AN AGENT-BASED MODEL TO ASSESS THE IMPACTS OF INTRODUCING A SHARED-TAXI SYSTEM IN LISBON (PORTUGAL)

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ABSTRACT

This paper presents an agent-based simulation procedure to assess the market potential for the implementation of a new shared taxi service in Lisbon (Portugal). The proposed shared taxi service has a new organisational design and pricing scheme which aims to use the capacity in traditional taxi services in a more efficient way. In this system a taxi acting in "sharing" mode offers lower prices to its clients, in exchange for them to accept sharing the vehicle with other persons who have compatible trips, (time and space) while also increasing the revenue for the operator. The paper proposes and tests an agent-based simulation model in which a set of rules for space and time matching between a request of a client and the candidate shared taxis is identified. It considers that the client is only willing to accept a maximum deviation from his direct route and establishes an objective function for selecting the best candidate taxi. The function considers the minimum travel time combination of pick-up and drop-off of all the pool of clients sharing each taxi while allowing establishing a policy of bonuses to competing taxis with certain occupancy levels. An experiment for Lisbon is presented with the objective of testing the proposed simulation conceptual model and to show the potential of sharing taxis for improving mobility management in urban areas. Results show that the proposed system may lead to significant fare and travel time savings to passengers, while not jeopardising considerably the taxi revenues.

Keywords: Agent-based models, shared taxi systems, ride-matching, intelligent transport systems

INTRODUCTION

The rising of automobile usage deriving from urban sprawl and car ownership growth is making traffic congestion more frequent and harder in urban areas. Moreover the majority of the trips are single occupant vehicle trips (SOV) resulting in more automobiles for the same persons. Numbers of 1997 show that the occupation rate of the automobiles in commuting trips for the 15 Countries of the European Union was, at that time, in the interval between 1.1 and 1.2 persons per vehicle (International Energy Agency, 1997). This results in air pollution, energy waste and unproductive use of the time that persons have. In 2001, the White paper on Transport Policy in the European Union stated that “if nothing is done, the cost of congestion will, on its own, account for 1 % of the EU’s gross domestic product in 2010” (Palacio, 2001). This is happening even in countries with high fuel prices, good public transport (PT) systems and dense land occupation (Shaheen, Sperling, & Wagner, 1999).

PT cannot be the only alternative because providing transport capacity for peak periods would result in too many vehicles staying idle in non-peak periods, and too many people would be served with two or more transfers. Thus, there is the need to consider other alternatives, besides the classical transport modes. This is actually not a recent idea. In the seventies, with the Arab Oil Crises, scientific interest arose for new transport alternatives, mainly in the United States. In 1974 Ron Kirby and Kisten Bhat of the Urban Institute in Washington, U.S., released their report named: “Para-transit: Neglected Options for Urban Mobility” (Kirby & Bhat, 1974), this term, “Para-transit” was used as a general term to describe the various forms of flexible transportation that do not follow fixed routes or schedules such as shared taxis or carpooling (Vuchic, 2007).

These services usually charge a lower fare when compared to the regulated transport services. Not surprisingly it was in third world countries that these alternatives flourished, nourished by poor quality PT services and a great latent demand for travelling. For instance, while illegal, it is still normal in Korea to share a taxi with people having similar destinations (Jeon, Amekudzi, & Vanegas, 2006). But these transport alternatives have also found their space in developed countries. One of the examples is carpooling which is present even in Europe where PT systems are traditionally of a superior quality in service and comfort (Correia & Viegas, 2011).

One the most interesting alternatives is shared taxis, which denotes the use of taxi-cabs by more than one person (or small party) serving multiple trips in the same taxi route (Teal, 1981). This allows charging a lower fare to each client of the system and increasing each taxi profit because costs should not vary significantly while there is the possibility of collecting a fare from each passenger. Being a PT option but at the same time a low capacity mode, it has been referred to as an interesting mode to act as a feeder system for other heavy transportation modes such as suburban trains (Lee, Lin, & Wu, 2005).

Taxis are one of the best transport options that a person can have when convenience, comfort and safety are considered. A person is driven in a private vehicle which picks him up at his door and drops him off at a precise destination, without worries about parking the vehicle, and carrying a load whenever needed. Travel time may be affected by traffic congestion during peak periods of the day but in many cities taxis are allowed to use Bus lanes. Moreover, as they are making a point to point trip, they can take detours recommended by GPS-based navigation systems, whereas in traditional PT options the route is fixed. The only problem remains to be the price of riding a cab. This varies from country to country, however it is never as low as other PT modes, hence it has been a transportation option for high income people or for those who do not own a private vehicle (Darbera, 2010).

Sharing taxis is not entirely new, both for economic reasons and for convenience there have been experiences in different countries of the world. The concept of collective taxi has been used for many years in Istanbul, Turkey, where it is a popular transportation alternative. There the taxis run a pre-determined route, with each passenger paying only a portion of the normal fare (Feibel, 1987). Advanced initiatives have been tested in order to take advantage of modern communication technology, namely cell phones, to help make viable the concept of shared taxi. A company in the UK has developed a system that collates requests for point-to-point travel from a dispersed set of clients via SMS and then packages clients going in the same direction into one vehicle at a discounted fare. Passengers are instructed to go to pre-determined pickup points to meet the driver (Cooper, Mundy, & Nelson, 2010).

In this paper we rethink this concept considering current communication technology and GPS in order to bring flexibility to the system by allowing managing virtually any possible origin and destination in an urban area. Trip requests are sent through a cell phone stating current position (or wished boarding point) and asking for a ride for a specific destination point. A central dispatcher collects these requests and must then find a taxi match.

Central dispatching is already used as part of regular taxi services in order to improve customer demand compliance by computing in real time the closest taxi available (Lee, Teo, Wang, & Cheo, 2004). However, the task of matching passengers and vehicles in shared taxi systems is obviously not straightforward as some of the taxis will already be transporting one or more passengers who have to be adequately served and reach their destination in acceptable time.

Several models have been developed in the past to study classical taxi systems or markets in the economic perspective. Most of them have used optimisation to devise better methods to dispatch a taxi to a client (Lee, Teo, Wang, & Cheo, 2004; Shrivastava, Chande, Monga, & Kashiwagi, 1997; Von Massow & Canbolat, 2010; Wang, Lee, & Cheu, 2011). Other studies have also focused in the same matching problem but using simulation based methods instead. Some of them used agent-based techniques (Alshamsi, Abdallah, & Rahwan, 2009; Kim, Oh, & Jayakrishnan, 2005; Kim, Yang, & Choi, 2011; Seow, Dang, & Lee, 2007). Many studies have dealt with designing algorithms for solving the so called pick-up and delivery problem which can be described as finding the optimal way of assigning a set of transportation requests to a fleet of vehicles (initially located at several depots), by minimizing a specific purpose objective function, subject to a variety of constraints (Cortés, Matamala, & Contardo, 2010; Min, 1989; Rahimi & Dessouky, 2001). Despite the similarities between this problem and the operation of shared taxis, namely the fact that the system could benefit from solving this problem for assigning taxis to clients if requests were known a priori, we are more interested in evaluating the operation of these taxis not as a fully optimized system but as a realistic operation that integrates human agents, the taxi drivers and the clients, who can be aided by a dispatcher system that does not know the requests at the outset and will not impose routes on drivers.

