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# Modelling and control of innovative car sharing services based on stackable electric vehicles

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## Abstract

Car sharing is one the pillars of an innovative transportation infrastructure, as it is expected to reduce traffic congestion, parking demands and pollution in our cities. However, drawbacks in terms of high deployment and operational costs (from the car sharing operators' perspective), as well as unreliable vehicle availability (from the customers' perspective), are currently hindering their massive deployment and popularity. In this work, we discuss the solutions proposed with the H2020 ESPRIT project to address the above issues, with special focus on what it can be done in terms of demand and operational modelling.

*Keywords:* Car sharing, relocation, discrete choice modelling, agent-based simulation.

## 1. Introduction

After decades of little innovation, personal urban mobility is undergoing rapid transformations due to the introduction of disruptive technologies and new IT applications, but also due to changes in individual preferences and social behaviours, with a growing trend towards a shift from car ownership to sharing. This gave new life to several shared, on-demand, mobility services which were conceived decades ago but never established themselves as viable mobility solutions (Shaheen et al. 2015). One of the most relevant of such services is car sharing, in which customers can rent a car from a fleet of shared vehicles operated by a company or a public organisation, typically for short-range trips. In cities where car sharing services are running, positive effects have already been measured: car sharing members use cars less, rely more on public transport or bicycles, and in some cases, they even renounce their car ownership.

Car sharing comes in many forms, with one-way car sharing (in which you can drop off your shared vehicle at your destination) rapidly prevailing over the others. One way car sharing market has significantly grown its maret share due to the reduction in user inconvenience to return the vehicle at the starting point (Schwieger et al. 2015). While one-way services are more flexible for the customers, they present more difficulties to operators. In fact, they are complex to manage, as the freedom given to the users creates imbalances in the fleet distribution. To address the issue, the operator can move the vehicles from areas with surplus availability to areas with high demand.

The economic viability of car sharing is still uncertain due to high investment cost for station and fleet deployment, as well as high operation cost for fleet management and rebalancing. It is important to point out that the relocation process is intrinsically inefficient: as one driver per car is needed, to relocate several cars a large workforce or many willing customers are necessary. This significantly complicates the relocation with respect to, e.g., bike sharing services, where a single worker with a van can redistribute a large number of bicycles. To address this issue, the **E**asily di**S**tributed **P**ersonal **R**ap**I**d **T**ransit (ESPRIT) H2020 European project (http://www.esprit-

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transport-system.eu/) aims at prototyping a new concept of stackable electric car that can be driven in a road train of up to 8 vehicles, which has the potential of enabling more efficient redistribution of fleets and a cost-efficient car sharing service. However, both the demand for use as well as the operating costs of the ESPRIT system need to be explored. In particular, understanding the pattern of the required redistribution of vehicles as well as the response of the public to using and indeed redistributing an additional vehicle themselves needs to be demonstrated.

In this paper, we report some of the main results of the ESPRIT project that have been achieved so far. We first describe the overall architecture of the ESPRIT vehicle and the key new technologies and components that are at the basis of this new vehicle concept. Then, we will overview the agent-based modelling framework that is under development in the project for predicting the economic viability of deploying the ESPRIT transport system in a variety of different urban and periurban configurations. Furthermore, the modelling tool will provide useful insights regarding the efficient planning and operations of electric vehicle-sharing systems, with a special focus on the effectiveness of the redistribution policies. Finally, we will describe the three use cases that will be used to validate the ESPRIT concept and to assess its impact on the individual users' behaviours, as well as the other transportation options, including public transport. Preliminary results on the mode share and system utilisation are also shown for one of these case studies.

