SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Mobility as a Service: Data-driven operational and economic feasibility of an autonomous urban car-sharing

Laurea Magistrale in Mathematical Engineering - MMF Quantitative Finance

Author: Stefano Provera

Advisor: Prof. Silvia Carla Strada

Co-advisor: Prof. Sergio Matteo Savaresi, Ing. Francesco Abbracciavento, Ing. Davide Penati

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1. Introduction

The world of mobility is moving towards three main mega-trends: the use of electric vehicles, the development of self-driving (autonomous) vehicles and the expansion of MaaS (Mobility as a Service) models; i.e. models of shared transportation, intended as a service for citizens, and no longer based on the use of private cars, [1]. All this expresses the need to develop intelligent and shared mobility systems, for example electric and self-driving car-sharing systems, which are often called robotaxis.
The spread of a shared urban paradigm can significantly change the vehicle ownership rate (i.e. the ratio between the number of vehicles and the number of people), reducing the number of existing vehicles by a factor of about 1:10, since most private cars are used less than 10% of the time, [2]. Intensively used, shared cars can also improve the efficiency of the transport sector, as high annual vehicle mileage generates a strong incentive towards the use of vehicles that are expensive, but clean and highly efficient, [3].
In this thesis, a pilot study that tries to combine the three mega-trends previously listed, describing and optimizing the feasibility (both in terms of service efficiency and in economic terms) of an autonomous, urban, electric car-sharing service is carried out. Compared to the state of the art in this field, the strength of this project is that it is totally based on real trips data made by private vehicles over a 2 years period of observation.

2. Telematic Dataset

Thanks to the collaboration with UnipolSai, for this research we were able to have access to a huge dataset containing approximately 115 million trips made between January 2019 and December 2020 by 33170 vehicles registered in the province of Brescia.
All these trips were constructed starting from events collected anonymously by GPS sensors (commonly called e-boxes) mounted inside the insured vehicles. These e-boxes, continuously active over time, constantly collect data on the vehicle's behavior and periodically send positions and movements to the Unipol servers.

Since these sensors are not always accurate, some trips are not effectively reliable and usable for the following research and must be removed, hence we initially proceeded with a

index	id_driver	latitude_start	longitude_start	latitude_end	longitude_end
1336530	33532	45.545379	10.219446	45.559111	10.191827

distance	stop_duration	trip_duration	time_start	time_end
3.311	15379	620	2019-01-07 00:00:11	2019-01-07 00:10:31

Figure 1: Example of a trip description in the dataset, associated to the vehicle with ID 33532

dataset cleaning and preprocessing . The final result is a dataset comprising approximately 74 million trips made by 27777 users.
In Fig. 1, it is possible to see an example of how a trip is described.

3. Data Processing and Simulator Implementation

Following the data cleaning process, the first step is to study the behaviour of the users within the dataset, in order to identify an optimal location and size of the coverage area of the urban car-sharing service.
As in the case of a traditional free-floating sharing services, the service coverage area is the region within which vehicles can be taken and released at the end of the trip. The trip itself can also be made, partially, outside the coverage area, but the point of departure and the point of arrival must be within that area.
Analysing the distribution of trip departures in the dataset, it was found that the area where most trips are made is the city of Brescia (hence the most suitable location for the coverage area), and also that the best and most straightforward shape for the coverage area is circular.
Next, it was necessary to identify the users for whom it would make sense to dismiss their private vehicles and switch to an autonomous car-sharing service. These users (who are characterised by an high activity within the limits of Brescia metropolitan area) represent 3%-15% (depending on the dimension of the sharing service) of the total citizens residing in the service coverage area. Once these users are identified, all their trips are merged together in a new dataset and ordered by the time_start parameter; this new dataset represents the input for the simulator of the sharing service.
Once the appropriate trip database has been created, it was necessary to build a tool capable of realistically simulating the urban and autonomous car-sharing service. The parameters that uniquely identify the simplified autonomous electric car-sharing service are three:

1. The number of in-sharing vehicles.
2. The number of charging stations.
3. The radius of the coverage area (from this parameter it is possible to create the dataset input of the simulator as described above).

Concerning the electric mobility part, it was necessary to evaluate recharging policies that would make the service as efficient as possible. Analysing the time distribution of the calls made, and proceeding by simulating the robotaxi service in different cases, it was noted that it is convenient to have differentiated recharging policies for the day (7-23) and night (23-7). In particular, it makes sense to fully recharge in service vehicles during the night (a moment when the number of trips to be served is extremely low), so to have the fleet fully charged during the day.
For what concerns the placement of the charging stations, inspired by the research of Cocca et al., [4], the most reasonable and efficient positioning is derived according to the spatial distribution of calls made in the service.

