A CAR SHARING SYSTEM FOR URBAN AREAS WITH FULLY AUTOMATED PERSONAL VEHICLES

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ABSTRACT
The paper concerns a transport system for pedestrian areas, based on a fleet of fully-automated Personal Intelligent Accessible Vehicles (PICAVs). Vehicles are available in stations and are shared through the day by different users. The following specific services are provided: instant access, open ended reservation and one way trips. All these features provide users with high flexibility, but create a problem of uneven distribution of vehicles between the stations. Therefore, relocation must be performed. A management strategy based on fully automated vehicles is proposed. To check the performance of the proposed management strategy, an object-oriented simulator has been developed. The simulator gives as an output the transport system performance, in terms of Level Of Service provided to users and of efficiency from the management point of view. The proposed transport system has been simulated for the historical city centre of Genoa, Italy.

Keywords: fully automated personal vehicles, automatic relocation, micro simulation.

1. INTRODUCTION
The paper concerns a new transport system, which is meant to ensure accessibility for all people in urban pedestrian environments. The research has been carried out within the PICAV project founded by the European commission (SST-2008-RTD-1). The project involves a new Personal Intelligent City Accessible Vehicle (PICAV) and a new transport system that integrates a homogeneous fleet of PICAV units.

The PICAV unit is a one person vehicle that is meant to ensure accessibility for everybody and some of its features are specifically designed for people whose mobility is restricted for different reasons, particularly (but not only) elderly and disabled people. Ergonomics, comfort, stability, assisted driving, eco-sustainability, parking and mobility dexterity as well as vehicle/infrastructures and intelligent networking are the main drivers of the PICAV design. The single units are networked and can communicate with each other, with the city infrastructure and with public transport in the surrounding area, which allows for a high level of inter-modal integration.

The PICAV transport system is a new multimodal shared use vehicle system for urban pedestrian environments. Stations are distributed at different locations throughout an area, and vehicle trips can be made between different locations. The PICAV vehicles can be rented for short term periods (usually a couple of hours at a time, with the latest return time being the end of the day). People commute into the city, reach the pedestrian area border by public or individual transport modes, jump in a PICAV vehicle, visit attractions (shops, monuments, museums) in the pedestrian area and drop the vehicle off at any PICAV station.

The PICAV transport system will provide high flexibility for users. However, the system will be prone to becoming imbalanced with respect with the number of vehicles at the multiple stations. Due to uneven demand, some stations during the day may end up with an excess of vehicles whereas other stations may end up with none.

One way trips, open ended reservation and instant access are the main characteristics of new car-sharing systems. For these systems, according to the literature, the two main categories of relocation strategies are user-based and operator-based, with some systems using a mixture of both. Operator-based relocation strategies resolve the balance problem through a strategy where some operators manually relocate a vehicle or a platoon of vehicles from stations having too many vehicles to stations having too few vehicles. Several transport systems of this type have been realized, for example the Coachella Valley in California (Barth and Todd, 1999), near Palm Spring's airport, the two CarLink experiences, and IntelliShare, established at RiverSide University campus, the Praxitèle in Paris, the Honda ICVS in Singapore, then also CarLink I and CarLink II.

User-based relocation strategies ensure that at least part on the relocations are performed by the transport system users. The most important issue regarding the user-based strategies is the possibility of giving users some incentives, such as a reduction in prices, in order make them improve the transport system performance.

A transport system of this type has been implemented in the city of Ulm (Firnkorn and Müller, 2011). A fully user-based relocation strategy has been proposed by Cepolina et al. (2010): a system supervisor is in charge of addressing at least part of the PICAV users (flexible users) to specific stations where they have to return the PICAV units. This management strategy is suitable when users reach the intervention area by public transport and then have alternative locations from which they can get a public transport service to return home. The system supervisor makes their decision knowing real time information about the traffic conditions, i.e. the number of vehicles available, the length of queues and waiting times at each parking lot and also the choice set of destination parking lots the user is happy to return their vehicle to.

