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Mobile phone records to feed activity-based travel demand models: MATSim for studying a cordon toll policy in Barcelona

Aleix Bassolas[a], José J. Ramasco[a,*], Ricardo Herranz[b], Oliva G. Cantú-Ros[b]

[a] Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), Campus UIB, 07122 Palma de Mallorca, Spain
[b] Nommon Solutions and Technologies, calle Cañas 8, 28043 Madrid, Spain

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ABSTRACT

Activity-based models appeared as an answer to the limitations of the traditional trip-based and tour-based four-stage models. The fundamental assumption of activity-based models is that travel demand is originated from people performing their daily activities. This is why they include a consistent representation of time, of the persons and households, time-dependent routing, and microsimulation of travel demand and traffic. In spite of their potential to simulate traffic demand management policies, their practical application is still limited. One of the main reasons is that these models require a huge amount of very detailed input data hard to get with surveys. However, the pervasive use of mobile devices has brought a valuable new source of data. The work presented here has a twofold objective: first, to demonstrate the capability of mobile phone records to feed activity-based transport models, and, second, to assert the advantages of using activity-based models to estimate the effects of traffic demand management policies. Activity diaries for the metropolitan area of Barcelona are reconstructed from mobile phone records. This information is then employed as input for building a transport MATSim model of the city. The model calibration and validation process proves the quality of the activity diaries obtained. The possible impacts of a cordon toll policy applied to two different areas of the city and at different times of the day are then studied. Our results show the way in which the modal share is modified in each of the considered scenarios. The possibility of evaluating the effects of the policy at both aggregated and traveller level, together with the ability of the model to capture policy impacts beyond the cordon toll area confirm the advantages of activity-based models for the evaluation of traffic demand management policies.

1. Introduction

Activity-based models (ABMs) offer advantages over more aggregated travel demand models for evaluating policies designed for traffic management. Rather than considering individual trips, ABMs consider the individuals performing them. The trips are seen as the consequence of individuals' desires of performing certain activities (see Balmer, 2007; Horni et al., 2009; Ortuzar and Willumsen, 2011 for a recent reviews). The change of locations needed to pass from one activity to the next constitutes thus a trip. The conception of trips linked to individuals make these models more flexible to adapt to different levels of policy application. In addition, it also makes them more appropriate to study the effects of policies aimed at modifying individuals' decisions, e.g., policies of fixed rates for multistage/multimodal trips or different pricing and toll schemes. In spite of the huge potential of these models, their use is mainly

* Corresponding author.
E-mail address: jramasco@ifisc.uib-csic.es (J.J. Ramasco).

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restricted to research and there are only few examples of their application for public policy planning. One of the reasons hindering their adoption in real environments is the high level of data requirements. Activity-based models require a full diary of activities for each user representing the population of the area of study, which is not always available for the population. Travel surveys, commonly used to obtain such data, provide rich information on travel behaviours but they suffer from major shortcomings. Survey collection is costly and time consuming and depends on users' availability and willingness to answer. This reduces drastically the size of the sample and the frequency with which information can be updated, limiting the information to punctual observations rather than to continuous monitoring. Additionally, the planning needed for survey collection does not allow to obtain data on unexpected events.

The vast amount of spatio-temporal data generated by the use of personal ICT mobile devices provide insights on people's actions and behaviours, bearing valuable information on when and where different actions took place. In particular, geolocated devices such as intelligent transport cards, mobile phones, Bluetooth, global positioning system (GPS), etc. allow for the collection of mobility information requiring minimal or no interaction with the users (collection of passive data). This avoids many of the intrinsic deficiencies of surveys, such as imprecisions on reported time and space, reduces drastically time and cost associated with data collection and provide larger sample sizes. The potential of these new data sources is huge, but it also comes with a number of challenges. On the one hand, we have much larger samples than those obtained from traditional surveys. On the other hand, the data have not been originally produced for the purpose of collecting activity-travel information, and, therefore, it is often noisy and/or biased. The reconstruction of activity and mobility patterns calls thus for the development of ad hoc data analysis methods addressing the specific characteristics of each dataset.

In the last decade, several studies, starting from the pioneer work of Gónzalez et al. (2008) to more recent ones like those of Bagrow and Lin (2012), Lenormand et al. (2014, 2017), Louail et al. (2014, 2015) and Picornell and Willumsen (2016) among others, have been carried out to investigate how data obtained from mobile phone records can be used to characterise people mobility habits and the factors influencing them (see Blondel et al. (2015) and Barbosa-Filho et al. (2018) for recent reviews). Mobile phone data has also been used for the characterisation of mobility patterns in specific situations such as in the work by Ahas et al. (2010) monitoring the movements of work trips in Tallinn, Calabrese et al. (2010) studying how people move during large social events, Becker et al. (2011) identifying the residences of workers and the nightlife of Morristown, Song et al. (2010) and Isaacman et al. (2011) identifying locations where people spend most of their time and characterising how they return to them. In the transport sector, research on the use of mobile phone records has been mainly focused on the estimation of aggregated variables related to travel demand, such as travel time (Bar-Gera, 2007), mode (Wang et al., 2010; Doyle et al., 2011) and route choice (Tettamanti et al., 2012), estimation of origin-destination matrices (Ma et al., 2012; Alexander et al., 2015; Cáceres et al., 2012), and traffic flows (Cáceres et al., 2012). Trip purpose characterisation from mobile phone records has also been approached by different authors (Alexander et al., 2015; Rose, 2006; Cáceres et al., 2008; Steenbruggen et al., 2013; Phithakkitnukoon et al., 2010; Gong et al., 2015). Most of the work previously discussed belongs to academic research and has not been applied to real-world planning projects (Lee et al., 2016). In terms of integration with simulation models, so far there are only few examples of traffic models fed with demand information (origin-destination matrices) generated from of mobile phone data (Lee et al., 2016; Solé-Ribalta et al., 2018). This is partly because the obtained information does not always meet the requirements of format, level of resolution and completeness.

The main contribution of the work presented here is to show the potential of mobile phone data to generate activity travel dairies to feed an activity-based travel model aimed at evaluating the impact of a traffic management policy. Activity diaries of residents of the metropolitan area of Barcelona are reconstructed from mobile phone records. Such diaries are used as input for the activity-based traffic model MATSim to evaluate the impact of a cordon toll applied to two different areas of the city. Results of the policy are obtained and discussed at an aggregated and at a resident-centric level. The paper is organised as follows: Section 2 describes the model and its implementation for the region of the study, including model calibration and validation. Section 3 presents details of the case of study, the cordon toll implementation. In Section 4 the results of the calibration and validation process as well as of the policy implementation are discussed. Finally, Section 5 presents the main conclusions of the work, divided into conclusions of the model implementation process and conclusions derived from the policy implementation.

2. Model description and implementation

2.1. MATSim: Multi-Agent Transport Simulation

MATSim is an activity-based multi-agent simulation framework used to simulate traffic flows and the possible congestion associated to them. In its typical configuration the simulations cover one generic day. In MATSim, travel demand and travel flows are generated by agents performing their daily activities. Each agent attempts to maximise the utility of its daily activity schedule while competing for space-time slots with all other agents on the transportation infrastructure. Agents maximise their utility by minimising the total travel cost, $V_{trav} = \sum_j V_{trav,j}$, and maximising the time spent performing activities, $\sum_i V_{act,i}$. The index for activities i runs between 1 and N, the total number of activities on schedule for the day. The trips occur between activities and, therefore, j goes from 1 to $N - 1$. $V_{act,i}$ is a logarithmic utility function associated with the time spent performing activity i and it is defined as

$$V_{act,i} = \beta_{dur} t_{typ} ln\left(\frac{t_{dur,i}}{t_{0,i}}\right), \tag{1}$$

where β_{dur} is the marginal utility of performing an activity, t_{typ} the activity typical duration, $t_{dur,i}$ the actual duration of the activity i,

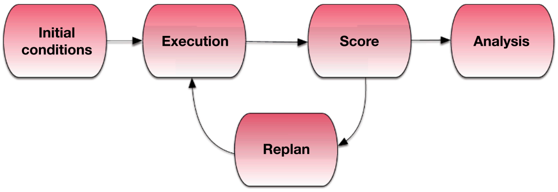

Fig. 1. Sketch of MATSim main flow diagram (see http://www.matsim.org/about-matsim for detailed information on the structure, the implementation and how to run MATSim).

and $t_{0,i}$ the minimal duration after which the utility starts to be positive. Although the possibility could be easily implemented (see Horni et al., 2016), in this work early and late arrivals to activities are not penalised. The trip utility function, $V_{trav,j}$, is associated to the cost (time and money) of travelling from one activity j to the next $j+1$ and it has the following linear expression:

$$V_{trav,j} = C_{mode(j)} + \beta_{trav,mode(j)} t_{trav,j} + \beta_m \Delta m_j + (\beta_{d,mode(j)} + \beta_m \gamma_{d,mode(j)}) d_{trav,j}, \tag{2}$$

where C_{mode} stands for a mode-specific constant, $\beta_{trav,mode}$ for the direct marginal utility of time spent travelling by mode, t_{trav} for the time taken to travel from activity j to activity $j+1$, β_m is the marginal utility of money, Δm the change in monetary budget caused by fares or tolls, $\beta_{d,mode}$ is the marginal utility of distance (normally negative or zero), γd is the mode specific monetary distance rate (negative or zero), and d_{trav} the distance travelled between activity j and activity $j+1$.

