracking, captured and recorded in the database.

3.4.2.2 Features Extracted from Waypoints

1. **Number of Points:** The total number of GPS waypoints recorded in the tracking.
2. **Bounding Box Area:** The area of the minimum bounding box that encloses all latitude and longitude waypoints in one tracking.
3. **Point density:** The number of waypoints divided by the bounding box area. This feature indicates how closely packed the points are.
4. **Average Segment Distance:** The mean distance between consecutive waypoints, computed using geodetic distance.
5. **Total Distance:** The sum of all segment distances between consecutive waypoints. (Later removed, since it is a more unreliable length metric compared to the length in the tracking metadata)
6. **Straightness:** The ratio between the geodesic distance from the first to the last point and the total distance of the route. Values close to 1 indicate a straight path, while lower values indicate loops and detours.
7. **Mean Heading Change:** The average change in bearing between consecutive segments of the path, in radians. It reflects how often and how severe the vehicle changes direction.
8. **Number of Stops:** Waypoints with speed of zero. (Later removed, due to low variance as most waypoints have a speed of zero)

3.4.3 Filtering and Preprocessing the Full Dataset

There are a lot of faulty datapoints that are not relevant for the clustering, that are filtered out. Before applying machine learning methods, extensive filtering was required to remove invalid and irrelevant data from the dataset. These included:

1. Trackings with a too low duration to be realistic collection trackings.
2. Trackings that recorded movement only in and around a parking lot.
3. Trackings left running overnight with no significant movement.
4. Trackings with unrealistic GPS jumps and anomalies (possibly due to device errors or compression errors introduced by *infeo GmbH*).

Removing these faulty datapoints was crucial for ensuring the quality of the clustering and reducing the computation times.

3.4.4 Clustering and Pattern Discovery

To discover patterns in the unlabeled dataset, clustering algorithhms were applied. Initially, K-Means++ was used to cluster the data into four clusters. However the result showed that one cluster mostly consisted of outlier routes, with unrealistic GPS jumps.

To solve this issue, the process was improved by detecting and removing outliers using DBSCAN (Density-Based Spatial Clustering for Applications with Noise). DBSCAN effectively removed most anomalies in the dataset. After filtering the outliers with DBSCAN, K-Means clustering was applied again, resulting clusters that represented the four defined categories better.

3.4.5 Training a Classification Model

To automatically classify new trackings into one of the four categories (Urban, Suburban, Town, Rural), a supervised machine learning model was trained using the labeled dataset from the clustering step.

The labeled dataset was split into training and test sets using an 80/20 split. Evaluation of the classifier on the test sset showed a high overall accuracy.

The trained classifier was saved for the later use in a sandbox API to classify new trackings.

3.4.6 API Integration

3.5 Structure of the Work

The remainder of this thesis is structured in the following chapters:

- **Chapter 4: Implementation:** Provides a detailed description of how the previously introduced methos and algorithms were implemented. This includes the data preprocessing, feature extraction, clustering pipeline and classifier training.
- **Chapter 5: Evaluation and Discussion:** Presents the results of the clustering and classification. Performance metrics, visualizations, and analysis of the results are discussed alongside future reasearch and application.
- **Chapter 6: Conclusion:** Summarization of the contributions of the thesis, highlighting key takeaways and shortcomings.

This structure follows the development of the project, from understanding the problem and analysing the data, to building and evaluating a solution to address the objective of classifying GPS trackings into structural categories.

4 Implementation

4.1 Implementation of the Big Picture

This section translates the conceptual pipeline from Chapter 3 into its concrete Python-based implementation. Each stage of the pipeline, from data processing to feature extraction, clustering and classification, was implemented in modular Jupyter Notebooks using libraries such as `pandas`, `scikit-learn`, `geopy` and `pyarrow`.

Each module was designed to run independently, allowing for quick experimentation and reproducability of results. The diagram in Figure 4.1 shows a more detailed view of the pipeline implementation.

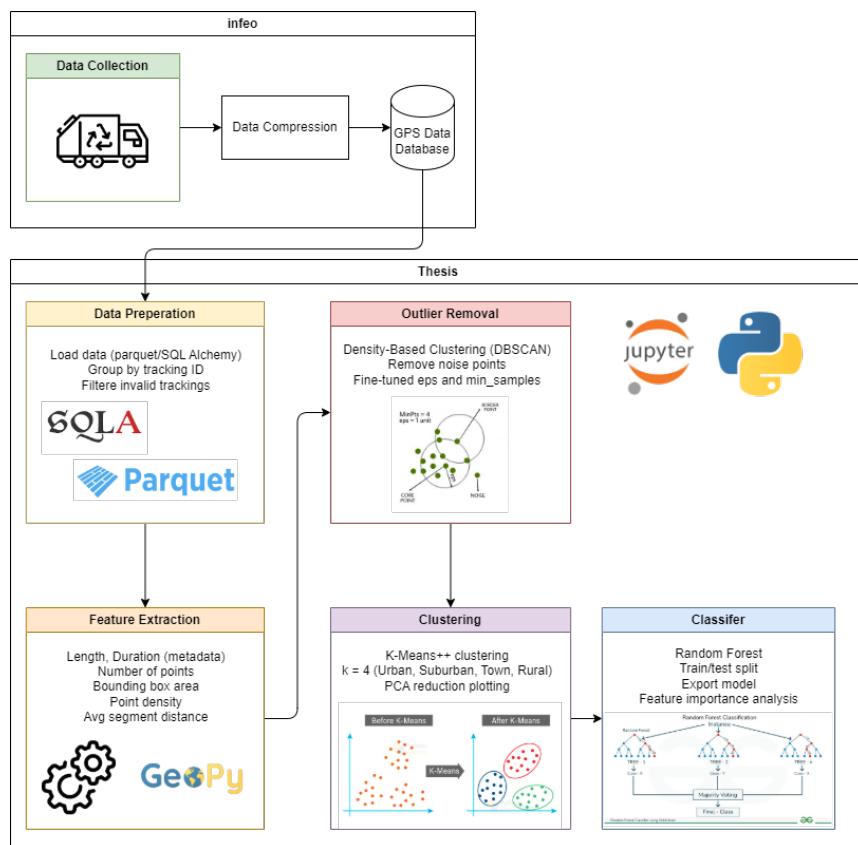


Figure 4.1: Big picture implementation pipeline

4.2 Data Handling and Preprocessing

Preprocessing is a crucial step in the machine learning pipeline.

Each row in the dataset is a single GPS waypoint and consist of the following columns:

- **id_tracking:** Unique identifier for each tracking.
- **sequence:** The order of the waypoint in the tracking.
- **latitude/longitude:** GPS coordinates.
- **speed:** Vehicle speed at the waypoint.
- **tracking_duration:** Total time of the tracking.
- **tracking_length:** Total distance of the tracking in km.

4.2.1 Data volume and loading

The data was provided via a MySQL database, containing two main tables relevant for this analysis. Trackings table containing the metadata of 101353 trackings and the waypoints table containing the corresponding GPS waypoints of the trackings. Due to the substantial size of database **13.5 GB** in total, with **12.6 MB** from the tracking table and **11.6 GB** from the waypoint table, an efficient data handling pipeline was necessary.

