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Taxi services modeling for decision making support

ABSTRACT

This paper presents two models for the evaluation of the performance of the taxi services. The first model is an economic aggregated model for the estimation of the key performance indicators of taxi markets in urban areas based on the probabilistic expected values of the waiting and traveling times. The second model is an agent-based model for simulating the taxi services and providing more detailed and realistic analyses and results on the performance of the taxi services in the real world. Models are an indispensable tool for decision makers when deciding the principal policy measures of the taxi services, such as fleet size, fares or operational modes of the services within the city. Key parameters of the taxi services are calculated by the mathematical model by using the expected statistical values of customer's trip and access distance, which include the supply for taxi services, waiting time of taxi users and the cost of the various involved actors, while the agent-based model measures these parameters in real world conditions by simulating the real taxi trips in the network. The identified actors are the taxi drivers, the taxi users and the city, represented by the other drivers and the citizens. The mathematical model is able to take into account externalities, such as environmental issues or delays, affecting citizens and other drivers respectively. Optimum values for the taxi supply are obtained from the mathematical formulations. These values depend on the demand level and the size of the city. The users waiting time and the unitary system costs related to this optimum fleet size are also presented. The simulation model is able to test and refine these values by testing them in the real network and adding the stochastic component. The models are applied to the taxi services of the city of Barcelona, presenting useful conclusions on the performance indicators of the taxi services and the impact of the applied policies.

Keywords: Taxi modeling, taxi services, taxi policy, taxicab problem

1. INTRODUCTION

Public authorities of current cities have the difficult task of providing the necessary infrastructure and services to their citizens in order to satisfy their complex mobility needs. The provision of taxi services is one of the traditionally adopted solutions, taking advantage of the combination of the positive characteristics of both individual vehicle transport and public transport services. Taxis are cars used for public transport services providing door to door personal transport services. They can be divided into three broad categories: rank, hail and dispatching market. Rank places are designated places where a taxi can wait for passengers and vice versa. Taxis are forming queues, and served with FIFO rules and usually passengers take the first taxi in the queue. Customers must walk until the nearest taxi stop. In the hail market customers hail a cruising taxi on the street. This case is the most unfavorable situation concerning the information aspects for the customers, due to the uncertainty about the waiting time and the quality/fare of the service they will find. On the other hand, customers don't need to walk until the nearest taxi stop. In the dispatching market customers call a dispatching center requesting for an immediate taxi service. Only in this kind of market consumers can choose between different service providers or companies. At the same time, companies can fidelize customers by providing services of good quality. The market in this case is competitive since companies with larger fleets can offer lower waiting times.

Taxi markets have been traditionally regulated by controlling the number of licenses and the prices of the services, but nowadays many taxi markets are being deregulated. The objective of this regulation is to correct the weaknesses of the taxi sector, such as externalities (congestion and contamination), low level of service offered and the imperfection of the competitive behavior of the market. A fundamental distinction in types of taxi regulations is between quantity regulation, quality regulation and market conduct regulation. Quality regulation includes the standard of vehicles (age, type of vehicle, maintenance), driver and operator standards (uniform, route knowledge). This type of regulation is a safety oriented regulation rather than competitiveness related. Market conduct regulation includes rules regarding pick up of customers or affiliation to a dispatching center. Quantity regulations include fare regulation and entry restriction. When entry is regulated, the control in fares limits the possibility of monopoly in the market.

Restrictions on entry to the taxi market have been applied by many cities around the world. The first city that restricted the number of cars was Aldermen in 1937, and nowadays most of the cities regulate the number of vehicles providing taxi services. The most common justification used for controlling the entrance to the taxi market are the externalities such as pollution and congestion, caused by the circulating taxis, but when decisions are taken without a good justification or implementation plan, entry restrictions and fare regulations are

affecting significantly the taxi sector, leading to important welfare losses. Due to the consequences of regulation, many cities are deregulating their taxi markets. Deregulation has most of the times positive impacts, and nowadays many cities have removed entry restrictions, resulting in lower waiting times, increased consumer satisfaction and fare reduction. In relation to fares, it is important to maintain a regulation, otherways customers must have the possibility of comparing prices, which means to know the price before hailing the taxi (not feasible) or choosing taxi in the rank market (opposed to the FIFO rules). Market liberalization is an interesting challenge, but in cities where high supply restrictions had been applied, there will be a strong opposition to reform proposals from the license-owners. Arguments support that license-owners must be compensated in that case: one approach (first used in Ireland) is to give the additional licenses to each license-owner, ensuring that the new monopoly will remain in their hands; alternatively the new license can be given to taxi drivers without taxi license. In Melbourne, a 12 year program is adding to the stock of licenses a number of licenses equal to the yearly demand growth. Other concepts are important in relation to deregulation. Most of the times quantity deregulation means quality regulation, ensuring safety and minimum service standards.