Users minimise the travel cost by taking decisions on the route choices, transportation modes and activities' sequence and timing, based on previous experiences (replanning process). Although some implementations of MATSim allow the modification of the location of activities in the replanning process ((Horni et al., 2009)), this is not the case of the work presented here. Activity diaries are modified iteratively until the system finds a stationary state, i.e., further changes in the activity diary do not produce qualitative changes in the total score of the system (sum of the individual utilities of each of the participating agents). The iterative process is depicted in Fig. 1. More details about how to implement and run MATSim can be found at (Horni et al., 2016).

The minimal required inputs to run the model can be summarised as: (i) travel demand, consisting of a population of agents and their plan of activities. This should contain a list of all activities to be performed by each agent during the day and the time and location where they take place. As initial condition, it is also required a transport mode for the trips that along with other details of the plan will be later subjected to changes during the simulation to improve agents utility. Due to the high cost in terms of computational time and memory, typically only a representative sample of the total population is simulated. And, (ii) supply network, consisting of the full information of the road and the public transport network of the studied area.

2.2. Model implementation

2.2.1. Region of study

Barcelona is the second largest and the densest city of Spain. The metropolitan area is conformed by 36 municipalities and according to the Spanish national statistical office, INE, in 2017 it had a population of 3,247,281 inhabitants. The municipality of Barcelona is the core of the area and it concentrates around one half of the population with 1,620,809 inhabitants. Jobs, retail and cultural offer make the municipality of Barcelona a trip attractor. Actually, up to 27% of the trips registered in the Barcelona municipality are due to residents of the rest of the metropolitan area. The metropolitan area is an official entity that manages a public transportation network composed of four transport modalities: bus, metro, train and tramway (Area Metropolitana de Barcelona). The network is organised in 6 concentric fare zones centred at Barcelona municipality, and covering virtually the whole province. The majority of traffic is concentrated in the first fare zone, whose residents are responsible for 85% of the trips in the Barcelona municipality. The road network, on the other hand, has three important landmarks: the central system, consisting of Barcelona Rondas, which is the ring around the city, and their distribution accesses to outer roads, the main axes of distribution and territorial structure, and the bypass defined by B-30 road. Barcelona Rondas are one of the most important infrastructures of the metropolitan road system. These are high capacity rings with annual average daily traffic intensities exceeding 166,000 vehicles per day, surrounding the city without interfering with the urban interior network. The Rondas are divided into two turn-offs: Ronda Litoral, seaside, and Ronda de Dalt, mountain side. They have a total length of 36 *km*, of which 8.5 are tunnels (see Fig. 2).

2.2.2. Assumptions and constraints in the model setting

Taking into account the characteristics of the region as well as the available data and the computational requirements of the model, the following constrictions are applied to the model settings:

- The model is implemented for the first fare zone of Barcelona;
- Only trips performed by residents in the area considered are simulated: passing by trips and freight trips are excluded from the study;
- Four different transport modes are considered: private car, public transport (including train, underground, tramway and bus), bike, and walking;
- Only travellers older than 15 years old are included in the simulations. This obeys to two reasons: (i) the use of mobile phones is

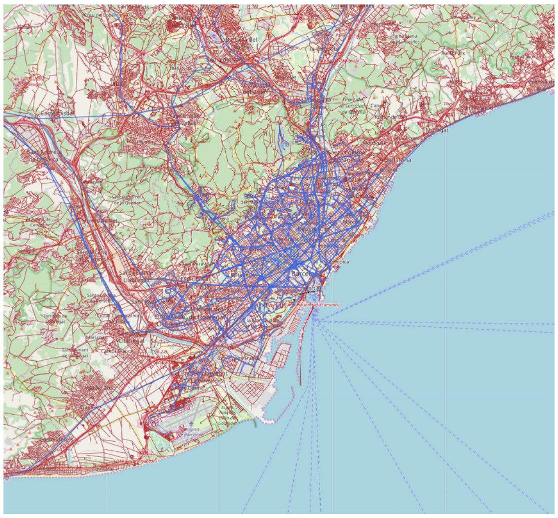

Fig. 2. Road network (red) and public transport network (blue) as obtained from Open Transport Maps (http://opentransportmap.info/). The layout of the maps was obtained from Open Street Map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not fully spread among the population below that age. And (ii), the official statistics used to calibrate the model only consider the mobility of people older than 15 years. Even though children are not explicitly included, some of their trips are indirectly contemplated (especially for the youngest ones) since, for instance, bringing them to school or to after-school activities is already part of the parents' activity diary.
- Due to the large number, ≈2,300,000, of inhabitants older than 15 years in the studied area and the high computational requirements in terms of memory and simulation time, a subpopulation of agents formed by 10% of the total population is taken as a representative sample.
- Three types of activities are considered: home, work and other.
- The base year for the study is 2014, since it corresponds to the time of the phone call records available.
- The location of each activity is fixed: even when some MATSim implementations allow activity locations to be modified by adding an extra layer with land use information, this option is not implemented in this work.

2.2.3. Travel demand: population generation

The use of transport infrastructures cannot be well-framed if the demand considered is not realistic, hence the agents should be representative of the full population. Different socio-demographic characteristics such as age, gender and residence place influence the way people move (Lenormand et al., 2015). This implies that the simulated population should be representative of the whole population not only in terms of a variety of mobility/activity patterns, e.g., number and length of trips, activities' locations, etc., but also of the socio-demographic characteristics.

In this work diaries of activity as well as residence place are reconstructed from Call Detail Records (CDRs), and census information is used to up- or down-scale the sample to the desired 10% of the population – a standard in MATSim (Horni et al., 2009, 2016; Bosch et al., 2016), reproducing the official aggregated age and gender statistics at census track level. A brief description of the CDRs main characteristics and an explanation of the process followed to build a representative sample from both data sources is given next.

2.2.3.1. Call detail records. .CDR data is produced every time a mobile phone interacts with the network through a voice call, a text message or an Internet data connection. The records contain information about the time and position of the tower to which the device connects. This provides an indication of the geographical position of the user at certain moments along the day with a time and space granularity depending on the level of activity of each user and on the technology deployment of the service provider. In this work, anonymised Call Detail Records for the period of October-November 2014 provided by Orange Spain are used to reconstruct activity diaries of users residing at the study region. Orange is currently the second largest mobile network operator in Spain, with a market share of around 35% in Catalonia. This ensures a large sample size in the area studied.

The CDRs used contain the following information: a unique anonymised identifier per user, the time when an interaction with the network occurred and the geographic coordinates of the tower at which the device is connected at that particular moment. There are two limitations that should be taken into account: (i) There is a time window between two consecutive events, typically between 20 and 30 minutes for the most active users. And (ii), the tower position is not the exact position of the user. The space granularity observed in the CDRs in the region of study is of around 100–200 m. Besides CDRs, also some extra information such as age and gender is known for the users.