To handle the data at a lower scale, the filtering query was executed directly within the database using SQL (see Listing 4.1). The resulting filtered dataset was streamed in chunks of 1,000,000 rows using `pandas.read_sql()` and saved incrementally to a compressed Apache Parquet file using `pyarrow`. The final Parquet file had a reduced size of approximately **1.5 GB**.

This chunk-wise approach ensured memory efficient loading without crashing the kernel with the limited hardware available. The full export operation took about two hours to fully complete, with an average processing speed of **6.40 iterations/second** (row group read and write cycles).

4.2.2 Filtering Faulty Trackings

The raw data included many invalid or irrelevant trackings that could impact the analysis and clustering. These trackings were removed based on these criteria:

- **Duration Filter:** Trackings shorter than 30 minutes or longer than 10 hours were excluded.

- **Length Filter:** Trackings with a total length lower than 50 km or above 850km were excluded.
- **Minimal Waypoint Count:** Trackings with less than 10 recorded waypoints were excluded.
- **Minimal Bounding Box:** Trackings with a bounding box smaller than about 50 meters in latitude or longitude were excluded. This was a helpful step to reduce the amount of trackings that were exclusively recorded in a parking lot.

The filters were directly implemented as a SQL query executed in an jupyter notebook. This reduced the further computatinal times for clustering and training the classifier model. The SQL query implementing these filters looked as follows:

```

SELECT
    wp.id_tracking, wp.id, wp.time, wp.type, wp.sequence,
    wp.comment,
    wp.speed, wp.heading, wp.duration, wp.block_type, wp.
    log,
    wp.latitude, wp.longitude, wp.altitude, wp.meta_tag,
    wp.meta_value,
    t.length AS tracking_length,
    t.duration AS tracking_duration
FROM waypoint wp
JOIN tracking t ON wp.id_tracking = t.id
WHERE
    t.duration BETWEEN 18000000000 AND 360000000000
    -- 0.5 to 10 hours
    AND t.length BETWEEN 50 AND 850 -- 50 to 850 km
    AND EXISTS (
        SELECT 1 FROM waypoint w
        WHERE w.id_tracking = t.id
        HAVING COUNT(*) > 10 -- Min. 10 waypoints
    )
    AND (
        (SELECT MAX(latitude) FROM waypoint WHERE
            id_tracking = t.id) -
        (SELECT MIN(latitude) FROM waypoint WHERE
            id_tracking = t.id)
    ) > 0.0005 -- Min. ~50m latitude span
    AND (

```

```

    (SELECT MAX(longitude) FROM waypoint WHERE
        id_tracking = t.id) -
    (SELECT MIN(longitude) FROM waypoint WHERE
        id_tracking = t.id)
) > 0.0005; -- Min. ~50m longitude span

```

Listing 4.1: SQL query used for filtering the GPS tracking dataset

Each Filter step reduces the dataset by this many trackings:

Filter Step	Remaining Trackings	Removed	Reduction (%)
All trackings	101353	—	—
Duration filter	66477	34876	34.410%
Length filter	45668	20809	31.303%
Minimal Waypoints filter	45599	69	0.151%
Min Lat/Long span filter	45598	1	0.002%
Total Remaining	45598	55755	55.011%

Table 4.1: Tracking reduction per filtering step

4.3 Feature Extraction

TODO: small text for section

4.3.1 Available Metadata Features

TODO: small text for subsection

4.3.1.0.1 Tracking length

4.3.1.0.2 Tracking duration

4.3.2 Computed Features from Waypoints

TODO: small text for subsection

4.3.2.0.1 Number of points The total number of waypoints n in a tracking:

$$num_points = n$$

4.3.2.0.2 Bounding box area Computed from the geodesic height h and width w of the minimal enclosing rectangle:

$$bbox_area = h \cdot w$$

$h = d((lat_{min}, long_{min}), (lat_{max}, long_{min}))$, $w = d((lat_{min}, lon_{min}), (lat_{min}, long_{max}))$
where $d(\cdot, \cdot)$ refers to the geodesic distance between two GPS points (in meters), calculated using the WGS84 ellipsoid model through *geopy* library [12].

4.3.2.0.3 Point density Density of GPS waypoints in the bounding box:

$$point_density = \frac{n}{bbox_area + \varepsilon}, \quad \varepsilon = 10^{-6}$$

where ε is a small constant to avoid division by zero.

4.3.2.0.4 Average segment distance The average geodesic distance between consecutive waypoints:

$$avg_segment_distance = \frac{1}{n-1} \sum_{i=1}^{n-1} d(p_i, p_{i+1})$$

where $d(\cdot, \cdot)$ refers to geodesic distance.

4.3.2.0.5 Total Distance The cumulative travel distance:

$$total_distance = \sum_{i=1}^{n-1} d(p_i, p_{i+1})$$

4.3.2.0.6 Straightness Ratio between the start-end distance and the total path length:

$$straightness = \frac{d(p_1, p_n)}{\sum_{i=1}^{n-1} d(p_i, p_{i+1})}$$

[13]

4.3.2.0.7 Mean Heading Change Average angle change between consecutive direction vectors (in radians):

$$\delta_i = \min(|\theta_{i+1} - \theta_i|, 2\pi - |\theta_{i+1} - \theta_i|), \quad mean_heading_change = \frac{1}{n-2} \sum_{i=1}^{n-2} \delta_i$$

with bearings θ_i computed via:

$$\theta = \arctan 2 (\sin(\Delta\lambda) \cos(\phi_2), \cos(\phi_1) \sin(\phi_2) - \sin(\phi_1) \cos(\phi_2) \cos(\Delta\lambda))$$

[9]

4.3.2.0.8 Number of Stops Amount of waypoints where the truck had a speed of zero:

$$num_stops = \sum_{i=1}^n \mathbb{1}(speed_i = 0)$$

4.3.3 Feature Storage and Output

The extracted features were stored in a structured csv file, with one row per tracking_id and all corresponding features. This resulting dataset forms the basis for all future analysis, clustering and classification applications in the next steps of the pipeline.

Feature	Unit	Description
num_points	Count	Number of GPS waypoints in a tracking
bbox_area	m^2	Area of bounding box enclosing all GPS points
point_density	points/ m^2	Number of points per square meter of bounding box
avg_segment_distance	m	Mean geodesic distance between consecutive waypoints
total_distance	m	Total geodesic distance covered by the tracking
straightness	Ratio (0–1)	Direct distance from start to end / total distance
mean_heading_change	rad	Average absolute angle change between segments
num_stops	Count	Number of waypoints with speed = 0
duration	100 ns	Total tracking duration in nanoseconds
length	km	Total tracking length from the database

Table 4.2: Extracted features with their units and descriptions

4.4 Clustering Implementation

4.4.1 Outlier Removal with DBSCAN

4.4.2 Semi-Supervised Clustering with Weighted and Seeded K-Means

To improve the interpretability and performance of clustering, a semi-supervised approach was used to guide the K-Means algorithm. A manually labeled subset of 8 samples, evenly distributed across the four target categories (URBAN, SUBURBAN, TOWN, RURAL), was utilized to derive feature weights and initialize cluster centroids. This allowed the unsupervised clustering algorithm to be seeded with domain knowledge.