In order to study the potential of shared taxis we develop a comprehensive simulation model that is able to reproduce as accurate as possible the interaction between clients and taxis in a realistic network for understanding what type of performance should be expected from the implementation of the proposed system. We chose to develop such model under the principles of agent-based techniques given the difficulty in representing the complex spatial-temporal relation between taxi supply and passenger demand by other types of aggregated and disaggregated approaches. The usefulness of agent-based models has been well demonstrated in several areas of transportation analysis (Arentze, Ettema, & Timmermans, 2010; Davidsson, Henesey, Ramstedt, Törnquist, & Wernstedt, 2005; Roorda, Cavalcante, McCabe, & Kwan, 2010; Tang, Alam, Lokan, & Abbass, 2012; Vliet, Vries, Faaij, Turkenburg, & Jager, 2010). These models allow a detailed representation of the interactions of multiple agents in a realistic synthetic environment where the intent is to re-create and predict the appearance of a complex phenomenon, which is the case of the taxi market. The objective is to obtain high level indicators from describing accurately the lower level reality of shared-taxi supply interacting with the current demand in three markets: hail on the street, phone and taxi rank.

In the next section the simulation model structure is explained presenting its main components, relationships, necessary input data and possible output indicators. In the following section we explain how the model was built for Lisbon, the case study used in the paper. Next we describe the experiment that was designed to test the shared taxi system for the case study city. Results are shown in the following section and the paper ends with the main conclusions that can be withdrawn from this work and ideas for future research.

THE AGENT-BASED SIMULATION MODEL

The simulation model is focused in reproducing in real time a typical working day in a city. The environment where the simulation takes place is a road network of the city where taxis circulate and clients should be created according to trip generation indicators. A Dispatcher system will manage a centralised operation of assigning taxis to clients using as its main information sources: the location of shared taxi vehicles, their current occupancy rate and the location of clients. The model also includes the possibility of hailing for a taxi on the street and going directly to a taxi rank.

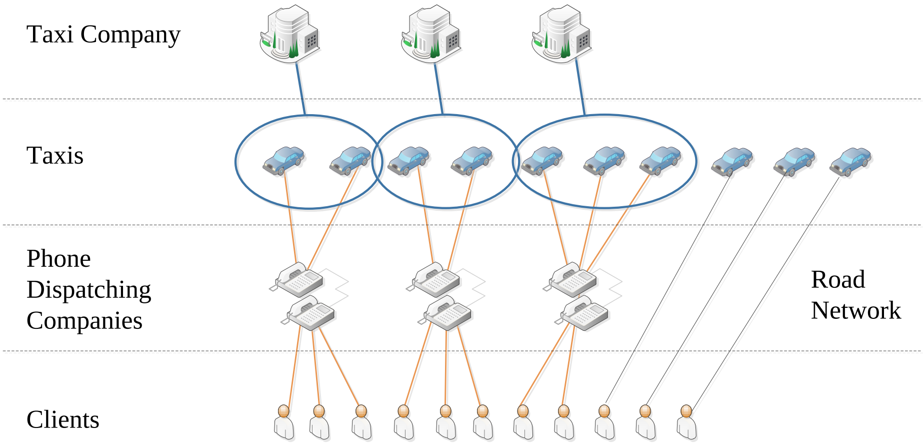

Figure 1 - Simulation model architecture

Client Agent

When a client decides to take a taxi, he first decides which type of service he will take: hail a taxi near his origin; walk to a close taxi rank; or call a dispatching company. The selection of the action is randomly generated but with different probability profiles according to the city area and time of the day, trying to reproduce the knowledge that clients have. The possible states of this agent are: searching for a taxi, waiting for an assigned taxi, or riding a taxi.
The general flowchart of the agent is presented in Figure 1, where the different states, transitions and choices are detailed.

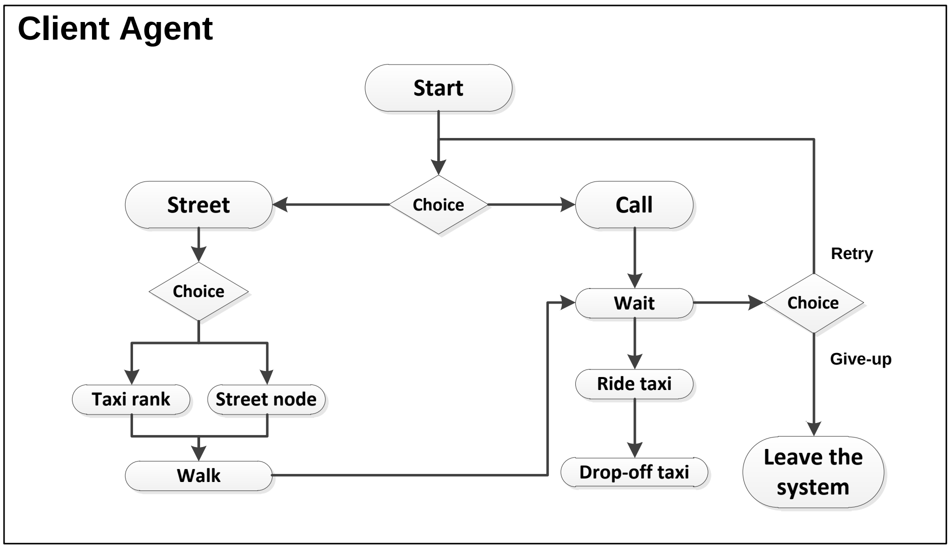

Figure 1 - Simulation flowchart of the clients' agent

The following are the main rules of behaviour of each client:

- When hailing for a taxi the client will do it at the initial node or walk to a better hailing location;
- Walk to the "best" taxi rank within a walking threshold of his current location (using a trade-off function between the probability of finding a taxi and the willingness to walk);
- When the client goes to a road node or taxi rank, he waits for a taxi using a FIFO serving procedure;
- If the client does not get a taxi after an initial threshold waiting time, he may re-evaluate the decision of waiting or calling a dispatcher company to get a taxi;
- After waiting up to a maximum of $waiting_{max}$, the client leaves the system.
- Dial to a dispatching service to ask for a share taxi service is done randomly selecting among the existing available options, where is taxi company has a proportional probability to their number of associates;
- When the client calls for a taxi and one is assigned to him, he automatically accepts that assignment;
- If a taxi is not assigned to the client immediately, he waits for a given period ($redial_{time}$) and places another taxi order, being the waiting time accounted since the first call for a taxi. After a maximum of three trials, the client considers selecting another dispatcher;

- After waiting more than the limit threshold ($waiting_{max}$) without a taxi being assigned, the client gives up and leaves the system.

Taxi Agent

A taxi can be connected to different taxi dispatching companies, being operated by a single driver (owner of the car) or belong to a taxi firm where several drivers work in shifts. The organisational model of the supply is an input of the model. The possible states of the agent are: being on route to pick-up a specific passenger (allocated by the Dispatcher); in service with passengers on board; being on route to a taxi rank; browsing the area for passengers; waiting at a taxi rank for an assignment; or being idle (taxi driver resting).
The general flowchart of the taxi agent is presented in Figure 2, where the different states, transitions and choices are detailed.

