DEPARTMENT OF INFORMATION AND COMPUTING SCIENCE

Applied Data Science Master Thesis

The Complementary Potential of Free-Floating Car Sharing Services to Public Transport in Turin

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Abstract

This thesis studies the potential of free-floating car sharing (FFCS) to supplement public transport in Turin, a city with a well-developed transit system and substantial car sharing network. The integration of FFCS with public transportation can enhance connectivity, particularly for first- and last-mile solutions, thereby improving the overall efficiency and accessibility of the transit system. Although existing research indicates a potential complementarity between car sharing and public transport, further detailed research is required to explore more specifically when and where car sharing is able to complement public transportation.

This study uses the proximity of car sharing trip start and destination points to public transport stations in order to examine the potential for complementarity between the two services. A temporal and spatial analysis, employing k-means clustering, revealed a specific potential complementarity between FFCS and public transport in Turin in the early morning. This is evidenced by the FFCS service connecting the outskirts of Turin with the city centre when public transport is limited in availability. The analysis of Turin's specific dynamics can provide valuable insights to other cities aiming for similar integration between car sharing and public transport, contributing to more sustainable urban mobility.

Keywords: free-floating car sharing, public transport integration, (sustainable) urban mobility, complementarity, proximity analysis, k-means clustering

Contents

List of Tables and Figures

1. Introduction

1.1 Context

Car sharing tends to play a fundamental role in integrating with public transportation, as it has the potential to function as a complement to public transport services (Borghettti et al., 2022). This integration can facilitate the connection of public transport stations to final destinations for travellers, particularly through first- and last-mile solutions, thereby enhancing the overall efficiency and accessibility of the transit system (Barth & Shaheen, 2002; Coll et al., 2014). Free-floating car sharing (FFCS) services, which enable one-way trips without the need for the vehicle to be returned to its starting point, have been identified as particularly effective in this regard (Becker et al., 2017; Boldrini et al., 2019; Shaheen & Chan, 2016; Shaheen et al., 2020). Studies have shown a significant demand for FFCS service at central stations, which facilitate short-duration trips to nearby neighbourhoods (Guirao et al., 2021). Furthermore, car sharing represents an alternative mode of transportation when public transit services are less frequent or unavailable, such as during nighttime or in areas with limited public transport accessibility (Becker et al., 2017; De Lorimier & El-Geneidy, 2013; D'Urso et al., 2021; Kopp et al., 2015; Rotaris, 2021; Silvestri et al., 2021; Wagner et al., 2016).

The use of public transport is strongly encouraged from an environmental perspective, as it reduces various emissions, such as carbon dioxide, compared to private transport (Chicco & Diana, 2021). The shift towards shared mobility is part of a broader trend described by Rifkin (2000) as the "Age of Access," a period in which the traditional concept of ownership is replaced by access. This trend is evidenced by the growing popularity of car sharing, which combines private and collective transportation characteristics, offering a flexible and affordable solution (Zhou & Kockelman, 2011). The European Commission targets, including becoming climate neutral by 2050 and reducing greenhouse gas emissions by at least 55 percent by 2030, stress the importance of developing alternative mobility sources such as car sharing (European Commission, 2018). By studying the potential for FFCS to supplement public transport in the development of an efficient transit system that is more appealing to travelers, this thesis can contribute to the enhancement of urban mobility sustainability in a city like Turin.

1.2 Previous studies

1.2.1 Characteristics of car sharing users

A number of studies have been conducted on the typical characteristics of car sharing users, often using clustering techniques (Caulfield & Kehoe, 2021; Pirra & Diana, 2020; Reiffer et al., 2019). One characteristic that is frequently mentioned in the literature is that car sharing users tend to use public transport services more frequently than non-car sharing users (Kopp et al., 2015; Münzel et al., 2019; Project M, 2010; Rotaris, 2021). Research indicates that car sharing can complement public transport, with several studies demonstrating an increase in public transport use among car sharing users (Koch, 2001; Katzev, 2003; Shaheen & Cohen, 2007;

Shaheen et al., 2020). In more specific terms, Baum and Pesch (1994) reported an increase of 39 percent in public transport use after joining a car sharing organisation. Lightfoot (1997) indicated an increase in public transport use of each type, with annual train use increasing by 7 percent among car sharing members and bus use by 18 percent. However, there are studies that indicate the opposite; car sharing may reduce demand for public transportation, particularly during certain time periods in which public transport is not efficient enough, suggesting its potential to substitute public transportation (de Luca & Di Pace, 2015; Martin & Shaheen, 2011). Additionally, Ramos et al. (2020) did not find higher levels of public transportation use among car sharing users. Moreover, Martin et al. (2011) asserted that multiple car sharing users reduced their rail and bus use after joining the service.

Rotaris (2021) indicated that car sharing users are most likely to use public transport services during weekdays. Loose (2010) noted that car sharing users are more likely to possess season tickets for public transport than the general population. Furthermore, Kopp et al. (2015) highlighted that FFCS users in particular have a greater number of public transport subscriptions in comparison to non-users. Moreover, Synovate (2007) acknowledged that car sharing users rely on public transport services for daily commuting trips. Furthermore, car sharing tends to be used the most in high-density areas, close to city centres, which also tend to have more public transport stations available nearby (Guirao et al., 2021; Kopp et al., 2015). As Cervero et al. (2007) and Klincevicius et al. (2014) have observed, individuals residing in areas with greater distances from city centres and poorer connections with public transport are more likely to own private vehicles and therefore less likely to use car sharing services. Moreover, car sharing is particularly appealing for journeys of a short distance, which may take longer than usual due to traffic congestion in urban areas (Ceccato & Diana, 2021). These trips have a typical duration of 15 to 30 minutes and cover a distance of 10 kilometres (Silvestri et al., 2021). The study of IPR Marketing (2009) found that Italian car sharing users show similar characteristics to those mentioned above, including the use of public transport on a daily basis.

1.2.2 Integration of car sharing into the public transport system

A number of studies have highlighted the importance of a dense public transport infrastructure for the success of car sharing services (ISFORT, 2018, Mastretta et al., 2005; Mukai & Watanabe, 2005). This is in line with the aforementioned car sharing users' characteristics, in which it is pointed out that car sharing users tend to use public transportation often. This indicates that public transportation, in conjunction with car sharing, can facilitate complete journeys.

A more detailed examination of the study area, Turin, demonstrated that car sharing is primarily regarded as a supplementary service to public transport, with the two modes often considered as an alternative to personal vehicles (Morgavi & Di Loreto, 2017). Furthermore, a study conducted for a university campus in Turin indicated that one of the most prevalent motivations behind the utilisation of car sharing is the desire to integrate with other transportation modes (Pirra & Diana, 2020).

1.2.3 Modelling relation between car sharing and public transport

In a temporal analysis of the availability of FFCS cars in Turin over a two-week period, Guirao et al. (2021) observed that there were more available cars near rail stations in the morning (between 8:00 AM and 12:00 AM) due to the start of working days. Additionally, Ceccato and Diana (2021) conducted research on the relationship between FFCS and existing transport modes in Turin, including public transport (metro, train, urban and suburban bus) and private transport (car as driver and passenger, taxi, bike). They identified some complementarity between car sharing and public transport as evidenced by the higher likelihood of car sharing members to also use public transport and the positive correlation between bus trip frequency and car sharing usage.

1.3 Research question

While existing research has demonstrated that users of car sharing tend to use public transport more frequently than non-users, suggesting a potential complementarity between these two modes of transport, there is a need for more detailed research to explore the circumstances ("when and where") under which car sharing is able to complement public transport. This is an area that is currently underrepresented within the literature. The objective of this study is to address this gap by investigating the potential complementarity between FFCS and public transportation in Turin.

Turin presents a unique case study, given its well-developed public transport system and extensive car sharing services. These are discussed in detail in subchapter 2.1. This study is relevant because it addresses the potential for integrated mobility solutions that improve public transport systems, reduce reliance on private vehicles and thus contribute to environmental sustainability. An understanding of the specific dynamics in Turin can provide valuable insights for other cities aiming to achieve similar integration between car sharing and public transport. The research question is as follows: "How can free-floating car sharing potentially complement public transport in Turin?"

2. Study case on data

2.1 Mobility in Turin

The metropolitan city of Turin offers a wide range of public transport services, including one metro line and 83 bus lines (GTT, n.d.-b). In particular, urban areas have a well-developed public transport system, although it is challenging to reach certain parts of the city centre by public transport due to the narrow roads (Caputo, 2012). Overall, public transport accounts for approximately 30 percent of all daily trips made in Turin (Chicco & Diana, 2021). The main train stations of Turin are Porta Nuova and Porta Susa, which are located in the city centre (Train Stations, n.d.). The train service at Porta Nuova typically commences at 4:45 AM and concludes at 10:45 PM (DB Navigator, n.d.). The train service at Porta Susa typically commences at 5:00 AM and concludes at midnight. The metro line is available from 5:30 AM from Monday to Saturday and from 7:00 AM on Sunday (GTT, n.d.-b). The metro line is operational until 10:00 PM, with the exception of Fridays and Saturdays, when it remains open until 1:30 AM. Bus services typically commence between 4:15 AM and 5:30 AM in the morning and terminate between 1:00 AM and 2:00 AM at night (GTT, n.d.-b). It is assumed that in Italy, including Turin, there are morning and afternoon/evening traffic peaks between 7:00 AM and 9:15 AM and 16:00 PM and 19:30 PM respectively (Hale & Charles, 2009).

The concept of car sharing in Italy originated from a series of experimental initiatives in Milan, which were developed under the auspices of European projects. This led to the National Car Sharing Program, which was launched between 1999 and 2000 (Caputo, 2012). This programme was employed as a strategic factor for the development of sustainable mobility in urban areas in Italy. Italy is the only country where the sought convergence between car sharing and public transport is "native", given that in most cases the public transport company is directly involved in the initiation of the car sharing services. Furthermore, Italy has a national coordination system, known as Iniziativa Carsharing (ICS), which is also unique in Europe. This system assists in the development of the car sharing system (Laurino & Grimaldi, 2012).

The general concept of car sharing was first introduced in Turin in 2002. In 2013, the “free-floating” concept of car sharing services was first introduced in the city of Milan, and today 29 cities in Italy, including Turin, own this mobility service (Osservatorio, 2016). The FFCS service is characterised by one-way trips. The vehicle does not have to be returned to its starting point and can be parked elsewhere within a restricted operational area (Shaheen et al., 2020). The car sharing services in Turin comprise three free-floating systems. Two of these systems use public parking spaces and are operational across the majority of the city, with approximately 750 cars since 2015. The remaining system uses 54 pool-and-charging stations with 130 electric vehicles, which were introduced at the end of 2016 (Osservatorio, 2016). In 2015, the total number of members was approximately 51,500 people. In recent times, there has been a notable reduction in the overall fleet size of car sharing services in Turin, with an 8 percent decrease in the number of vehicles available for sharing. This compared to a significant increase of 54 percent in the number of trips taken by car sharers from September 2016 to February 2017 (Urbi, 2017).