2.2.3.2. Diaries reconstruction from CDRs. The process of activity and mobility reconstruction consisted of the following steps:

1. **Data pre-processing and cleansing**. Mobile phone registers are pre-processed to ease their storage and management. An integrity analysis is also performed to filter out errors in the raw data, in order to ensure the quality of the results.
2. **Sample selection**. Only those users from whom it is possible to extract useful information about their daily activities and trips were kept for the diaries reconstruction. The selection of these users is based on a set of criteria related with their mobile phone activity, which shall be enough to determine their mobility patterns with an adequate level of accuracy and reliability. For instance, if a user disappears most part of the day he/she is filtered out from the sample for that specific day, as it will not be possible to determine his/her activities and trips during that period. After keeping the most active users we were left with a sample corresponding to 15% of the total population os Spain.
3. **Identification of common locations (home, work, other)**. To perform this analysis the space is divided into Voronoi areas according to the base transceiver station (BTS) tower position. Using longitudinal information recorded during the whole October-November period an activity profile at a Voronoi area level is built for each user. This profile contains information of the higher-lower phone activity times and the position of the most common locations. This constitutes the core of the activity profile of the user and is used to identify the home and work positions. In contrast with other approaches where typical time intervals are used to identify home (most visited location from 9 pm to 7 am approximately) and work (most visited location from 9 am to 5 pm approximately), here home is identified as the most frequent location visited during the period of lower phone activity and work is assigned to the most frequent location with an activity's duration equal or superior to a given threshold and occurring in the period of higher phone activity. This allows us to capture workers of atypical working hours. Based on the identified home location non-residents of the Metropolitan area of Barcelona were filtered out.
4. **Extraction of the activity diaries**. For the day of study all the registries of each user in the sample are analysed. Activities, stops and passing by positions are distinguished using criteria of time spent in an area. According to the user's activities' profile, a probability function is used to adjust the start and end time of each activity. The start time of activity i is chosen to take place between the last register corresponding to activity i-1 plus the estimated travel time between locations i and i-1, and the first register at activity i. The end time of activity i-1 is thus the start time of activity i minus the estimated travel time. For each activity, if is it a "non-home" activity, an x, y position inside the activity's Voronoi area is randomly chosen. The concatenation of activities for each user constitutes the user's activity travel diary. The information associated to each activity includes its location, the start and end times, and the type of activity (home, work, other frequent, non-frequent).

2.2.3.3. Sample expansion. The residence records (*padrón*) of 2014 are used to obtain a sample representative of the 10% of the total population. The expansion is performed at the geographical level of census tract. For each tract, the information of the *padrón* is aggregated in six categories separating the population by gender and in the following age ranges: 0–15, 16–64 and over 64 years. Since the CDR data is restricted to individuals over 15, only the last two age groups are considered for the expansion.

Since there is not an exact correspondence between Voronoi cells and census tracts, residents located at a given Voronoi area are assigned to one of the census tracts intersecting it or one of its neighbouring areas with a probability function. The probability of assigning a resident to a given census tract is directly proportional to the square of the population of the census tract and inversely proportional to the square of the number of users already assigned to that tract. The assignation process ensures a local homogeneous sample density among neighbouring census tracts. Finally, for each user an x, y home position is randomly chosen inside the assigned census tract area.

For each age-gender category in every census tract, the sample is either expanded (agents are "cloned") if the sample under-represents the pre-established threshold of 10% of the population of the given category, or reduced (agents are randomly selected) if its number exceeds the threshold per category. In this way, the distribution of users by category matches that provided by the population records in every tract. For the expansion, given the gender g, the age group a and the tract i, each agent is copied n times where n is given by the integer part of the ratio between the 10% of the population, $P_i^{a,g}$, and the sample size for the given category and census tract $S_i^{a,g}$ minus one, $n = [P_i^{a,g}/S_i^{a,g}] - 1$. Finally, some agents, $P_i^{a,g} - [P_i^{a,g}/S_i^{a,g}]S_i^{a,g}$, are randomly selected to be cloned one extra time.

2.2.4. Supply network: metropolitan area of Barcelona transport infrastructure

2.2.4.1. Road network. The data used to build the road network was obtained from Open Transport Maps (http://opentransportmap.info/). The information provided, by Open Transport Maps, for each link conforming the road network includes: coordinates for start and end nodes, traffic directions allowed, type of the road (from highways to pedestrian streets), free speed in km/h and road capacity per link. This information was treated in order to build the network for MATSim implementation: link length was calculated using the link's start and end coordinates, links capacity was scaled down to the 10% of actual capacity to take into account the sampling of the population. Additional links were generated to account for bi-directional links, since MATSim only accepts unidirectional links. The new links inherit all properties of the original ones but their start and end nodes are swapped. Pedestrian streets and bike lanes as well as unconnected and loop links (those where start and end nodes are the same) were removed. For those links with no information of free speed and/or capacity, an average value was imputed according to the road type. For all links the number of lanes, information required by MATSim and not available in Open Street Maps, was assigned according to the road type. The resulting network, depicted in Fig. 2a, contains 17,690 road links and 9217 nodes.

2.2.4.2. Public transport network. **Bus and metro**. Information about stops, routes, schedules and departures has been obtained from the public information available at the Barcelona Open Data platform (http://opendata.bcn.cat/opendata/en). The bus network of Barcelona has 192 lines and 2464 stops. The metro network is composed of 22 lines and 139 stops.

Train and tram. Train and tram networks data was obtained by querying web sites of the public companies managing the service (Renfe and Rodalies de Catalunya Rodalies de Catalunya) and extracting structured data from them. The Barcelona metropolitan rail network is composed of 38 lines and 181 stops. The tram has two networks with a combined total of 12 lines and 56 stops.

Although specific code was written to download and parse the data, the process was the same for all the sources: to detect the lines, to assign a unique identifier to each line and to extract the stops in both directions (and give them a unique identifier). It has to be noted that in some cases the stops are not the same in both directions. For every pair of consecutive stops along every line, we extract the duration of the journey and for every head stop (in both directions) we also get the time the convoy starts the journeys. The resulting public transport network is depicted in Fig. 2b.

2.3. Model calibration and validation

2.3.1. Model calibration

The calibration consists of adjusting the values of the parameters described in Section 2.1 such that certain outputs of the simulation (in our case, modal split) are consistent with baseline values. The output of MATSim contains the resulting route and mode used by each agent during his/her displacements between activities. This allows us to extract the modal split and to compare it with the one in the EMEF survey (*Encuesta de Mobilitat en Dia Feiner* 2014 Working day mobility survey). This is done at two different geographical scales: the full metropolitan area and the shire of Barcelona, called Barcelonès, which includes the municipality of Barcelona and four other municipalities. The calibration was performed with a trial-and-error process – matching the simulated modal split with the observed ones in the two areas at the same time – through a wide sweep of parameters; yet we started with a relation between the values of the transport modes which accounted for their usual drawbacks. The rank of the penalties for each transport modality was maintained after the calibration, which indeed seems very reasonable. In principle moving by bike is much faster than walking and is not susceptible to congestion, so if not penalised over walking, it would lead to an over representation of bike trips. This penalty accounts the fact that not everybody knows how to ride and that there is a perception of danger associated with riding. In the case of private transport, it has a higher penalty than public transportation as it presents much more difficulties not captured by MATSim; namely, a driving license is required, they are costly to maintain and are hard to park in the centre of cities. The results from the calibration are shown in Section 4.1.

2.3.2. Model validation

Traffic counts of some of the main entrances of the city were used to validate the results of the model once calibrated. This data was obtained from the web portal of statistics of the Barcelona City Council (Ajuntament de Barcelona). Only those links with a traffic volume higher than 10,000 vehicles per day were considered. Traffic statistics at the different links reported by MATSim are obtained from the agents final travel diary, hence the "traffic" volumes in each road correspond to people's car trips rather than real number of cars. Since a car may be occupied by more than one person, people's car trips should be converted into actual number of cars. The conversion is made by applying an occupancy factor. The value of this factor may vary depending on the road, the time of the day and the trip purpose. In this work, we consider the occupancy factor reported by the city's council in the sustainable urban mobility plan (SUMP) (PMU), which is 1.25. For the validation exercise, we have considered possible values ranging from a minimum simulated car volume, corresponding to an occupancy factor equal to this 1.25, and a maximum volume corresponding to a unit occupancy factor. The validation process consists in corroborating that for each road for which information was available, the observed number of cars passing by the road falls within the interval of possible values obtained by MATSim for the given road. Details on the observed and simulated number of cars passing by the main roads are given in Section 4.1.

3. Case study: cordon toll policy

A case study has been designed to accomplish the twofold objective of this work: (i) test the potential of using ICT data sources, in particular mobile phone records, to reproduce mobility patterns able to feed, the information demanding ABM, and (ii) demonstrate the advantages of Activity Based Models to assess the impact of different policies for traffic management. The application of a cordon toll has been simulated in the central area of the city, a policy that has been applied in other places to reduce the use of private cars and decrease congestion and pollution, both major issues in Barcelona too.

The toll policy is implemented as follows: a ring delimiting the toll area is set. A fee is charged every time a user enters the toll area by car. Trips performed by public transport and soft-modes (walk and bike) are exempted of charge. Once in the area, the user can circulate freely of charge regardless the time or distance travelled inside. The charge is applied to all users independently of their residence place, i.e. residents of the toll area are not excluded from the payment when they enter into it. Two different areas are considered: one comprising the city centre (red line in Fig. 3), and a peripheral area surrounded by the Ronda Litoral and the Ronda de Dalt (blue dotted line in Fig. 3). In both cases, circulation within the Rondas delimiting the charging zone is free of charge.