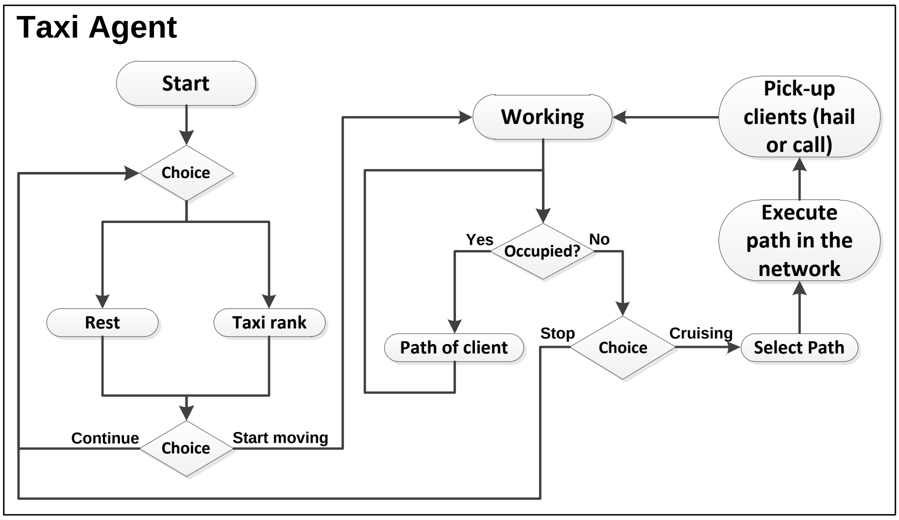

Figure 2 - Simulation flowchart of the taxi agent

The following are the main rules of behaviour of each taxi:

- The taxi is normally heading to a taxi rank to wait for the next service. This next service may be picking up a client at that taxi rank or, if in the meanwhile the central dispatch assigns him a passenger, he will deviate from the current destination. When the taxi decides to stop at a taxi rank, it uses a route going through areas where the probability of finding a customer is higher;
- A taxi not connected to a central dispatch system also routes through the network covering mainly the areas which historically have had a higher demand for taxi trips;
- The taxis located at a taxi rank give up waiting for a passenger if the service time in the taxi queue leads to a waiting time greater than a threshold ($maxrank_{time}$). In this situation, the taxis either search for another taxi rank or route through the network;
- Taxis present different periods of operation, constrained by the shifts of their drivers, thus they are not always active. Those shifts are city and country specific and must be set because they determine the percentage of active taxis. If the taxi is connected to a central dispatch system, the company office location will be selected as stop

location; otherwise, the taxi will select randomly a node of the network to become inactive.

Simulation environment

The environment where the agent-based simulation takes place is an urban road network where taxis circulate and clients are created according to mobility survey data of the city. The road network contains a link attribute with the travel time for each period of the day. In each period, the network should accurately translate the impedance of travelling from point to point in the simulated urban area, reproducing the measured average congestion of the road sections. The consideration of a static non equilibrium travel time reduces considerably the computational burden of this type of simulation model because it avoids the inclusion of other modes (i.e. private cars and PT vehicles).

The model assumes that taxi drivers are experienced and that they are able to choose the shortest path for their destination, thus the Dijkstra's Algorithm is used for computing routes. It is assumed that the variation of the number of taxis in service does not affect the predefined travelling speeds on the network links.

The environment is used as interface for the different agents of the system, which interact through this platform and generate new data that changes its state. A key element of the model is the taxi request, which can activate the three different types of taxi operational modes (rank, hail and call). Depending on the option selected by the user, other processes are activated. If a client chooses to dial to a taxi company, a dispatcher service is activated to match the user and the active taxis. Otherwise, the client will meet the taxi in the walking network: either by hailing a taxi or by walking to the most desired taxi rank nearby. This demand data is collected by the system to provide information to the taxi driver about the historical space and time distribution of the clients. The information is then used by taxi drivers to choose the most adequate taxi ranks to stop at different hours of the day and choose the most attractive routes for finding clients in the street. An important element of interaction between the agents and taxis in the environment is introduced in the hailing market, where the "vision" that clients have of an approaching taxi and vice-versa is modelled. This component considers the geometry of the road network (length of the road links and angles at intersections) assessing the maximum range of visibility at a certain location ($clientvisibility_{range}$). The probability of a taxi being able to stop and pick-up the client is also a function of the estimated traffic flow on the street where the client is located ($Edge_{flow}$). If the arc is congested it is more difficult for a taxi driver to switch to the right lane and stop for a passenger boarding ($taxiflow_{awareness}$) (see Equation 1).

$$\begin{cases} Edge_{flow} \leq 100: taxiflow_{awareness} = 1 \\ 100 < Edge_{flow} < 1500: taxiflow_{awareness} = \dfrac{(1500 - Edge_{flow})}{1400} \\ Edge_{flow} \geq 1500: taxiflow_{awareness} = 0 \end{cases} \quad (1)$$

The client, when detecting an empty taxi in a link, is added to a FIFO array of potential clients for a taxi at that link and waits for the taxi acceptance. For the taxi agent, the visibility model is activated at each node of the road network, with an approximate average distance of 25 m. Another important role of the environment is to provide real time information to the taxi fleet. The location of taxi trips origins is used to estimate the density of trips exiting from each zone which allows building an historical dataset to which we can compare, at every hour, the available taxis thus allowing computing a deviation. This information is then used to determine the most suitable destinations in the network for each taxi that is searching for passengers at a given simulation period *t* (hours).

The historical demand for each Zone i in the k^{th} simulated day for time period t (in hours) is done through the following function (P) which can be interpreted as a probability of demand in each particular zone:

$$P_{ki}^{t} = \frac{ED_{ki}^{t}}{\sum_{j=1}^{N} ED_{kj}^{t}} \qquad (2)$$

Where N is the number of zones in the city and ED_{ki}^{t}, which is the estimated taxi demand of zone i for time period t in the k^{th} day, is given by:

$$ED_{ki}^{t} = \theta \cdot \sum_{h=1}^{k-1} \frac{D_{hi}^{t}}{h-1} + \rho \sum_{j=1}^{N} Sh \cdot OD_{ij}^{t} \qquad (3)$$

Where D_{hi}^{t} are the shared taxi trips originated at zone i, at time period t in the h^{th} simulated day, Sh is the estimated taxi mode share for the study area, and OD_{ij}^{t} is the total number of estimated trips from the mobility survey for period t which go from zone i to zone j. The relation between θ and ρ should reflect the relation between the taxi trips simulated historical data and the surveyed travel demand of each zone, whose taxi share is fixed for the whole city. After one day of simulation the model should consider preferentially the collected simulated data, changing θ close to 1 and ρ close to 0. Using this process we avoid a large difference between the first and the following days of simulation.

The obtained probabilities are used for each taxi to select a destination zone by comparing these probabilities to the percentage of taxis present at each zone. If in a k^{th} day a zone i has a low taxi density at hour t when compared to P_{ki}^{t}, taxis will have higher chances to choose that area as a destination of their search process. The specific destination node is chosen randomly within the zone.

The dispatcher

The Dispatcher is an entity that defines a set of rules for matching together taxis and passengers, centralizing all real-time information required to produce and monitor these trips. The choice of which taxi to match with a client's request should be done with the aim to combine the minimisation of passenger travel time (the one(s) riding and the one requesting a taxi), while also considering the revenues of each individual taxi and the equity among them (always a strong concern in the real world).