## 2. Understanding one-way car sharing in Europe

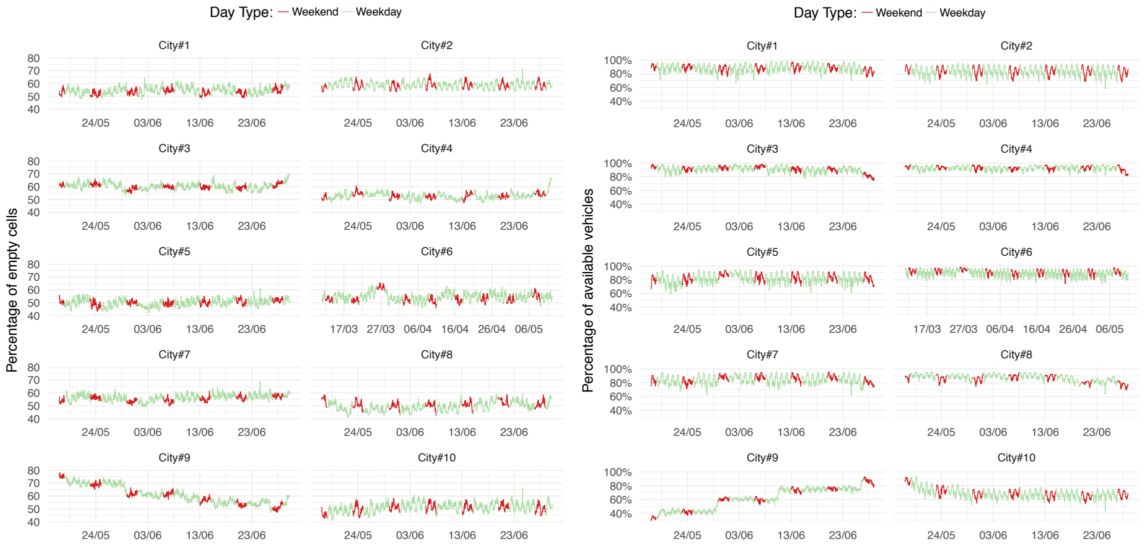
As more companies enter the fast-growing business of car sharing, operational data about car sharing is becoming increasingly available. In Boldrini et al. (2017) we exploited the availability of data about free floating car sharing in 10 European cities to carry out a statistical analysis of typical car sharing usage patterns to point out which are the service pitfalls that stackable cars could help to address more efficiently. In the following we summarise the main findings of this study.

Our dataset consists of the pickup and drop-off times and locations in 10 European cities for a major free-floating car sharing operator. Table 1 summarises the main characteristics of the ten car sharing systems.

Table 1. Summary of dataset.

| City | Trips | Vehicles | Date trace starts | Trace duration | City Area | Population density |
|---|---|---|---|---|---|---|
| City#1 | 49901 | 349 | 2015-05-17 | 45 days | 165.76 | 5147.8 |
| City#2 | 223044 | 981 | 2015-05-17 | 45 days | 891.68 | 3947.6 |
| City#3 | 18944 | 198 | 2015-05-17 | 45 days | 102.32 | 3742.4 |
| City#4 | 12168 | 194 | 2015-05-17 | 45 days | 88.25 | 6339.2 |
| City#5 | 156080 | 686 | 2015-05-17 | 45 days | 181.67 | 7533.3 |
| City#6 | 81862 | 499 | 2016-03-11 | 63 days | 310.70 | 4668.1 |
| City#7 | 99515 | 584 | 2015-05-17 | 45 days | 1287.36 | 2232.8 |
| City#8 | 15612 | 250 | 2015-05-17 | 45 days | 187.16 | 5018.3 |
| City#9 | 25091 | 299 | 2015-05-17 | 45 days | 130.17 | 6812.9 |
| City#10 | 144474 | 829 | 2015-05-17 | 45 days | 414.87 | 4501.6 |