2.2 Description of the data

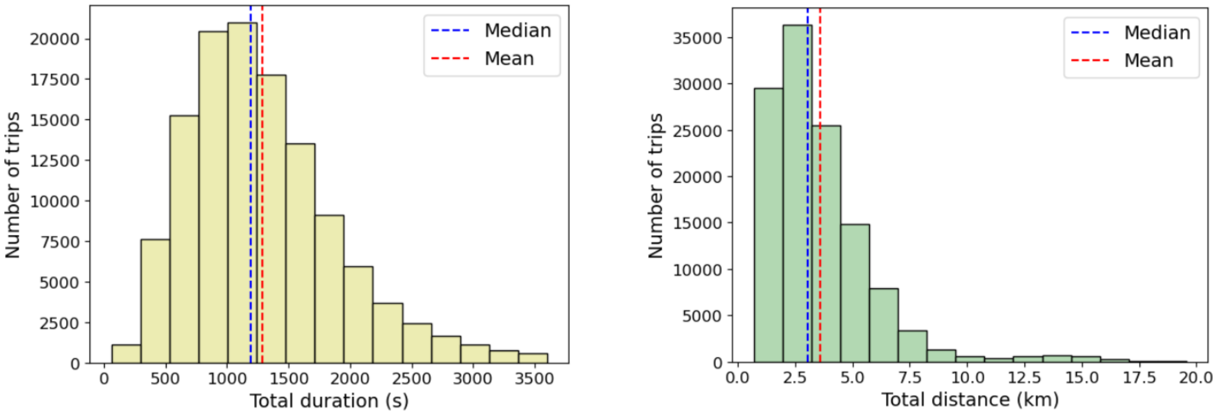
Vassio et al. (2019) retrieved a dataset on FFCS trips with temporal coverage from September 2017 to November 2017 and geospatial coverage of the city of Turin in Italy. The dataset comprises 122,016 entries and contains data regarding the latitude and longitude values, in Coordinate Reference System (CRS) EPSG:4326, of the start and destination points of the electric cars used. Additionally, it contains the start and end time of the car sharing trips in UNIX timestamp format; the number of seconds elapsed since 1 January 1970 at 00:00:00 UTC.

The open data portal of the city of Turin, AperTO, maintains a dataset on existing and under construction train stations (Stazioni ferroviarie, n.d.). The dataset comprises 12 entries, with each entry providing the name of the station, the type of station (i.e., whether it is an existing or new station), and the geometry of the location of the stations in EPSG:23032. The most recent update to the dataset was conducted by the municipality of Turin in July 2019. The municipality of Turin maintains also a dataset regarding the metro stops, which comprises 19 metro stations (Fermate metropolitana, n.d.). For each station, the name of the station with associated location in x and y coordinates is maintained in EPSG:3003. The dataset was last updated by the Municipality of Turin in January 2020. The Regional Government of Piedmont has published a dataset concerning the bus stops of Gruppo Torinese Trasporti (GTT, n.d.; Servizio programmato del trasporto pubblico Regione Piemonte (TPL) - GTFS Autobus, n.d.). As this dataset encompasses a wider area than Turin alone, it comprises a total of 18,042 entries. Each entry contains the name of a bus stop and the latitude and longitude of the stops in EPSG:4326. The data is valid for the year 2024 and is updated daily.

2.3 Preparation of the data

The Python programming language was employed to process and analyse the data. Initially, the car sharing trips data was subjected to a preliminary examination to identify missing values and duplicate records. Furthermore, feature engineering was employed to expand the dataset. This involved the creation of a new column representing the duration of each car sharing trip, derived from the start and end times of the trips. Additionally, the latitudes and longitudes of the start and end points of each trip were converted to a specialised format, known as “Point” objects. Furthermore, the date, weekday, and daily hours were determined from the start and end timestamps of the car sharing trips. In addition, a column was created to indicate whether the car sharing trip started and/or ended on the weekend, specifically Saturday and Sunday. This was achieved through a weekday categorisation. A column was subsequently added to the dataset, which identified a specific part of the day. In this case, the morning period was defined as 6:00 AM until 11:59 AM, midday as 12:00 PM until 17:59 PM, the evening period as 18:00 PM until 23:59 PM, and night as 0:00 AM until 5:59 AM. Additionally, a Euclidean distance formula was used to estimate the distance travelled by car sharing users, utilising the start and end locations of the trips.

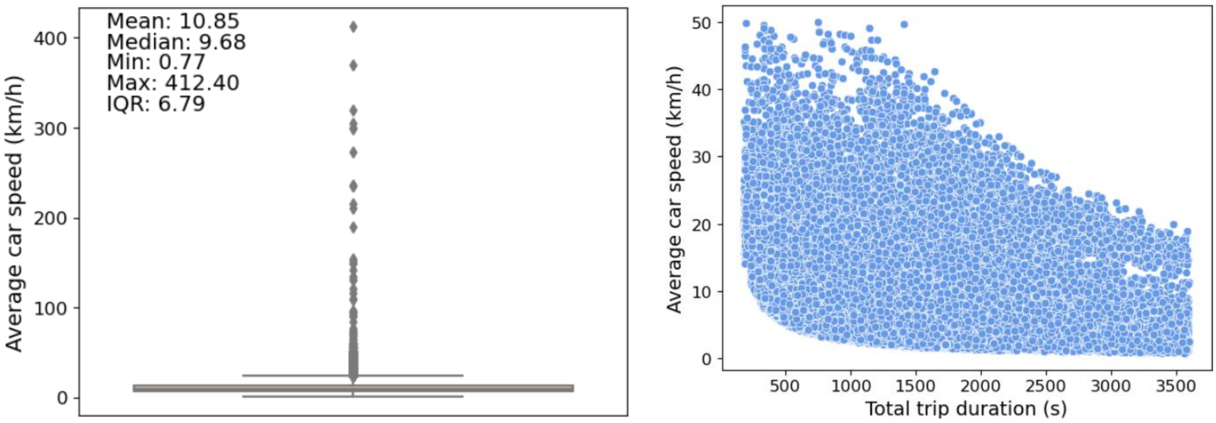
An outlier analysis was performed on the created car sharing trip duration and distance columns. Histograms of both features, see Figure 1, were created to investigate whether the data fell within normal ranges, given that the car sharing trips were all within the area of the city of Turin.



(a) (b)

Figure 1. Car sharing trip characteristics: (A) Duration of car sharing trips and (B) Distance of car sharing trips.

In addition, the average car speed was calculated by dividing the distance, in kilometres, by the duration, in hours, in order to quantify the relationship between duration and distance. A boxplot of the average car speed revealed some outliers with exceptionally high average car speeds, see Figure 2 (A). Cocca et al. (2018) used the same dataset in their study and used thresholds of a minimum trip duration of 180 seconds and a minimum trip distance of 700 metres to exclude outliers. After adopting the aforementioned threshold values and plotting the trip duration against the car speed using a scatterplot, as illustrated in Figure 2 (B), this resulted in a reduction of the maximum average speed to approximately 50 km/h. This was considered plausible given that the maximum speed permitted in urban areas in Italy is 50 km/h (Driving in Italy – requirements, speed limits & car parking advice, n.d.).



(a) (b)

Figure 2. Car sharing data outlier analysis: (A) Average car speed distribution and (B) Average car speed versus distance of car sharing trips.

After pre-processing the car sharing data, the data related to public transport stations was prepared. The datasets containing information on metro and bus stops were converted to GeoDataFrames. This involved transforming the original comma-separated values (CSV) and plain text (TXT) files into GeoDataFrames using the locations present in the original data to create geometry columns. The dataset containing train stops was already a shapefile, therefore the data already contained a geometry column, which could be loaded directly as a GeoDataFrame. As the bus stop data's geospatial range extended beyond Turin, and to ensure that all metro stops and train stations were within the boundaries of Turin, the datasets were first clipped to a polygon of the city of Turin (GADM, n.d.). This was achieved by utilising "level3" Global Administrative Areas (GADM) data, which is also known as city-level data. A column was then added to each dataset, specifying what public transport station the data contains (i.e., "train," "metro," or "bus"). This was useful later when the datasets were merged. In the case of the train dataset, the stations that were included in the analysis were those that are currently operational. In order to merge the GeoDataFrames into one GeoDataFrame, it was necessary for each GeoDataFrame to have the same CRS. Consequently, the CRS of all three geodata frames were converted to EPSG:4326, as the car sharing GeoDataFrame already had this CRS. A column was then added to the merged GeoDataFrame with a unique identifier for each station. The GeoDataFrame eventually comprised 8 train stations, 19 metro stops and 1,250 bus stops. All train, metro and bus stations present in the GeoDataFrame have been visualised using Quantum Geographic Information System (QGIS), see Figure 3.

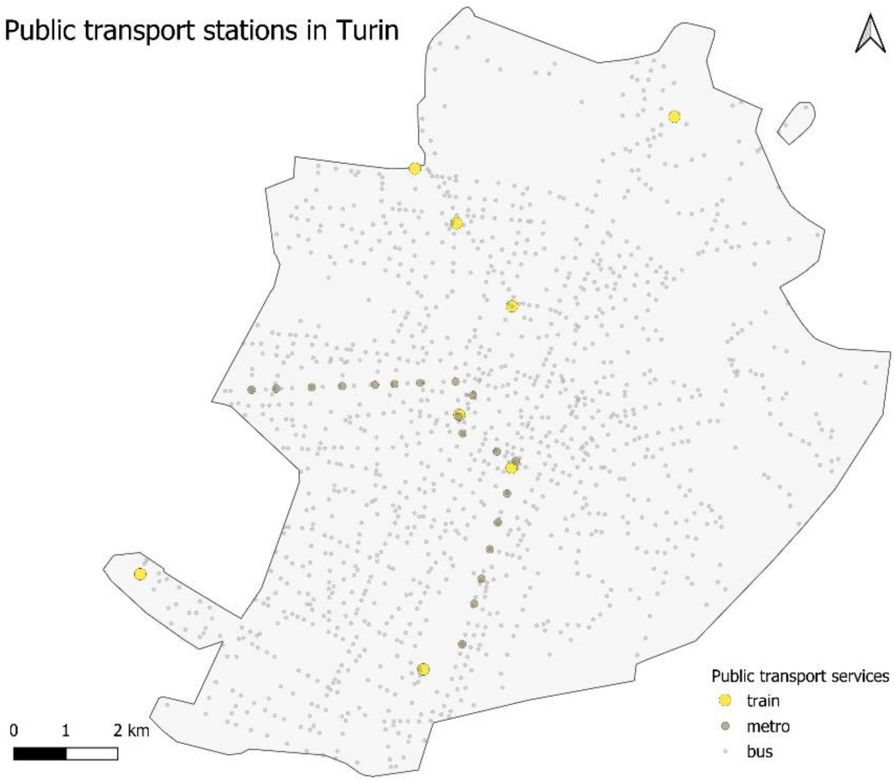


Figure 3. Public transport stations in Turin, Italy.

3. Method

The research question of this thesis is as follows: "How can free-floating car sharing potentially complement public transport services in Turin?" To investigate this, the research question is translated into a data science question that can be addressed through quantitative analysis: "How does the proximity of free-floating car sharing trip start and destination points to public transport stations indicate potential integration of car sharing with public transport in Turin?"