3.1. Policy implementation in the MATSim model

The cost of entering the tolled area by car reflects in the user's utility function. A list of links entering from the non-toll to the toll zone is provided to MATSim. Every time a traveller uses a link connecting a point outside the toll area with a point insider the toll

Fig. 3. Inner toll area delimited by the red solid line and peripheral toll area delimitated by the blue doted line. The maps and the layout were produced with Open Street Map. The point marked as city centre corresponds to "Plaça Catalunya". (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

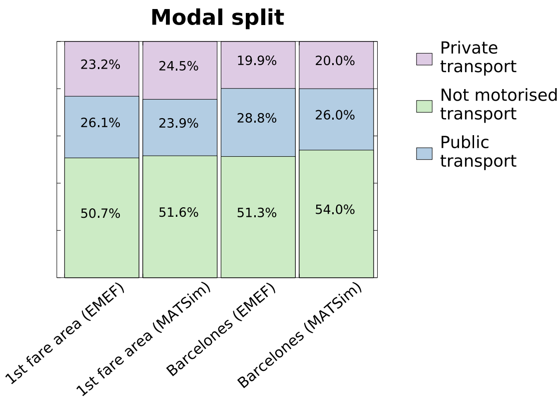

Fig. 4. Comparison between observed and simulated modal split for the Metropolitan area and the Barcelonès (inner shire of Barcelona).

Table 1
Parameter values.

Parameter	Value
β_{dur}	6
$C_{mode(car)}$	− 13
$C_{mode(walk)}$	0
$C_{mode(bike)}$	− 22
$C_{mode(publictransport)}$	− 4
$\beta_{trav,mode}$	− 6 for all modes
$\beta_{d,mode}$	0 for all modes
$\gamma_{d,car}$	-7.7×10^{-5}
$\gamma_{d,mode}$	0 for all modes but car
β_m	1

Table 2
Road counts comparison between estimated vehicles, considering an occupancy factor of 1.2 (lower limit) and an occupancy factor of 1 (upper limit), and official counts.

Road	Observed counts	Simulated counts lower-upper limit
Gran via (Besos)	102,788	89,616–112,020
Guipuscoa	18,940	23,864–29,830
Pont de Potosi	39,435	35,168–43,960
Pg Santa Coloma	17,835	19,456–24,320
Ronda de Dalt/Pota de Nord	78,683	81,416–101,770
Av. Meridiana	109,885	95,784–119,730
Ronda de Dalt/Diagonal	131,159	120,464–150,580
Av Diagonal (Pedralbes)	116,766	79,472–99,340
Gran via (Pl Cerda)	100,546	101,510–126,888
Ronda Litoral (Morrot)	111,548	82,952–103,690
Collblanc (Hospitalet)	32,155	30,920–38,650

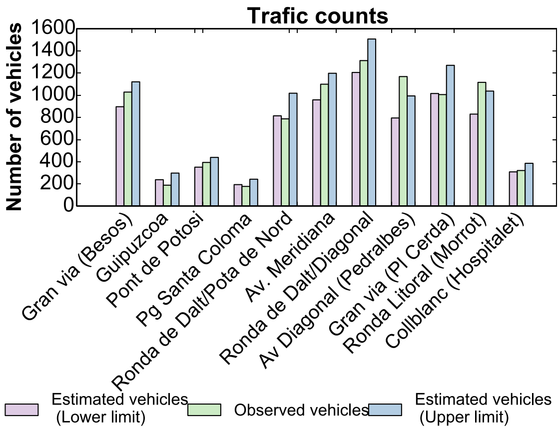

Fig. 5. Comparison between vehicle counts observed and obtained from simulation.

area, the cost is charged in the utility function via the Δm_j described in Eq. (2).

3.2. Policy scenarios

Four different policy options are tested:

1. Fixed congestion rate along the day;
2. Congestion charge applied only during the morning (08:00–10:00) and afternoon (16:00–20:00) rush hours;
3. Congestion charge applied only during the morning peak;
4. Congestion charge applied only during afternoon peak.

All-day congestion charge is expected to affect all kinds of trips, while congestion charge for the peak hours is expected to affect mainly commuting trips. The asymmetric congestion charges for morning or afternoon peak are expected to affect only one direction commuters: congestion charge in the morning peak will mainly affect those commuters travelling from outside to the centre of Barcelona (toll area), while congestion charge applied during the afternoon peak will mainly affect commuters living in the city centre of Barcelona (inside the toll area) and working outside the toll area, since they will have to pay it in their way back home during the afternoon peak.

For the first policy option charges of 2 €, 5 € and 10 € are considered. For the policy options 2–4, only a 10 € charge was tested.

4. Results and discussion

4.1. Calibration and validation results

4.1.1. Calibration

A comparison between the modal split reported by the EMEF and the one obtained after the model calibration for both the first fare zone of the Barcelona metropolitan area and for the Barcelonès are shown in Fig. 4. Observed and simulated car mode shows a

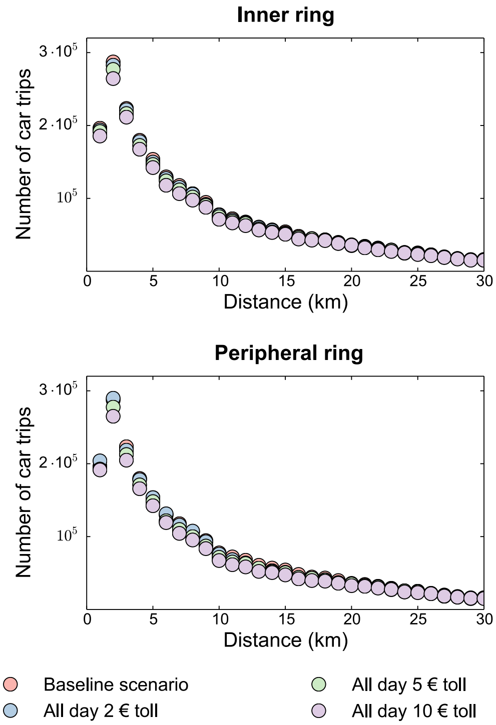

Fig. 6. Number of car trips per travelled distance. (a) Inner toll zone and (b) peripheral toll zone.

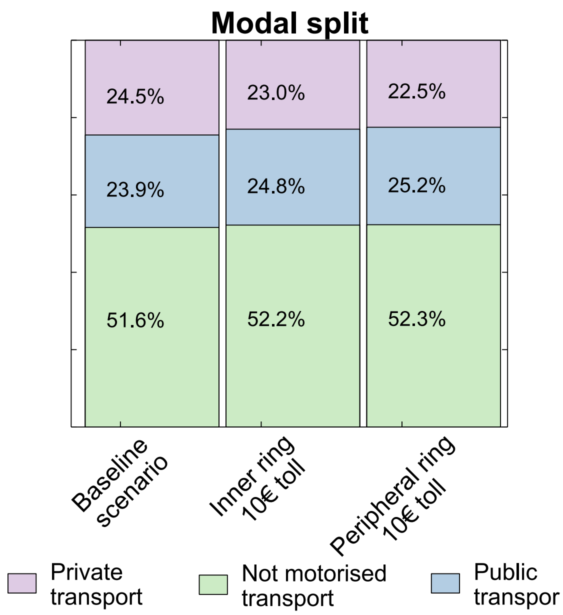

Fig. 7. Comparative of modal split for the region of study before and after the policy implementation for both the inner and the peripheral ring.

difference of less than 1.5%. The parameter values leading to this modal split are reported in Table 1.