Each entry in the dataset provides the geographical coordinates of the position of available vehicles in the car sharing system, plus additional information such as fuel/battery level, cleaning level, and so on. Due to faulty GPS systems, the reported coordinates may be inaccurate. For this reason, the dataset has been pre-processed and coordinates that are manifestly invalid have been discarded. Then, a pick-up event is inferred by observing a vehicle that becomes unavailable, while a drop-off event is inferred by observing a vehicle that becomes available again. Clearly, we do not have any information on the routes followed by the vehicles, if the customers made intermediate stops (e.g., for doing shopping activities), or if the vehicle is unavailable due to cleaning and maintenance rather than regular customer trips. Nevertheless, a useful insight can still be obtained from this data about the system usage over timer and space. Since vehicles can be scattered throughout the operational area it is necessary to aggregate the information about vehicles' locations. To this end, we divide the operational area into smaller cells, and we study what is the behaviour, over time, in each of these cells. In the following diagrams, we consider cells with side length equal to 500m.



(a) (b)

Fig. 1 (a) Percentage of empty cells over time (b) Percentage of available vehicles over time.

First of all, in Fig. 1(a) we show how the number of empty cells varies over time in each city. The results clearly show that several cells are empty, i.e. without available vehicles, with peaks of 70%-80%. In addition, we can also observe that there are recurrent behaviours and the number of empty cells is maximum during the day and minimum during the night. On the other hand, if we compare this situation with what is observed at system level in terms of vehicle availability (Fig. 1(b)), it is immediate to detect a clear discrepancy: although there are a lot of empty cells, it is also true that there are many available vehicles. This behaviour indicates that there is a strong concentration of vehicles in certain areas[†]. Even more importantly, it also suggests that that macroscopic properties (i.e. at system level) are not very informative when it comes to car sharing. For this reason, we believe that it is crucial to properly characterise the microscopic usage patterns (i.e. at the cell level) to understand similarity and differences between car sharing systems, and to pinpoint possible service pitfalls. To this end, we applied a methodology used in Boldrini et a. (2016) to categorise cells in a car sharing system in terms of their average usage patterns. More precisely, we focus on the time series of vehicle availability in each cell and we measure how close these time series are with what we observe in other cells using the Dynamic Time Warping (DTW) technique developed by Esling et al. (2012). Then, we cluster cells based on their DTW-distance using PAM clustering. For each city, the optimal number of clusters is obtained using the silhouette method. In order to be able to compare our time series, we discretise time into bins with a duration of 10 minutes. For each cell, we extract one availability value per bin by averaging the availability in the bin in different days. In addition, in order to detect variations above and below the average behaviour, we normalise the measured availability using the average availability at the cell.

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[†] City#9 represents a very special case as its car sharing system was opened just weeks before we started collecting our dataset. It seems evident that the behaviour in the city has not stabilised during the 45 days of the trace.