There is a need for evaluating the taxi services by the decision makers responsible for the regulations and the modeling of the taxi services is a powerful tool for quantifying and helping them in taking the right decisions. Various models have been developed for this purpose; most of them aiming at supporting decisions related to planning issues more than to operational issues. The models proposed by the author cover both planning and operational aspects, providing decision makers with the minimum and optimum number of taxis together with the respective performance of the system, but also withdetails of this performance for the users, the taxi drivers and the city. The first model is an aggregated model developed for analyzing the most important variables of the taxi services and optimizing the number of taxis at a planning level while the second model is an agent-based simulation model developed for analyzing in detail the operational performance of the system. The presented models are applied to the taxi services of the city of Barcelona, comparing the current number of taxis with the values obtained by the models and proposing modifications in the current policies for increasing the performance of the sector.

The paper is organized as follows: the second chapter briefly reviews the different models presented in the literature; the third chapter presents the aggregated and the agent-based models and the fourth chapter is dedicated to the application of both models to the city of Barcelona, presenting and discussing the obtained results.

2. LITERATURE REVIEW

Various works have been presented dealing with the modeling of taxi services. The first models were basically developed by economists and focused on the profitability of the taxi sector; they mostly used aggregated values for representing all the variables of the taxi services. Later studies presented much more realistic models, taking into account the network and the different zones within the city as well as real characteristics of the mobility and economic variables, such as traffic congestion or demand elasticity. The third group of taxi models is the simulation based ones, dealing with discrete-event models of dispatching or stand markets for reproducing the complex multi-agent system of the taxi services provision.

2.1. Aggregated and equilibrium models

The first model developed for evaluating the performance of the taxi services was developed by Douglas (1972). He presented an aggregated model using economic relationships from the goods and services sectors. De Vany (1975), Beesley (1973), Beesley and Glaster (1983) and Schroeter (1972) used the model presented by Douglas for developing their own models. They used their models for assessing the different market configurations (e. g. competitive or monopoly market). Manski and Wright (1976), Arnott (1996) and Cairns and Liston-Heyes (1996) developed structural models, obtaining more realistic results and paving the way for the model proposed by Yang and Wong (1998). The sophisticate models presented by Yang and Wong (1998, 2000, 2005 and 2010) take into account the spatial distribution of demand and supply in the city using traffic assignment models and are able to simulate congestion, elasticity of demand, different user classes, external congestion and non-linear costs.
Some of the presented models have been applied to real world using various data sources. Beesley (1973), Beesley and Glaster (1983) used questionnaires in London; Schroeter (1972) used data from taximeters in Mineapolis; Schaller (2007) used interviews and questionnaires in the USA; Kattan et al. (2010) developed regression models for work trips made by taxi in 25 Canadian cities. A detailed review of the aggregated and equilibrium models is presented in Salanova et al. (2011), where the different assumptions of the models are discussed. The limitation of these models is related to the complexity of modeling the real behavior of the taxi markets since they are composed by many independent actors and the local spatial and socio-economic characteristics have a significant impact on the performance of the axi markets.

2.2. Simulation based models

Bailey and Clark (1987) simulated taxicab services and concluded that the waiting time is relatively insensitive to changes in demand but highly sensitive to changes in the number of taxi cabs, while Bailey and Clark (1992) used a discrete-event method to simulate dispatching

taxi services concluding in that there is a lineal relation between the total distance and the fleet size. Kim et al. (2005) proved that the use of information technologies can improve the quality of the taxi offered services by 20% using a simulation based stand taxi services model. Song and Tong (2006) and later Tong (2006) simulated a taxi stand market for analyzing the dynamic taxi demand and highlighted the limitations of the aggregated models such as the time-dependent patterns or the non-equilibrium in the regulated taxi markets. Recently, Lioris et al. (2010) developed a simulation model of the real taxi demand market conditions, she pointed out that the mathematical models are out of reach of such a complex multi-agent system (taxis and users). The limitations of these models are related to their complexity, data requirements and processing time, which can be simplified by using the first group of models for obtaining a good starting point.

3. PROPOSED MODELS

Two models have been developed for estimating the optimum number of taxis and the waiting time and unitary costs associated to this supply level. The first model is an aggregated model developed by defining the system costs function, relating all the variables to the number of taxis and minimizing the costs. The second model is an agent-based model, where the real taxi trips are simulated in a controlled environment, recording and analyzing the most important operational variables.

The reference values are related to the later application to the Barcelona taxi sector in order not to repeat the variables list. They have been obtained from the literature review, from the taxi trips database that is presented in the next chapter, from taxi surveys and studies realized by CENIT in Barcelona or estimated by the author.