4. Optimization "simulator in the loop"

After the creation of an efficient simulator, written in Python language, it was necessary to introduce the optimization part of this work. We had to find the optimal values of the input variables of the car-sharing service (number of in sharing vehicles, number of charging stations and radius of the coverage area). The optimization problem proposed in this work follows an economic logic. In particular, it is a cost-minimisation problem, with constraints that ensure an acceptable performance of the service, i.e. the variables describing the overall effi-

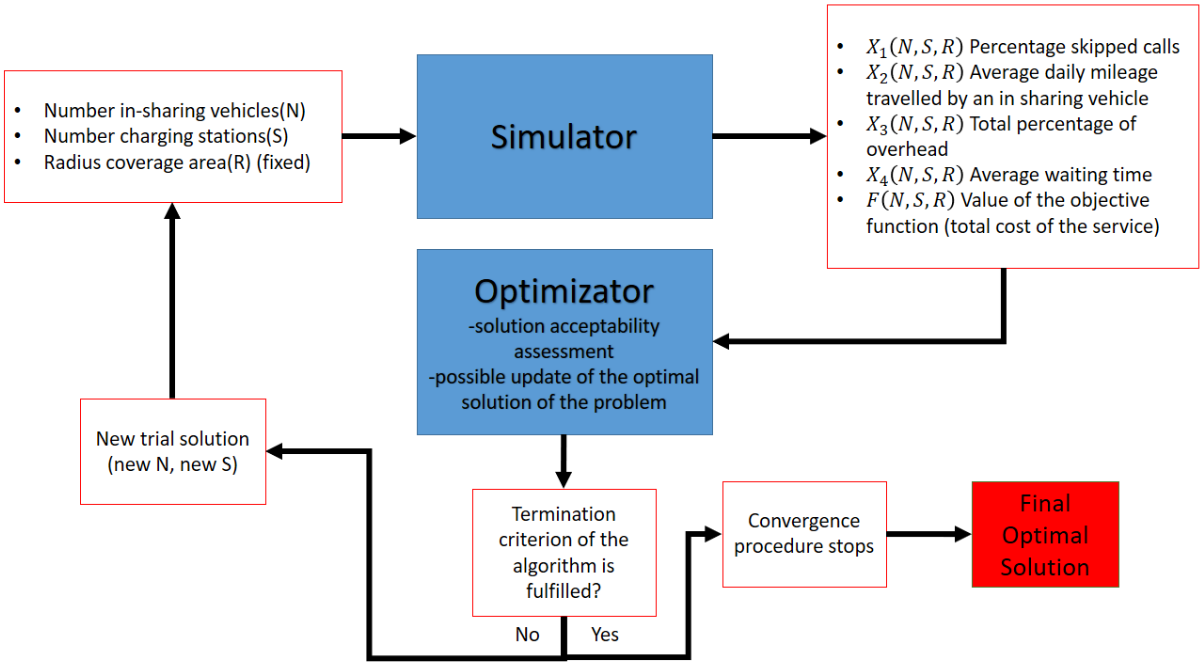

Figure 2: Schematic diagram of the 'simulator in the loop' optimization process

ciency of the service, such as the percentage of skipped calls or the average waiting time for a user, must comply with certain conditions. The objective function, which must be minimized, is constructed to be the total cost of the electric autonomous car-sharing service, following assumptions and models used by Richter et al. [5].

In Fig. 2 it is possible to see the logic of the simulator "in the loop" used in order to reach the solution of the optimization problem.

It is important to notice that the objective function is only minimised with respect to the variables N (number of in-sharing vehicles) and S (number of charging stations), although it also depends on R(radius of the coverage area). This is because it is clear that a smaller coverage area implies lower costs (mainly due to a smaller fleet size). However, any revenues would also be lower, as there would be fewer customers to serve. To overcome this problem, it was decided to carry out several separate optimizations, each one maintaining a fixed radius of the coverage area. Eventually, other simulator output statistics (in particular the price of the minimum fares that would guarantee economic break-even) were evaluated to determine the optimal radius of the service.

The following challenge to face was to find a suitable iterative method for this kind of optimization problem. The main features that don't allow to use the most common iterative methods are:

- having also discrete value variables
- the high non linearity in the objective function and in the constraints (because they depend on variables which are output of a simulation process based on real data)

The most suitable algorithm is the so called "Nelder Mead Algorithm" which is a non-linear optimization method for functions defined on an n-dimensional domain (n=2 in this case). It is a heuristic search method, which does not make use of derivatives, but it's based on the concept of simplex, a particular type of polytope with n+1 vertices in an n-dimensional domain (a triangle in the plane in the specific case).