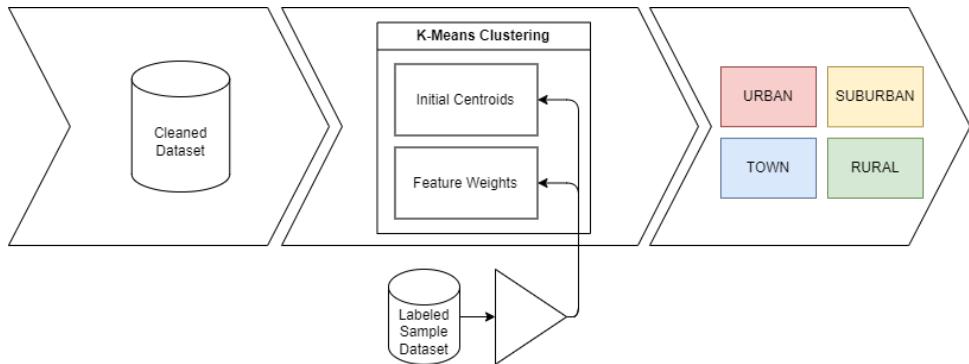


Figure 4.2: K-Means semi supervised clustering pipeline

4.4.2.1 Feature Weighting Based on Sample Label Spread

In order to emphasize features that varied significantly across known classes and downweight features with less discriminative power, relative variability of feature medians between the categories was used. Specifically, for each feature f_i , the relative median range was calculated as:

$$w_i = \frac{\max_i - \min_i}{\text{mean}_i}$$

where \max_i , \min_i , and mean_i represent the maximum, minimum, and mean median value of feature f_i across the four labeled classes. These weights were then normalized by dividing by the mean of all w_i to ensure comparability:

$$w_i^{\text{norm}} = \frac{w_i}{\frac{1}{n} \sum_{j=1}^n w_j}$$

Finally, the weights were clipped to the range $[0.5, 2.0]$ to avoid extreme scaling effects [14].

4.4.2.2 Seeded Cluster Initialization

The cluster centers were initialized using the scaled and weighted medians of the labeled sample set. For each class, the feature medians were calculated, scaled using the `StandardScaler`, and then multiplied by the learned feature weights. The resulting $4 \times d$ matrix was used to seed the k centroids of the K-Means algorithm:

$$\mu_k = \text{scale}(\text{median}_k) \cdot w_i^{\text{norm}} \quad \text{foreach } k \in \{1, 2, 3, 4\}$$

This strategy ensured that the initial centroids already reflected meaningful differences in the data as identified by the sample set.

4.4.2.3 Constrained K-Means Clustering

The clustering was performed using the `KMeansConstrained` algorithm with the following configuration:

- Number of clusters: 4
- Initialization: Manual (from scaled, weighted medians)
- Minimum cluster size: 5% of total data
- Maximum cluster size: 60% of total data
- Number of restarts: 10

This method produced clusters that closely aligned with the known class distribution and improved the stability and interpretability of the clustering outcome compared to random initialization.

4.5 Classification Model

To predict the category of new or unlabeled GPS trackings, a classification model was trained using the extracted and clustered features. A Random Forest classifier was chosen due to its robustness, ability to handle high-dimensional data, and interpretability via feature importance.

4.5.1 Model Selection and Training

The full labeled dataset, enriched with cluster labels from the K-Means process, was split into a training and a test set using a 2:1 ratio. A grid search with 3-fold cross-validation was performed to identify the best hyperparameters for the Random Forest model. The following parameter grid was used:

- Number of estimators: [100, 200, 300]
- Maximum depth: [10, 15, 20]
- Minimum samples split: [2, 5]
- Minimum samples leaf: [1, 2]
- Class weight: [None, 'balanced']

The best model was found with 300 trees, a maximum depth of 20, and default class weights. The model achieved an accuracy of 98.3% on the test set.

4.5.2 Model Evaluation

The classifier was evaluated using standard metrics:

- **Accuracy:** 0.983
- **Macro F1-score:** 0.981
- **Weighted F1-score:** 0.983
- **Cohen's Kappa:** High agreement with actual labels

A confusion matrix and class distribution bar plots were created to assess prediction quality. All classes were well-separated with minimal confusion. The silhouette score of -0.1393, although typical for high-dimensional data, reflects some overlap near decision boundaries.

4.5.3 Feature Importance Analysis

The feature importance plot revealed which GPS tracking characteristics had the strongest influence on classification. The most informative features included bounding box area, point density and length.

SHAP (SHapley Additive exPlanations) values were also computed to explain individual predictions. Global and per-class SHAP summary plots confirmed the consistency of the feature contributions with domain expectations.

4.5.4 Prediction Analysis and Visualization

Several visual analyses were performed on the test set:

- **Boxplots** showing feature distribution across predicted labels
- **Normalized heatmaps** comparing average feature values per predicted class
- **PCA scatterplot** visualizing predicted clusters in 2D space
- **Geographic maps** of randomly sampled predicted routes for each label

These visualizations support that the classifier not only performs well statistically but also produces geographically and behaviorally consistent results.

4.5.5 Saving and Exporting the Classifier

The trained Random Forest model was serialized using `joblib` and exported as `rf_area_classifier_full.pkl`. This model can be directly integrated into production pipelines or reused for further research. Predictions from the classifier were stored for visualization and evaluation purposes in a CSV file.

4.5.6 Cross-Validation Results

To validate model stability, 10-fold stratified cross-validation was applied to the full dataset. The mean accuracy across folds was approximately 98% with a very low standard deviation, confirming the generalizability of the classifier.

4.5.7 Conclusion

The Random Forest classifier achieved high performance and provided interpretable insights into how GPS tracking data reflects urban, suburban, town, and rural driving patterns. The combination of clustering, semi-supervised learning, and explainable AI techniques created a robust classification pipeline for real-world tracking analysis.