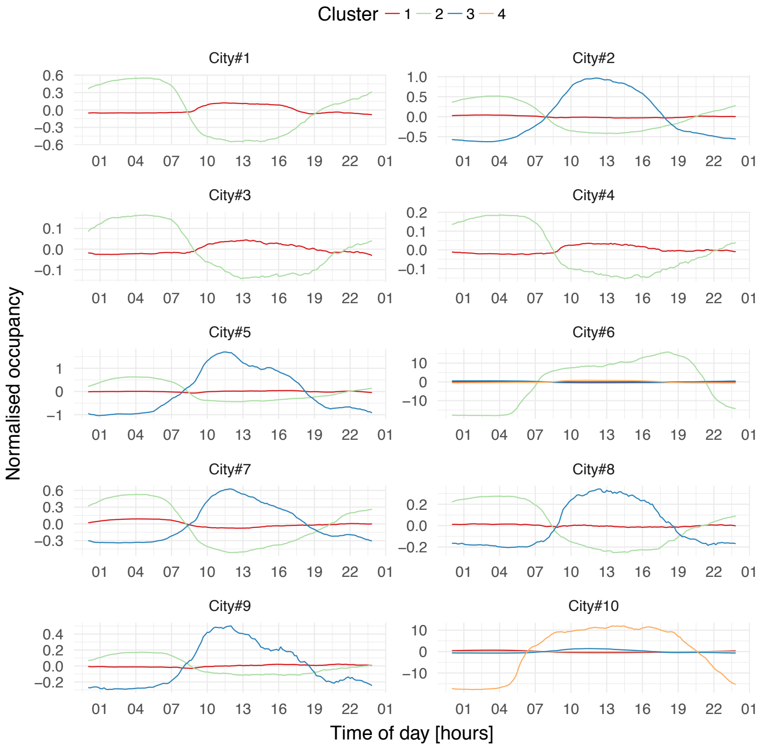
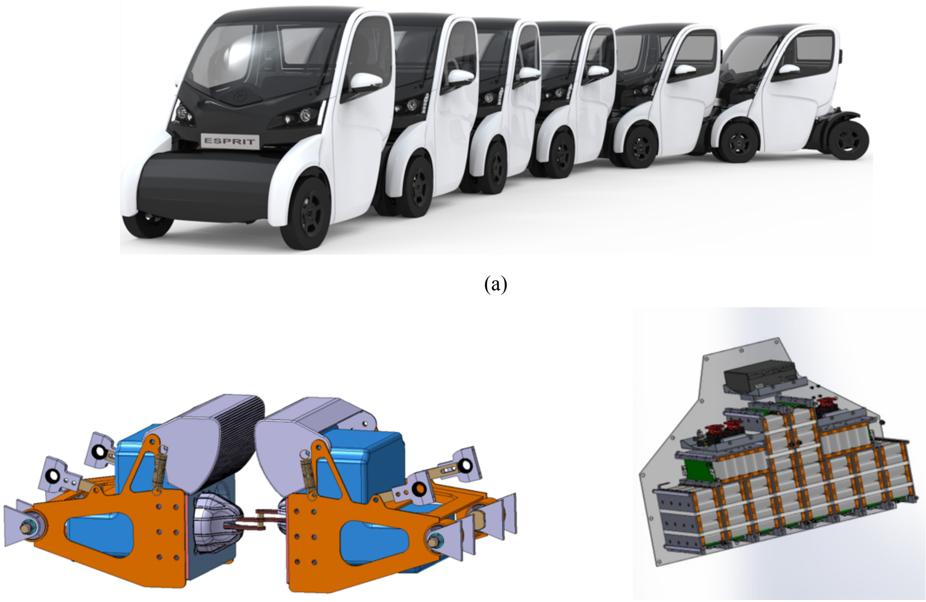


Fig. 2 Time series of vehicle availability per cluster in the ten cities.

The results are shown in Fig. 2. The optimal number of clusters in all cities ranges from 2 to 4. However, the fourth cluster, when present, is a very special cluster, composed of just a single cell. This single cell is a very special one in the city ecosystem, and in both cities where the fourth cluster is present, this cluster comprises the airport zone. If we plot the availability time series within each cluster (obtained by computing the availability in the cells belonging to the cluster), it is striking to see that the clusters highlight very characteristic cell usages. Some cells have above average availability at night and below average availability during the day. Other cells have exactly the opposite behaviour. Finally, there is a group of cells with an intermediate behaviour, where apparently no significant different in usage is detected over the whole day. It is easy to map this behaviour into the "nature" of the area covered by the cell: people leave residential areas in the morning and come back in the evening, while the opposite is true for commercial/business areas. Fig. 2 also highlights the outlier behaviour of airport zone (which constitute the fourth cluster, when available). Airports in City#6 and City#10 see a huge variation in availability. However, the behaviour of their time series is simply a scaled version of the commercial/business pattern discussed before. The results in Fig. 2 are important also because they show that the vehicle availability is highly heterogeneous in the city and this usually leads to system imbalance, with shortage of vehicles where they are most needed. However, there are also areas where there is a clear surplus of vehicles. This suggests that suitable relocation policies could be designed to balance supply and demand on the car sharing system. The main concern is the ability of the relocation scheme to keep pace with the systems dynamics, as well as the relocation cost in terms of additional staff.