3.1. Aggregated model

The aggregated model is based on the minimization of the total costs of the system. The system costs are composed by the costs of the users, the costs of the drivers and the costs of the city, which are basically the externalities caused by the provision of taxi services such as congestion or pollution. The aggregated model has been presented in Salanova et al. (2013b), together with a detailed review of the formulations proposed in the literature and the results of the application of the proposed model to a virtual taxi stand-dispatching market. The model has been applied to a virtual market where the cruising taxis are hailing the users along the streets and the obtained results are compared to the results obtained for the application of the model to the stand-dispatching market in Salanova et al. (2013c). The proposed objective function is the following:

$$Min\ Z = Z_d + Z_u + Z_c + G \quad (1)$$

$$Z_u = \lambda_u \cdot A \cdot \left[\alpha_A \cdot T_A + \alpha_W \cdot T_W + \alpha_{IV} \cdot T_{IV} + \frac{\bar{c}}{VoT_u}\right] \quad (2)$$

$$Z_d = \frac{\lambda_d \cdot A}{VoT_d}\left[-\bar{n} \cdot \bar{c} + \left(\bar{n} \cdot \bar{d} \cdot C_{km} + C_h\right)\right] \quad (3)$$

$$Z_c = \lambda_v \cdot A \cdot \Delta T_v + \frac{\lambda_d \cdot A \cdot C_E \cdot E_d}{VoT_d} + \frac{\lambda_v \cdot A \cdot C_E \cdot \Delta T_v \cdot E_d}{VoT_v} \quad (4)$$

Where,

	Variable	Reference value (Barcelona)
Model outputs	Z is the cost of the system (€) - z is the unitary system cost (€/trip)	-
	Z_d is the cost of the drivers (min) - z_d is the unitary cost of the drivers (min/trip)	-
	Z_u is the cost of the users (min) - z_u is the unitary cost of the users (min/trip)	-
	Z_c is the additional cost for the city (min) - z_c is the unitary cost for the city (min/trip)	-
	G is the cost of the infrastructure (min) - g is the unitary infrastructure cost (min/trip)	-
	T_W is the waiting time of users (min)	2 - 6
	T_A is the access time of users (min)	-
	T_{IV} is the in-vehicle time of users (min)	12 - 14
	$\bar{c}$ is the average trip cost (€)	7 - 10
	$\bar{d}$ is the average distance of the trip (km)	5 - 6
	$\bar{n}$ is the average number of trips per hour and driver (trips)	1 - 3
	ΔT_v is the increase in the travel time of the other drivers caused by taxis (min)	-
Decision variables	λ_d is the taxi hourly supply (vehicles per hour and area of service)	20 - 60
	D is the flag-drop charge (€)	2
	τ_{km} is the taxi fee per unit of distance (€/km)	0.86
	τ_{sec} is the taxi fee per unit of time (€/min)	0.30
Model inputs (variables)	λ_u is the hourly demand for taxi trips (trips per hour and area of service)	50 - 250
	A is the area of the region (km^2)	100
	λ_v is the hourly circulating vehicles (vehicles per hour and area of service)	8.000
	$\bar{v}$ is the average speed of the trip (km/h)	30
	E_d are the hourly vehicle emissions (kg of CO_2)	-
Model inputs (parameters)	VoT_u is the value of time of the taxi users (€/min)	20
	VoT_d is the value of time of the taxi drivers (€/min)	20
	VoT_v is the value of time of the other drivers (€/min)	20
	α_A is the user perception factor of the access time	3
	α_W is the user perception factor of the waiting time	3
	α_{IV} is the user perception factor of the in-vehicle time	1
	C_{km} is the operational cost per unit of distance of taxis (€/km)	0.35
	C_h is the hourly operational cost of the moving taxis (€/min)	0.33
	C_E is the emission unitary cost for all vehicles (€/kg of CO_2)	-

	r is the area and network parameter	1.27

The above metrics are expressed in terms of output per hour, analyzing the characteristics and providing the results for the typical peak hour of the market. Longer periods can be also selected if there is homogeneity in their characteristics along time. The constraints presented below must be taken into account when modeling taxi services in order to reflect physical or time restrictions of the real world:

$$T_A < T_{Amax} \quad (5)$$

$$T_W < T_{Wmax} \quad (6)$$

$$Z_d < -B_{dmin} \quad (7)$$

$$E_d + E_v < E_{max} \quad (8)$$

$$\Delta T_v < \Delta T_{vmax} \quad (9)$$

$$G < G_{max} \quad (10)$$

$$\lambda_d < \lambda_{dmax} \quad (11)$$

$$\lambda_d > \lambda_{dmin} \quad (12)$$

The above constraints correspond to the following limitations:

- Access and waiting time of users lower than maximum values (eq. 5 and 6).
- Benefit of taxi drivers higher than minimum value (eq. 7).
- Emissions lower than maximum value (eq. 8).
- Congestion level lower than the maximum congestion level (eq. 9).
- Infrastructure cost lower than maximum value (eq. 10).
- Number of licenses between minimum and maximum values (eq. 11 and 12).

The problem is to minimize the objective function while respecting the above constraints.