4.6 Integration with API

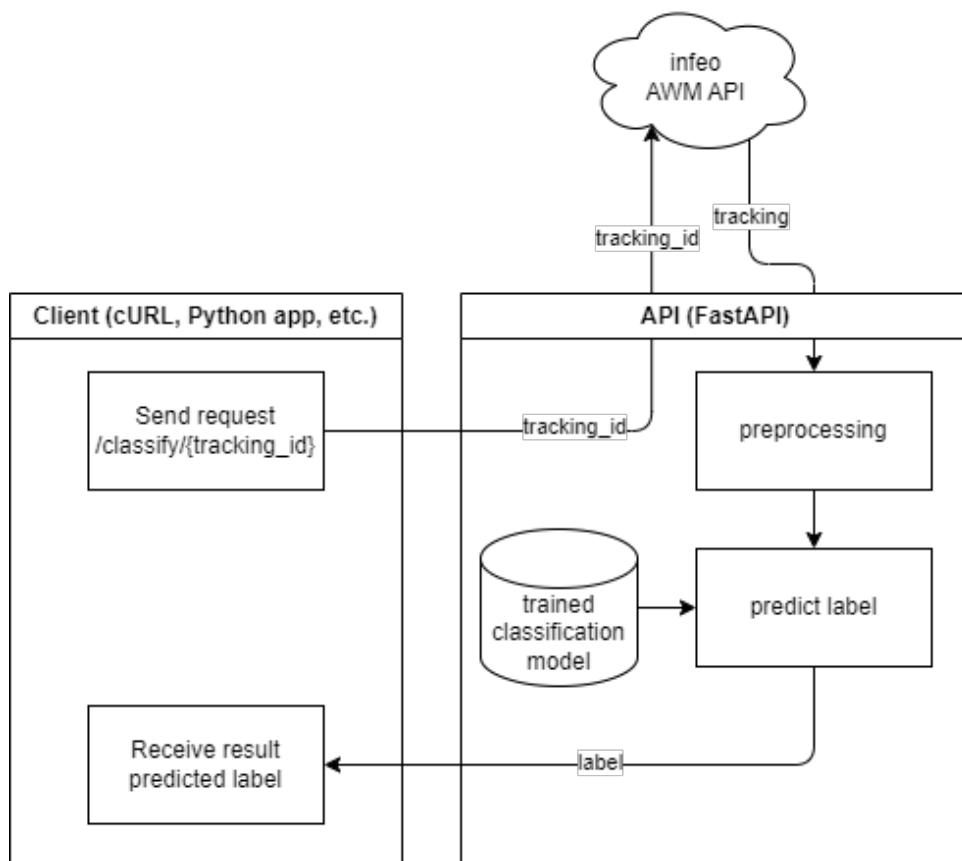


Figure 4.3: API Implementation Diagram

FastAPI 0.1.0 OAS 3.1

openapi.json

default

GET /classify/{tracking_id} Classify Tracking

Parameters

Name	Description
tracking_id <small>required</small>	string (path) 100914

Cancel

Execute Clear

Responses

Curl

```
curl -X 'GET' '\
http://127.0.0.1:8000/classify/100914' \
-H 'accept: application/json'
```

Request URL

```
http://127.0.0.1:8000/classify/100914
```

Server response

Code Details

200 Response body

```
{ "tracking_id": "100914", "predicted_class": "TOWN" }
```

Download

Response headers

```
content-length: 49
content-type: application/json
date: Thu, 12 Jun 2025 10:34:18 GMT
server: uvicorn
```

Responses

Code Description Links

200 Successful Response No links

The screenshot shows the FastAPI documentation interface for a classification API. At the top, it displays the API title 'FastAPI 0.1.0 OAS 3.1' and a link to 'openapi.json'. Below this, under the 'default' section, is a detailed view of a GET endpoint: '/classify/{tracking_id}' with the description 'Classify Tracking'. The 'Parameters' tab is active, showing a required parameter 'tracking_id' of type string (path) with the value '100914' entered into the input field. Below this are 'Execute' and 'Clear' buttons. The 'Responses' tab is also present. Under the 'Responses' tab, there's a 'Curl' section with a command to make a GET request to 'http://127.0.0.1:8000/classify/100914' with an 'accept: application/json' header. The 'Request URL' is shown as 'http://127.0.0.1:8000/classify/100914'. The 'Server response' section shows a JSON response: { "tracking_id": "100914", "predicted_class": "TOWN" }. This response is displayed in a code block with a 'Download' button. Below the JSON is a 'Response headers' section with the following content: 'content-length: 49', 'content-type: application/json', 'date: Thu, 12 Jun 2025 10:34:18 GMT', and 'server: uvicorn'. The 'Responses' tab also lists a successful response with code 200 and the description 'Successful Response'. There is no link provided for this response.

Figure 4.4: FastAPI documentation of classificationo API

5 Evaluation and Discussion

As a result of the implementation, many insights were gathered on the characteristics of the clustering and classifier.

This chapter presents a comprehensive evaluation of the clustering and classification results. It provides insights into the performance, limitations, and robustness of the developed system.

5.1 Definition of the data sets used for the evaluation

To assess the quality of the clustering and classification steps, various datasets at different stages of the pipeline were used. The final labeled dataset was split into training and test sets using a 2:1 ratio to evaluate the classifier's generalization ability.

5.2 Evaluation of the Results

5.2.1 Clustering Results

The DBSCAN clustering algorithm was used to remove noise points and outliers, resulting in the removal of 1,539 trackings. The PCA projection in Figure 5.1 shows the detected outlier cluster (-1), subsequently removed resulting in a cleaner structure for the K-Means clustering.

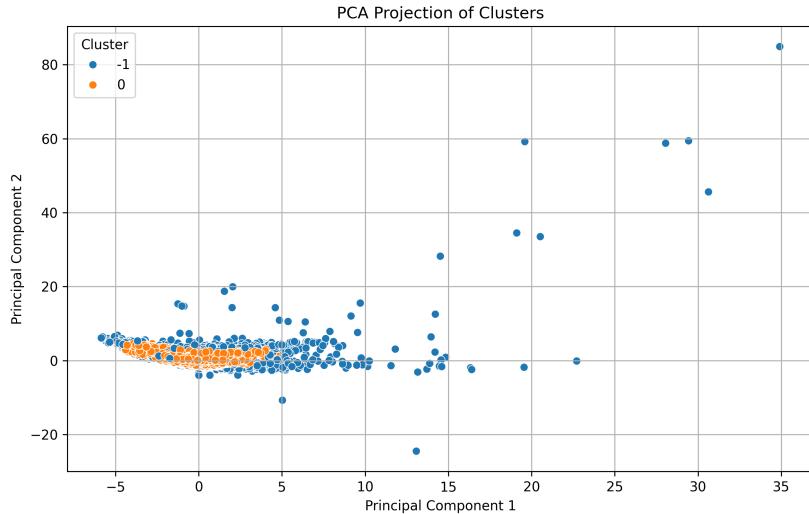


Figure 5.1: PCA Projection of DBSCAN clustering for noise removal

The feature weights calculated from the manually selected sample data showed that `bbox_area`, `point_density`, `straightness` and `length` were the most informative features. The concrete values are depicted in Figure 5.2.

Weighted K-Means clustering with custom initial centroids produced four distinct clusters. Each cluster was mapped to a label (0-URBAN, 1-SUBURBAN, 2-TOWN, 3-RURAL) based on feature statistic and visual inspection. The PCA projection in Figure 5.3 visualized the resulting cluster structure, with a final silhouette score of **0.2621** indicates a moderate clustering separation.