The performance of a relocation strategy is generally assessed as a function of users waiting times and number of relocations. For the operator-based strategies, an optimization procedure has been proposed by Kek et al. (2007) for assessing the staff strength and the shift hours which maximize the system performance. For the fully user-based strategies, a procedure for finding the fleet dimension and its distribution among the stations that maximize the system performance has been proposed by Cepolina and Farina (2011a). Several authors, such as Shaheen et al. (2009) focus on modal split issues: the capability of these new transport systems to attract users from private transport modes. An overview about existing shared vehicle systems, with a particular focus on vehicles relocation techniques, has been performed by Cepolina and Farina (2011b).

The level of automation of car-sharing vehicles is increasing so rapidly that a fully vehicle based relocation strategy will soon be possible. In this paper a fully vehicle based relocation strategy is proposed: instead of having people that manually relocate a vehicle or a platoon of vehicles, vehicles automatically relocate among the stations. This removes the need of operators and also eliminates any constraint on users. In the transport system proposed in this paper the users decide to which parking lot they return the PICAVs and are not restricted in this choice by a system supervisor.

The paper is organised as follows: Section 2 describes the proposed transport system. Section 3 outlines the architecture of the transport system microscopic simulator. Section 4 describes the model implemented for the historical city centre in Genoa, Italy. Major conclusions and future work follow.

2. MAIN CHARACTERISTICS OF THE PROPOSED TRANSPORT SYSTEM

2.1. The user trips

We consider only visits to the urban pedestrian area during a day, therefore the number of users that enters the area during a day equals the number of people that exits the area in the same day.

If during a trip the PICAV user makes a stop that lasts more than 1h, the PICAV unit will need to be parked in a station. If the stop duration is less than or equal to 1h short-term parking along the street is permitted and the PICAV unit does not need to be returned to a station.

In the area of study we identified stations for the PICAV units. Trips by PICAV units begin (source) and end (sink) in these stations. Generally speaking, the trip between two stations could be travel single trip on board the PICAV unit or a sequence of trips on board with activities that require short term parking along the street. We take into account only visits to the pedestrian area and we consider only the following three types of trips in the pedestrian area:

Type A is a multi-task trip, the PICAV user has a sequence of short term activities to perform in the pedestrian area. The user arrives on the pedestrian area border, they pick-up a PICAV unit, they make an activity travel pattern , which comprises of a number of short term activities (like shopping, visits to: banks, post office, etc.) within the pedestrian area, they then return the PICAV unit in a PICAV parking lot and they go back home again.

Type B is a single-task trip, the PICAV user has to perform an activity that requires a long rest in the pedestrian area. The user arrives on the pedestrian area border, they pick-up a PICAV unit, and go to the PICAV parking lot closest to their activity place where they return the PICAV unit and they reach the activity by foot.

Type C is the return part of the single-task trip, the PICAV user has finished their activity within the pedestrian area and would like to go back home. The user thus goes by foot to the PICAV parking lot closest to their activity place, they pick-up a PICAV unit, they return the PICAV unit to the pedestrian area border in a parking lot and go back home again.

If the user reached the pedestrian area by a private mode, their overall trip in the pedestrian area is a round trip. If the trip is of type A, the origin and destination will coincide. If the trip is a single task trip, the origin of a type B trip coincides with the destination of the related type C trip.

If the user reached the pedestrian area by public transport, their overall trips in the pedestrian area could be one way trips: they may exit the area from a different point from the one they entered the area.

2.2. The PICAV vehicle

A PICAV vehicle is about 0.8 m wide and 1.1 m long. A draft idea of the vehicle is shown in figure 1. Its net weight is about 250 Kg.

The PICAV vehicle will be provided with a clean efficient power module to ensure greenhouse emissions are below the targets set in the Kyoto agreement and Euro V. This will be done by regenerating braking energy and using it to supplement the batteries and by targeting the conversion efficiency of standard electric vehicles to obtain a satisfactory power system for very small vehicles in the pedestrian environment.

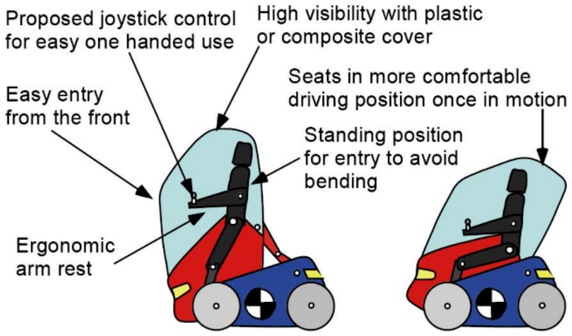

Figure 1: The PICAV vehicle characteristics

The power system is in charge of supplying the energy for traction and electric and/or electronic devices. In the configuration of energy accumulators that we take into account there are two batteries: one dedicated to traction and the other one dedicated to electric and electronic devices.