Firstly, in order to ascertain the proximity of the start and destination points of the car sharing trips to public transport services, a series of calculations were conducted. For each type of public transport, namely train, metro and bus, the number of stations situated within a radius of 500 metres from the start and destination points of the car sharing trips was determined. The distance of 500 metres was selected as it was found to be the most reasonable maximum distance that people are generally willing to travel on foot until reaching an FFCS car (Herrmann et al., 2014). The shortest distance from each start and destination point of the car sharing trips to each nearest train, metro and bus station was also determined. Both calculations used the haversine distance formula. The features presented in Table 1 were employed in the subsequent analyses, which are divided into two categories: temporal and spatial features.

Table 1. Temporal and spatial features used during analysis.

Temporal features		**Spatial features**	
Name	*Explanation*	*Name*	*Explanation*
Hours	All hours of a day from 0 to 23.	**Longitude and latitude**	Location of the start and destination points of the car sharing trips.
Day parts	Daily hours divided into periods: morning (6:00 AM to 11:59 AM), midday (12:00 PM to 17:59 PM), evening (18:00 PM to 23:59 PM), and night (0:00 AM to 5:59 AM).	**Trip duration**	Duration of car sharing trips in seconds.
Weekdays	Categorisation of days; Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, and Sunday.	**Trip distance**	Distance of car sharing trips in kilometres.
Weekend	Indicates whether the weekday falls within the weekend (Saturday and Sunday).	**Minimum distance to public transport stations**	Minimum distance in metres between the start and destination points (two distinctive features) and a train, metro and bus station (three different features, making a total of six features).
		Amount of public transport stations within 500m	Number of train, metro, and bus stations (three distinctive features) within 500m of a car sharing trip start and destination point (two distinctive features, making a total of six features).

3.1 Temporal analysis

As the FFCS data covers only a three-month time span, the temporal analysis focused on dayparts and weekdays. To facilitate temporal analysis of dayparts, an additional column was added to the dataset, consisting of timestamps of every 15 minutes during a day. The data, comprising the number of public transport stations within 500 metres of each start and destination point of the car sharing trips, was then grouped according to the 15-minute time intervals. Additionally, the number of unique trip IDs was counted per 15-minute time interval. This number is used to ascertain the proportion of start and destination points situated within 500 metres of public transport stations in comparison to all start and destination points within one 15-minute time span. Both the absolute count of public transport stations within 500 metres of the start and destination points and the relative percentage were visualised using line plots in order to identify potential temporal trends. For the temporal analysis of weekdays, the data was grouped according to the weekday. In this instance, the absolute count and relative percentage were analysed using bar plots.

3.2 Spatial analysis

In addition to investigating temporal trends in the proximity of car sharing trips to public transport stations, spatial patterns were also examined. These spatial patterns were attempted to be captured using clustering. Initially, this involved determining which features could potentially be clustered on. Both temporal and spatial features were used, encompassing categorical variables such as dayparts, weekdays and weekends, and numerical variables including trip duration and distance, location (latitude and longitude), minimum distance to public transport stations and the number of public transport stations within 500 metres of each start and destination point of the car sharing trips (Table 1). Prior to clustering, one-hot encoding was applied to the categorical features and min-max normalisation was applied to the numerical features. The locations of the start and destination points of the car sharing trips were also normalised, given the limited range of latitudes and longitudes within the study area, which is restricted to Turin. This feature would otherwise be deemed less important during clustering than the other features that have a wider range of values. Three distinct cluster analyses were conducted. The initial analysis employed both temporal and spatial features. Subsequently, the analysis was repeated with the sole inclusion of spatial features, and a post-analysis was conducted on the temporal features. The post-analysis involved investigating the values of the temporal features across the various clusters resulting from the spatial features. Additionally, an ensemble clustering method was employed in which the cluster assignments derived from solely clustering on temporal features were used as additional features when performing clustering on spatial features.

K-means clustering was employed due to its computational efficiency. As k-means clustering requires prior specification of the number of clusters, the elbow method was used to determine the optimal number of clusters (k). The elbow method used Within-Cluster-Sum-of-Square (WCSS) values as a measurement of distortion. The optimal k value is the point where the graph forms an elbow. The method of initialization employed was “k-means++”, which selects initial cluster centroids through sampling based on an empirical probability distribution of the car sharing trip start and destination points’ contribution to the overall inertia. This method was selected due to its ability to accelerate convergence, thereby enabling the exploration of higher values for the maximum number of iterations and the number of times the algorithm is run with different centroid seeds to identify optimal clusters. A maximum number of iterations of 300 was used, with 20 initial runs conducted in total. (KMEANS, n.d.)

To analyse the resulting clusters from the k-means algorithm, heatmaps of the cluster centroids were created representing the feature values of the centroid point in each cluster. To determine the goodness of the clustering, silhouette coefficient values were used, which quantify the separation distance between the resulting clusters. This distance is a measurement of the proximity of each car sharing trip start and destination point in one cluster to the points of neighbouring clusters. The silhouette score typically ranges from -1 to 1, with 1 indicating that the sample is far away from neighbouring clusters and a value of 0 indicating that the sample is remarkably close to the decision boundary between two neighbouring clusters. Negative values indicate that samples are assigned to the wrong cluster. (Selecting the number of clusters with silhouette analysis on KMeans clustering, n.d.)

To conduct a spatial analysis of the clusters, a scatter plot was created with the longitude on the x-axis and the latitude on the y-axis. Each cluster was assigned a unique colour. Additionally, the cluster centroids were visualised. This was achieved by first performing an inverse transform of the identified normalised latitude and longitude values, which unnormalized the values, allowing the centroids to be plotted on the scatter plot.

3.3 Comparison analysis

The temporal and spatial analyses of the car sharing trip start points were compared with those of the car sharing trip destination points. Identifying potential similarities or differences in the proximity of car sharing trip start and destination points to public transport stations was an essential step for determining the circumstances in which car sharing can complement public transport in a city like Turin. In the temporal analysis, the comparison consisted of pointing out differences in daily and weekly trends from the plots of the car sharing trip start and destination points. In the spatial analysis, the resulting clusters of the car sharing trip start and destination points were compared based on the visualization of the clusters on the map of Turin, while comparing the cluster centroids values. Finally, in the post-analysis of the clusters, a comparison was also drawn between the car sharing trip start and destination points.

4. Results

4.1 Temporal analysis

4.1.1 Daily trend

The analysis of the number of car sharing trips starting and ending within 500 metres of public transport stations revealed certain peaks and troughs in the daily trend, see Figure 4 and Figure 5. For example, the number of start points within 500 metres of train, metro and bus stations exhibited an early morning peak between 6:30 AM and 6:45 AM and a late afternoon peak between 4:45 PM and 5:00 PM. Smaller peaks could be observed at 10:30-11:00 AM, 12:30 PM, and 8:30-9:00 PM. The lowest number of start points within 500 metres of train, metro and bus stations was observed between 1:15 AM and 2:45 AM. With regard to the number of destination points within 500 metres of public transport stations, the same peaks could be observed. For instance, the morning peak was only slightly later, occurring around 7:00 AM, while the late afternoon peak occurred around 4:15 PM for train and metro stations and from 4:15 PM to 5:45 PM for bus stations. Additionally, the narrow peaks corresponded to the following times: 11:00-11:15 AM, 12:45-1:00 PM, and 9:00 PM. However, counts of destination points within 500 metres of public transport stations also showed a small peak around 2:15 PM. The lowest number of destination points within 500 metres of the public transport stations was also approximately the same as the start points, occurring between 1:30 AM and 3:00 AM.

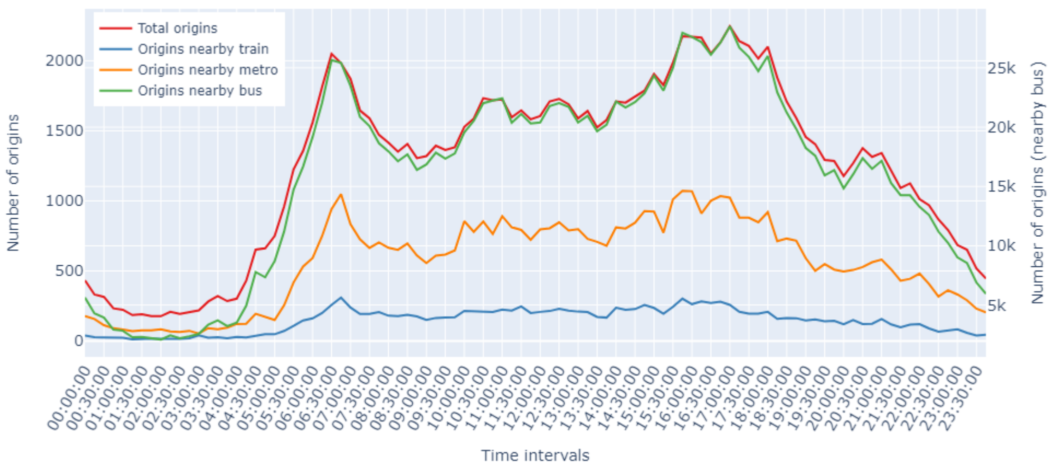


Figure 4. Daily trend of car sharing trip start points within 500m of public transport stations.

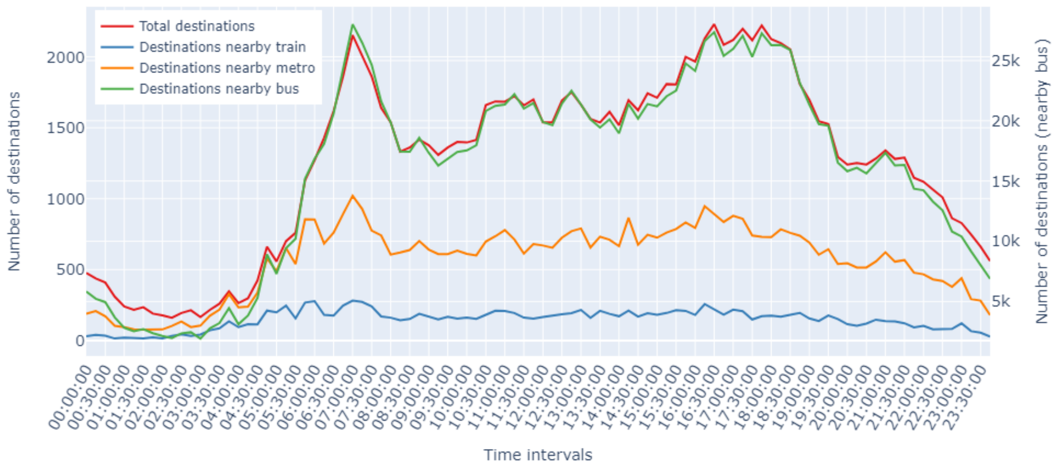


Figure 5. Daily trend of car sharing trip destination points within 500m of public transport stations.