There are several ride-matching optimisation algorithms formulated in the literature (Agatz, Erera, Savelsbergh, & Wang, 2011). Yet, most of these algorithms formulate a simultaneous matching between several drivers, going to their destinations, and several ride requests, aiming to achieve a system optimum considering all demand and supply bundled in a time interval. This is especially important when there is great density of clients and drivers, but in this case we believe that the simplicity of considering just one client at a time makes the simulation run faster and the solution will not be significantly far from the optimum due to the low density of requests in the city (average distance between callers is too high for there to be a considerable competition for the same taxi).

We should note however that it is possible to integrate in the simulation model any kind of algorithm to match passengers and clients, which is one of the advantages of the simulation framework.

The strategy for selecting candidate taxis is shown in Figure 3 where we may see multiple taxis available within a coverage area centred in the coordinates of the client.

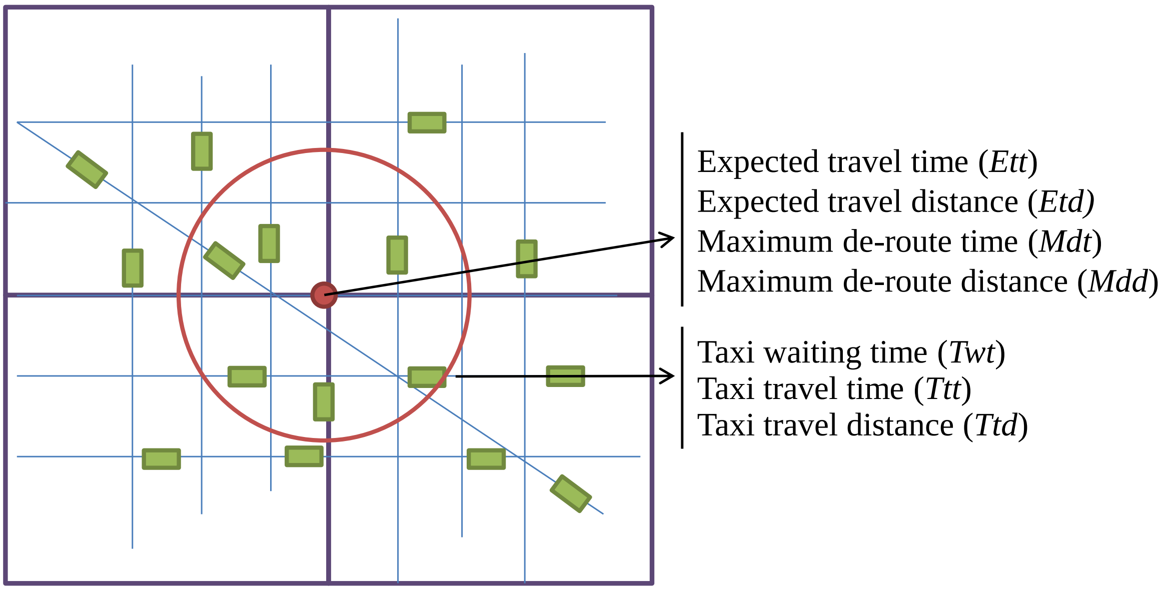

Figure 3 - Choosing a taxi for a client's request

In order to assign a taxi to the client, there is the need to define the maximum de-route time (Mdt) and de-route distance (Mdd) that the passenger is willing to accept for his trip. These parameters are computed for the client as a percentage of the expected travel time (Ett) and expected travel distance (Etd) computed as a single-occupant taxi trip from his origin to his destination. This percentage is set by a decreasing function with the travel time value increase.

For each candidate taxi, we must define the time that the client placing the request will have to wait for that taxi (Twt); the minimum travel time sequence for the taxi to pick up the client and deliver him and the other passengers already on board to their destinations (Ttt); Ttd is the distance associated to the Ttt travel time.

The estimation of the minimum taxi travel time sequence (Ttt) considers the different combinations of pick-up and delivery of passengers depending on the number of persons already on-board of the taxi (Figure 4). The search is exhaustive but it is done very fast for a maximum number of 3 passengers on board of a taxi.

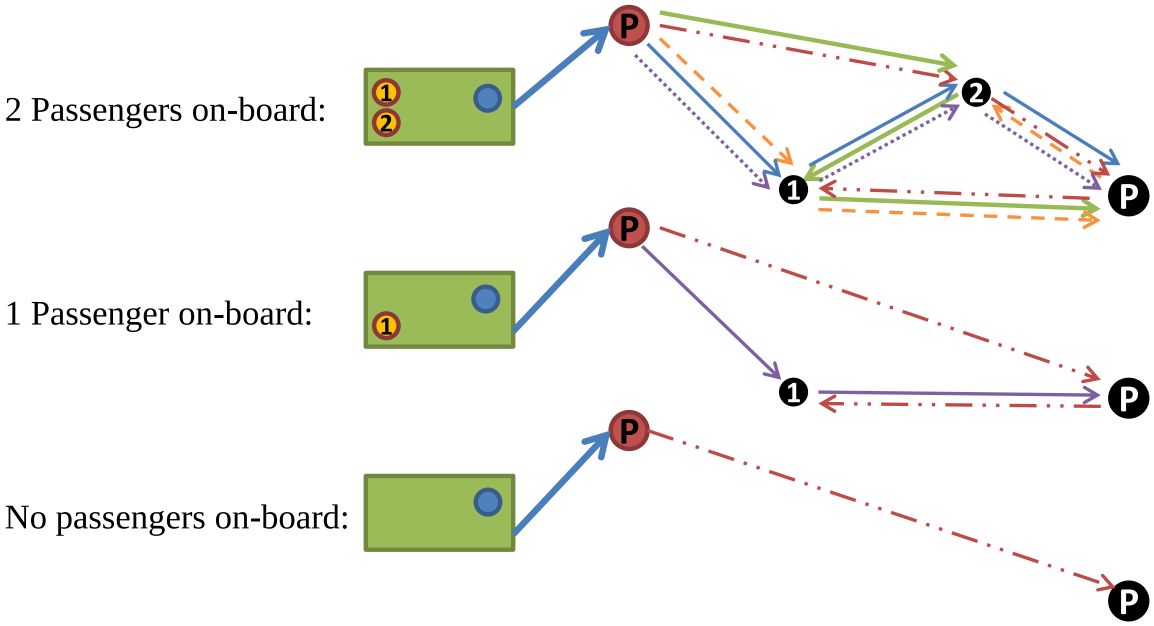

Figure 4 - Example of the Taxi travel time ($\boldsymbol{Ttt}$) estimation for different number of on-board passengers

There are penalty and bonus coefficients added to favour some of the taxis. This is done through a group of binary variables that represent the current state of the candidate taxi: $Empty$ which takes the value 1 if the taxi is empty; EB which takes the value 1 if the taxi has been without passengers for the last 5 minutes; $1Pass$ which takes the value 1 if the taxi has one client already on-board; and finally $2Pass$ which takes the value 1 if the taxi has already two clients on-board.