5. Final Results

5.1. Optimization results

As previously mentioned, different optimizations with fixed radius were carried out. The optimal values of the number of sharing vehicles and the number of charging stations to be placed were found. From this optimal values it is also possible to extrapolate many useful statistics, de-

Optimization results

	Optimization Outputs		Minimum fare to reach economic break-even	
Radius of the coverage area	**Number in sharing vehicles**	**Numero charing stations**	**Cost per kilometer [in €]**	**Cost per minute [in €]**
8 km	2049	693	0.2144	0.0762
9 km	2804	986	0.2013	0.0739
10 km	3780	1043	0.1969	0.0744
11 km	4873	1217	0.1958	0.0759
12 km	5857	1792	0.1939	0.0777
13 km	8438	2007	0.2138	0.0884
14 km	9374	2141	0.1995	0.0818
15 km	10324	2417	0.1964	0.0812

Table 1: Optimization results

scriptive of the car-sharing service, from the operational and from the economic perspective. In Tab. 1 just a couple of this statistics are shown. From this statistics it was found that the optimal radius is 9km, since it gives the best performance in terms of usage of the fleet and it also gives very good economic results, in particular the minimum fare based on duration (i.e. cost per minute) that must be applied in order to reach economic break-even is the lowest, as it can be seen in Tab. 1.
In general it has been noted that, for any radius between 8km and 15km, the shared robotaxi service is always feasible, and the minimum fares remain quite similar to the best case.

5.2. Analysis in the optimal case

The optimal final solution is therefore obtained considering 9 km of radius, 2804 vehicles and 986 charging stations.
The price of a trip made in the service was estimated to be on average 1.48 €, which is in line with public transport prices in the city of Brescia (ordinary ticket 1.40 €). It was also found that using this form of shared mobility could reduce the number of vehicles circulating in the metropolitan area by a factor of 9, enormously decreasing the area allocated to parking in the cities.
This thesis project assumes that all target users identified as sharing compatible switch instantly to the car-sharing service and get rid of their private car immediately. In everyday reality, the transition process from a private to a shared mobility system can be expected to be very slow and gradual, hence the economic impacts of this progressive transition are studied. Two different scenarios are analyzed, one in which the car-sharing service parameters are always re-optimised, Fig. 3(this simulates a service that is built up gradually, adding vehicles and charging stations as the actual number of users switching

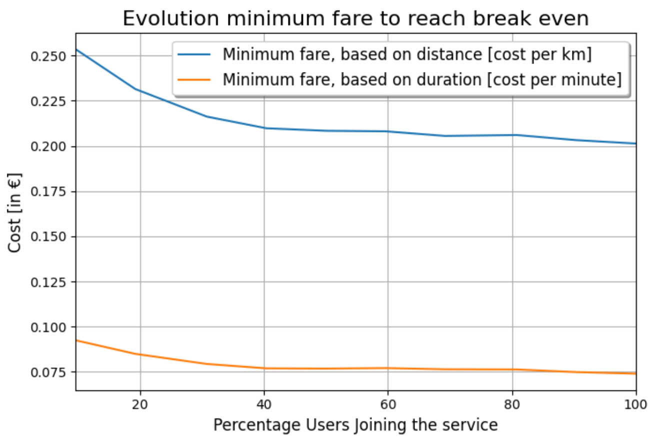

Figure 3: Mimimum fare evolution in case of optimized service parameters

to this form of shared transport increases) and the second in which the car-sharing service parameters are always fixed, Fig. 4 (this situation simulates a service built immediately for all target users, and analyses what happens if fewer people than expected actually use it).

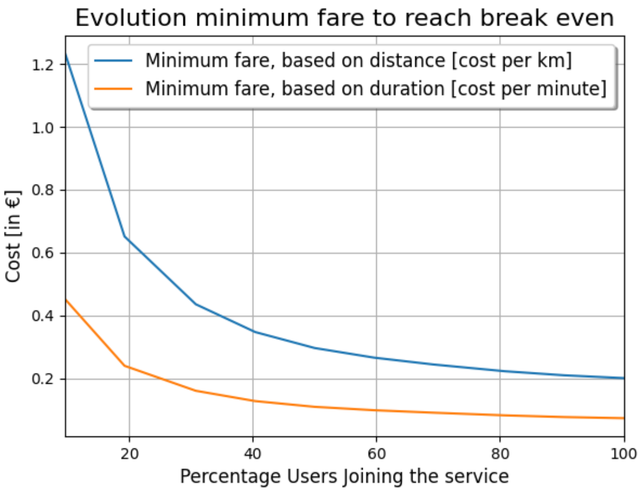

Figure 4: Mimimum fare evolution in case of fixed service parameters

It can be clearly noticed how the minimum fares rises enormously when considering only a few users in the second case. If there were only 35% of the expected users, the service would cost more than twice. In terms of economic feasibility, it is therefore necessary to estimate the number of target users as precisely as possible in order to keep service costs low (while maintaining efficiency).