The temporal analysis, which considered the proportion of the number of start and destination points within 500 metres of public transport stations to the total number of start and destination points over the same time period, also revealed certain patterns, as illustrated in Figure 6 and Figure 7. However, this excluded the number of start and destination points within 500 metres of bus stations as a proportion because this exceeded 100 percent. This is due to the fact that there are so many bus stops in Turin that (almost) every start and destination point of the car sharing trips was within 500 meters of multiple bus stops.

With regard to the train stations, a substantial proportion of the start points were located within 500 metres at approximately 3:00 AM, namely 20 percent. With regard to the destination points, the peak occurred slightly later, at 3:45-5:15 AM, and was twice as large, around 40 percent. During the day, the proportional trend remained somewhat consistent for both the start and destination points. In this regard, the percentage remained 12 to 15 percent between 6:45 AM and 4:45 PM for the start points. For the destination points, a longer, more consistent period from 6:30 AM to 11:30 PM represented approximately 10 percent. The lowest lows for the start points were observed between 1:15 AM and 4:15 AM, while for the destination points, the lowest lows were observed around 11:30 PM and 1:30 AM.

In general, there were always, more start and destination points within 500 metres of metro stations than train stations. With regard to metro stations, the proportion of start points within 500 metres reached a maximum at approximately 6:45 AM and 10:00 AM, with values of approximately 53 percent and 57 percent, respectively. For destination points, the highest peaks occurred at approximately 3:45 AM and 5:15 AM, with both a proportion of approximately 95 percent. Furthermore, two additional peaks were observed for the destination points, occurring at approximately 2:30 AM and 11:00 PM, with proportions of 69 percent and 53 percent, respectively. Once more, the proportional trend observed during the day remained consistent. With regard to the start points, the aforementioned trend was observed from 6:00 AM to 2:15 AM, with a value of just below 40 percent. For the destination points, the trend remained consistent throughout the same period, with a value just above 40 percent. For the start points, a noticeable trough was observed at approximately 3:00 AM and 5:00 AM, with values of approximately 25 and 20 percent, respectively. No discernible trough was evident in the data for the destination points.

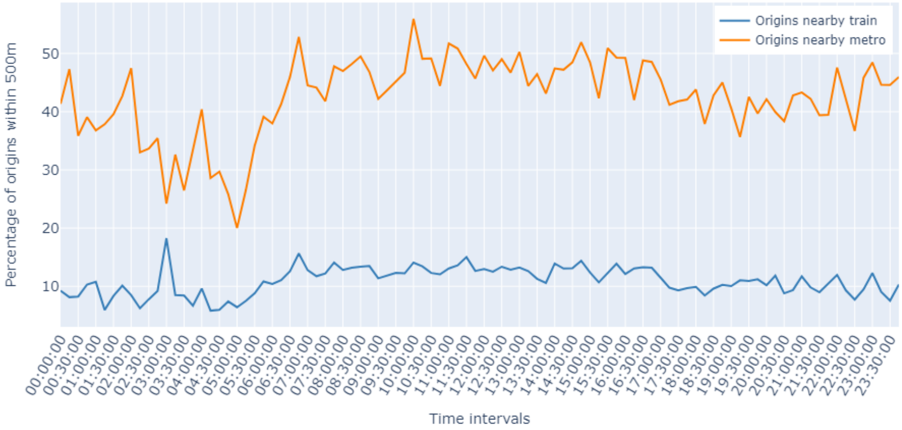


Figure 6. Number of car sharing trip origins within 500m of public transport stations as a percentage of all start points.

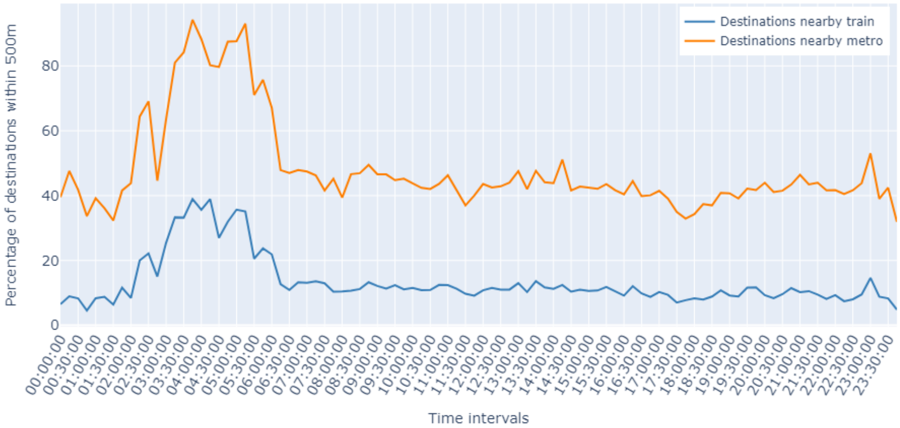


Figure 7. Number of car sharing trip destinations within 500m of public transport stations as a percentage of all destination points.

4.1.2 Weekly trend

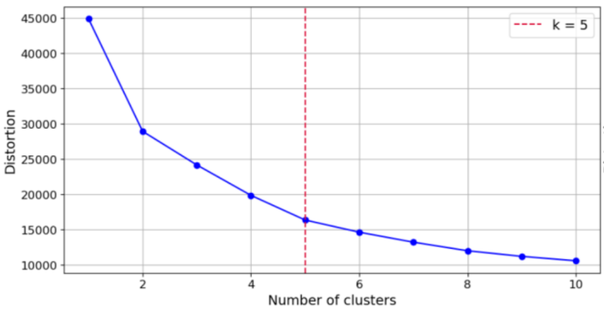
Furthermore, the grouping of data by weekday allowed the identification of certain trends, see Appendix I. Here too, the number of start and destination points within 500 metres of bus stations was considerably higher than that of train and metro stations for the same reason as previously stated. For both start and destination points, it could be observed that most points were within 500 metres of public transport stations on Wednesdays and Fridays. The lowest number of points within 500 metres of public transport stations was observed on Sundays and Mondays. The proportional weekly trend, that was, the number of start and destination points within 500 metres during a given weekday compared to the total number of start and destination points on that same weekday, remained relatively consistent for both train and metro stations. It could be observed that, in the case of train and metro stations, there was a slight decrease in the percentage of start and destination points within 500 metres of the stations on Sundays. However, the findings were less compelling than those related to the daily trend. This was due to the relatively minor fluctuations observed in the proportion of car sharing trip start and destination points in proximity to public transport stations.

4.2 Spatial analysis

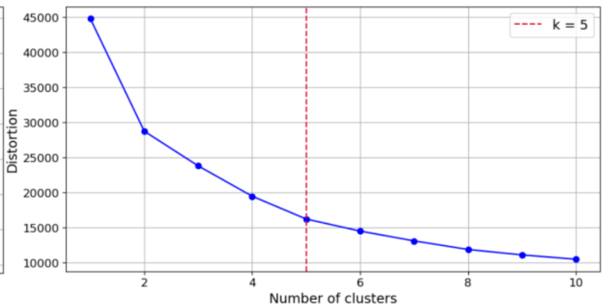
4.2.1 K-means clustering

The analysis of the cluster centroids resulting from the k-means clustering on both temporal and spatial features (Table 1) indicated that the temporal features were dominant (Appendix II). This also emerged from the ensemble clustering analysis. This implied that the clusters formed differed solely based on the temporal features, with all the spatial features exhibiting similar values and therefore no clustering was performed on them. Given the objective of this thesis, which was to investigate when and where car sharing could potentially complement public transport, it was not desirable for the temporal features ("when") to be more dominant than the spatial features ("where").

The use of spatial features alone resulted in the formation of distinguishable clusters for both the car sharing trip start and destination points, as evidenced by a silhouette score of 0.28 and almost no negative silhouette coefficient values. According to the elbow method, it was optimal to divide the start and destination points into five clusters each, see Figure 8. The cluster sizes ranged from 1,307 to 48,935 for the car sharing trip start points and from 1,325 to 49,069 for the car sharing trip destination points. Figure 9 and Figure 10 show the centroids of the clusters for the start and destination points, respectively, and illustrate the characteristics of each cluster. The greater the variability in the values of each feature in the cluster centroid plots, the more crucial these features were in the formation of the clusters.



(a)



(b)

Figure 8. Optimal number of k-means clusters for (A) car sharing trip origins and (B) car sharing trip destinations.

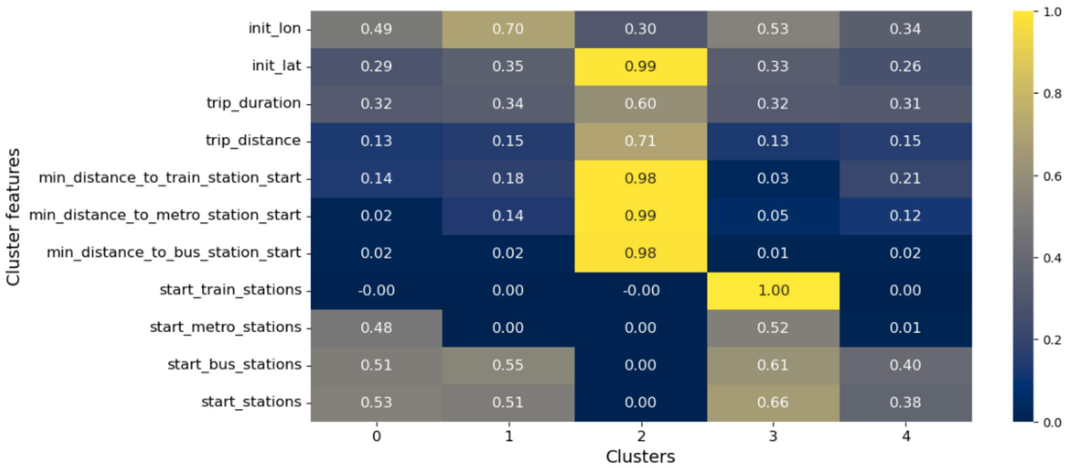


Figure 9. K-means cluster centroids result from using spatial features (start points).

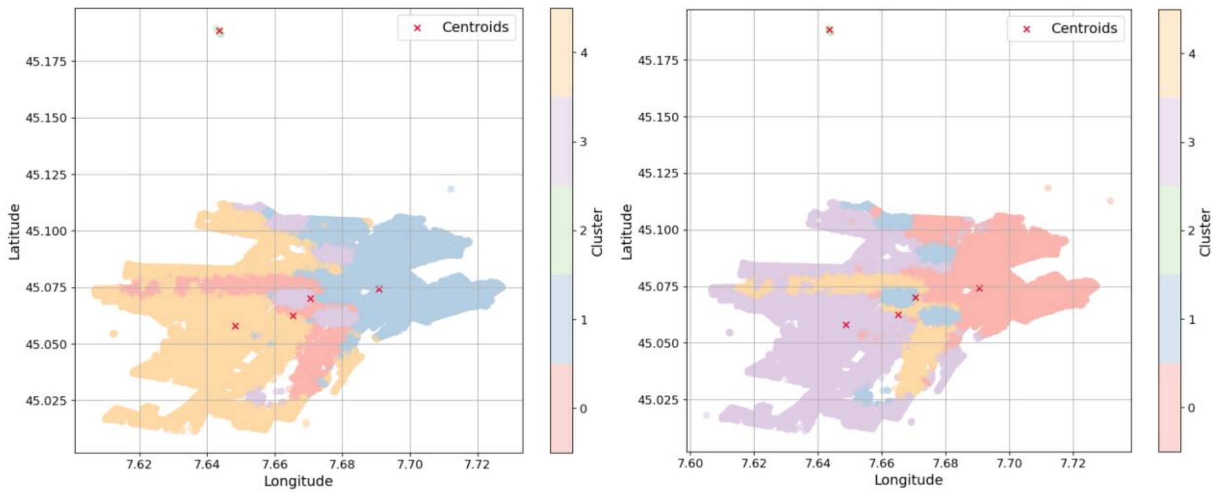
Figure 10. K-means cluster centroids result from using spatial features (destination points).