Having these variables and the minimum travel time combination of pick-up and deliver (Ttt) the problem is to select the taxi that minimizes the following objective function:

$$min(Z) = Twt + Ttt - \beta \cdot EB - \gamma \cdot 1Pass - \mu \cdot 2Pass \tag{4}$$

Which must comply with the maximum de-route time and de-route distance constraints of the client (Mdt and Mdd).

The objective function Z, while aiming at minimising the client travel time ($Twt + Ttt$), it is designed to assign preferentially clients to taxis which have been empty for more than five minutes ($\beta \cdot EB$) and to taxis with one or two clients already on-board ($\gamma \cdot 1Pass$, and $\mu \cdot 2Pass$ respectively).

The objective function weight parameters can give a premium to taxis that have one client already on-board, which may lead to greater taxi revenues and maximum discounts to the clients.

LISBON CASE-STUDY

The simulation procedure has been applied to the municipality of Lisbon, Portugal. Lisbon is the Capital city of Portugal and is the largest city of the country with approximately 565,000 inhabitants in an area of 84.6 km^2. Lisbon is situated in the Atlantic Ocean coast on the

Tagus estuary, being the most western capital in mainland Europe. The city is the centre of the Lisbon Metropolitan Area (LMA), which has approximately 2.8 million inhabitants, representing roughly 25% of the Portuguese population, with an area of about 3,000.0 km^2, formed by other 18 municipalities.

The taxi market in Lisbon is formed by approximately 3,500 taxis, which have to apply and pay a municipal license. The number of available licenses is capped, and has not increased in recent years, which led to a significant enhancement of its (unofficial) value. Taxis have to apply and pay a municipal license (IMT, 2006). These licenses cannot be traded directly on the market, still companies are the owners of the licenses and companies are tradable which indirectly leads to a license market.

This license allows taxis to operate simultaneously on three market types: rank, hail and pre-booked by phone:

- Ranks are designated places where a taxi can wait for passengers and vice versa. Taxis and customers form queues regulated by a FIFO system. Lisbon counts 82 taxi ranks;
- In the hail market, clients hail a cruising taxi on the street, but in Portugal they can only do it by law when being at a distance greater than 250 m from a rank. A taxi can be stopped at a street of any hierarchical level,
- In the pre-booked market, consumers telephone a dispatching centre asking for a taxi. It is only in this kind of market that consumers can choose between different service providers or companies. At the same time, companies can get clients' loyalty providing a good door to door service. In Lisbon there are 3 main dispatching companies.

In Lisbon any taxi may operate in more than one of these markets at the same time. In order to be associated to a taxi phone dispatching company the taxi driver or taxi Company must pay a fee to have access to that pool of clients. The client also has to pay the phone call when he wants to access that service. A recent study performed by the Portuguese Mobility and Transport Institute (IMT) showed that approximately 48% of the taxis in Lisbon are associated to a dispatching company, and the other 52% only work on the hailing and rank markets (IMT, 2006). These three service configurations have different market expression across the world, although they are almost all the times present in the taxi market at the same time. For instance in New York most of the passengers hail the taxi on the street (90%) while in Stockholm 55% of the clients call a taxi by phone, 20% by going to a taxi rank and only 25% hail the taxi on the street (Darbera, 2010).

The fact that in Lisbon taxis may operate in the three markets simplifies significantly the regulation of the market. In parallel, the taxi drivers' profession is also regulated by the national transport regulator (IMT). Taxis have to be driven by licensed drivers, who have do take a course and pay a levy. IMT has surveyed taxi drivers and their shifts recently and results showed that from the 3,500 taxis registered in Lisbon, only about 3,100 are active daily. In that survey five main types of taxis drivers' shifts were identified, which mainly depend on the ownership of the taxi (owned by the driver or by a taxi company) (Table 1):

Table 1 - Taxi driver shift considered in the simulation

Shift	1st driver shift	2nd driver shift
Type 1	6 am to 7 pm (idle from 12 pm to 1 pm)	
Type 2	8 am until 9 pm (idle from 2 pm to 3 pm)	
Type 3	1pm to 2 am (idle from 7 pm to 8 pm)	
Type 4	7 am until 6:30 pm (idle from 1 pm to 2 pm)	6:40 pm to 5:40 am (idle from 0:40 am to 1:10 am)
Type 5	9 am until 8:30 pm (idle from 3 pm to 4 pm)	20:40 pm to 9 am (idle from 2:40 am to 3:10 pm)

Taxi fares are also strictly regulated by specific legislation, which set the price of the trip by three different components: a fixed starting fee, a distance related fee and a time related fee, linked to the delay time produced by congestion, set for the time that the speed is under 30km/h.

Besides the regulations and market configuration of taxi services in order to simulate the behaviour of the taxi market in the city of Lisbon the following data needed to be included:

- the origin and destination of the taxi trips as well as their starting time;
- the road network;
- a calibrated traffic assignment model to obtain realistic travel times in the road network;
- the taxi ranks location; and
- a zoning system.

The demand component of the model was obtained through a mobility survey developed for the Lisbon Mobility Plan of 2004. From this survey 21,075 taxi trips were extrapolated during a week day inside the city of Lisbon. The distribution of these taxi trips along the day is presented in Figure 5, where we may observe a higher concentration of trips during the morning peak and some periods during the lunch break and the afternoon.

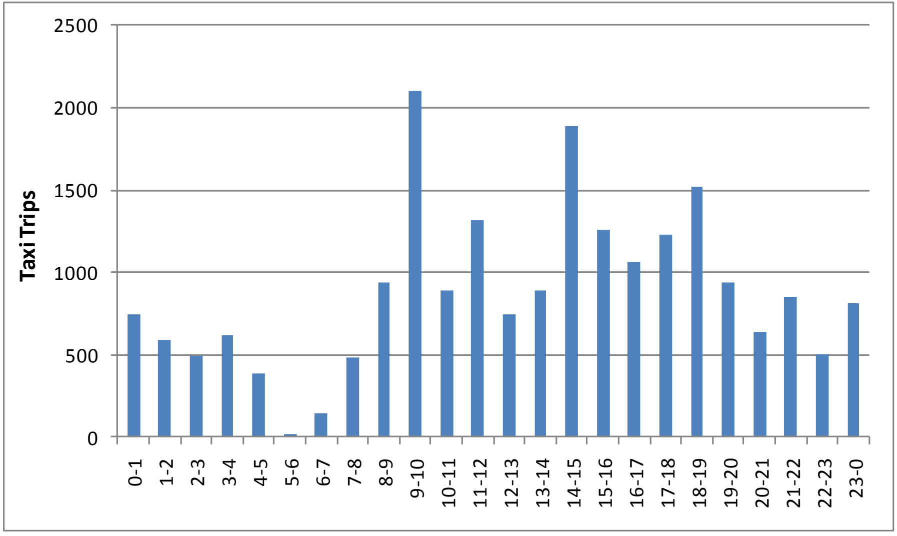

Figure 5 - Distribution of taxi trips throughout a working day

We have to acknowledge that the number of estimated taxi trips is lower than the real demand, because the estimated demand does not include trips from Lisbon to other municipalities and trips by non-residents of Lisbon such as tourists and other visitors (e.g. business trips from other parts of the country). Furthermore lower demand shares tend to be under-represented in surveys due to random sampling procedures. Despite these limitations, the purpose of the paper is not to fully represent current demand, but to show the proof of concept in using this agent-based simulation procedure to model the shared taxi alternative, and obtain general trends for the impact of shared taxis.