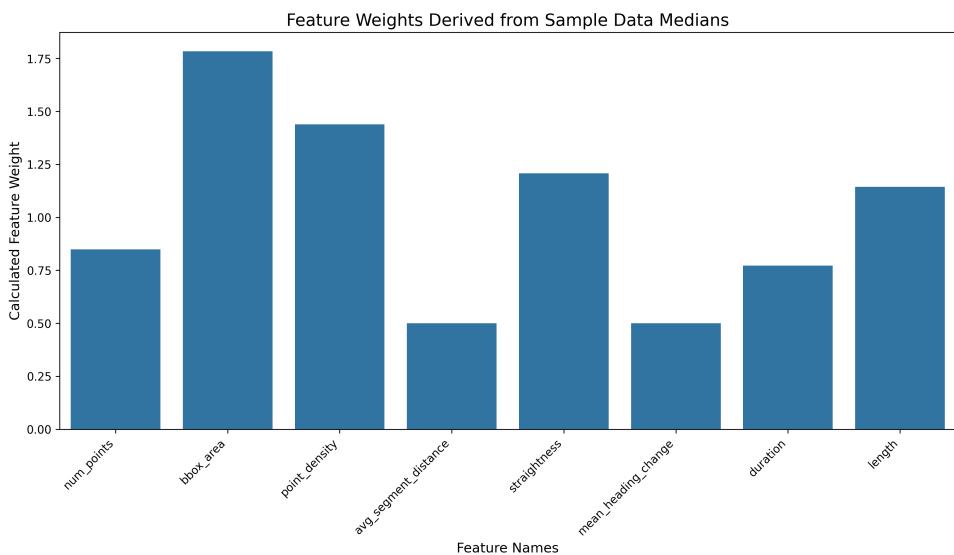


Figure 5.2: Feature Weights used for K-Means clustering

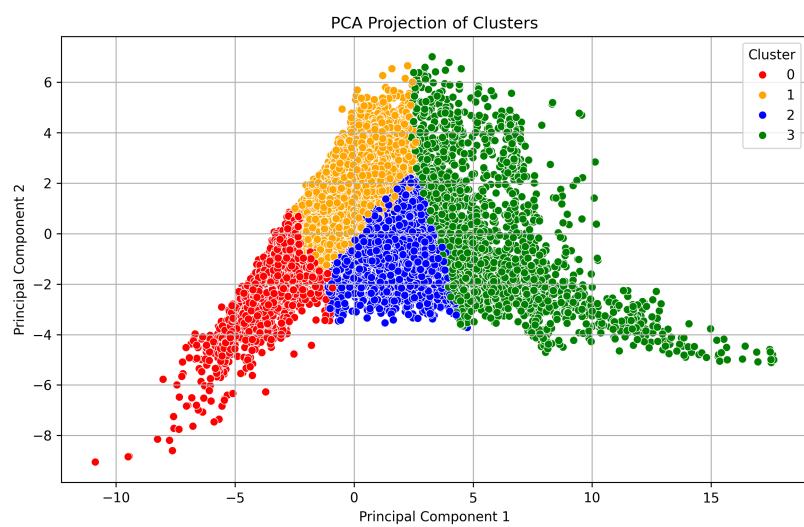


Figure 5.3: PCA Projection of K-Means clustering

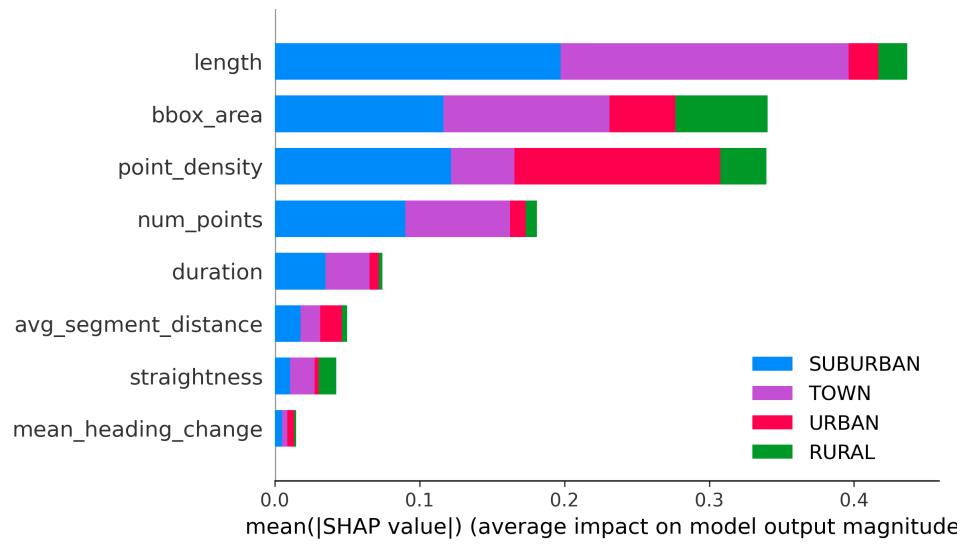


Figure 5.4: SHAP Summary for all Classes

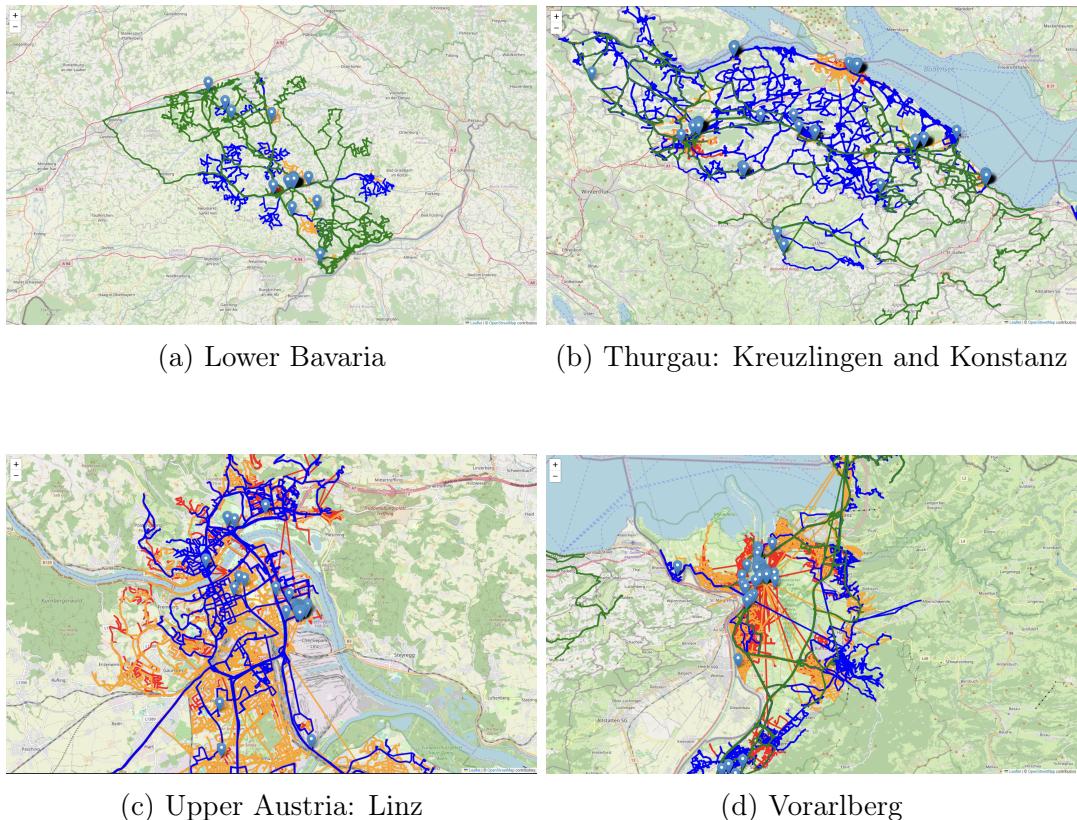


Figure 5.5: Map Visualization of Clustered Trackings (Red: URBAN, Orange: SUBURBAN, Blue: TOWN, Green: RURAL)