The formulations for the optimum supply, the waiting time and the unitary cost related to this supply are presented below. They have been obtained by deriving the presented formulation in relation to the taxi fleet size. For the dispatching market:

$$\lambda_d \mathbf{A} = \lambda_u \mathbf{A} \frac{\mathbf{r A}^{1/2}}{2\bar{v}} \boldsymbol{\varepsilon} + \mathbf{A} \left(\frac{\lambda_u \alpha_W VoT_u \mathbf{0,4 r}}{2\bar{v} C_{\mathbf{h}}} \right)^{2/3} \quad (13)$$

$$T_W = \left(\frac{\alpha_W VoT_u}{0{,}32 \cdot C_{\mathbf{h}} r^{\mathbf{2}}} \lambda_u \bar{v}^{\mathbf{2}} \right)^{-1/3} \quad (14)$$

$$\frac{Z_u + Z_d}{\lambda_u \cdot A} = C_{\mathbf{h}} \frac{\mathbf{r A}^{1/2}}{2\bar{v}} \boldsymbol{\varepsilon} + \left(28{,}125 \frac{\bar{v}^2 \lambda_u}{(\alpha_W VoT_u \mathbf{r})^2 C_h} \right)^{-1/3} + \frac{\mathbf{r A}^{1/2}}{2\bar{v}} \cdot \left(C_{km} + \frac{\alpha_{IV} VoT_u}{\bar{v}} \right) \quad (15)$$

For the hailing market:

$$\lambda_d^{\bullet} A = \lambda_u A \frac{r A^{1/2}}{2\bar{v}} + A \left(\frac{\lambda_u \alpha_W VoT_d}{\bar{v}(\bar{v} \cdot C_{km} + C_{\mathbf{h}})} \right)^{1/2} \quad (16)$$

$$T_W^* = \left(\frac{\alpha_W VoT_d}{\bar{v} \cdot C_{km} + C_h} \lambda_u \bar{v}\right)^{-1/2} \quad (17)$$

$$\frac{Z_u + Z_d}{\lambda_u \cdot A} = 2\left(\frac{\alpha_W(\bar{v} \cdot C_{km} + C_h)}{VoT_d \bar{v} \lambda_u}\right)^{1/2} + \frac{rA^{1/2}}{2\bar{v}} \cdot \left(\frac{\bar{v} \cdot C_{km} + C_h}{VoT_d} + \alpha_{IV}\right) \quad (18)$$

The details of the aggregated model and the proofs of the above formulations can be found in Salanova et al. (2013b and 2013c).

3.2. Agent based model

The agent based model has been developed in MATLAB and simulates the movement of the taxi fleet (vacant and occupied taxis) in the network recording all the performance variables. The model is able to simulate the three taxi markets: hailing, dispatching and stand. The model has been presented in Salanova et al. (2013a), where it was applied to the Sioux Falls network and results for the three taxi markets are presented and discussed. The model is composed by four sequential modules: the generation module, the movement module, then intersection module and the taxi-user meeting and user destination modules.

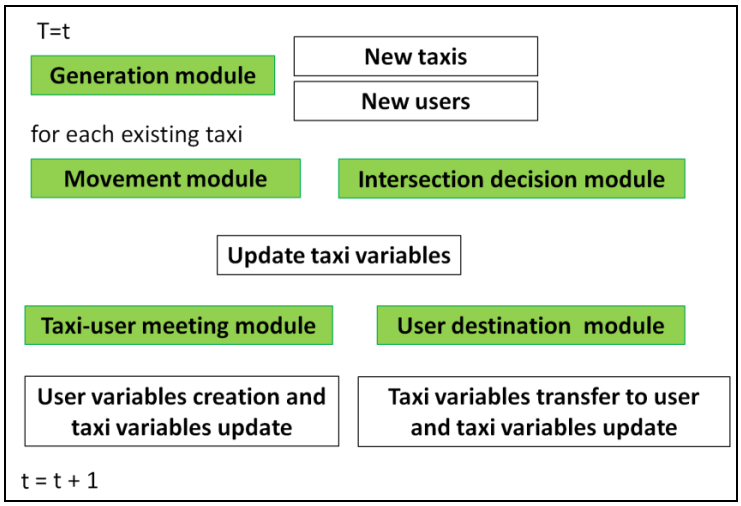


Figure 1. Flow chart of the proposed agent-based taxi services model

The generation module is responsible for the generation of users and taxis in the network, taking into account the OD demand matrix and the supply profile. The movement module and the intersection decision module are responsible for the movement of the taxis within the network, guiding them to the users' origin or destination. Finally, the taxi-user meeting and destination modules are responsible for the users' pick-up and delivery. All modules record the related data in the users and drivers performance databases. The variables of the model are the following:

Variable	Reference value

		(Barcelona)
Model outputs	Waiting time of users (min)	5 - 6
	In-vehicle time of users (min)	11
	Trip cost of users (€)	6
	Distance of the trip of users (km)	5
	Number of trips of drivers (trips/hour)	1 - 6
	Vacant distance (km/h)	8 - 18
	Occupied distance (km/h)	8 - 18
	Vacant time (min)	25 - 44
	Occupied time (min)	16 - 35
	Driver income (€/h)	14 - 30
	Driver earnings (€/h)	(-6) - 5
Model inputs	Network geometry	-
	Taxi hourly supply (total number of vehicles per hour and km^2)	20 - 60
	Hourly demand for taxi trips (OD matrix)	14000
	Average speed of each link (km/h)	4 - 90
	D is the flag-drop charge (€)	2.05
	τ_{km} is the taxi fee per unit of distance (€/km)	0.86
	τ_{sec} is the taxi fee per unit of time (€/min)	0.3

4. USE CASE: BARCELONA

The study area in Barcelona is composed by 18 municipalities, with a total population of 2.650.000 habitants and 330 km^2. Various transport modes satisfy the mobility needs of the population, which are more than 12.800.000 daily trips, from which more than 5.200.000 are non-motorized trips. More than 5.300.000 trips are realized using the private vehicle or motorcycle, while the other 2.300.000 trips are realized by public means of transport (tram, metro, interurban rail, urban and interurban buses and taxi).