## 3. The ESPRIT solution

The emergence of increasingly stricter emission standards and government-mandated efficiency goals are forcing the automotive manufacturers to radically change the classical design principles of cars to look at new vehicle concepts for personal mobility in urban areas. This entails the development of new a generation of electrified powertrains to make electric transport an attractive and affordable option, as well as lightweight materials and compact design for energy efficiency improvements (e.g. the mass of a small vehicle can determine up to 75% of the required electrical consumption when operated in an urban area). The long-term vision is to invent new and more efficient mobility concepts for congested cities with scarce parking space, leveraging L-category vehicles with significant smaller spatial use and carbon footprints, as well as considerably less expensive to own and operate (Mitchell et al., 2010). Examples of prototypes of foldable two-seat urban electric cars developed in the framework of recent academic and industrial research programs are the MIT BitCar (Vairani, 2009), or EO Smart (Birnschein et al., 2012). A step forward is taken by the ESPRIT European Project, which aims at designing and demonstrating an innovative 2-passenger lightweight L6 category electric vehicle with the ability be stacked (like shopping trolleys) and driven in articulated road trains of up to 8 vehicles at a time (equivalent to the length of an urban bus) as a single car with traction and braking being performed by all vehicles. An example of such road train is illustrated in Fig. 3(a).



(a)

(b)

(c)

Fig. 3 (a) Road train of ESPRIT vehicles (b) Coupling system (c) Battery pack.

Key to the ESPRIT concept is the coupling device that should ensure an automatic coupling and decoupling process of the vehicles within the station, and provide a secure mechanical and electrical connection between the vehicles in all anticipated driving conditions. Existing coupling concepts do not fulfil the needs of the ESPRIT vehicle, so one of the technical objectives of the ESPRIT project is to design a new coupling system (see Fig. 3(b) for an illustration of a first prototype), as well as a Kinematic and Dynamic Behaviour Management System (KDBMS) linked to the steering, propulsion and braking equipment, enabling the road train to work safely in forward and reverse gear. In particular, it will prevent lateral oscillations (sway) and toppling, jack knifing and trajectory drift of the road train. It is important to point out that the ESPRIT vehicles will not only be mechanically connectable but they can also be electrically connected to one another to enable single charging for a whole train of vehicles. Optimised balancing between vehicles with different levels of charge will be possible within the road train. This smart power solution will reduce the number of required charging stations and help downsizing the batteries by mutualising the available energy (e.g. during charge, ESPRIT vehicles with a greater charge will transfer electricity to the ones having a low battery charge). An optimised battery pack has also been designed (see Fig. 3(c) for an illustration of a first prototype), compliant both with standard charging infrastructures and fast charging technologies, which adapts to the available layout and limited volume, identified by the vehicle layout architecture, while ensuring to fulfil the vehicle minimum requirements.

One of the major benefits of the ESPRIT vehicles is its potential to enable a more efficient station-based one-way car sharing system in which vehicles can be redistributed in a more cost-effective manner, as groups of vehicles can be moved with as few drivers as possible. In addition to dedicated operators redistributing trains of vehicles, redistribution of two vehicles at a time by the users themselves will also be possible. There will also be significant saving in parking space requirements, given the vehicles length and ability to stack. The ESPRIT system will minimise the need for infrastructure by optimising the use of parking areas and charging an 8-vehicle road train from a single charging station. Given the lower operating costs and higher affordability and availability as opposed to conventional car sharing systems, we expect that the ESPRIT system will not only enable users to reach a public transport hub from their house, but will also enable them to leave a public transport hub to reach their final destination (e.g. their work place). This increases significantly the door to door efficiency of public transport and therefore its popularity.