4.1.2. Validation

Observed and simulated number of cars passing by the main roads are shown in Table 2 and Fig. 5. Note that traffic counts were not used during the calibration process, i.e., the resulting travel counts from the simulation have not been influenced by the observed ones in any way. We can see that observed vehicle counts of most of the main roads lay between the minimum (when considering an occupancy factor of 1.2) and maximum (when considering an occupancy factor of 1) counts estimated from the simulation. For occupancy factor of 1.25, 9 out of the 11 roads compared in Table 2 present a GEH statistic below 10. The Ronda Litoral and Avenida

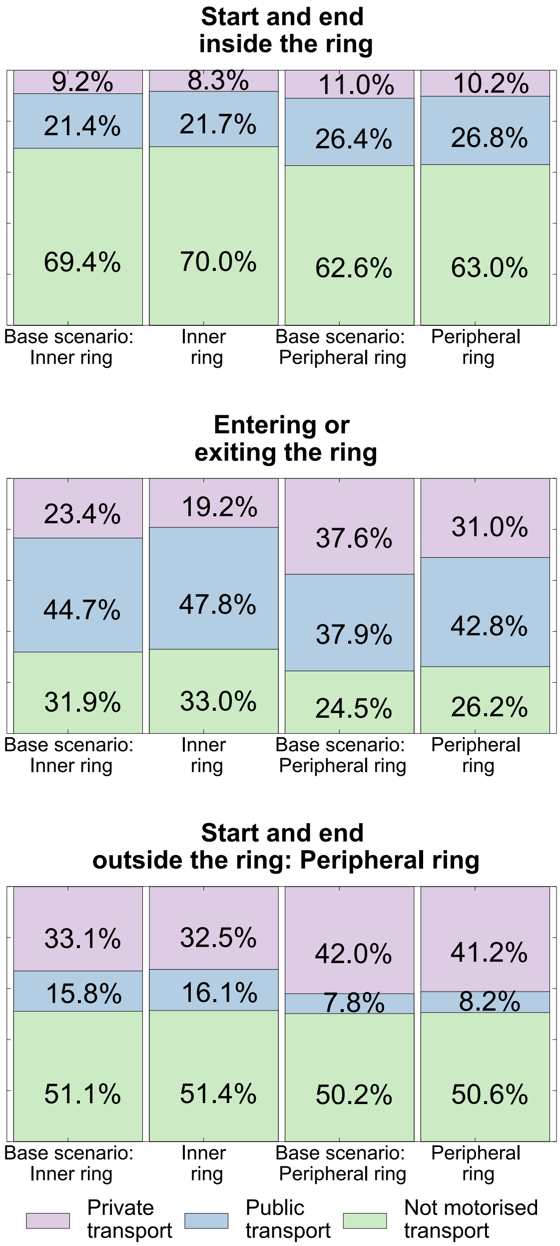

Fig. 8. Modal split for trips starting and ending at different zones for:i (a) Baseline scenario considering the different zones separated by the inner ring; (b) policy applied to the inner toll zone, (c) baseline scenario where the different zones are split by the peripheral ring and (d) policy applied for the peripheral toll zone. For an all day 10 € charge.

Diagonal are the two outliers having more observed vehicles than the maximum estimated. A reason for this is that we are not considering freight and passing by traffic. Ronda Litoral is one of the main access for freight traffic to the premisses of the port of Barcelona and to Mercabarna, the main logistic centre of the city. Avenida Diagonal is the main road crossing the city from West to East and hence it has a lot of passing by traffic.

4.2. *Policy results*

Results are analysed at two different levels: at an aggregated level, e.g., total or average travel time, modal split, total number of car trips, etc., and from a user centric perspective, e.g., the residents most affected by the different levels of the policy application.

4.2.1. *All-day toll charge aggregated results*

The most relevant results from the simulation of the different scenarios are discussed here. Details and numerical values of the

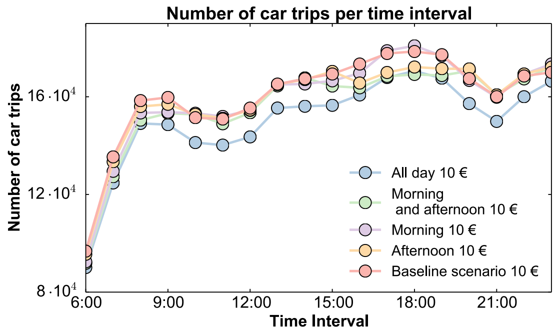

Fig. 9. Detail from 6:00 to 22:00 h of the number of car trips per time interval for different timing toll schemes.

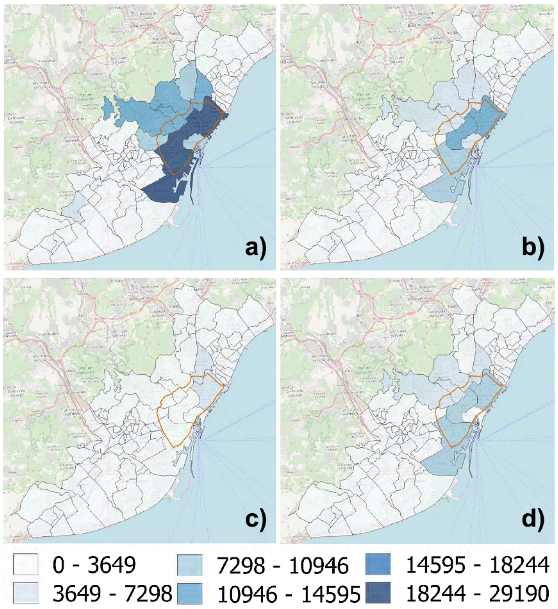

Fig. 10. Number of residents entering by car the area surrounded by the inner ring, before any policy is applied, at: (a) any time of the day; (b) only during the morning and the afternoon peaks; (c) during the morning peak and (d) during the afternoon peak. The maps are generated using the standard layout of Open Street Maps.

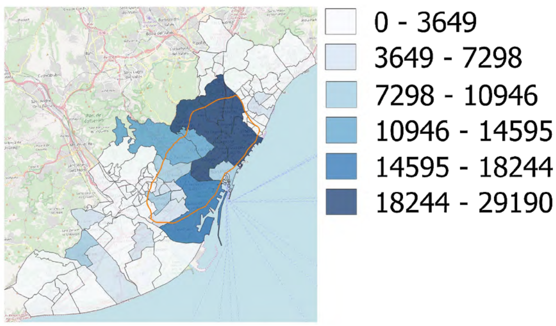

Fig. 11. Number of residents entering by car the area surrounded by the peripheral ring, before any policy is applied. The maps are generated using the standard layout of Open Street Maps.

aggregated results for all the different scenarios can be found at Tables 3 and 4 in Appendix A.

For both inner and peripheral rings, results show that the number of car trips decreases with a growing toll price. Car trips reduction also intensifies with the area covered by the ring toll: the bigger the area the less car trips are observed (see Fig. 6). A reduction of 1.2%, 3.2%, 6% of car trips for the inner ring and of 1.7%, 4.4%, 8% for the peripheral ring are observed for 2 €, 5 € and 10 € toll charge, respectively. Car use decrease occurs mainly for short distance trips (Fig. 6). This may be due to a low connectivity of

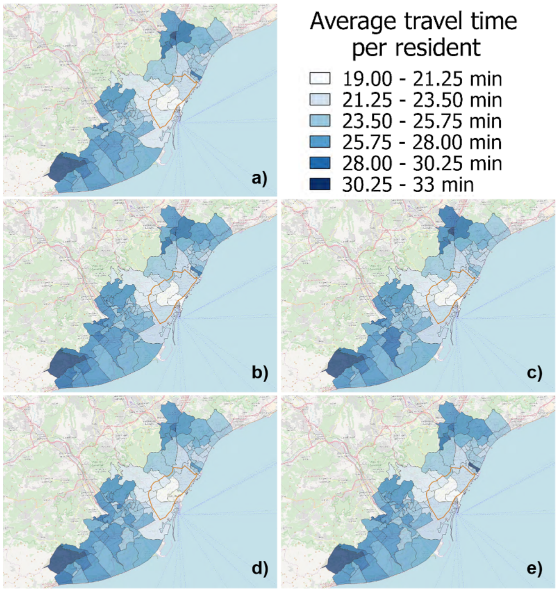

Fig. 12. Average travelled time per district (a) Baseline scenario, (b) 10 € all day toll, (c) 10 € morning and afternoon toll, (d) 10 € morning toll and (e) 10 € afternoon toll. The maps are generated using the standard layout of Open Street Maps.

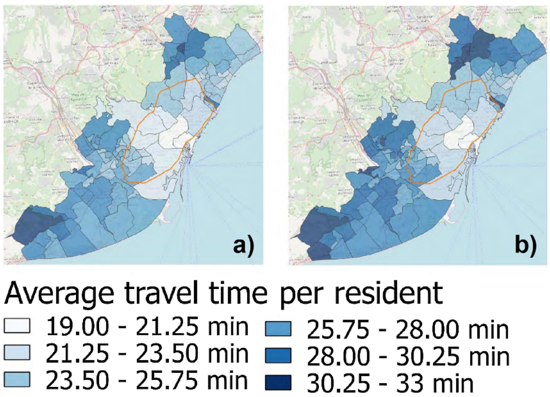

Fig. 13. Average travelled time per district. (a) Baseline scenario, (b) 10 € all day toll. The maps are generated using the standard layout of Open Street Maps.

the public transport at long distances. If the public transport is not optimum, driving is still a good option even with a tolling scheme. We discuss next only the results of the 10 € charge (for the results of the other charges see Tables 4 and 3 in Appendix A). Car use decrease not only for trips entering the toll zone but also for trips exiting the zone or trips starting and ending inside or outside the toll zone. As expected, the higher reduction occurred for trips entering and exiting the toll zone with 18% less cars crossing the ring toll in any direction for both inner and peripheral rings cases. A reduction of 9.8% for the inner ring and of 7% for the peripheral ring resulted for car trips starting and ending inside the toll zone. For car trips starting and ending outside the toll zone, a reduction of 1.8% and of 2.5% is observed for the inner and peripheral ring tolls respectively (Tables 4 and 3).