The clusters of the car sharing trip start points could be addressed as follows. Cluster 0 contained the start points of short trips, which were situated in close proximity to public transport stations. It had a moderate number of train, metro, and bus stations within 500 metres. Cluster 1 also contained start points of short trips, but with only a moderate proximity to train and bus stations. There were no metro stations within 500 metres distance. Cluster 2 contained start points of long trips, which were situated at a considerable distance from all stations. Consequently, there were no stations within 500 metres of these start points. Cluster 3 was comparable to Cluster 0, yet it exhibited a markedly higher number of train stations within 500 metres. Cluster 4 also contained start points of short trips with a moderate proximity to all stations. However, it had a sparse number of train and metro stations within 500 metres distance, while the number of bus stations was moderate.

The clusters of the car sharing trip destination points could be addressed as follows. Cluster 0 contained destination points of short trips, situated in close proximity to numerous bus stations. There were no train or metro stations within 500 metres. Cluster 1 also contained destination points of short trips, located remarkably close to public transport stations. The cluster had the highest number of train stations within 500 metres and also the highest number of total stations within 500 metres distance. Cluster 2 contained destination points of long trips, which were situated at a considerable distance from all stations. There were no stations within 500 metres of these points. Cluster 3 contained destination points of short trips with no train stations, a sparse number of metro stations, and a moderate number of bus stations within 500 metres distance. Cluster 4 also contained destination points of short trips, which were situated in close proximity to metro and bus stations. There were no train stations within 500 metres of these points.

A visual comparison of the car sharing trip start and destination point clusters on a map of Turin, as presented in Figure 11, together with a comparison of the cluster centroids (Appendix III) indicated that the following clusters were most similar:

- Cluster 0 (start) and Cluster 4 (destination) are henceforth referred to as the "Metro line" clusters.
- Cluster 1 (start) and Cluster 0 (destination) are henceforth referred to as the "East Turin" clusters.
- Cluster 2 (start) and Cluster 2 (destination) are henceforth referred to as the "Torino Airport" clusters.
- Cluster 3 (start) and Cluster 1 (destination) are henceforth referred to as the "Central Turin" clusters.
- Cluster 4 (start) and Cluster 3 (destination) are henceforth referred to as the "West Turin" clusters.



(a) (b)

Figure 11. Spatial k-means clustering result of (A) car sharing trip origins and (B) car sharing trip destinations.

Another notable observation was the similarity between the car sharing trip start and destination points when visualizing them on the map of Turin. This similarity could be attributed to the fact that the dataset comprised solely trips of free-floating cars, which were mainly short journeys of up to one hour in duration and a total distance of 20 kilometres. Consequently, the data exhibited a high degree of spatial dispersion throughout the city of Turin.

4.2.2 Post-analysis

Upon post-analysis of the temporal features, refer to Table 1, within each cluster and comparison of the most similar clusters between the start and destination points, the following observations were made (Appendix IV). In general, the Metro Line clusters exhibited a greater number of start than destination points during the midday period, while exhibiting a greater number of destination than start points during the morning and evening periods. In the case of the East Turin clusters, there was a greater number of start points during the midday and nighttime periods, while there were more destination points during the morning and evening hours. The Torino Airport clusters had a greater number of start points during the morning, midday, and especially evening than destination points. However, they exhibited a greater number of destination points during the night than start points. The Central Turin clusters exhibited a greater prevalence of start points during the morning and midday periods, and a higher number of destination points during the evening and nighttime hours. In contrast, the West Turin clusters exhibited a different pattern of car sharing activity. They had a greater number of start points during the morning and nighttime periods, while the number of destination points was greater during the midday and evening periods. When comparing the number of start and destination points grouped by day of the week, it was observed that there are minimal discernible differences across all clusters.

When examining the data in greater detail, it became evident that the pattern observed in daytime hours was consistent across all clusters, with the exception of the Torino Airport clusters. The number of car sharing trip start and destination points was lowest between 1:00 AM and 3:00 AM, with a gradual increase observed from 4:00 AM to 5:00 AM. The first peak was observed around 6:00 AM to 7:00 AM in the morning. During the day, the number of start and destination points remained consistent, oscillating around an average level slightly lower than the 6:00-7:00 AM peak. A second peak occurred at the earliest at 3:00 PM, and at the latest around 6:00 PM, or somewhere in between. After that, the number of start and destination points decreased evenly until midnight.

The Metro Line clusters, and the Central Turin clusters were considered to be the most central clusters in Turin, in comparison to the other clusters. This was due to their proximity to the city centre, where the metro line is operational and the largest train stations are located, namely Porta Nuova and Porta Susa. The clusters situated in the city centre had more car sharing trip destination points in the morning (starting from 3:00 AM until 7:00 AM) than start points, and around midday (starting from 2:00-3:00 PM until 4:00 PM) more start points than destination points, see Figure 12 and Figure 13. This suggested that commuters were more likely to travel towards the city centre in the morning and leave the city centre in the midday.

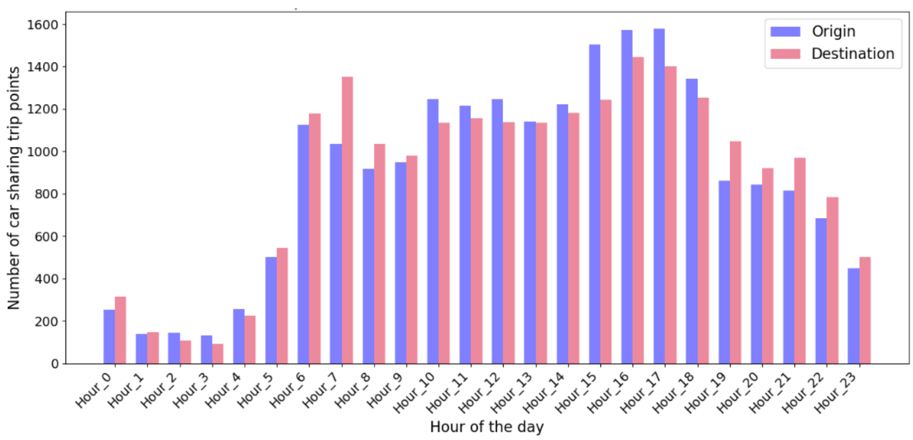


Figure 12. Number of car sharing trip origins and destinations per hour of the Metro Line clusters.

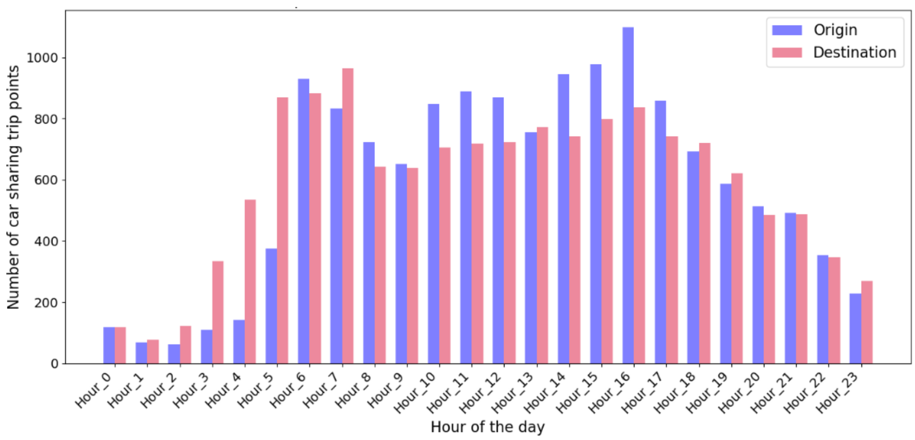


Figure 13. Number of car sharing trip origins and destinations per hour of the Central Turin clusters.

The East Turin clusters and the West Turin clusters were situated in areas that are less affected by the city's busiest traffic, which is located outside Turin's city centre. This could be attributed to the fact that almost exclusively bus stops were situated within the clusters, with a small proportion of metro stations, at the end of the line, also located within the clusters. For these clusters situated further from Turin's city centre, there was a greater prevalence of car sharing trips start points between 3:00 AM and 6:00 AM than destination points, and conversely, a greater prevalence of destination points than start points between 4:00 PM and 6:00 PM, see Figure 14 and Figure 15. Consequently, the movement of car sharing trips in the opposite direction of the aforementioned clusters was observed, indicating a greater number of journeys leaving the clusters in the morning and a greater number of journeys returning to the clusters in the afternoon.

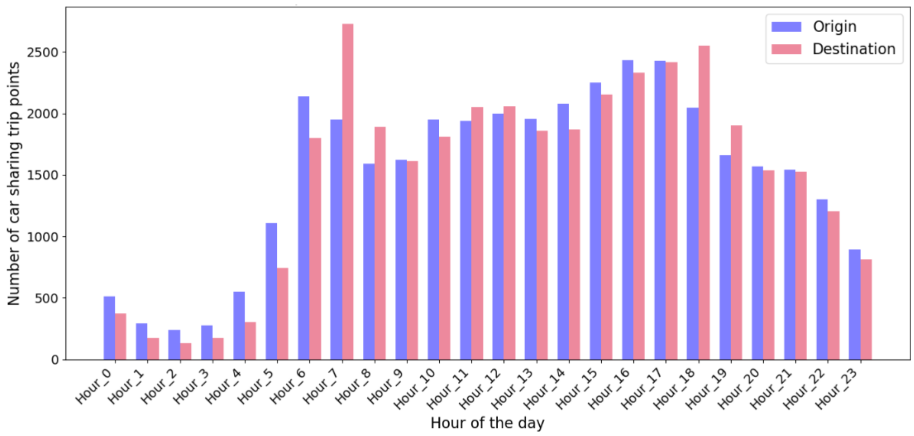


Figure 14. Number of car sharing trip origins and destinations per hour of the East Turin clusters.