5.2.2 Classifier Results

A Random Forest classifier was trained with hyperparameter tuning. The model achieved high performance on the test set: Accuracy **98.3%**, Macro F1-score: **98.1%**, Weighted F1-score **98.3%** and Cohen's Kappa **97.3%**. The classifier showed balanced performance across all four classes, with precision and recall values above **97%** for all classes.

The feature importance analysis (Figure 5.7) highlighted [length], bbox_area, point_density and num_points as key contributing features.

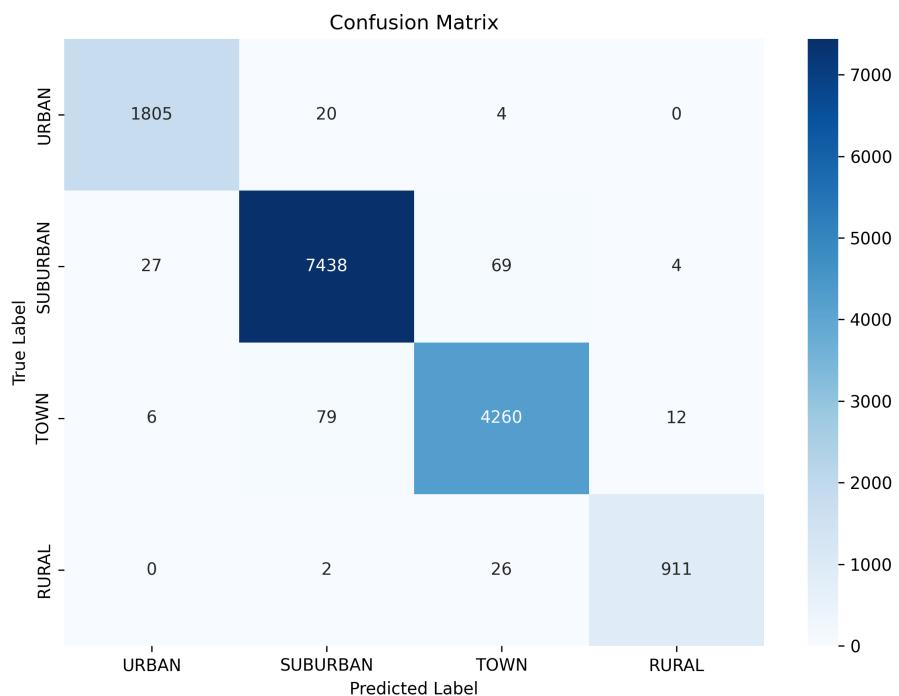


Figure 5.6: Confusion Matrix of Random Forest Classifier

The mean feature values across all four classes (Figure 5.8) confirm a monotonic relationships between classes in increasing rurality (e.g., URBAN to SUBURBAN to TOWN to RURAL) for the features bbox_area, point_density, avg_segment_distance and length.