## 4. The ESPRIT Demand and Revenue Model

One of the main objectives of the ESPRIT project is to develop an operation and business model estimation tool to be able to accurately predict the economic viability of deploying the ESPRIT transport system in a variety of different urban and periurban configurations, as well as to predict the public transport modal share induced by the system. The overall model consists of a demand and supply model which interact with a business case model tool. Fig. 4 shows the links between the models.

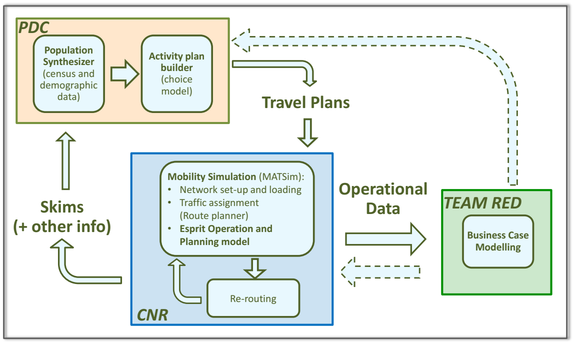


Fig. 4 Interaction of model components.

Our tool is based on a novel agent-based demand modelling framework that applies discrete choice techniques to forecast car sharing demand by considering the influence of individual preferences, behaviours and lifestyles in the utility associated with each transportation alternative. A population synthesizer is then used to create a population of synthetic agents, whose individual decisions are each determined by discrete choice modelling. This will include decisions about the scheduling and locations where activities are undertaken, as well as longer term lifestyle decisions such as where to live and work. Then, the probability of a decision is calculated using a logit based approach (Ortúzar et al. 2011). ESPRIT journeys made in conjunction with Public Transport services and purely by ESPRIT are considered as separate modes within the model. Multimodal trips that combine ESPRIT with public transport match to the concept of “first and last kilometre”. Application of a Monte Carlo process allows the calculated probabilities to be translated to binary decisions, so that the decisions made by each agent can be passed to the agent-based transport simulator as a set of travel itineraries, one for each agent (Davidson et a. 2016). Then, we have combined the car sharing demand forecasting engine with an operational model of the ESPRIT system that has been developed in MATSim.

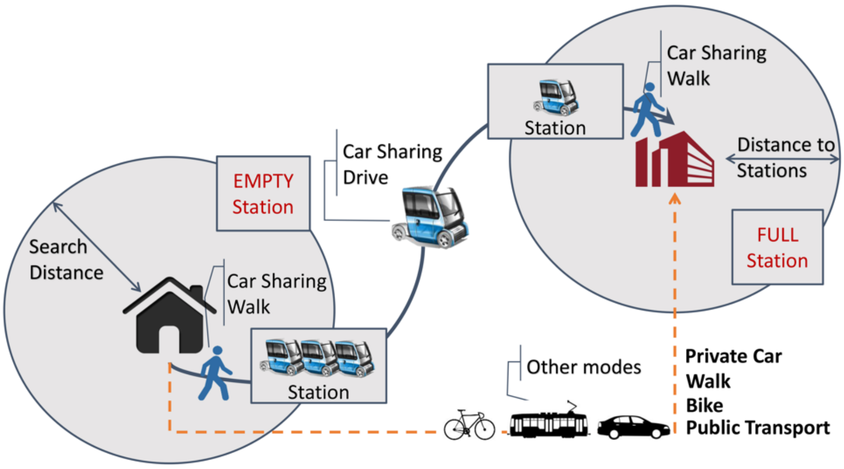


Fig. 5 The car sharing simulation model.