The model was implemented in a road network model of the Lisbon municipality formed by the first four levels of the road hierarchy, comprising urban motorways, ring-roads, major arterials and the main local distribution network. This network is formed by 11,242 links and 7,106 nodes. The simulated trips are randomly assigned to one of the network nodes within 200 meters away of the origin or destination points of the survey. The shared taxi passengers are then picked up and dropped off in one of these nodes for simplicity purposes.

For determining the travel times of all links and intersections of the road network along the day, we used a calibrated micro-simulation traffic assignment model (AIMSUN - TSS) for the morning peak hour (8 to 9 o´clock), the travel times for the other time periods are weighted according to this hour.

The model also includes the location of all taxi ranks in the city of Lisbon, where taxis can be idle or wait for a passenger call. All the agents and objects of the simulation were aggregated into a zoning system formed by 115 different zones. This zoning system was obtained through an optimisation procedure for the city of Lisbon according to (Martinez, Viegas, & Silva, 2009). The model parameters used for this simulation are presented in Table 2, resulting from a detailed assessment of the stability of the model to its values.

Table 2 - Model parameters

Parameter	Value adopted in the simulations
$maxrank_{time}$	30 minutes
$waitingmax$	30 minutes
$redial_{time}$	1 minute
γ	3000 minutes
μ	1500 minutes
β	60 minutes
θ	1(initial)
ρ	0 (initial)

Our objective was to give preference to taxis with more than one occupant on board and that is why the scale of the weights γ and μ is so great when compared to normal travel times in minutes in the city of Lisbon. Between taxis carrying 2 and 3 passengers we give preference to two passengers, which may maximize the system welfare, by improving the productivity of each taxi travelled kilometer and reduce the client taxi fare at an acceptable penalty in time and presence of only one unfamiliar passenger. When comparing several empty taxis, priority is given to taxis that have been empty for more than 5 minutes (β parameter).

TESTING THE SHARED TAXI SYSTEM

The simulation experiment developed for this paper consisted in comparing the performance of the current regular taxi system in the city of Lisbon with the new shared taxi system proposed. The experiment was run for 4 business days of operation considering the current taxi demand subject to the new market configuration that might occur from introducing shared taxis. This allows measuring the expected reduction of waiting time and fare paid by the clients. Yet, no demand elasticity to price or waiting time was considered, the only change introduced was an increase in the probability to dial for a taxi in the scenario with shared taxis which is set equal to the expected savings of using the proposed system. This probability parameter was set for all simulations as 20%, reducing the number of clients going to the street to catch a taxi.

This static demand model configuration represents a first step on the assessment of the potential impact of the implementation of the new service, focusing on the users' perspective. We have compared the performance indicators for two scenarios: one with the current taxi fleet and another with a mixed fleet of both conventional and shared taxis. In the scenario with shared taxis we consider that the number of taxis currently connected to a central taxi dispatcher company will switch to shared mode which is approximately 48% of the fleet. Thus for the different taxi fleet sizes that were tested in this experiment (1800 to 2500 taxis in 100 intervals), the percentage of shared taxis in the shared scenario is always 48%, what varies is the total number of taxis.

The taxi discount scheme used in the experiment can be seen in Figure 6 where the reference is passenger 1, meaning that it is the only passenger in the scheme for whom the whole trip is presented.

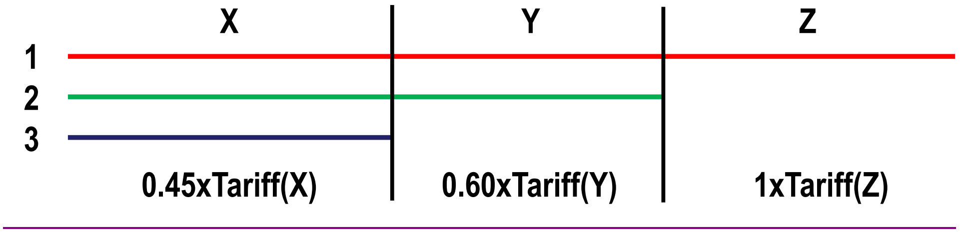

Figure 6 – Tariff system for passenger 1

In this discount scheme we consider that:

- Riding a shared taxi alone has no discount;
- Sharing a taxi with another client has a 40% discount to each client which leads to a 20% revenue increase in relation to the single passenger trip;
- Sharing a taxi with two other clients has a 55% discount to each client which leads to a 35% revenue increase in relation to the single passenger trip;

Thus the tariff for passenger 1 is computed as follows:

$$Tariff_1 = Fixed\ fee + 0.45xTariff(X) + 0.60xTariff(Y) + 1xTariff(Z) \qquad (5)$$

The fare paid by each client results from the sum of the trip segments with different occupancy rates, which have different discounts. The simulation measures the discount obtained for each client of a shared taxi compared to the reference price of riding alone, thus allowing estimating the savings of each client introduced by the new system.

In order to validate the model results in the base scenario without the sharing possibility, one validation simulation run was performed for a fleet of 2,500 taxis, which represent approximately 80 percent of the total number of taxis that daily operate in the city of Lisbon. The use of a smaller taxi fleet intends to reproduce the lack of demand in the model from people with destinations outside Lisbon and of non-residents (i.e. tourists). This validation considered three main aggregate indicators from the taxi supply characterisation collected in a study from IMT and a log-file of the operation of one taxi dispatching Company during the month of May 2011.The following table presents the obtained results from the simulation against the available data, showing a considerable adherence. Nevertheless, the average number of services does also contain services outside the Lisbon municipality and trips of non-residents, which explains the observed deficit in this indicator in the simulation results.

Table 3 - Comparison of the daily model simulation results (2,500 taxis fleet) with real aggregate data

Indicator	Simulation outputs	Real data source
Average daily revenue	76.46	79.06 euros[1]
Average number of travelled kilometres	208.16	207.18 km [1]
Average number of services	9.38 services	15.98 services[1]
Average number of dial services per connected taxi	4.46 services	4.47 services[2]

Then the experiment with both scenarios varying the fleet size was performed in a 64 bits Windows 7 operating system with 16 RAM an i7 CPU. In total the model was run 16 times, 8(fleet dimension) x 2(scenarios). Each run of the shared taxi fleet scenario took about 1.5 days to solve, while the conventional market took about 6 hours, this is due to the extra computing necessary in the shared taxi scenario.

RESULTS

In order to compare the results from having or not having shared taxis in the fleet, a set of indicators were defined to measure the performance of the system. These outputs of the model are shown in Table 4 these allow comparing the performance of both scenarios for the different fleet sizes.

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[1] Relatório IMTT 2010.

[2] Retatis - Radio Táxis log file May 2012.