As it concerns the battery for traction, a lithium-ion battery has been selected in a first scenario by MAZEL (2011). The characteristics of the cell are: Specific Energy:132 Wh/Kg; Energy density: 345 Wh/l; Total Energy: 1000,00 Wh; Net Weight: 8,33 Kg; cell capacity: 20 Ah. A battery pack formed of 18 cells has been selected for simulation.

The PICAV units are able to recharge when they are idle at stations.

The battery discharging law depends on: the average up and down slopes of the path, the PICAV speed, the air density, the PICAV frontal area, the aerodynamic and rolling coefficients, the mechanical and electrical efficiency, the motor voltage and the overall weight of the vehicle.

A normal charging process has been considered. The battery charging law depends on: initial charging level, the final charging level and balancing time.

The PICAV unit can be fully user driven, its control system can provide driving assistance or the unit can automatically move thanks to the sensors and control techniques. Sensors and control techniques are being developed by INRIA, Ronquecourt, Versailles.

The PICAV speed is a function of pedestrian density on the street. It is envisaged that the PICAV will move more quickly when driven by the user compared with when it travels in a fully automatic way. Herewith are reported the two relationships between the PICAV speeds and pedestrian density depending on driving mode. The two equations are:

PICAV user driven:

$$v = -1.44677 \cdot K + 1.57751 \quad (1)$$

PICAV automatically driven:

$$v = -1.44677 \cdot K + 1.37751 \quad (2)$$

Where:

v = PICAV speed [m/s]

K = pedestrian density [ped/m^2]

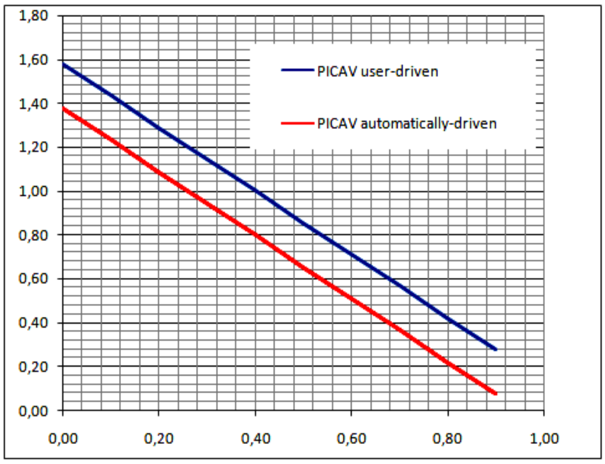

Figure 2: PICAV speeds against pedestrian density

In the case of a user driven PICAV, its speed-density relationship is the result of a linear regression performed on empirical data (Holloway et al. 2011). If PICAV travels in a fully automatic way, we will assume a lower speed. However this speed is not the one allowed by the current technologies but it is a speed close to the pedestrian one that therefore allows the PICAV motion to disturb as less as possible pedestrian flows. Therefore the proposed transport system could be implemented only in a next future when technologies will be further developed.

2.3. The management strategy

Characteristics of the PICAV transport system are: open ended reservation, instant access and one-way trips. The main problem of the proposed transport system is that it may quickly become imbalanced with respect to the number of vehicles at the multiple stations. Due to uneven demand, some stations during the day may end up with an excess of vehicles whereas other stations may end up with none.

When relocations are required, a system Supervisor has the duty to redirect unused vehicles from a station to another, according to the system needs and the actual waiting times at the stations. According with the Supervisor hints, PICAV vehicles automatically relocate themselves, thanks to their high level of automation.

A relocation is required when a critical situation occurs. A critical situation occurs when the number of vehicles in a given station at a given time instant goes below the station's critical threshold. This situation is referred as ZVT, i.e. zero vehicle time (Kek et al. 2005). When this condition occurs, the station has a shortage of vehicles and some users may need to queue. When a queue forms a request for a vehicle is generated. The critical threshold could be assumed constant in time or a function of time.