A diagram of the model workflow is shown in Fig. 5 and summarised by the following steps:

1. *Booking Vehicle*: after the agent finishes an activity, it starts looking for the closest station, within a search distance radius, that has an available (i.e., non-booked) vehicle. If an available vehicle is found then the agent books it, and this makes the vehicle immediately unavailable to other agents;
2. *Access Walk*: agent walks from its current location (e.g. home) to the selected station;
3. *Pick-up*: agent picks up the vehicles and frees the parking spot;
4. *Booking Spot*: agent looks for the closest station to his final destination with an available parking space and books it, which makes the spot unavailable for others;
5. *Drive*: agent drives the vehicle to the destination station while interacting with other vehicles on the network;
6. *Drop-off*: agent drops off the vehicle on the booked spot, which terminates the rental period;
7. *Egress Walk*: agent starts walking towards the location of his next activity;
8. Finally, agent carries out the remaining of the daily plan.

A more detailed description of the various components of our car sharing model for MATSim is reported in Laarabi et al. (2016). The integration between the demand model and the supply model is based on a skimming process. In conventional network modelling network skims are created at the model assignment stage, whereby the generalised cost the characteristics of every destination from each origin is recorded. The skims will vary between iterations, because as roads become more or less congested, travel times change. In this model, the skims were produced by MATSim by recording the characteristics of every alternative as well as the alternatives finally selected. We remind that this generalised cost is used to calculate the probability that that alternative is selected using *random utility model theory* (RUM) consistent with logit choice modelling. Note that both demand and supply models can be iterated to achieve convergence.

## 5. Use cases and preliminary results

In ESPRIT project, three complementary use cases have been defined to provide real-life mobility scenarios for modelling and assessing business, behaviour and operating aspects (including infrastructure and planning requirements) of the ESPRIT transport system. The Glasgow use case is based on the largest business park in Scotland, with offices and industrial units to let, and it is especially suitable to the last kilometre scenario. The L'Hospitalet de Llobregat use case is concerned with a city centre scenario where the use of one-way carsharing would resolve current mobility issues related to access to the Gran Via Barcelona Exposition Centre. Lastly, the Lyon use case is based on a highly populated periurban area currently fed by a major public transport hub. In the following we describe more in details this last scenario.

### *5.1. Lyon study area*

The study area consists of 93 zones with a further 51 zones across Grand Lyon. The area is served by buses and the T3 tram line which has 5 stops within the study area. Park and Ride is available close to each of these tram stops except at Grand Stade. In addition, RhoneExpress services pass through the area from Lyon airport (which is to the south west of the study area) stopping at Meyzieu Industrial in the study area and Vaulx-en-Velin to the west of the study area.

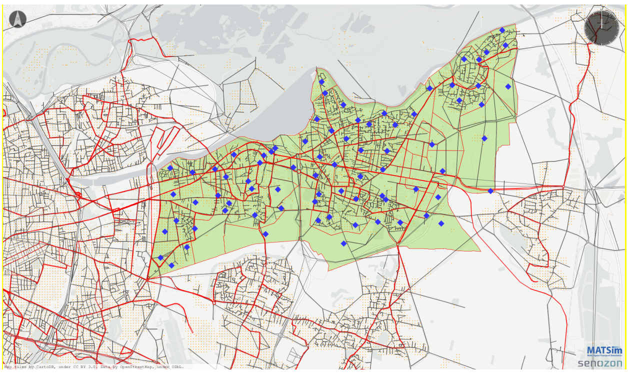


Fig. 6 Map of the simulated area, with blue diamond referring to the Esprit stations deployed within the study area. The red lines refer to the PT network, while the grey lines refer to the car network.

In order to create the synthetic population for Lyon we used census data from the INSEE website. This version of the model also uses data from the Lyon Travel Diary Survey 2015 for the calibration. Specifically, we leverage the travel diary survey to estimate coefficients to use in the demand model. The records were split according to whether the respondent had both a driving licence and the household a car (car available) or not (non car available). The trip records were fitted to a nested mode (Car or PT) and destination choice model, and the coefficients at both levels of the nest were estimated simultaneously.