Table 4.Performance indicators of the shared taxi system for different fleet sizes

Fleet size (48% shared)	**Av. pass. waiting time [min]**	**Av. taxi fare paid by the client [€]**	**Av. savings of shared riders (%)**	**Av. total travel time [min]**	**Av. daily revenue per taxi [€]**	**Av. revenue per taxi km [€/km]**	**Shared taxi trips (%)**
1800	10.27 (-9.36%)	7.49 (-1.11%)	8.39%	25.25 (0.06%)	104~~,~~.7 (-1~~,~~.27%)	0.62 (0.91%)	12.39%
1900	9.91 (-10.02%)	7.49 (-1.08%)	8.59%	24.85 (0.03%)	98~~,~~.65 (-2~~,~~.32%)	0.6 (0.94%)	12.53%
2000	10.03 (-6.1%)	7.49 (-1.23%)	8.75%	24.95 (1.57%)	93~~,~~.9 (-1~~,~~.27%)	0.6 (3.24%)	12.47%
2100	9.78 (-9.57%)	7.49 (-1.28%)	8.50%	24.64 (-0.28%)	89~~,~~.23 (-1~~,~~.6%)	0.56 (0.26%)	12.46%
2200	9.36 (-12.19%)	7.49 (-1.31%)	8.95%	24.2 (-1.33%)	84~~,~~.64 (-2~~,~~.74%)	0.56 (1.27%)	12.35%
2300	9.61 (-9.25%)	7.49 (-1.22%)	8.65%	24.43 (-0.09%)	81~~,~~.09 (-2%)	0.55 (4.64%)	12.04%
2400	9.49 (-10.47%)	7.5 (-1.23%)	8.65%	24.35 (-0.45%)	77~~,~~.8 (-2~~,~~.38%)	0.52 (1.76%)	12.32%
2500	9.38 (-8.63%)	7.49 (-1.26%)	8.89%	24.16 (0.55%)	74~~,~~.45 (-2~~,~~.63%)	0.48 (-4.13%)	12.38%

From this set of indicators, the most significant results are the average passengers' waiting time and the average savings resulting from the shared taxi system. The observed trend of these indicators shows that although not monotonously there is a decrease on the first indicator and an increase on the second one with the fleet size, although with a small variation for the tested fleets – 9.36 to 10.27 minutes for the average waiting time and 8.39% to 8.95% to the average shared taxi clients' savings.

Another relevant indicator is the average passenger travel time, which presents an unstable performance. In some fleet tests the reduction in waiting times may be enough to compensate the increase in travel time generated by the shared taxi configuration, while in other cases it is not. Nevertheless, even in the cases where the total travel time increases, the average penalty is never greater than 2%, which is always compensated by the fare reduction.

These results show that the shared taxi system may lead to considerable changes in the taxi system performance from the users' perspective. This change, not considering demand elasticity to the fare and waiting time reductions, leads to a decrease on the taxi revenues due to the discount offered to clients. The average reduction in revenues for taxi drivers is approximately 3% for the taxi fleets considered (see Table 4), which has to be compensated by a similar demand increase if the shared system is to produce a win-win situation for the clients and the taxi drivers.

The tested fleets showed that the system would serve approximately 12% of the total taxi trips of the current taxi market. These are mainly concentrated during the traffic peaks and the lunch time as shown in Figure 7 where we plot the average number of shared trips during the day across all fleet sizes tested.

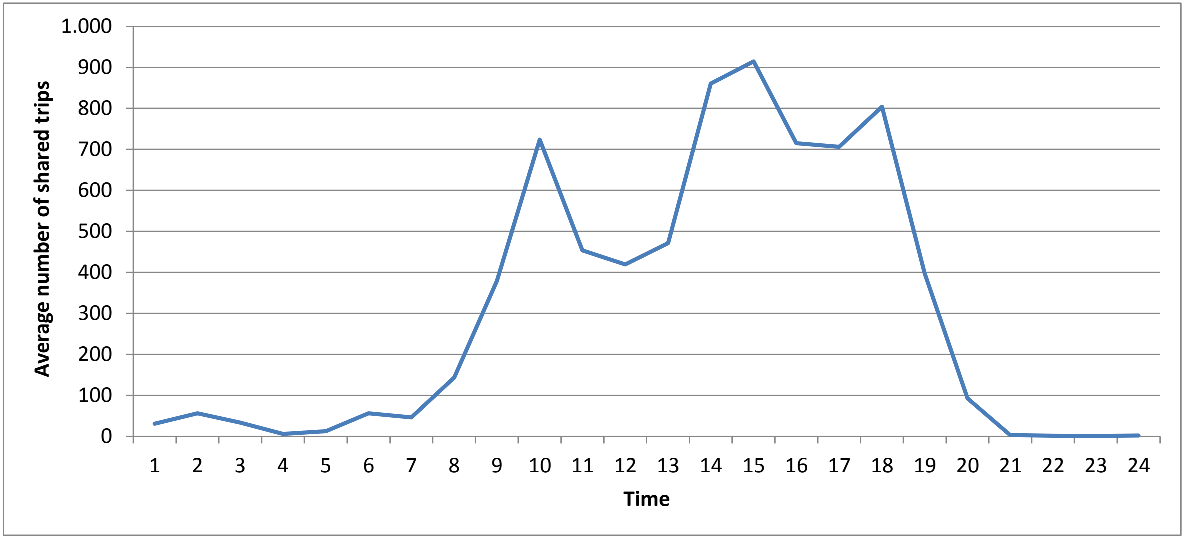

Figure 7 – Average number of shared taxi trips during the day

Furthermore the spatial distribution of this shared taxi demand is presented in Figure 8 and Figure 9, where the average number of daily shared taxi trip origins and destinations are aggregated in a 500 meter size grid. side. The obtained spatial distribution shows a greater dispersion of the trip origins comparing to the destinations. The trip destinations are strongly concentrated in the city centre while a significant number of trip origins are concentrated in peripheral neighbourhoods.

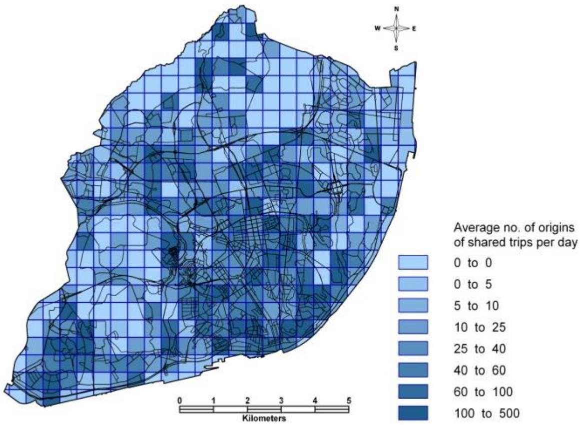

Figure 8 – Spatial distribution of the daily average number shared taxi trips origins

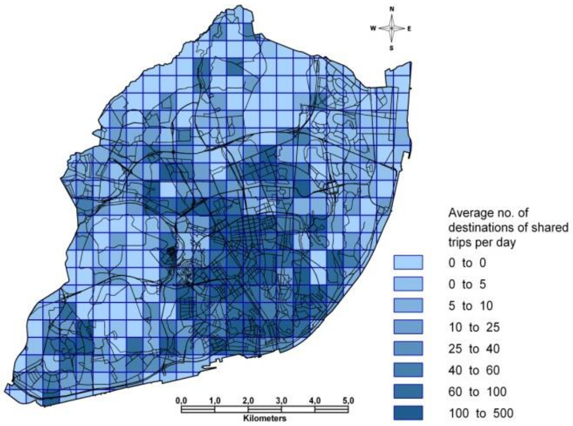

Figure 9 – Spatial distribution of the daily average number shared taxi trips destinations

A detailed assessment of the variations in the average waiting time of the shared taxi clients and the average waiting time of all taxi passengers along the day is presented in Figure 10. This chart reveals that the largest difference between both curves happens during the morning peak period where there is a high taxi demand and the clients are more willing to search for a taxi by hailing or walking to a taxi rank. Although we have imposed a 20% reduction on the probability of searching a taxi in the street in the taxi shared scenario, due to the low average waiting times in the street, especially in the city centre, taxi clients still prefer to walk to a rank than call for a shared taxi.