When a ZVT situation takes place, the system Supervisor addresses the vehicle request only to stations where the number of vehicles is above the low buffer threshold. According with Kek et al. (2005) the low buffer threshold is the minimum number of vehicles that a station needs to have in order to be able to send vehicles.

Among the stations to which the vehicle request could be addressed, the providing station will be selected by the system Supervisor according to two criteria: the closest station (shortest time criterion) and the station having the highest number of vehicles (inventory balancing). The shortest time criterion relates mainly to service levels, while the inventory balancing mainly focuses on cost efficiency. Therefore, an appropriate choice of relocation technique should be made according to the current system situation.

3. THE MICRO SIMULATOR

The simulator is written in Python language and it follows an object – oriented logic. The simulator receives in input the transport demand, the characteristics of the network, the relocation strategy and the PICAV fleet.

Each run of the simulator represents a day. The simulator allows to track the second-by-second activity of each PICAV user, as well as the second-by-second activity of each vehicle.

The simulator gives in output the transport system performances, in terms of Level Of Service provided to users and in terms of efficiency from the management point of view.

3.1. Input data

3.1.1. The transport demand

The transport demand is given to the simulator in the form of OD matrices. Rows and columns in the OD matrix represent stations; each cell gives the hourly number of trips from the station the row refers to to the station the column refers to. Each OD matrix refers to a specific type of trip (A, B and C). The day has been divided in time periods. In each time period the transport demand has been assumed constant. If *n* is the number of time periods within one day, the transport demand is represented by 3x*n* OD matrices, one for each type of trip and for each period of the day. The time at which a user arrives on the area border is generated randomly, accordingly with the OD matrixes.

3.1.2. The road network

The road network is defined by: the position of each station and the most used path for each pair of stations. For the paths, we are interested in the overall length, the average up and down slope and average pedestrian density in the different periods of the day. The average pedestrian density on a given path in a given period of the day allows one to assess the average speed at which the PICAV vehicle is able to move on the path. The average slope and average speed allows one to accurately simulate the battery discharging process.

Paths are created in Google Maps and imported into Google Earth where the elevation profiles of the paths are viewed and inspected visually to determine upslope, flat and downslope sections. For each path the total distance of that path and the average slope needs to be assessed. Distances, average slope and densities are given as data input in the simulator in the form of matrixes.

3.1.3. The PICAV fleet

The PICAV fleet is described by: the fleet dimension, the number of PICAV units at each station at the beginning of the day, the battery capacity, the charging and discharging laws.

The battery charging technique is the *opportunity charging*. The term opportunity charging refers to the charging of the batteries wherever and whenever power is available. Simply put, rather than waiting for the battery to be completely discharged, or for the duty cycle or work shift to be over, opportunity charging is the “power as you go” opportunity to extend the capabilities of your equipment during every stop in a station. If in a station a vehicle is charging and its current battery level is above the threshold of 10% and a user arrives or a relocation is required, the vehicle stops the charging process and becomes available either to the user or to be relocated.

3.1.4. The relocation strategy

The relocation strategy is described by two vectors. Their dimension equals the number of stations in the area, the value of each vector component is the station’s critical threshold for the first vector and the station’s low buffer threshold for the second vector. The transport system performance is considerably affected by these two vectors, therefore their values should be carefully selected. The authors are working on defining a methodology for their optimisation.

In periods of low usage, the most appropriate relocation technique is by inventory balancing. In periods of high usage, then the shortest time technique performs best.

3.2. Output data

3.2.1. Level of Service (LOS)

LOS measurement are assessed based on the statistical distribution of wait times. Castangia and Guala (2011) proposed a new LOS measurement scale using as reference the average waiting time of the 50th, 90th and 95th percentile of users at stations.

3.2.2. Efficiency

From the management point of view, the transport system efficiency is inversely proportional to the PICAV fleet dimension and the number of required relocations. Another measure of the system efficiency is the ratio between number of PICAV available or occupied by users at each time instant and the PICAV fleet dimension.

4. A STUDY CASE

The proposed transport system has been planned and simulated for the historical city centre of Genoa, Italy. The historical city centre of Genoa has an area of about 1,13 km^2 and it is a pedestrian area.