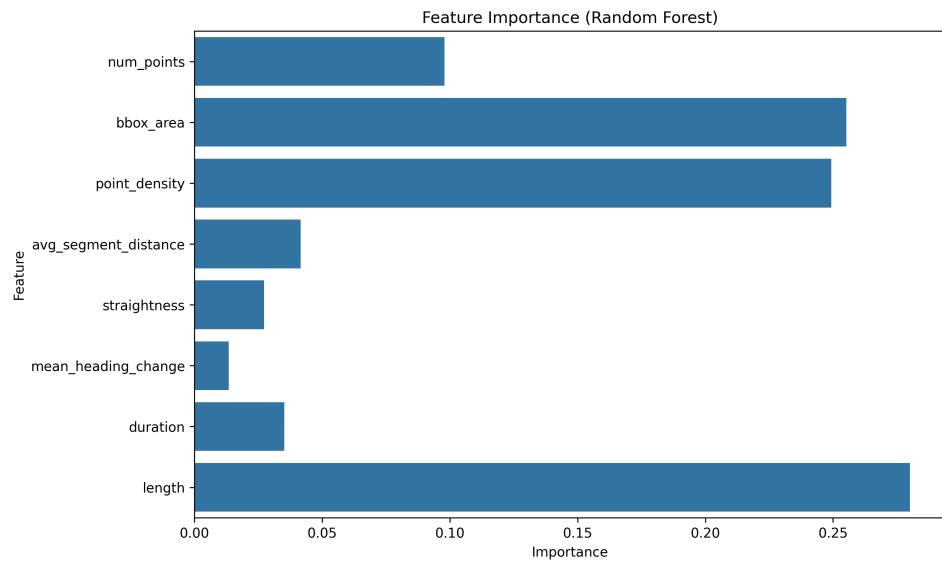


Figure 5.7: Feature Importance Barchart of Random Forest Classifier

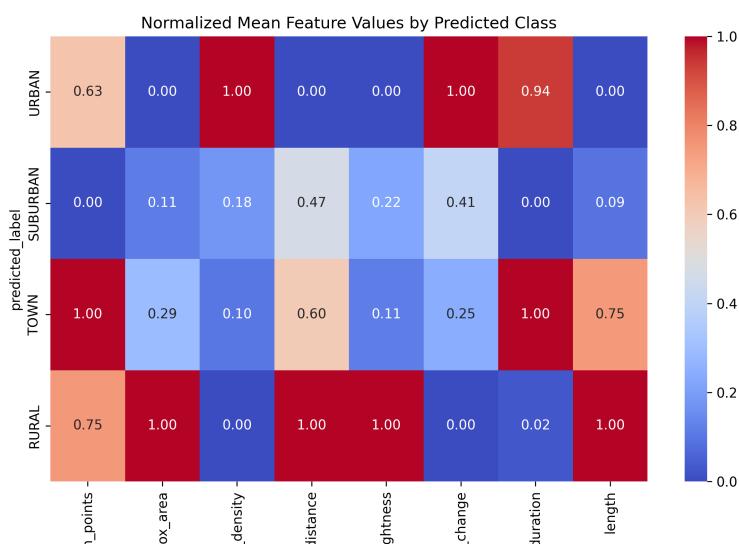


Figure 5.8: Normalized Mean Feature Values by Predicted Class

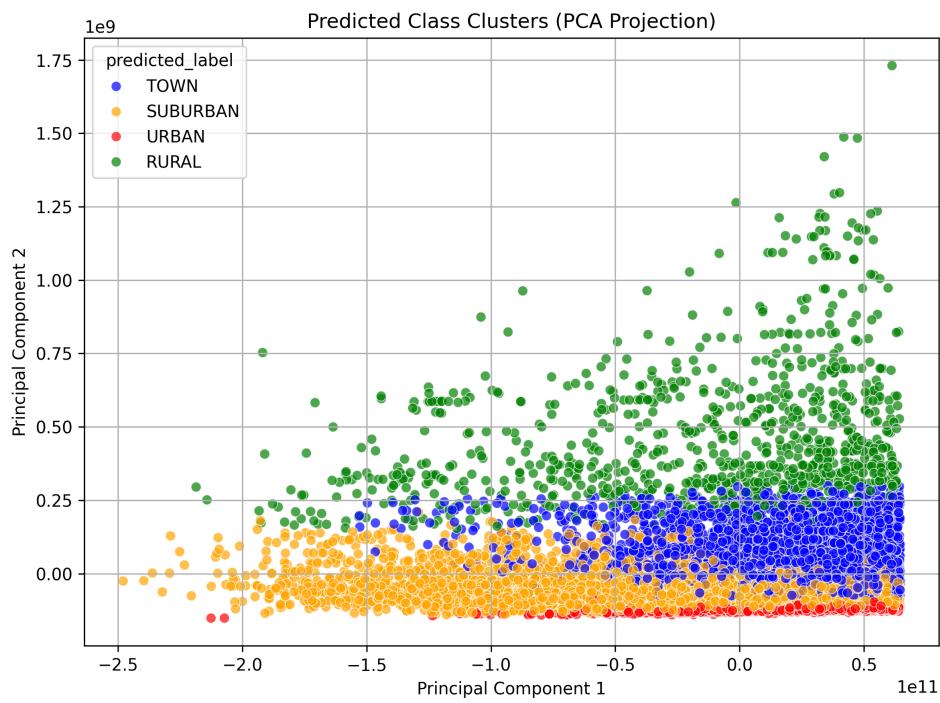


Figure 5.9: PCA Projection of Test Set with Predicted Labels

Finally four random trackings from each category were selected from the classified test set and visualized on map segments 5.12, validating the structural and spatial differences of the labels.