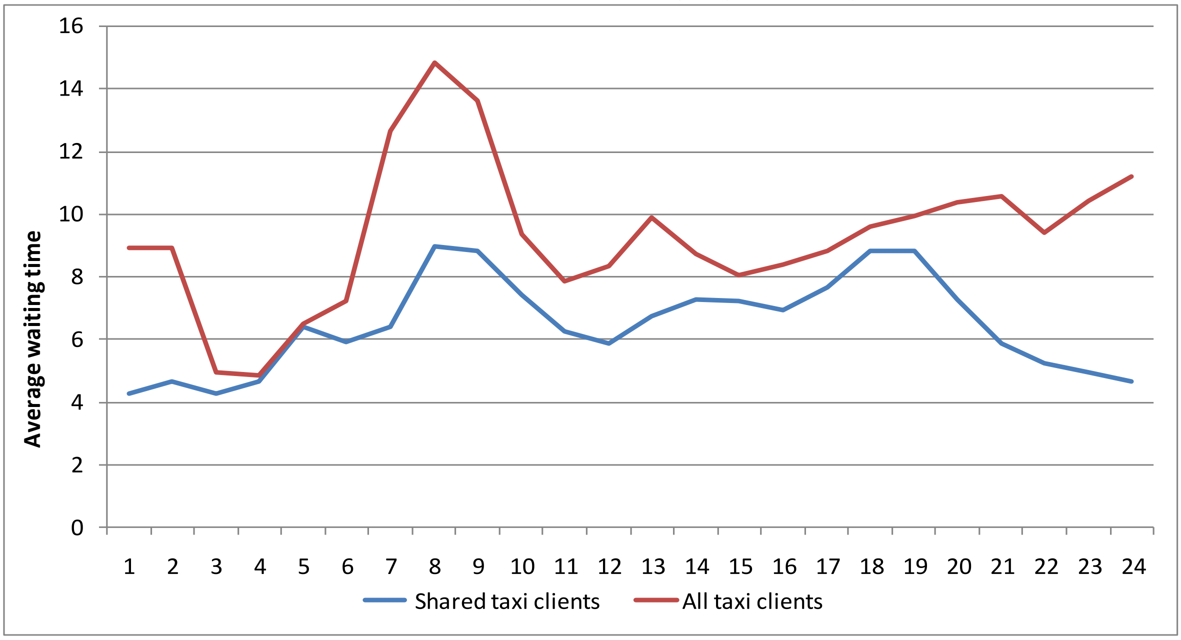

Figure 10 – Average waiting time for a taxi

The distribution of the average percentage savings for each client and the total savings for all the taxi clients during the day is also presented in Figure 11. The comparison of both plots shows that, although the greatest individual savings may be obtained during the night, the total market savings derived from a greater number of clients happens during the peak periods as expected, resulting in a maximum of 712 euros per hour of total savings at 15:00, and a total of 4,700 euros per day.

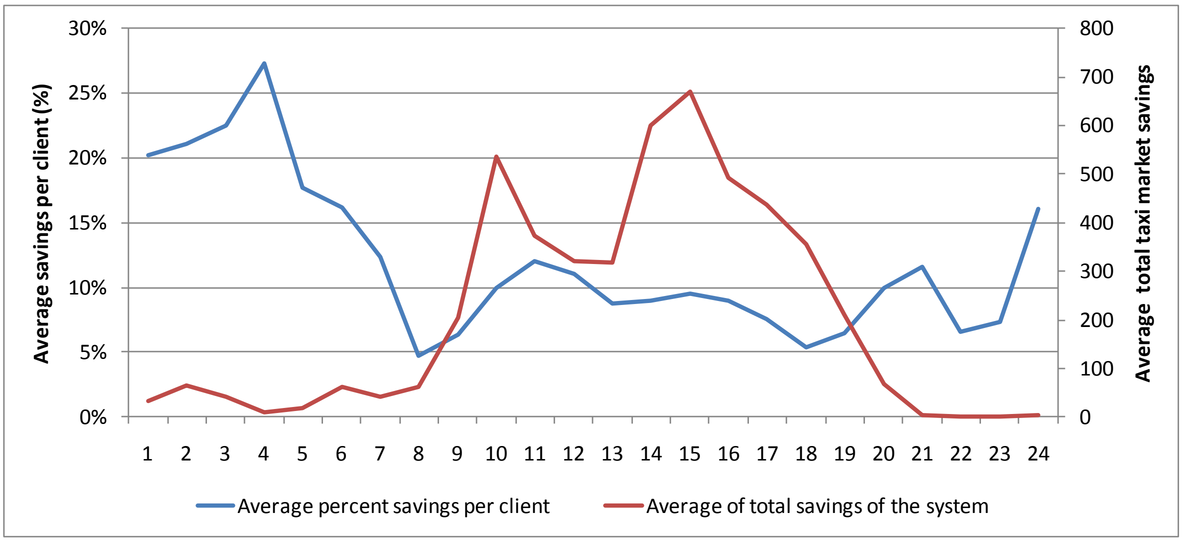

Figure 11 – Average savings per taxi client

CONCLUSIONS AND FUTURE WORK

This paper sets an innovative simulation procedure to assess the market potential of a shared taxi service. This model was developed using agent-based simulation taking the advantage of modelling taxis and clients as agents who take decisions which are specific to their interests. At the same time an entity that manages the assignment between these two types of agents was identified and programmed to act in both the interest of the passenger and taxi in order to improve the system's performance offered by taxis while still improving this business overall profit.

The developed agent based model proved to be efficient and able to characterise in detail all the elements of the different agent involved in the system in order to evaluate different scenarios of demand and supply of the taxi market.

This procedure was implemented in a large scale example: the municipality of Lisbon that counts about 3,500 taxi vehicles, from which 3,100 operate daily. This example allowed comparing different taxi fleet compositions of normal and shared taxis with the current fleet, where all taxis serve just one trip at a time.

The performed tests to the model show that this proposed shared taxi system may be a good transport alternative, especially between locations where origins and destinations are significantly aligned. The obtained results demonstrate that the passengers may benefit from an average 9% fare reduction compared to the traditional system, while the taxis do not reduce so significantly their revenues.

Further developments of this research will include a thorough characterisation of the taxi market behaviour and also the assessment of the impact on the demand for taxi trips and operator revenue introduced by offering the shared taxi system.

The effect of the expected taxi travel time and the travel cost savings on the passengers' choice may be further investigated using a mode share model. This may allow assessing the modal diversion from private car or other public transport modes towards this new transport option, as well as the probability of dial for a taxi against walking to a good hail location or to a taxi rank.

ACKNOWLEDGMENTS

This research was supported by the Portuguese National Science Foundation (FCT) under the SCUSSE Project - MIT Portugal Program. Thanks go also to Intergraph Corporation for the use of Geomedia Professional 6.1 (GIS software)

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