The localizations of: bus stops, underground stations and car sharing parking lots have been identified. We have identified as well the localization of hotels, museum, offices, schools and commercial activities (food shops, clothe shops, handicraft shops and other shops). We designed 9 stations: 2 internal to the area (parking lots n. 10 and 11) and 7 on the area border (parking lots n. 1,2,3,4,5,6,7).

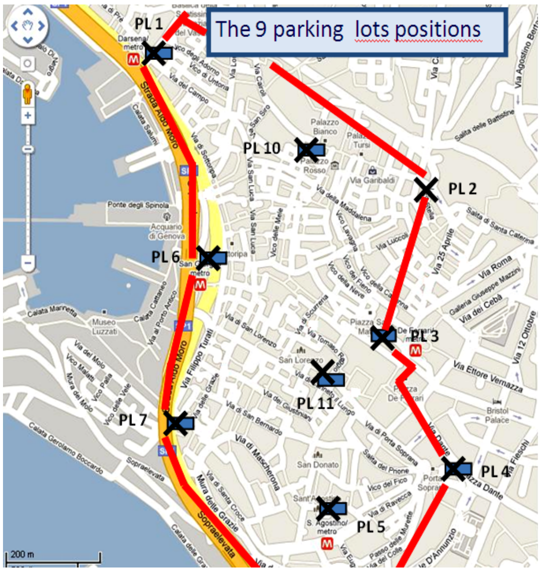

Figure 3: The intervention area and the parking lot positions

From the data collected in the field (Cepolina 2010), an off-peak period in the morning (starting at 8 a.m. until 4 p.m.) and a peak period in the afternoon (from 4 p.m. to 8 p.m.) were identified. The peak transport demand is almost 1.5 times the off-peak demand.

We assume that 1% of the people that currently enter the historical city centre by foot will use the PICAV transport system. The overall PICAV travel demand in the reference day is 1060 users. The OD matrices in the off peak period are reported in figure 4 for the different types of trips. From the data collected in the field (Cepolina 2010) it was found that 55% of the people exiting the historical city centre, perform a single trip (Type B) while 45% perform a multi task trip (Type A). The OD matrices in the off peak period are shown in figure 4.

The most used path for each pair of stations have been identified via Google Maps and imported into Google Earth where the elevation profiles of the paths were viewed and inspected visually to determine upslope, flat and downslope sections. An example of a path is reported in figure 5 and in table 1 the data from each of these paths are summarised.

OD - type A off-peak period

	1	2	3	4	5	6	7
1	0	1	2	1	1	1	0
2	1	0	0	0	1	1	0
3	1	0	0	0	2	1	0
4	1	0	0	0	1	1	0
5	1	1	2	2	0	1	0
6	1	1	2	1	1	0	0
7	0	0	1	1	0	0	0

OD - type C off-peak period

	1	2	3	4	5	6	7
1	0	0	1	1	1	0	0
2	1	0	0	0	1	1	0
3	1	0	0	0	1	1	0
4	0	0	0	0	1	0	0
5	0	0	1	1	0	0	0
6	1	1	2	2	1	0	0
7	0	0	1	1	0	0	0
10	1	1	3	3	1	1	0
11	1	1	3	2	1	1	0

OD - type B off-peak period

	1	2	3	4	5	6	7	10	11
1	0	1	1	0	0	1	0	1	1
2	0	0	0	0	0	1	0	1	1
3	1	0	0	0	1	2	1	3	2
4	1	0	0	0	0	1	1	3	2
5	0	1	1	0	0	1	0	2	1
6	0	1	1	0	0	0	0	2	1
7	0	0	0	0	0	0	0	1	0

Figure 4: OD matrices (hourly number of trips) in the off peak period

Figure 5: Test route, going from Darsena metro to Piazza de Ferrari.

For assessing average pedestrian density in the different periods of the day, we recorded by video cameras pedestrian flows in Via san Luca in different periods of a day (Holloway et al. 2011) . According with the data collected in the field, we found an average pedestrian density of 0.15 ped/m^2 in the off-peak period and 0.35 ped/m^2 in the peak period in Via San Luca. For the current simulation we assumed these densities are the same for all paths in the area.