4.1. The supply and the demand for taxi services in Barcelona

The road network of the city of Barcelona consists of more than 1.600 kilometers of streets and more than 8.000 intersections. The network used for the modeling of the city consists of more than 13.000 links, 62% of them bidirectional, what means that the total number of one direction links is near to 20.000 (TMB 2007).

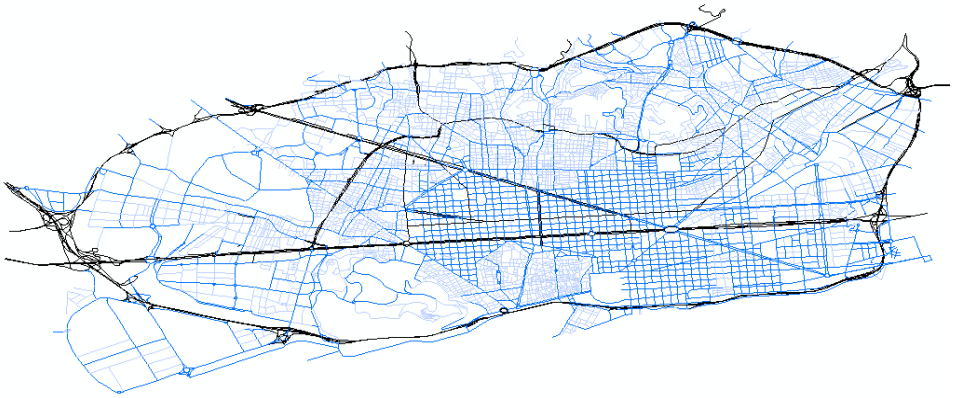


Figure 2. Barcelona network used in the agent-based taxi services model

The number of taxi vehicles in the city is 10.482 (Amat 2010) while the number of active taxi license holders is 11.076 (Amat 2010), from which a 33% (Amat 2010) is related to one of the 24 (Amat 2010) dispatching centers of the city. The total number of stops dedicated to the taxi services is 272 (Amat 2010) with a total capacity of more than 1.700 vehicles (Amat 2010).

The total number of daily trips in Barcelona is 12.800.000 (TMB 2007), from which more than 225.000 (Amat 2010) are realized using the taxi services offered by the city. The average waiting time during the years 2004 and 2009 was 2 - 6 min (Amat 2010), the average distance 5 - 6 km, the average time 12 - 14 minutes and the average cost 7 - 10 euros.

A sample of the taxi trips realized in the city during 9 years has been used for the creation of the trips database. This sample has been provided by the Center for Innovation in Transport (CENIT) from the University of Barcelona. The data is continuously collected in the framework of their collaboration with the Metropolitan Institute of Taxi Transport Services (IMT) for the taxi Observatory. The database contains more than 1.200.000 valid taxi trips realized during the years 2004 – 2012. The trips used for the purpose of this paper have origin and destination within the city, the airport has not been included due to its special characteristics. Consequently, the study area is the whole city, and the results obtained apply to the entire city area.

Although the number of drivers is low in comparison with the total number of taxi drivers in Barcelona, the collected trips are representative of the total trips population since they cover the whole city and the whole day, and their characteristics have been validated with the questionnaires realized to most of the drivers by the IMT.
Tables 1 and 2 below present the evolution of the main indicators of the database during the recording period.

Table 1. Average cost, travel and idle time, distance of the database of taxi recorded trips

	2004	2005	2006	2007	2008	2009	2010	2011	2012
Average cost	6,69	7,18	7,83	7,94	8,47	8,58	9,22	9,51	9,84

Average travel time	13,12	12,85	13,38	12,73	12,58	12,23	12,64	12,71	12,70
Average distance	4,97	5,40	5,45	5,23	5,05	5,09	5,69	5,76	5,83
Average idle time	15,62	17,16	15,98	16,13	17,89	20,07	23,42	26,50	27,31
Average idle distance	4,64	4,62	4,50	3,64	3,82	3,13	2,52	5,21	6,46

Table 2. Total number of trips, vehicles, drivers, costs, occupied ad vacant time and distance of the database of taxi recorded trips