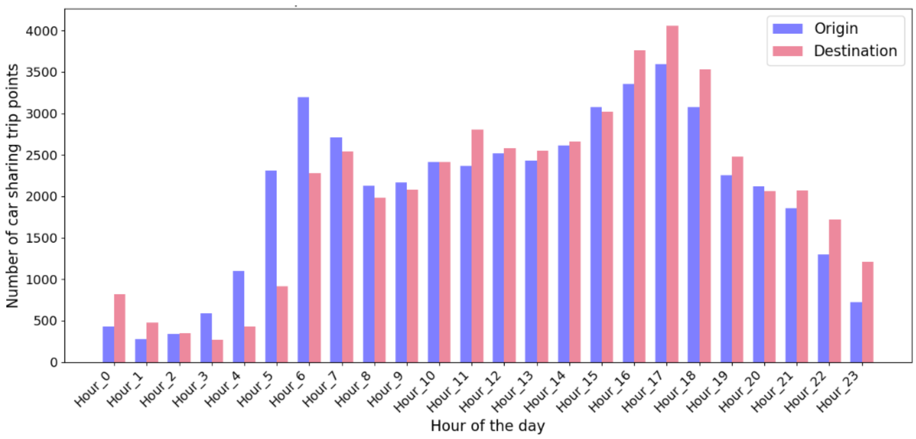


Figure 15. Number of car sharing trip origins and destinations per hour of the West Turin clusters.

The car sharing trip start and destination points located within the Torino Airport clusters exhibited a markedly different pattern to those observed in the other clusters, see Figure 16. During the early morning hours (1:00-5:00 AM), there were (almost) exclusively destination points, while during the early midday and afternoon (11:00 AM-12:00 PM and 6:00-9:00 PM, respectively), there were significantly more start points than destination points. Furthermore, only start points were observed during the late evening hours (10:00-11:00 PM).

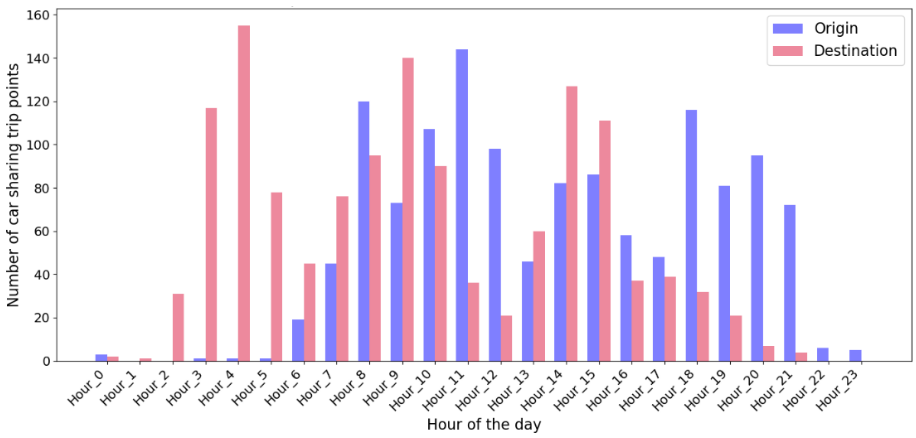


Figure 16. Number of car sharing trip origins and destinations per hour of the Torino Airport clusters.

5. Discussion

The outcomes of this research provide insight into the circumstances under which FFCS service is able to potentially complement public transportation in Turin. The main finding of this research is the considerable number of car sharing trip destination points in the city centre of Turin in the early morning. From the daily trend temporal analysis, fewer car sharing trip start points are observed in the vicinity of train and/or metro stations during the early morning, while more destination points are observed in the vicinity of train and/or metro stations during the early morning. From the post-analysis of the spatial clusters using temporal features (Table 1), it can be seen that the clusters identified as being close to Turin’s city centre are those with a greater number of car sharing trip destination points early in the morning, while those clusters identified as being more peripheral to Turin’s city centre are those with a greater number of start points early in the morning.

The evaluation of these results indicates that the FFCS service is used for trips starting outside Turin's city centre and heading to the city centre early in the morning. Given that the early morning period between 03:00 AM and 07:00 AM is characterised by a lack of public transport availability, it can be assumed that individuals use car sharing to gain access to the city centre, with the possible intention of subsequently travelling further by public transport to reach their place of work. However, for those arriving at the earliest hours, between 03:00 AM and 04:30 AM, it is more probable that individuals will remain in the city centre and potentially commence their workday at an early hour downtown. In this scenario, the FFCS service serves to bridge the night gap in public transportation. From approximately 04:30 AM, when train traffic is present, it is postulated that individuals will make use of, for example, the major train stations located in the city centre, Porta Nuova and Porta Susa, and continue their journey over a greater distance to other Italian cities. This assumption is based on the fact that the typical workday in Italy commences around 9:00 AM (Work-life Balance in Italy, 2024).

The results of this study are consistent with the findings of other studies demonstrating a potential complementarity between car sharing and public transport services (Borghetti et al., 2022; Ceccato & Diana, 2021). In this regard, some research identified the complementarity between car sharing and public transport through an increase in public transport use among car sharing users (Koch, 2001; Katzev, 2003; Shaheen & Cohen, 2007; Shaheen et al., 2020). Furthermore, the utilisation of car sharing in the early morning hours due to the unavailability or limited accessibility of public transportation is corroborated by multiple studies (Becker et al., 2017; Silvestri et al., 2021; Wagner et al., 2016). Moreover, the assumption that car sharing trips are used as a first-mile solution for daily commuting trips is considered a plausible explanation by Barth & Shaheen (2002), Coll et al. (2014), and Synovate (2007). In particular, the results of car sharing trips heading to rail stations in the morning align with the findings of Guirao et al. (2021). A more unexpected result in this study is the afternoon peak around 2:00 PM and 4:00 PM of car sharing trip start points in the city centre of Turin, as this has not been mentioned in previous studies as a finding.

This study contributes to a better understanding of the circumstances under which FFCS services has the potential to complement public transport in Turin. However, the absence of data on the complete travel journeys of FFCS users precludes the possibility of confirming this potential. The availability of data on complete travel patterns could enable the confirmation or otherwise of the potential complementarity between shared car travel in the early morning to the city centre, and subsequent travel by public transportation to the place of work. The methodological choices were constrained by the limited availability of memory usage when selecting the clustering algorithm. As temporal features were consistently dominant during clustering, it is recommended that a hierarchical clustering method, such as DBSCAN, is used, as this may be more effective at identifying complex relationships. This approach has the potential to consider both temporal and spatial features simultaneously, which may result in a higher average silhouette score and consequently improved clustering.

6. Conclusion

The objective of this research was to investigate the potential for free-floating car sharing (FFCS) to complement public transport in Turin. To this end, an attempt was made to answer the following research question: “How can free-floating car sharing potentially complement public transport in Turin?” This was achieved by addressing the following data science question: "How does the proximity of free-floating car sharing trip start and destination points to public transport stations indicate potential integration of car sharing with public transport in Turin?" The temporal and spatial analysis of the proximity of car sharing trip start and destination points to different public transportation services, including train, metro, and bus, indicate that there is potential complementarity between car sharing and public transport in Turin.

The temporal analysis comprises an investigation of the daily and weekly trend of the number of car sharing trip start and destination points within 500 metres of public transport stations, as well as the proportion of these points in comparison to all start and destination points within a specific time range. The spatial analysis involves the application of clustering techniques to spatial features, quantifying the proximity of car sharing trip start and destination points to public transport stations. Furthermore, temporal features, such as dayparts and weekdays, are used in the post-analysis of the clusters. The results of both analyses indicate a potential complementarity in the use of car sharing to connect the outskirts of Turin to the city centre in the early morning. This is observed to bridge the gap in public transportation between approximately 3:00 AM and 7:00 AM. For those arriving in the city centre between 3:00 AM and 4:30 AM, it is found most probable that they will remain in the city centre and commence their workday early downtown. From approximately 4:30 AM, when train traffic is present, it is found most likely that individuals will continue their daily commuting trips by public transport, as the FFCS service facilitate as a first-mile solution.

In light of these findings, this research provides evidence of specific circumstances under which FFCS service can potentially complement public transportation in Turin. Nevertheless, it prompts the question of the extent to which this potential is being exploited in practice. This concerns in particular whether those car sharing trips arriving in the city centre in the early morning are actually travelling further by public transport. To fully comprehend the potential for complementarity, further research is required using data on the complete travel journeys of FFCS users, including public transport use. Furthermore, future research should consider using a hierarchical clustering method, such as DBSCAN, to potentially enhance the clustering process by considering both temporal and spatial features simultaneously. Further research should also consider excluding car sharing trip start and destination points in the vicinity of Torino airport, as these do not contribute to an understanding of the dynamics between car sharing and public transport in the city centre. Moreover, it is recommended that future research should investigate the peak between 2:00 PM and 4:00 PM of car sharing trip starting in the city centre of Turin. This could help to identify other specific circumstances under which FFCS service can potentially complement public transportation in Turin.

In conclusion, this study has succeeded in filling a gap in the existing literature by examining the circumstances ("when and where") under which FFCS can complement public transportation in Turin. The study clearly demonstrates the potential complementarity of FFCS in the early morning, connecting the outskirts of Turin with the city centre. Furthermore, the results corroborate the findings of previous research indicating the use of car sharing during nighttime due to the unavailability of public transport and the potential of car sharing functioning as a first-mile solution for daily commuting trips. Overall, the analysis of Turin's specific dynamics provides valuable insights to other cities seeking similar integration between car sharing and public transport, thereby contributing to more sustainable urban mobility.

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Appendix I

This appendix contains the bar charts with the results of the temporal analysis of the weekly trend of the number of car sharing trip start and destination points within 500 metres of a train, metro and/or bus station in Turin (Figure 17 and Figure 18). Furthermore, the appendix contains bar charts of the number of car sharing trip start and destination points within 500 metres of a train and/or metro station in Turin, expressed as a percentage of the total number of start and destination points per weekday (Figure 19 and Figure 20). The number of start and destination points within 500 metres of bus stations is presented on the second y-axis, as the values are considerably higher than those of train and metro stations. It should be noted that the percentage bar plots do not include the bus stations, as the number of bus stations within 500 metres of the start and destination points exceeds 100 percent. This is due to the fact that there are a considerable number of bus stations in Turin, which may result in multiple bus stations lying within the range of a single start and/or destination point.

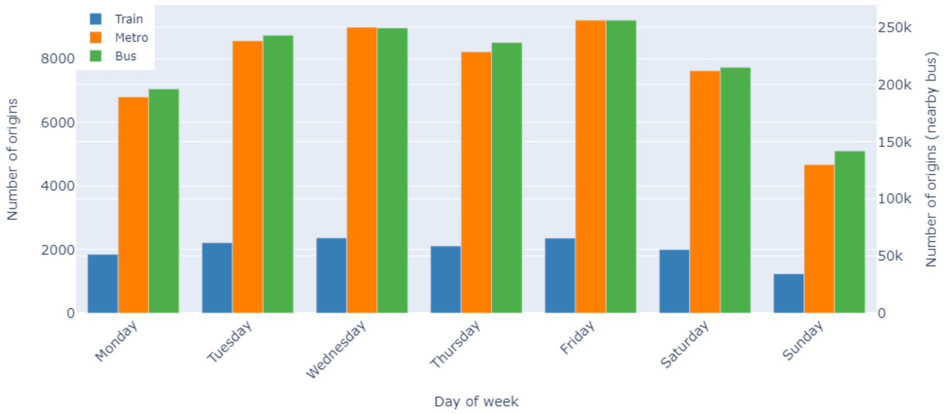

Figure 17. Weekly trend of car sharing trip start points within 500m of public transport stations.