For the PICAV fleet, we considered 100 PICAV units. This fleet dimension seems reasonable since it is in accordance with the outcomes from the Barth and Todd's research (Barth and Todd 1999). Barth and Todd found that for all the various travel demand cases they analysed, the best number of vehicles to place in the system ranges from 3 vehicles per 100 trips to 6 vehicles per 100 trips. We have 1644 trips per day. This number of trips results from the overall PICAV travel demand, which consists of 1060 users. 45% of these users (i.e. 477 users) make 477 Type A trips whilst the other 55% (i.e. 583 users) make 583 Type B trips plus the return way trips (Type C trips), i.e. other 583 trips. A fleet dimension of 100 for 1644 trips gives 6.08 vehicles per 100 trips.

Table 1: Lengths and gradients of some routes between stations

Origin	Desti-nation	Total Distance [m]	Up [m]	Down [m]	Flat [m]	Up Slope [%]	Dn Slope [%]
1	2	1060.00	805.60	247.50	0.00	3.87	-2.88
1	3	976.00	717.80	258.00	0.00	3.97	-3.67
1	4	1200.00	911.00	323.00	0.00	3.99	-2.94
1	5	1400.00	682.00	719.00	0.00	4.18	-3.51
1	6	604.00	319.90	285.80	0.00	5.27	-7.17
1	7	1100.00	589.50	492.90	0.00	3.89	-5.03
1	8	489.00	408.70	77.40	0.00	6.63	-3.90
1	9	1060.00	762.30	290.90	0.00	3.71	-2.67
2	3	316.00	28.96	287.00	0.00	9.17	-2.06
2	4	846.00	611.90	233.71	0.00	2.61	-3.89
2	5	1180.00	660.70	517.00	0.00	2.52	-3.33
2	6	732.00	264.30	465.75	0.00	2.82	-4.99
2	7	1100.00	144.80	451.00	308.00	15.07	-5.75
2	8	489.00	310.50	177.76	0.00	7.35	-9.09
2	9	747.00	341.80	405.03	0.00	4.68	-4.47
3	4	414.00	255.51	158.30	0.00	6.25	-4.44
3	5	516.00	264.50	250.10	0.00	13.67	-13.4
3	6	569.00	146.90	417.10	0.00	2.97	-4.76
3	7	829.00	437.29	386.00	0.00	4.28	-6.39
3	8	563.00	399.10	163.60	0.00	6.89	-9.68
3	9	326.00	174.01	152.30	0.00	4.79	-6.28
4	5	481.00	309.06	171.80	0.00	5.68	-11.4
4	6	848.00	219.80	476.00	149.00	2.22	-6.81
4	7	1080.00	558.76	518.00	0.00	2.87	-8.28
4	8	866.00	435.80	429.96	0.00	3.48	-4.37
4	9	379.00	248.50	130.17	0.00	3.98	-11.6
5	6	834.00	231.90	603.20	0.00	4.10	-5.30
5	7	804.00	269.20	531.94	0.00	5.22	-7.11
5	8	1050.00	440.50	606.50	0.00	4.29	-3.72
5	9	372.00	210.60	160.26	0.00	6.52	-9.55

The proportion of vehicles in each station at the beginning of the day is shown in table 2 . This initial distribution was established from the fleet optimisation procedure carried out by Cepolina and Farina (Cepolina and Farina 2011a) for the same case study, however, in that research a fully user-based relocation strategy was used.

As it concerns the relocation strategy, the critical thresholds and low buffer thresholds are reported in table 3. The relocation technique used is the shortest time technique.

Table 2: The proportion of vehicles in each station at the beginning of the day

station n°	1	2	3	4	5	6	7	10	11
n° of Picav units	11	12	13	13	14	10	9	9	9

Table 3: Critical thresholds and low buffer thresholds for the stations

Station n°	1	2	3	4	5	6	7	10	11
critical threshold	2	2	2	2	2	2	2	2	2
low buffer threshold	4	4	4	4	4	4	4	4	4

The performance of the proposed car sharing system for the case study of Genoa has been assessed by simulation.