As the number of total trips by the simulated agents is conserved, the reduction of car trips implies an increase in the use of other modes of transport. Figs. 7 and 8 show the resulting modal split before and after the 10 € charge application. As can be seen on Fig. 7, most of the car trips have been transferred to public transport. However, this transfer depends on the area where the trips start and end (Fig. 8). For trips starting and ending inside the ring, car trips are almost equally transferred to soft modes (walk and bike) and public transport with a slight preference for soft modes. Car trips crossing the ring in any direction are transferred mainly to public transport. Car trips starting and ending outside the ring are evenly transferred to public transport and soft modes with a slight preference for soft modes in the case of the inner ring and for public transport in the case of the peripheral ring.

Despite the decrease of car traffic, the resulting total average travel time per trip and average travel time for car trips are not considerably modified. The average travel time for car trips is reduced by 25 s, which corresponds to less than 3% of the car trip travel time for the baseline scenario. For the inner ring, the higher car trip travel time reduction is observed for trip lengths between 16 and 25 km showing a time reduction of around 6% (1–2 minutes) and between 70 and 73 km with a reduction of around 7–8%

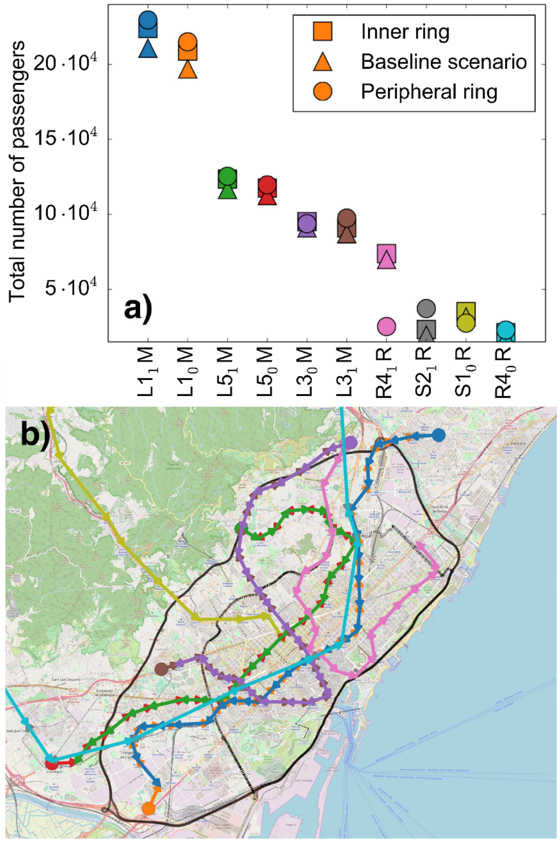

Fig. 14. In (a), total number of passengers per line for the train and metro in the baseline scenario (△), the inner ring (□) and the peripheral ring 10 € scenarios (○). The lines selected are the ten with the largest change in absolute numbers due to the implementation of the toll policy. Their codes are composed of the number, the direction in subscript (0 or 1) and a letter M for metro or R for train. In (b), map of the metropolitan area displaying the lines. The arrows point to the line direction, while the large circle is the first station. The colour code is maintained in both panels. The maps are generated using the standard layout of Open Street Maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(4.5–6.5 minutes). In contrast to the inner ring, for the peripheral ring a car trip travel time is increased by around 6% for trips of lengths between 19 and 26 km. This may be due to trips surrounding the city by the Rondas, which are more congested after the toll implementation. Car travellers that used to cross the city are forced to surround it to avoid the toll charge imposing more congestion to the roads surrounding the toll area. In addition, in the peripheral ring scenario trips of length between 70 and 73 km show the higher travel time reduction with a reduction of around 6–7%. The average travel time per trip for all lengths has slightly increased, a bit more than one minute, which corresponds to 5% over the baseline scenario's average travel time. The higher travel time increment is observed for trips of lengths between 12 and 36 km showing an increment of 4–8 minutes (corresponding to 10–20% of the baseline scenario travel time). This may be due to the modal change, since alternative modes are less time efficient than cars.

4.2.2. Aggregated results for different timing schemes

It should be recalled that for the different timing schemes only the 10€ charge was tested. In terms of net number of car trips the all day charge scheme reports the highest reduction compared with those applied in the morning and afternoon peaks or only in one of them for both inner and peripheral toll rings. From now on we will only discuss in detail the results of the inner ring toll, however the same trend is observed for the results of the peripheral ring toll as can be seen on Table 3. Total car trips reduction for the morning and afternoon toll charge amounts to 2.24%, very close to that obtained for the all day 5€ charge (showed in Section 4.2.1). Similarly, afternoon (morning) toll charge results in a car trip reduction of 1% (0.8%) which is very similar to that of the all day 2€ charge. This means that the same total number of car trips reduction can be obtained with different combinations of charging times and prices. In terms of revenues raised by the policy application the all day policies generate a higher revenue. The all day 5€ charge scheme report a 33% more revenues raised than the morning and afternoon charge scheme. And the all day 2€ charge scheme raise 28% (20%) more revenues than the morning(afternoon) 10€ charge scheme.

Beyond the number of car trips and the revenues raised, the toll policies applied at specific times have some specificities. As a general statement, the effect of toll charge applied at specific times of the day goes beyond the time at which it is applied. In Fig. 9, one can observe that car reduction occurs even for those times where no charge is applied. The toll charge applied during the morning

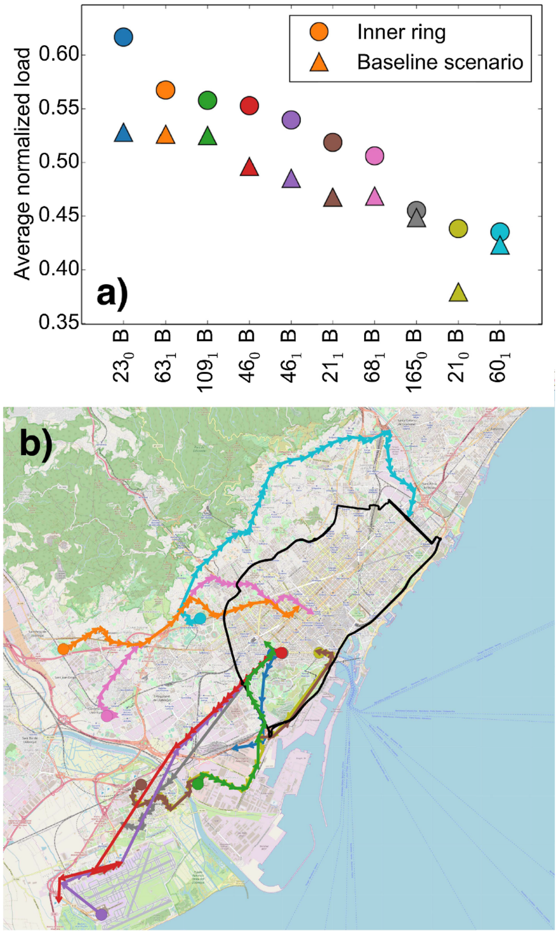

Fig. 15. In (a), average normalised load per line in the baseline scenario (△) and the inner ring 10 € scenario (◦). The lines selected are the ten with the largest change after the implementation of the toll policy. Their codes are composed of the number, the direction in subscript (0 or 1) and a letter B for bus. In (b), map of the metropolitan area displaying the lines. The arrows point to the line direction, while the circle corresponds the first station. The colour code is maintained in both panels. The maps are generated using the standard layout of Open Street Maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and afternoon peak (form 08:00–10:00 to 16:00–20:00) reduces the car traffic at rush hours not only by reducing the net number of car trips but also by shifting the time at which some of them occur. The dark blue curve on Fig. 9 shows that the number of car trips at 8:00 h is considerably reduced at the price of being slightly increased at a later time (10:00 h) compared with the baseline scenario (red curve). A considerable reduction of trips is also observed between 14:00 and 15:00, before the afternoon charge is applied. This may correspond to return trips of those that decided to leave the car at home to avoid the morning charge or to travellers that decide to leave the car at home in the morning to avoid paying the afternoon charge in their return trip. Some car trips have been shifted from the afternoon peak to just after the toll charges ends, 20:00 h. Similar effects are observed for only morning (light blue curve on Fig. 9) and only afternoon (purple curve) toll charges. For the first one a net reduction of car trips with respect to the baseline scenario is observed not only during the charging time but also in the early afternoon, 14:00–16:00, supporting the hypothesis that these trips corresponds to return trips of users who left the car at home to avoid the morning toll. Also some of the trips occurring at the morning peak are shifted to slightly after the toll timing, 11:00 h. For the afternoon toll, as expected, car trips at the afternoon peak are reduced with respect to the baseline scenario. Most of these trips were shifted to other modes, while a smaller amount were still performed by car but at a later time, once the toll disappears (see the small car trip increment with respect to the baseline scenario occurring just after 20:00 h for the purple curve on Fig. 9).