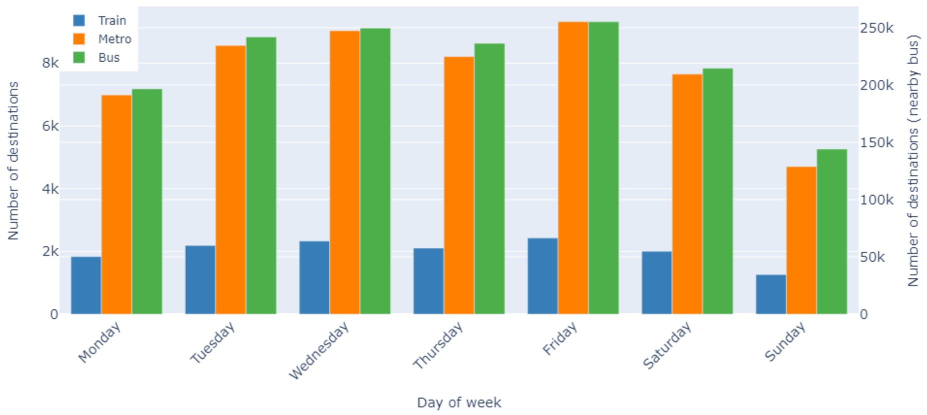

Figure 18. Weekly trend of car sharing destination points within 500m of public transport stations.

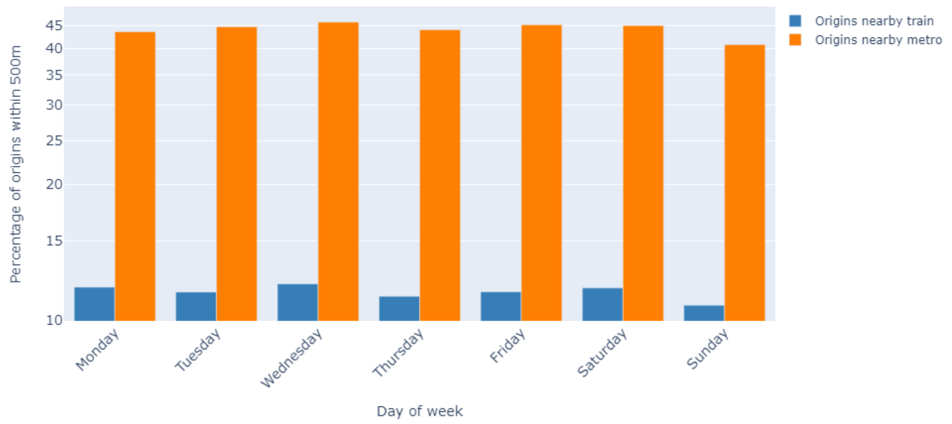

Figure 19. Number of car sharing trip origins within 500m of public transport stations as a percentage of all start points per weekday.

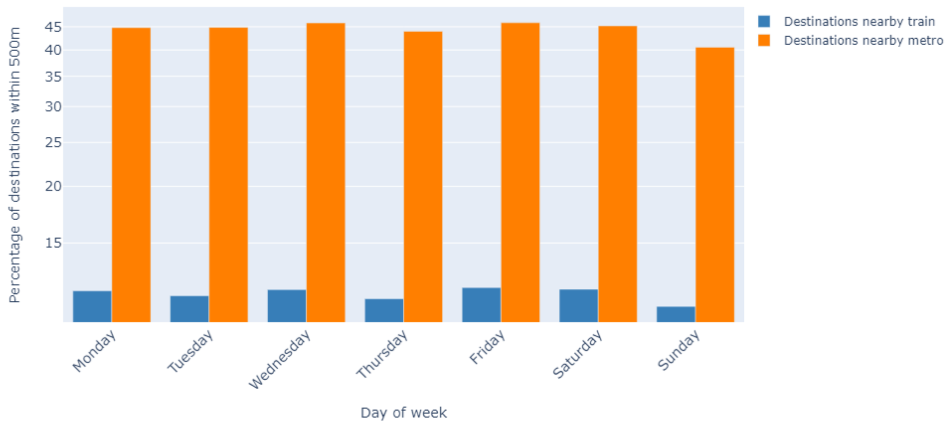

Figure 20. Number of car sharing trip destinations within 500m of public transport stations as a percentage of all destination points per weekday.

Appendix II

This appendix presents the cluster centroids of the k-means cluster analysis, incorporating both temporal and spatial features, on both the car sharing trip start and destination points (Figure 21 and Figure 22). For this clustering analysis, the elbow method indicated that six clusters were found most optimal. Furthermore, this appendix contains the cluster centroids of the ensemble cluster analysis on both the car sharing trip start and destination points (Figure 23 and Figure 24). For the ensemble clustering analysis, the elbow method indicated that five clusters were found most optimal.

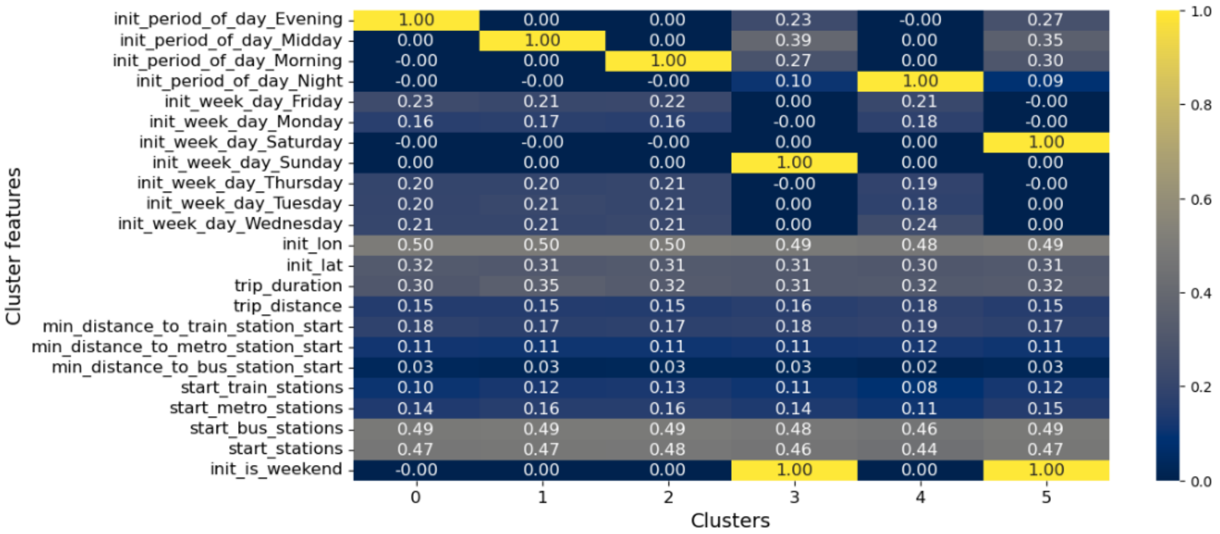

Figure 21. K-means cluster centroids result from using spatial and temporal features (start points).

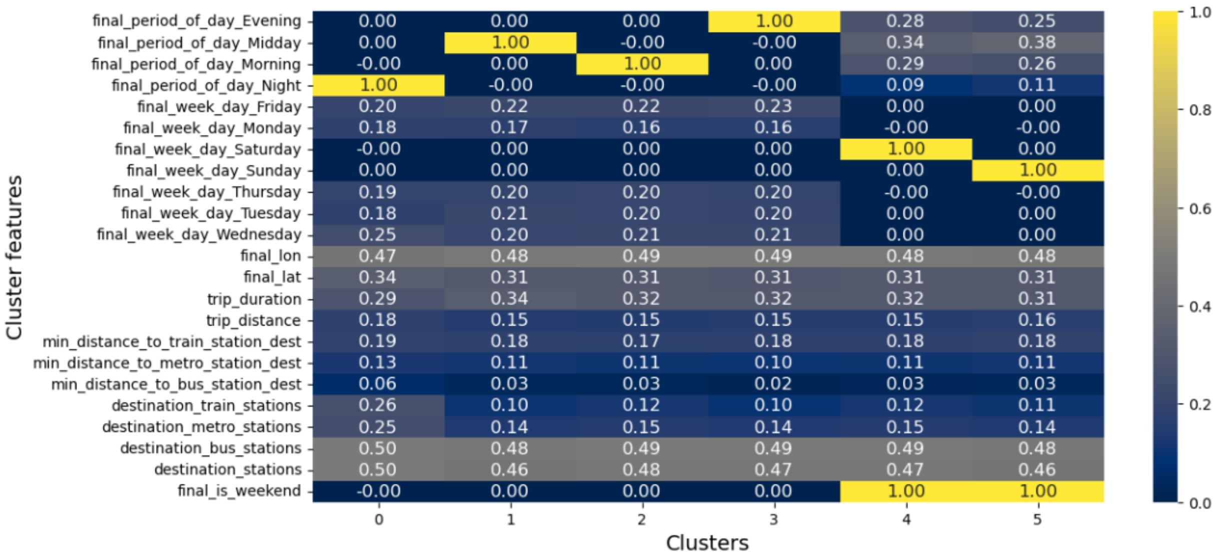

Figure 22. K-means cluster centroids result from using spatial and temporal features (destination points)

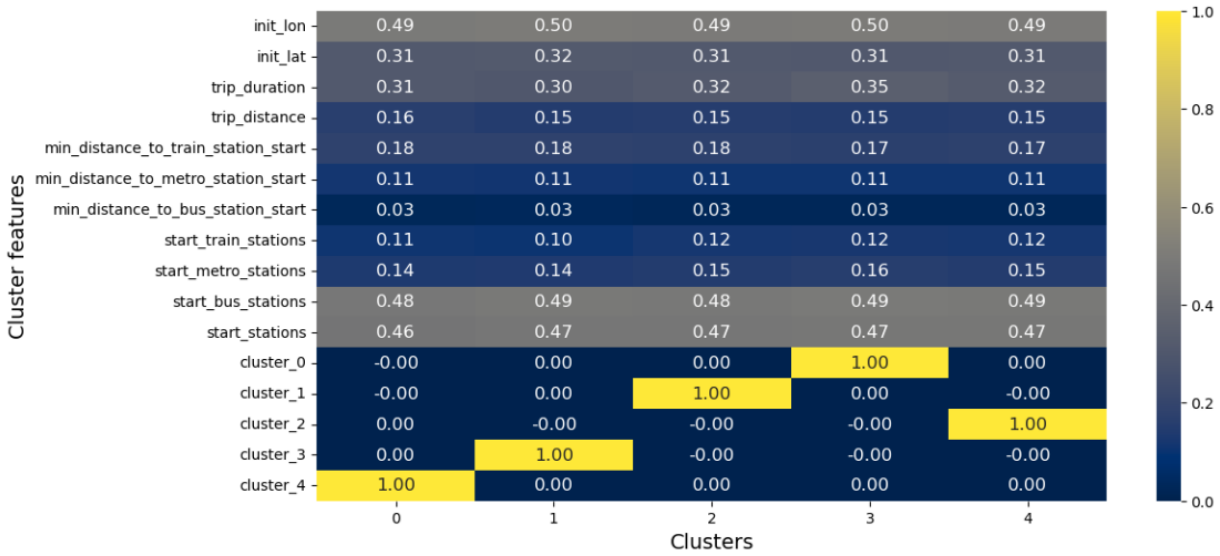

Figure 23. K-means cluster centroids result from ensemble clustering (start points).