	2004	2005	2006	2007	2008	2009	2010	2011	2012
Taxi trips	17.760	114.988	90.250	64.779	54.820	256.140	313.127	147.996	119.858
Taxi vehicles	15	25	29	18	12	39	69	40	26
Taxi drivers	15	27	29	18	12	108	130	77	68
Daily trips per driver	20,6	22,2	21,7	20,7	19,5	17,5	18,0	15,3	14,2
Total trip costs	119.253	855.299	738.266	556.369	485.987	2.421.596	1.651.637	1.554.178	1.295.433
Total occupied time	233.030	1.477.992	1.207.482	824.763	689.612	3.131.664	2.024.899	1.880.590	1.522.234
Total occupied distance	88.323	621.348	491.830	338.782	276.581	1.302.949	911.998	851.843	698.963
Total vacant time	277.460	1.973.712	1.441.912	1.045.087	980.459	5.141.504	3.751.581	3.922.250	3.273.474
Total vacant distance	82.480	531.118	406.054	235.461	209.286	802.126	403.835	771.542	774.303

The cost of the trip has increased significantly since year 2004, but at the same time the number of daily trips per driver has been reduced. The characteristics of the trips (duration and length) have remained more or less the same, with a small increase in the trip length during the last years. Five periods can be recognized in the above tables:

- 2004-2005: increase in the number of daily trips per driver and the trip cost, what means more income for the drivers. Increase of the daily working time and distance of the drivers.
- 2005-2008: decrease of the number of daily trips and their length, increase in the trip cost. Drivers reduce the variable costs bu reducing the idle distance while maintaining the working hours.
- 2008-2009: decrease of the number of daily trips but small increase in their length, increase in the trip cost.
- 2009-2010: stable number of daily trips and significant increase in their length, increase in the trip cost. Increase in the total distance, significant increase of the working hours together with a reduction of the idle distance, the drivers wait at taxi stands. Small increase in the working hours.
- 2010-2012: decrease of the number of daily trips but small increase in their length, increase in the trip cost. Redution of the working hours and significant increase in the idle distance, which means significant reduction of the income per kilometer. The total distance remains stable.

4.2. Results of the aggregated model

The reference values have been obtained from a database of more than 1.200.000 taxi trips recorded during 9 years (2004-2012) by more than 100 vehicles and 200 drivers and a total cost of more than 10.000.000 euros. The total number of kilometers driven by the drivers is roughly 10.000.000, half of them occupied. The total number of hours driven by the drivers is roughly 600.000, a third of them occupied. The data presented in the above table has been introduced in the model. The table below presents and compares the obtained results with the measured values from the database.

Table 3. Average cost, idle time and travel time and distance comparison between the observed and the modeled values

	Model result	Measured value (2012)
Average cost (euros)	7,96	9,84
Average travel time (min)	11,2	12,70
Average distance (km)	6,35	5,83
Average idle time (min)	30,3	27,31

The results obtained by the model in terms of waiting time and costs for the different actors are presented in the figure below:

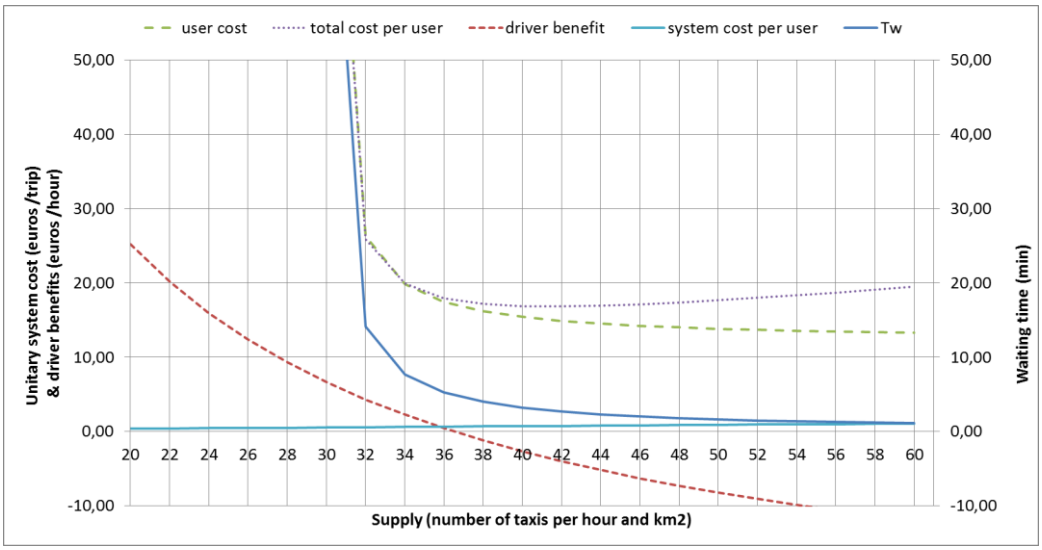


Figure 3. Waiting time, driver earnings and unitary costs for each supply level obtained by the aggregated model

It can be observed that the satisfactory number of taxis per hour and km^2 is higher than 31 since the waiting time for smaller fleets is very high due to the low number of free taxis. The minimum fleet size is 29 taxis/hour*km^2, what means that with this taxi fleet size the number of demanded passenger hours are equal to the offered vehicle hours. The operational

minimum fleet is 32 taxis/hour*km^2 since smaller taxi fleets cannot provide all the requested services due to the necessary idle distance between customers. It can be also observed that the maximum number of vehicles is 36 taxis/hour*km^2 since more taxis than this value will generate losses to the drivers, also known as second best. The optimum number of taxis taking into account the system costs is 40 – 42 taxis/hour*km^2, known as first best. There is a need for subsidization of 3 to 4 euros per trip in order to maintain this optimum fleet.