4.2.3. Results from a resident-centric perspective

The way a toll charge affects residents of different areas is also influenced by the time at which the toll is applied and by the area covered by the ring. Figs. 10 and 11 show the districts that will result more affected by the policy application, in terms of number of residents that usually, before any charge is applied, cross the ring toll by car. It can be seen in Figs. 10a and 11 that the application of an all day toll policy virtually affects all districts intersecting the toll area. This is also the case, although to a lesser extent, for the application of the toll at the morning and afternoon peaks (Fig. 10b) or at the afternoon peak (Fig. 10d) mainly affecting most of the

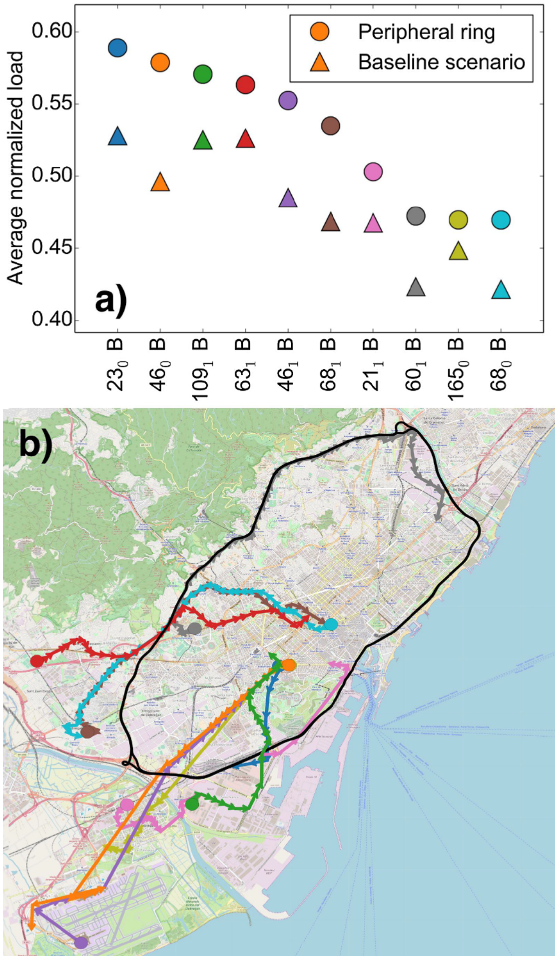

Fig. 16. In (a), average normalised load per line in the baseline scenario (△) and the peripheral ring 10 € scenario (◦). The lines selected are the ten with the largest change after the implementation of the toll policy. Their codes are composed of the number, the direction in subscript (0 or 1) and a letter B for bus. In (b), map of the metropolitan area displaying the lines. The arrows point to the line direction, while the circle corresponds the first station. The colour code is maintained in both panels. The maps are generated using the standard layout of Open Street Maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

districts intersecting the ring. In a qualitatively different way, the case of applying the toll only during the morning peak (Fig. 10c) would mostly affect the residents of a couple of districts intersecting the toll area.

As discussed in Section 4.2.2, the average travel time is not reduced by the application of the policy. On the contrary, it increases slightly. However, this increment does not affect in the same way residents of the different areas. In terms of travel times, the districts intersecting the inner ring toll seem to be less affected by the policy. The average travel time per district, calculated as the average travel time for those trips performed by the district residents from any origin to any destination, remains unchanged before and after the policy application regardless the timing scheme (Fig. 12) and the coverage area of the toll zone (Fig. 13) for these districts. An explanation may be that, although most of the residents of these zones were "forced" to change the transport mode, these districts are well connected by public transport infrastructure. Still, the coverage area of the toll zone and, to a lesser extent, the timing scheme determine which districts are more affected. For the inner ring: all day, morning and afternoon and only morning tolls seem to affect more districts than the only afternoon toll charge (from the comparison of Fig. 12 a with b, c and d). The application of the policy at a larger area, the peripheral ring, affects a greater number of districts including those intersecting the ring toll (comparison of Fig. 13a and b). This may be due to the lower public transport services for areas distant from the city centre.

4.2.4. Impact on the public transport network

The reduction of car trips is associated to a growth in the demand for public transport. Metro lines are the ones suffering the largest passenger increase after the policy application. For example, in absolute numbers the line most impacted is line $L1$ from Hospital de Bellvitge (West of the city) to Fondo (East) in both directions, which sees its passengers increased in more than 11,000 (>6%) in each direction (Fig. 14). In relative numbers, there are lines like the rail R4 going from Sant Vicenç de Calders to Manresa that in both directions would see its demand enhanced by 19% in the case of the inner ring toll and over 29% with the peripheral one.

Despite these strong increases, the train and metro lines are not expected to get congested thanks to their high frequency and the high capacity of every vehicle.

To identify which are the most impacted lines and hence need to be reinforced, we focus next on the ratio of load (demand) over capacity. The lines are divided in segments between subsequent stops, and for each segment i we define the normalised load as

$$\ell_i = \frac{\text{Passengers per day in } i}{\text{Vehicles per day} \times \text{Capacity of each vehicle}}. \tag{3}$$

The load is then averaged over all the segments of the line to obtain $\langle \ell \rangle$. This metric singles out the lines running over capacity (although since we are taking daily totals it lacks fine temporal resolution). As a transport manager, the most critical lines are those with largest $\langle \ell \rangle$, especially those close to one. We calculate next the difference between the normalised load of lines in the baseline and the tolled scenarios.

We studied the effects of the toll policies in detail for all the scenarios but we will focus next on the most interesting results: those for the 10 € all day toll. Figs. 15 and 16 show the ten lines with highest $\langle \ell \rangle$ in the network after the toll policy has been applied for both rings. We can see that the ten lines correspond to bus lines (there is no rail or metro). The next fact to highlight is the similarity between the results for both toll scenarios. All the lines connect the centre with the West side of the city. This stresses the high dependency of the West side of Barcelona on the public transport system. Finally, as common result, we find that the lines that suffer the highest increase in its load are those connecting to the airport.

In the case of the inner ring (Fig. 15), we observe that only three lines out of ten do not suffer a significant change after the policy application. One of them (line 60 in Fig. 15) does not cross the ring, while the other two have a high overlap with other more affected lines. In the case of the peripheral ring (Fig. 16), we find in the top ranking nearly the same lines as for the inner ring. However, the increase of load compared to the inner ring scheme is significant. One of the most interesting cases is the bus line 60 in direction North-East (code 60_1), which, unlike in the inner scheme, crosses the ring in the peripheral scheme. This difference causes an increase of 25% of the load in comparison with the scenario with the inner ring. Also note that the line 165 in direction South, which connects with the West side of the city, emerges in this case in the top ten ranking. Regarding the lines that cross both toll schemes, a significant increase in comparison to the inner ring means that the destinations or origins are located in the region between both toll areas.

5. Conclusions

5.1. Model implementation

The results obtained for the calibration and validation process support the idea that alternative data sources can be used to meet the data needs of agent-based models and confirm the quality of the activity-travel diaries obtained from mobile phone data. In this context, it is important to stress the good match obtained for the road counts even for a very simple and naif calibration based only on aggregated modal split values. Agent-based models, in this case MATSim, allow us to look at the effects of the policy implementation at an aggregated level but also from a disaggregated, passenger-centric perspective. This includes the observation of side and memory effects not contemplated by aggregated models. For example, a trip going from A to B in MATSim is not seen as a single trip but as part of a full day plan. A person going from B to C cannot do it by car if it has not arrived at B by car from his/her original position A. Similarly, the agent cannot return home by public transport if he/she has arrived at the previous position by car, i.e., all the decisions of travel mode are taken in a single full day plan. This feature may have some drawbacks in exceptional situations, but it reflects the practice in daily mobility. A policy affecting trips from A to B may have different effects for people performing the same A-B trip depending on their residence place or on the moment of the day at which they need to travel. Therefore, policies applied to the route A-B may have an impact in very different areas of the city, not necessarily only the local ones. The activity-based agent-based nature of MATSim allows such effects to be captured and quantified.