The synthetic population is of the order of 1.4 million agents, all of whom pass through the choice model to determine the destination and mode of trips. For this model, the types and numbers of each type of facilities are:

- home, 35,853
- work, 354
- education, 362
- shopping, 402
- leisure, 431

### 5.2. Preliminary results

The simulated scenario as depicted by Fig. 6 considers a network of 141.795 links, not only limited to the study area, with 19.186 households, 326 work facilities as well as additional 1.090 facilities for different purposes.
Initial results have been obtained under a scenario where car sharing 77 stations were deployed (blue diamonds in Fig. 5), the fleet consists of 350 shared vehicles, and the cost of ESPRIT is based on in-vehicle minutes only (at 0.27 euros per minute), and ESPRIT use is restricted to journeys covering 500m or more (to prevent ESPRIT being used for very short journeys).

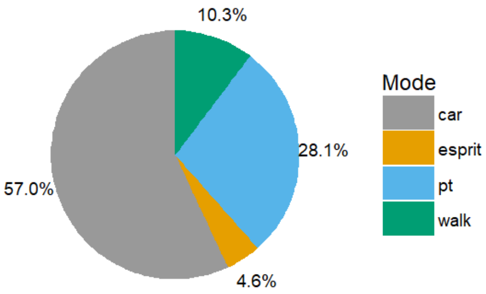


Fig. 7 Modal split of the simulated demand.

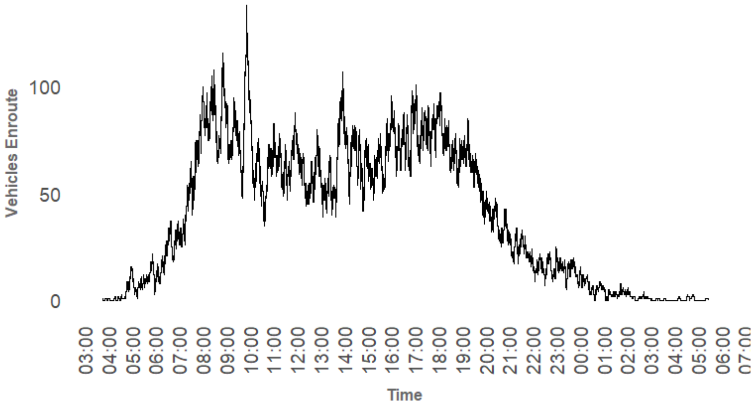


Fig. 8 Esprit activity during the simulated day.

The demand contains a total number of 80.740 agents and a customer base of 6.416 agents. The modal split, as shown in Fig. 7, is composed of four main modes: private cars (car), ESPRIT vehicles (esprit), public transport (pt) and walk. ESPRIT represents 4.6% of the modal share, while private car is leading by a modal share of 57%, then public transport 28.1% and finally walking mode representing 10.3% of the modal split. Fig. 8 shows the number of car sharing trips during the day. The diagram illustrates quite clearly the morning and afternoon peaks (customers going to and returning from work, respectively) but also a non-negligible activity in early afternoon. More results can be found in Laarabi et al. 2017.

## 6. Conclusions

In this paper, we have provided an overview of the activities, from the point of view of transport modelling, carried out within the European project ESPRIT, which is aimed at addressing the limitations of current car sharing systems leveraging L-category vehicles with small spatial and carbon footprints optimised for vehicle redistribution. We have first discussed the lessons learnt from the analysis of available car sharing datasets, in terms of vehicle availability and spatial distribution. In particular, we have found that the percentage of unused vehicles is typically quite high but these vehicles are not uniformly distributed across the city, so there are areas that are underserved at certain times of the day. Then, we have presented the demand model that has been designed with the project. This model is a novel agent-based demand modelling framework that applies discrete choice techniques to forecast car sharing demand by considering the influence of individual preferences, behaviours and lifestyles in the utility associated with each transportation alternative. Finally, we discussed how the ESPRIT vehicle and car sharing concept has been implemented in the MATSim simulator, and, considering the Lyon study area, we have shown some preliminary results obtained from simulations to which the obtained demand has been fed.

## Acknowledgements

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