4.3. Results of the simulation model

For the purpose of this paper the agent-based dispatching model has been applied to the Barcelona network. The supply side is composed by more than 20.000 links and 8.000 nodes, representing most of the streets of the city. The demand side is composed by more than 270.000 recorded taxi trips during 6 years (2007-2012) and the OD matrices of 2007 for all modes. The figure below shows the matching of the origin coordinates of the 270.000 trips with the network. It can be observed an important concentration of origins in the two airport terminals of the city on the left side of the picture.

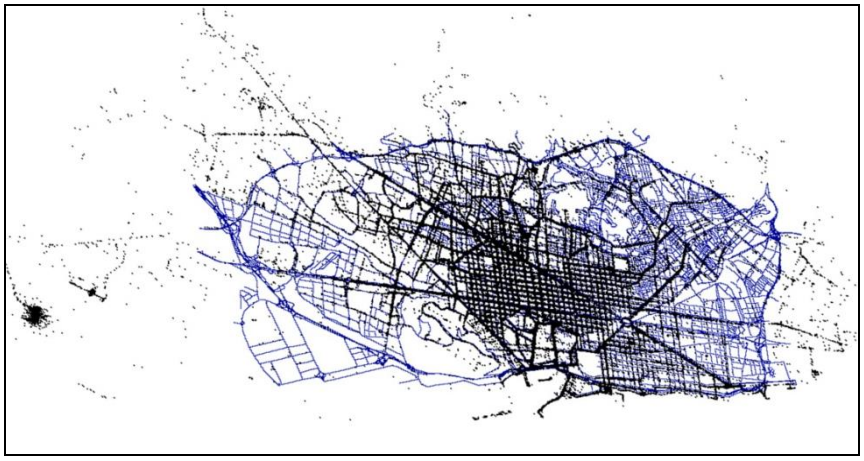


Figure 4. Matching of taxi origins recorded by the GPS system and the real Barcelona network

The data has been filtered in order to use the trips with origin and destination within the city network, generating a total of 235.000 valid trips. A small sample of 1.200 trips between 8 and 9 of all Tuesdays has been used for validating the model in terms of travel distance, time and cost. The results of the validation are presented below:

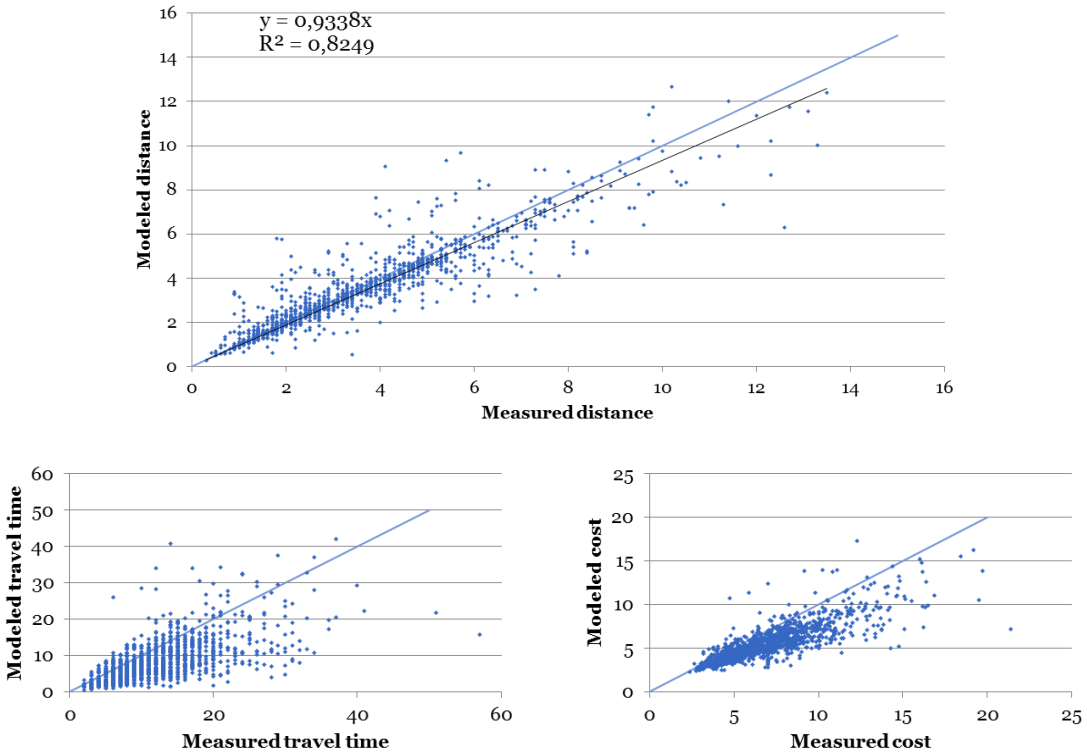


Figure 5. Validation of the agent-based model in terms of travel time, distance and cost

The relation between the measured travel distance and the modeled ones shows the validity of the model. There are two issues that affect this relation, one is the detail of the net used in the model, where the lowest street categories have been eliminated; the second issue is the route chosen by the taxi driver that it cannot be the shortest one in some cases. The relation between the measured travel times and the modeled ones present a more scatter results. The reason is that the model uses an average congestion factor for each link, but since this value is changing within the days, it will not be always representative of the real congestion levels. This fact influences in the relation between the measured costs and the modeled ones, which presents a small deviation of the 45 degree line.