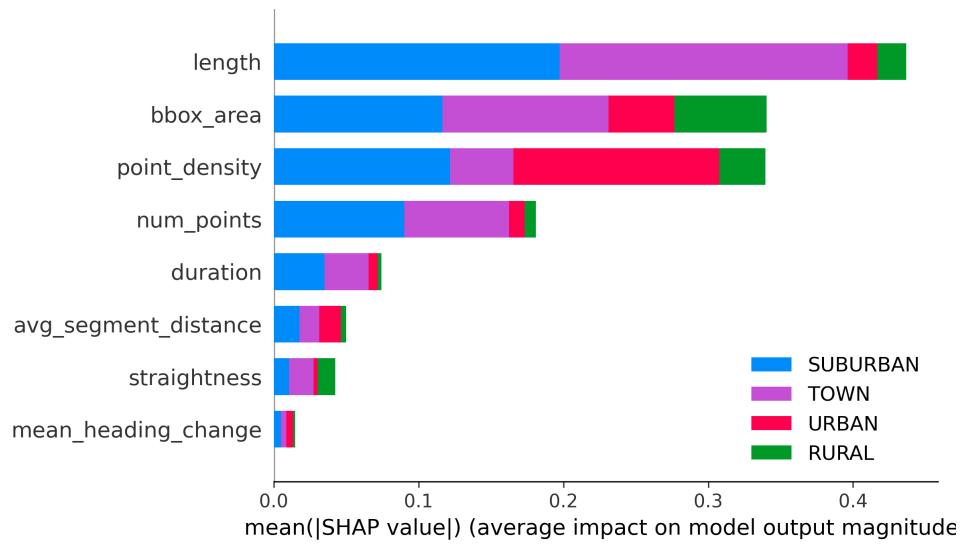


Figure 5.10: SHAP Summary for all Classes

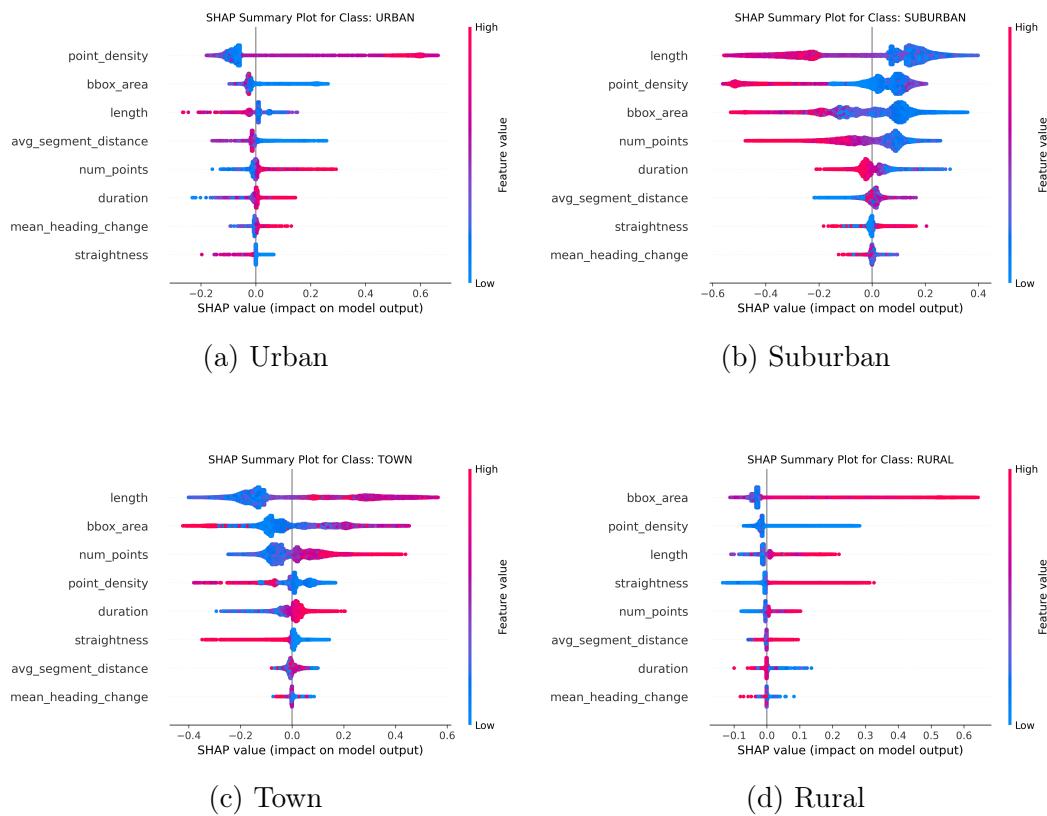


Figure 5.11: SHAP summary plots for all classes

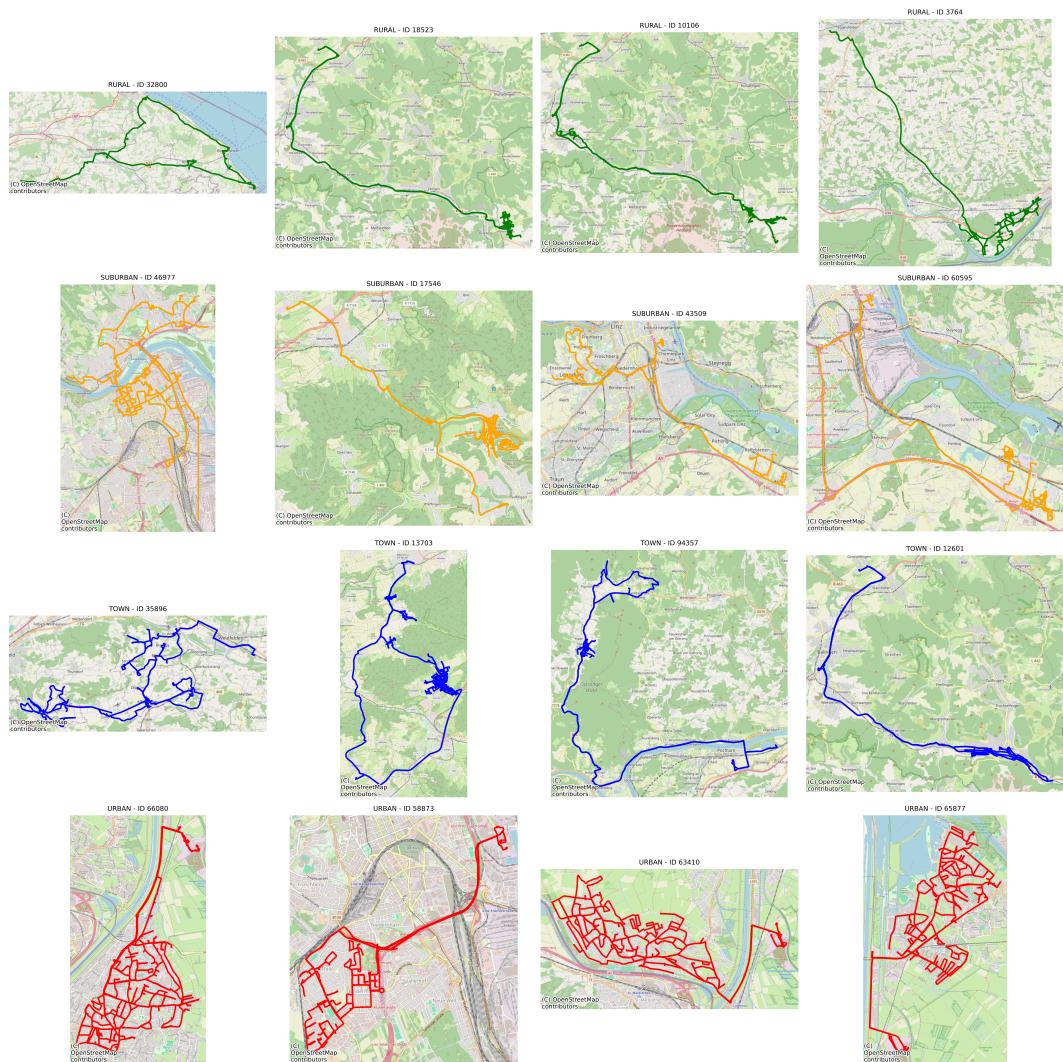


Figure 5.12: Sample Predictions on Test Set

5.3 Reflection on the Results

The clustering and classification pipeline effectively distinguishes between urban structures based on GPS tracking data, with the classifier achieving high accuracy with over **97%** in all key metrics. While the clustering silhouette score was moderate, visual and statistical inspection validate the cluster integrity.

However the negative silhouette score on the test set shows some significant overlap between classes. This could indicate the need to lower the amount of clusters to three, which might prove a better distinction between classes with less overlap.

The features `bbox_area`, `point_density` and `duration`, initially deemed suitable for distinction between classes, because of their monotonic behavior, were confirmed to be indicative discriminators. Furthermore, the classification results show that `avg_segment_distance` and `mean_heading_change` also follow monotonic behavior among classes, reinforcing the effectiveness of this pipeline.

The methods used demonstrate a reproducible and scalable framework for GPS-based route classification, applicable to waste management and beyond.

6 Conclusion

This thesis demonstrates that it is feasible to classify the structure of road networks using only GPS tracking data collected by waste collection vehicles. A robust pipeline to categorize trackings into four distinct urban structure types: URBAN, SUBURBAN, TOWN and RURAL was developed using feature engineering, semi-supervised clustering, and supervised classification.

6.1 Future Directions

Several opportunities exist to improve and extend this work.

One promising direction involves the integration of OpenStreetMap (OSM) data to augment the GPS based features with real-world structural information. On the one hand this could improve the classifier's ability to differentiate between trackings with similar GPS structure, while on the other hand enabling the comparison with areas where no data is collected.

Additionally, enhancing the preprocessing pipeline with a filter to remove transit segments between depots and services areas in the trackings can focus the analysis on the actual waste collection behavior.

Improving the selected sample for the semi-supervised clustering process, both in terms of amount and variation of manually labeled trackings could improve the feature weights and initial centroids heavily affecting the clustering process.

Finally, deploying the trained classifier as a REST API, would enable waste management companies to automatically classify GPS trackings in real-time, potentially enabling smarter planning, anomaly detection, and route optimization.

6.2 Limitations

Despite the promising results of the classification pipeline, several limitations must be acknowledged.

Firstly, the dataset used in this work is not raw GPS data but rather a compressed and preprocessed version provided by *infeo GmbH*. While this process

is necessary for storage and performance, it might have removed information that could improve the clustering and classification accuracy and reveal more fine grained distinction between the categories.

Secondly, while the dataset provides accurate GPS coordinates, the meta-data is limited or unreliable. Attributes such as speed are missing entirely, and loading and unloading events were only sparsely available. As a result only GPS-based features were used for feature extraction, potentially limiting the detection of behavior patterns initially deemed as valuable differentiators between classes, such as distance between loadings of the vehicles.

Furthermore, the dataset is not suitable for a direct comparison with Open-StreetMap (OSM) street data. Such a comparison would require the enrichment of the dataset with strucutral data from OSM or a complete derivation of route segments from OSM.

Lastly, the classification pipeline relies heavily on the semi-supervised clustering to generate labels. While it is effective for this dataset, it might require adjustments when extending the dataset to other cities and regions.

6.3 Final Remarks

Overall, this thesis provides a practical framework for analysing and classifying GPS tracking data in the waste management domain. It bridges the gap between raw GPS data and operational insights, laying the foundation for smarter, data-driven waste management systems.

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Affidavit

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Dornbirn, on 15. May 2025

Matthias Hefel