5.2. Cordon toll policy

To illustrate these abstract ideas, we have studied the implementation of a toll ring for cars entering in the city of Barcelona. The implementation of the cordon toll policy has positive effects in terms of car use reduction, which may directly affect the level of contaminants and greenhouse gas emissions due to private car usage. The main insights gained from the simulation are the following:

1. The intensity of cars trips reduction depends on the toll price and on the area enclosed by the ring toll.
2. All-day charge schemes seem to be more effective (in terms of car reduction) than charges applied to only specific hours of the day. However, playing with the time of the toll may help to tune the effect of the policy on residents of different areas and shift the traffic peaks.
3. In terms of number of residents entering the toll zone by car before the policy application, the most affected districts are those intersecting the toll area. In terms of travel time, the most affected districts are those located farther from the city centre, especially for the case of a toll applied to the peripheral ring, which indicate a bad alternative transport option for peripheral areas.

4. The effects of the cordon toll policy go beyond the tolled zone and the charge period, reducing car trips not only crossing the toll cordon but also modifying those within and outside the toll zone and at travel times different from those of toll application.

The cordon toll policy does not seem to improve travel times by car in a significant manner, while the average travel time actually increases due to modal shift. This effect could be compensated by earmarking the revenues generated by the congestion pricing scheme for the improvement of public transport. In this sense, some preliminary analysis has been made to see the public transport lines that have received the highest impact (in terms of load raise) as a consequence of the cordon toll policy application. Recently, more elaborated toll schemes charging higher prices for crossing more congested areas have been proposed (Solé-Ribalta et al., 2018). This idea requires heavier information processing capability from the managing authority, although it is today technically possible. It would be interesting as a future development to explore with techniques similar to the one used here the impact of these more involved toll schemes on public transportation and how the demand may migrate between modes.

Acknowledgement

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Appendix A. Tables

Aggregated results for both inner and peripheral rings for all toll charges and time schemes tested are presented in the Tables below (see Tables 3 and 4).

Table 3
Aggregated results for the peripheral ring.

Peripheral ring	Baseline scenario	Toll 2 € all day	Toll 5 € all day	Toll 10 € all day	Toll 10 € morning and afternoon	Toll 10 € morning	Toll 10 € afternoon
Total number of trips	10,368,560	10,350,070	10,368,850	10,366,690	10,370,410	10,369,390	10,370,040
Total number of car trips	2,541,700	2,497,220	2,427,580	2,336,560	2,468,770	2,513,920	2,506,770
Total travel distance (km)	55,471,436	55,568,329	55,578,228	55,784,940	55,700,637	55,574,185	55,585,917
Average travel distance per trip (km)	5.35	5.37	5.38	5.38	5.36	5.37	5.36
Total travel distance by car (km)	28,954,043 s	28,118,672	28,026,161	27,101,526	28,389,794	28,748,463	28,645,363
Average travel distance by car	11,392	11,260	11,545	11,599	11.500	11.436	11.427
Average travel time	00:23:09	00:24:17	00:23:45	00:24:17	00:24:00	00:23:43	00:23:45
Average travel time by car	00:14:15	00:13:26	00:14:25	00:14:41	00:14:49	00:14:31	00:14:24
Number of users paying toll	0	378,200	350,490	309,470	122,440	35,070	94,030
Number of trips paying toll	0	504,040	442,750	382,690	140,990	38,510	102,780
Car trips in the toll zone	604,350	671,390	562,120	582,37	585,300	596,940	598,300
Average travel time for trips in the toll zone	00:18:57	00:20:07	00:19:05	00:19:10	00:19:05	00:19:00	00:19:02
Average travel time for car trips in the toll zone	00:04:49	00:05:05	00:04:51	00:04:52	00:04:55	00:04:54	00:04:54
Car trips entering the toll zone	396,040	366,270	356,220	325,350	367,170	381,680	379,780
Average travel time for trips entering the toll zone	00:33:45	00:35:34	00:36:44	00:38:53	00:36:32	00:35:2	00:35:13
Average travel time for car trips entering the toll zone	00:19:54	00:19:42	00:23:06	00:25:14	00:24:15	00:21:55	00:22:5
Car trips exiting the toll zone	396,490	367,390	357,710	327,400	368,340	382,920	381,150
Average travel time for trips exiting the toll zone	00:34:13	00:36:22	00:36:08	00:38:03	00:35:46	00:34:50	00:35:2
Average travel time for car trips exiting the toll zone	00:19:59	00:19:05	00:19:37	00:20:19	00:20:24	00:19:51	00:19:59
Car trips occurring outside the toll zone	1,144,820	1,092,170	1,131,280	1,121,690	1,107,330	1,097,980	1,096,560
Average travel time for trips occurring outside the toll zone	00:24:41	00:24:52	00:36:22	00:25:00	00:25:05	00:24:00	00:25:02
Average travel time for car trips occurring outside the toll zone	00:15:18	00:14:33	00:14:58	00:14:55	00:15:3	00:15:16	00:14:57

Table 4
Aggregated results for the inner ring.

Inner Ring	Baseline scenario	Toll 2 € all day	Toll 5 € all day	Toll 10 € all day	Toll 10 € morning and afternoon	Toll 10 € morning	Toll 10 € afternoon
Total number of trips	10,368,560	10,371,190	10,368,940	10,368,170	10,369,640	10,372,050	10,369,910
Total number of car trips	2,541,700	2,510,470	2,458,000	2,384,000	2,484,540	2,521,250	2,515,220
Total travel distance (km)	55,471,436	55,562,930	55,585,261	55,596,113	55,543,099	55,548,521	55,503,081
Average travel distance per trip (km)	5.35	5.36	5.36	5.36	5.36	5.36	5.35
Total travel distance by car (km)	28,954,043	28,743,170	28,275,243	27,711,234	28,521,102	28,799,604	28,736,127
Average travel distance by car mode per trip (km)	11,392	11,449	11,503	11,624	11,479	11,423	11,425
Average travel time per trip	00:23:09	00:23:17	00:23:28	00:23:43	00:23:40	00:23:34	00:23:36
Average travel time per trip by car	00:14:15	00:14:14	00:14:04	00:14:04	00:14:02	00:14:10	00:14:10
Average travel time per trip by car in the morning peak	00:15:46	00:15:41	00:15:39	00:15:36	00:15:42	00:15:38	00:15:51
Average travel time per trip by car mode in the afternoon peak	00:16:23	00:16:21	00:15:58	00:16:00	00:15:32	00:16:19	00:15:37
Number of users paying toll	0	319,300	292,260	264,430	112,390	57,970	63,560
Number of trips paying toll	0	411,810	363,410	322,270	121,820	59,110	65,440
Car trips occurring within the toll zone	254,510	248,190	242,580	229,470	244,400	251,150	249,450
Average travel time for within toll zone trips	00:15:37	00:15:40	00:15:44	00:15:47	00:15:42	00:15:40	00:15:41
Average travel time for car trips within the toll zone	00:03:24	00:03:24	00:03:23	00:03:23	00:03:25	00:03:23	00:03:24
Car trips entering the toll zone	276,910	264,620	247,640	225,880	257,340	267,990	266,720
Average travel time for trips entering the toll zone	00:30:11	00:30:41	00:31:15	00:32:11	00:30:50	00:30:31	00:30:29
Average travel time for car trips entering the toll zone	00:17:18	00:17:26	00:17:28	00:17:45	00:16:59	00:17:26	00:16:52
Car trips exiting in the toll zone	277,200	265,160	248,410	227,000	257,660	268,670	267,360
Average travel time for trips exiting the toll zone	00:30:33	00:30:57	00:31:34	00:32:34	00:31:19	00:30:49	00:30:58
Average travel time for car trips exiting the toll zone	00:17:33	00:17:34	00:17:23	00:17:33	00:17:28	00:17:23	00:17:40
Car trips occurring outside the toll zone	1,733,080	1,732,500	1,719,370	1,701,650	1,725,140	1,733,440	1,731,690
Average travel time for trips occurring outside the toll zone	00:24:35	00:24:36	00:24:39	00:24:41	00:24:33	00:24:33	00:24:34

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