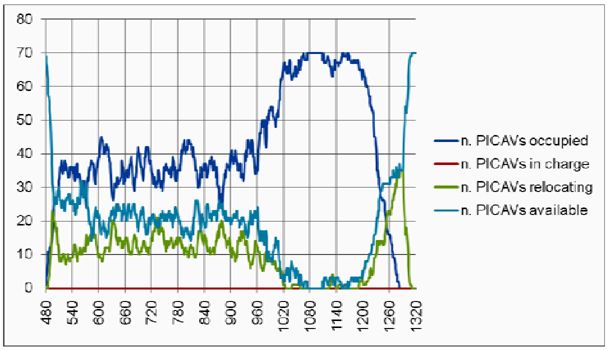

Fig. 6 number of PICAVs in each state against time

As it concerns the transport system efficiency, in figure 6 the number of PICAVs is each state (occupied by users, available, in charge and relocating) is plotted against time: the time is expressed in minutes starting from midnight, therefore a time of 480 refers to 8a.m, a time of 960 refers to 4p.m. and a time of 1200 refers to 8p.m.

At least 70% of the fleet is available to users (occupied by users or available at stations) in all the simulated period. As it concerns the power system, all the vehicles do not reach a battery level below the 10% threshold: therefore when they are at stations, they are always available to users. As it concerns the management strategy, in the peak period, the maximum number of vehicles simultaneously allocated is 9. The number of performed relocations was 531. This means that the proposed transport system works quite well from the management point of view.

According with Castangia and Guala (2011), the Level Of Service (LOS) provided is between LOS C and D. In fact, the average wait time of the 50th, 90th and 95th percentile of users result equal to 0s, 180s and 420s respectively.

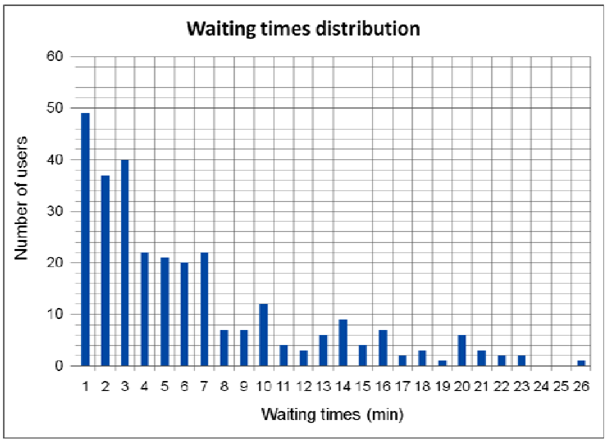

Fig. 7 waiting times distribution

According to the simulation results, a specific LOS can be attributed to each station. The following table shows the LOS assessment.

Table 4: The LOS assessment.

	Wait time (s) at stations			LOS
Station ID	50th percentile	90th percentile	95th percentile	
1	0	60	180	B
2	0	0	0	A
3	0	60	120	A/B
4	0	120	300	B/C
5	0	300	540	D/E
6	0	420	480	D/E
7	0	1380	1560	F
10	0	120	360	C
11	0	600	1140	F

5. CONCLUSIONS AND FUTURE WORK

A new operator-based shared vehicle system is proposed in this paper. In this shared system vehicles are fully automated, they are able to travel without being driven by a user, therefore they can automatically relocate among the stations, according to the station's needs. This transport system is simulated through an object – oriented logic, and the characteristics of the roads, their degree of crowd, the transport demand are the simulator inputs. The simulator follows each user and each vehicle within the simulation period, and gives the distribution of waiting times and the number of vehicles available at each parking lot in each simulation time instant. Therefore, the transport system performance can be assessed.

As stated before, vehicles are available only at specific stations, this is despite the fact that capillarity (i.e. the possibility that vehicles are available also along the roads), is a very good way to satisfy better user demand. As stated in the work by Ciari et al. (2007), the capillarity is a key way to ensure a high level of user satisfaction. Therefore, a new transport system where vehicles are available along the roads should be investigated in future studies. In this scenario, users may book, require and check-in vehicles of the system via a cellular GPRS technique, the overall system management would then identify a user actual position and deliver them a shared vehicle, or also tells them the position of the nearest vehicle . Then, as users trips are performed, they can leave the vehicles at any position within the intervention area. This new kind of transport system may be the topic of further research.

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