The demand between 8 and 9 of all Mondays, all Wednesdays and all Thursdays (4.800 trips) has been introduced in the model and different supply levels have been tested, obtaining the waiting time and the system costs presented in figure 7.

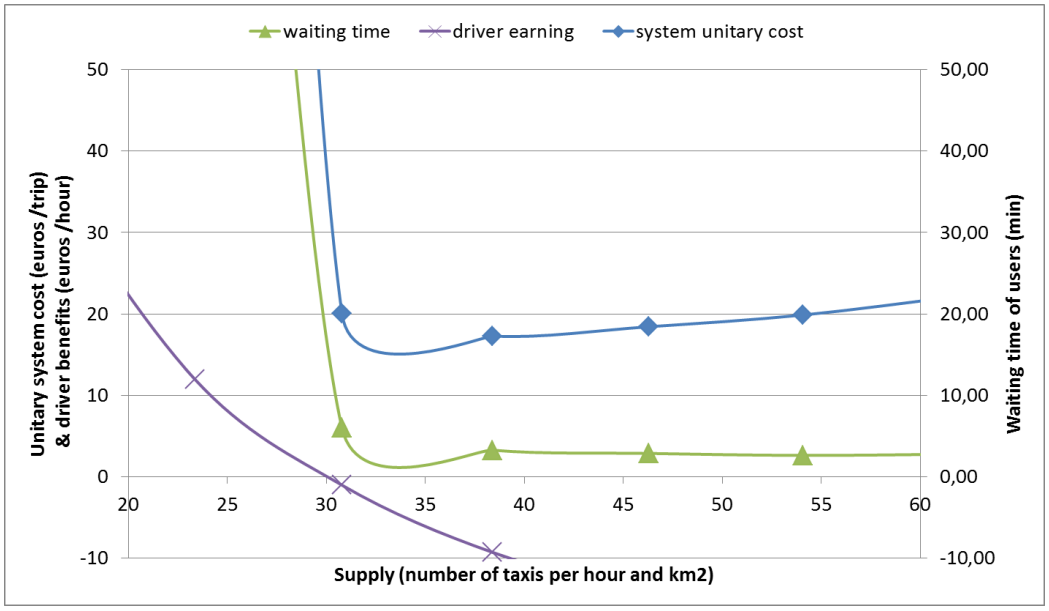


Figure 6. Waiting time, driver earnings and unitary costs for each supply level obtained by the agent-based model

It can be observed that the satisfactory number of taxis per hour and km^2 is higher than 30 since the waiting time for smaller fleets is very high due to the low number of free taxis. It can be also observed that the maximum number of taxis is 30 taxis/hour*km^2 since more taxis than this value will generate losses to the drivers, also known as second best. The optimum number of taxis taking into account the system costs is 33 – 34 taxis/hour*km^2, known as first best.

4.4. Conclusions

Aggregated models can analyze global performance of the taxi services system but they cannot reflect local particularities of the network or provide detailed results for different parts of the city. They are also limited in terms of outputs, being unable to provide detailed results for all the involved actors. They are based on average and statistical values, therefore the data necessities are easier to fulfill than in more detailed models and their process time is zero.

Simulation models can provide much more detailed outputs, both in spatial and time terms. They need much more detailed data which is difficult to collect and process, and their process time is much higher than the one in the aggregated models.

The combination of both models can produce significant benefits to decision makers since they can analyze the taxi market macroscopic planning using aggregate models and then refine the results by using simulation models, from which they can obtain operational performance values and fine-tune their policies taking into account particularities of the network.

The demand used in both models is inelastic, which is a strong limitation for testing taxi policies. This is a major issue and the author is already working in a bi-level model where the demand is obtained in the upper level taking into account the waiting time and trip cost while these values are updated in the lower level.

The two proposed models have been applied to the city of Barcelona using real data form both, the real network and the real taxi trips. The models have been validated with real data collected during 9 years from the taximeters of more than 100 taxis, which have realized more than 1.200.000 trips during this period. The results obtained in terms of vehicles per hour and area by the simulation model are slightly lower than the ones obtained by the aggregated model. The models have concluded that the system optimum number of taxis in Barcelona is 34 – 40 vehicles per hour and km^2, while the drivers optimum is slightly lower (30 – 36 vehicles per hour and km^2). They also provide the subsidization value needed for obtaining the first best and having the lowest unitary cost without causing losses to taxi drivers. These results can be used by decision makers when planning policy for the taxi sector while more detailed and localized data can be obtained from the simulation model in order to analyze the operational performance level of the taxi services.

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