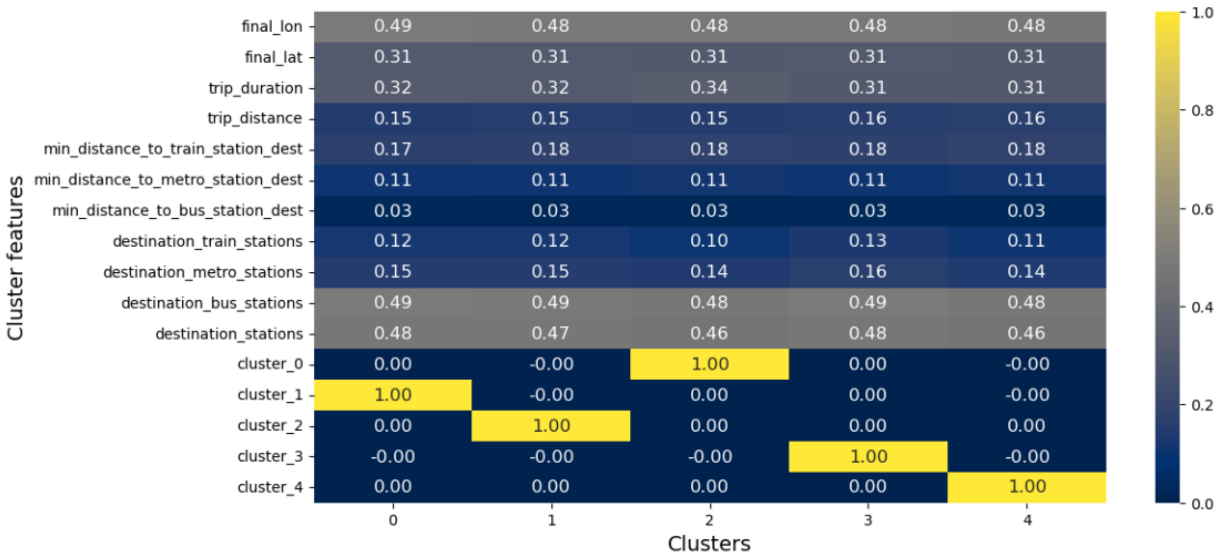

Figure 24. K-means cluster centroids result from ensemble clustering (destination points).

Appendix III

This appendix presents the comparison of the centroids of the k-means spatial clustering of the car sharing trip start points with those of the destination points. The smaller the distance between centroids of clusters, the more similar they are. This comparison is used in determining which clusters of the start and destination points are most similar.

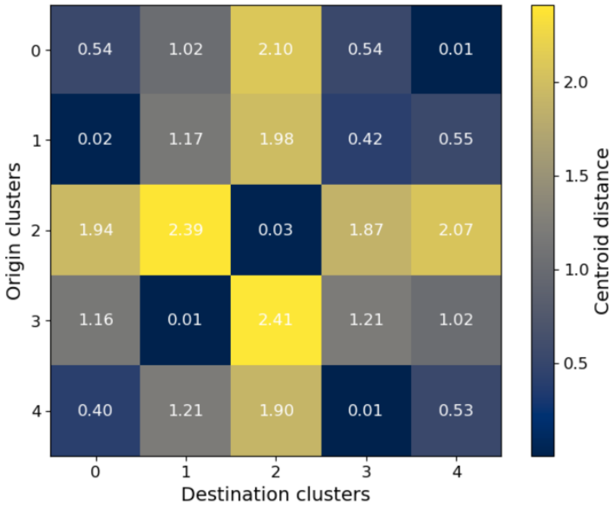

Figure 25. Comparison between centroids of k-means clusters of car sharing trip origins and destinations.

Appendix IV

This appendix presents the results of the post-analysis of temporal features, including dayparts, weekdays, and weekends, within the spatial clusters of the car sharing trip start and destination points. In each bar plot, the most similar clusters of the start and destination points are contrasted.

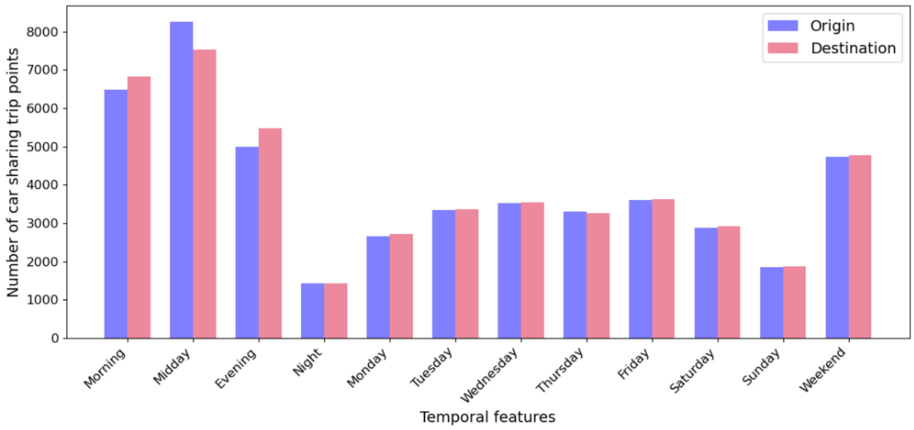

Figure 26. Temporal data of the Metro Line clusters.

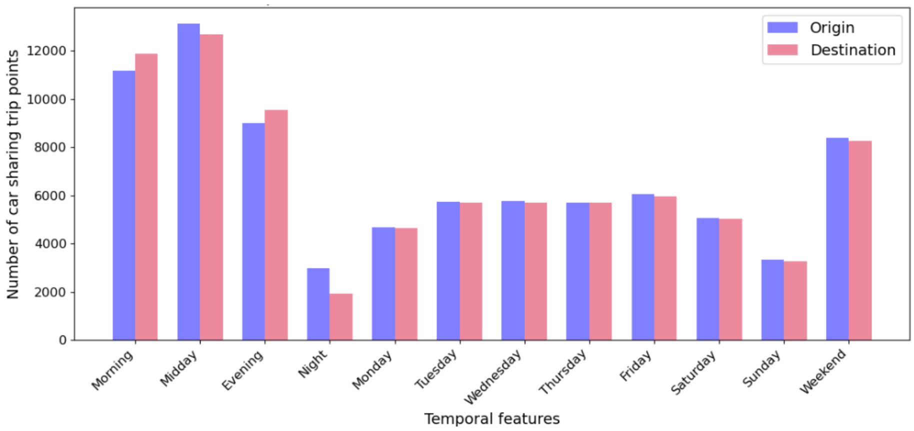

Figure 27. Temporal data of the East Turin clusters.

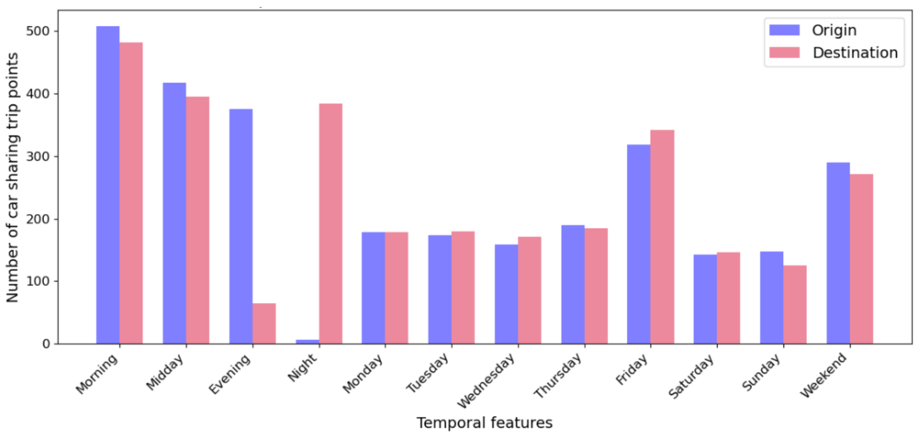

Figure 28. Temporal data of the Torino Airport clusters.

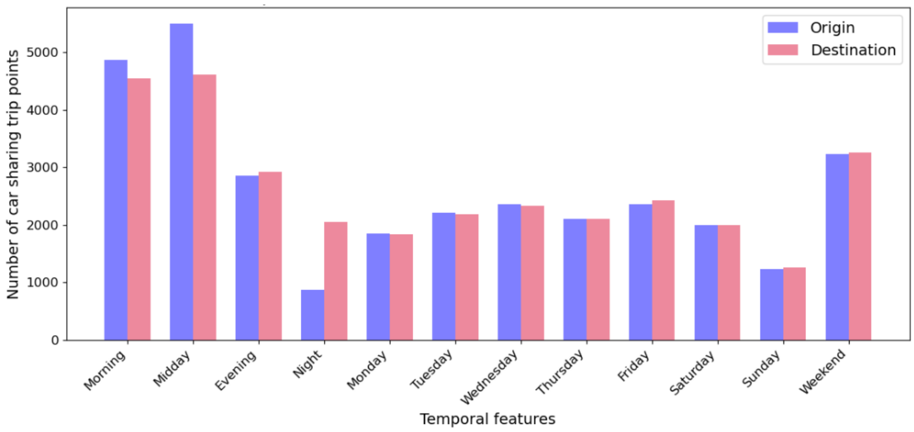

Figure 29. Temporal data of the Central Turin clusters.

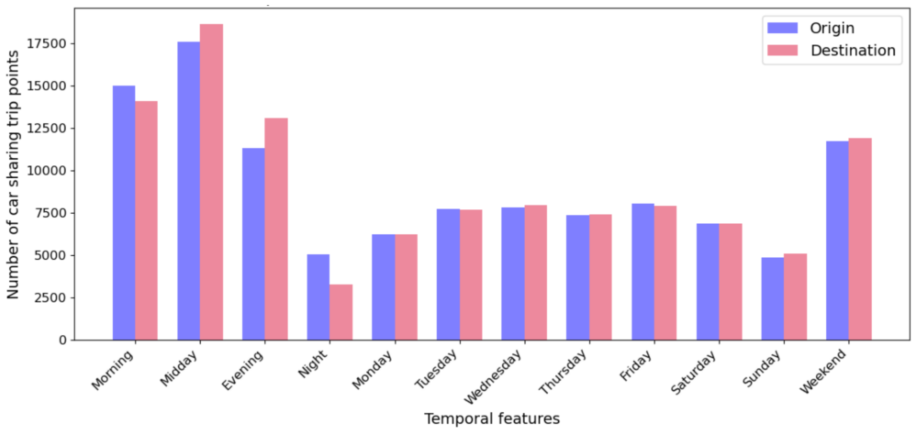

Figure 30. Temporal data of the West Turin clusters.