Furthermore, the primary reason that might lead users to abandon their car in favour of a shared service is the economic one. It is therefore necessary to check whether it is actually advantageous for target users to use an electric and autonomous car-sharing service as described in this paper. With certain assumptions it was possible to evaluate the cost of owning a car for a typical citizen living in the urban area of Brescia. This cost, as a function of the yearly mileage, can be seen in Fig. 5.
Hence, for all the citizens whose yearly mileage is lower than 12000km, it is economically convenient moving to this urban and autonomous car-sharing service. These users are the vast majority and represent 95% of the total sharing compatible users.

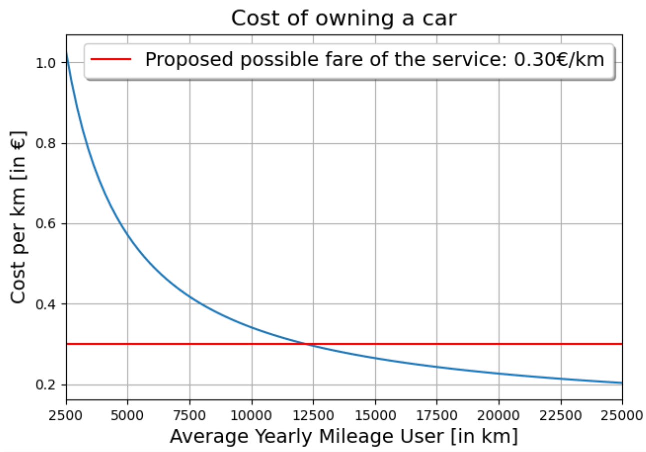

Figure 5: Cost of owning a car, compared to cost of the service

Finally an analysis on the overhead generated by the trips served in the sharing service is carried out, Fig. 6. Trips that have a distance lower than 0.8km generate an overhead greater than 50% (i.e. on average the distance travelled by robotaxis, without a user on board, to go to the place of call is greater than the length of the trip itself). Intuitively, it would be therefore appropriate to have a banded tariff scheme, based on the length/duration of the trip to be made (in fact this is the case with all currently existing car-sharing services).

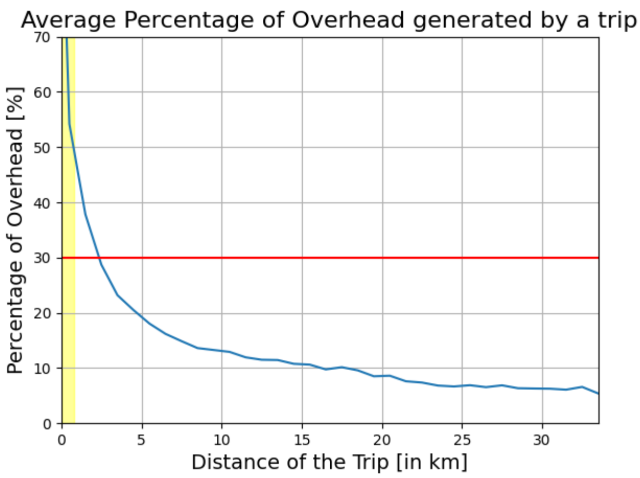

Figure 6: Overhead generated from a trip in the service

6. Conclusions

In undertaking this research, the following question was posed: **Would it be feasible, both in terms of efficiency and in economic terms, at present day, to replace private vehicles, used for urban mobility, with an autonomous and electric car-sharing service?** The development of shared mobility is still in a embryonic stage, so that many citizens still need to use private vehicles to move around.

However, as identified in this research, there is a segment of citizens for whom it would already be fully feasible to replace their private vehicles with robotaxis in an autonomous and urban car-sharing service. These sharing-compatible target users represent about 10% of the total citizens. For them, it is also economically favourable to use the service in 95% of cases.

This form of shared mobility could reduce the number of vehicles circulating in the metropolitan area by a factor of 9, thus greatly reducing the area allocated to parking in cities.

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