Enhanced Passenger Characterisation through the Fusion of Mobile Phone Records and Airport Surveys

A case study of Madrid-Barajas Airport

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***Abstract*— This work presents a methodology to extract a series of passenger indicators from anonymized mobile phone records, with the aim of improving the available knowledge on passenger needs, behaviors and characteristics. The methodology is applied to study passenger behavior at Madrid Barajas Airport, and results are validated against the information provided by passenger surveys. The paper also shows how anonymized mobile phone records can help complement and enrich the information provided by passenger surveys regarding airport catchment areas, intermodality and passenger behavior. Finally, we discuss how the information extracted from the fusion of mobile phone records and passenger surveys can be leveraged for the modelling and evaluation of novel intermodal solutions.**

Keywords- passenger behaviour, intermodality, airport demand analysis; mobile phone records.

I. Introduction

The European high-level vision on transport depicts a passenger-centric system that takes travelers from their origin to their destination in a seamless, efficient, predictable, environmentally-friendly and resilient manner [1]. In line with this vision, the report 'Flightpath 2050 - Europe's Vision for Aviation' envisages an air transport system thoroughly integrated with other transport modes [2]. The airport of the future is expected to become a multimodal connection platform, creating the conditions for travelers to reach their destination by the most efficient and sustainable combination of modes.

Achieving this vision calls for enhanced modal integration not only in terms of physical infrastructure, but also of business models, operational processes and information systems. The development of a multimodal, passenger-centric air transport system requires enhanced situational awareness of both the status of the airport processes, the ground transport system and the door-to-door passenger flows. In recent years, different studies have been carried out to explore how the digital traces generated by personal mobile devices, in particular mobile phone records, can be exploited to improve the understanding of passenger behavior, measure door-to-door travel times and characterize airport catchment areas ([3], [4]). These studies also identified a number of challenges that must be faced when using mobile phone records as a primary data source for airport demand analysis: (i) the analysis of international trips, which is not trivial due to the national spatial scope of mobile phone networks [5]; (ii) the distinction between different airport users, namely arriving and departing passengers, transfer passengers, workers and short-term visitors; (iii) the full characterization of passenger tours, including access and egress modes, stay durations and trip purposes. This paper presents a methodology that addresses these challenges by blending the information extracted from mobile phone records with travel surveys and passenger counts. This improved methodology has been evaluated in the Madrid-Barajas Airport.

The rest of the paper is organized as follows: Section II reviews how airport intermodality has been tackled in the literature and discusses the current approaches for monitoring passenger behavior; Section III describes the case study selected to develop and evaluate the proposed methodology; Section IV describes the datasets used in the study and the algorithms used for data fusion and analysis; Section V presents the main results of the case study; Section VI presents the main conclusions of the study and discusses future research directions.

II. Intermodality and Air Transport

Door-to-door trips that involve air transport are intermodal by nature. In the past decades, the airport access paradigm has progressively changed from the encouragement of the use of private car, based on building parking facilities and links with the main road system, to the integration of airports with the public transport system [6]. More recently, the integration of airports with the high-speed rail (HSR) network has gained importance: HSR is seen as a candidate for complementing air transport by absorbing part of the demand for short-haul flights, releasing airport capacity that can be used for long-haul flights [7]. Examples of this integration are the German AIRail service, born from the collaboration between Lufthansa, Fraport and Deustche Bahn, and the Air France-SNCF cooperation for guaranteeing air-rail connections in case of delays. However, despite all these efforts, taxi and private car still play a dominant role in airport access [8].

In order to develop and deploy solutions that facilitate the sustainable integration of airports with the ground transport network, a detailed characterization of passenger flows is needed. Traditionally, this information has been obtained through passenger surveys, such as those carried out at airports (e.g. UK CAA surveys, AENA EMMA surveys) and other stakeholders (airlines, IATA, national statistical offices, etc.). However, surveys suffer from several drawbacks: they are expensive, they need to be planned in advance, which prevents the study of the system during disruptions, and they need to be carefully designed to keep a balance between the duration of the survey (and therefore the amount of information obtained) and the willingness to answer of the passenger. In addition, surveys are most often conducted on departing passengers, while they wait in the boarding area, thus not capturing the behavior of arriving passengers and passengers that have short connecting times and cannot stop to answer a survey because they risk missing their flight. Passenger surveys are typically used to collect information about the flight (destination, hour, if it is a connection or not), the access to the airport (mode of access, time of arrival to the airport, ground origin of the trip) and the passenger profile (business/leisure, place of residence, sociodemographic characteristics, etc.). Passenger surveys are carried out by airports, airlines, national statistical offices and international organizations.

To fill the gaps present in traditional data collection methods, a number of research projects have recently addressed the analysis of data generated by personal mobile devices to extract insights about passenger behavior. This was the approach taken by the SESAR's BigData4ATM project, which developed a set of methodologies to analyze mobile phone records in order to analyze airport catchment areas, study the impact of airport accessibility on air transport demand, and measure the time spent by the passengers on each stage of the door-to-door trip ([3],[4],[5]). Similar work has been carried out in the US, focusing on the use of data from mobile devices to study different passenger-centric performance indicators ([9], [10]).

III. Case Study

In this communication we present a case study of the use of mobile phone data for the characterization of short-term visitors, workers and passengers arriving at/departing from the Adolfo Suárez Madrid-Barajas airport. The Madrid-Barajas is the main Spanish airport in terms of passenger traffic, cargo and aircraft movements. During 2018, it had more than 58 million passengers, being the 6th busiest airport in Europe. The airport operator, AENA, conducts periodic passenger surveys. However, these surveys present some additional shortcomings to those identified in section II. First, due to the large affluence to the airport, it is difficult to cover all possible passenger types and seasons while also keeping a reasonable budget. In addition, these surveys are made only to passengers that depart from the airport, which might introduce some biases in asymmetric flows. Also, limited information is available on the activity of people visiting the airport for a short period of time (e.g., relatives accompanying travelers before they leave) and airport workers, which are also users of the airport ground access network and are out of the scope of the survey.

The main goal of the proposed case study was to develop a methodology that could complement the survey methodology, filling some of the main gaps identified. Anonymized mobile phone records were used to extract and analyze the following aspects:

- Point-to-point trips: ground origin and destination, long distance access and egress modes, flight departure and arrival time, arrival and departure time to/from the airport.
- Transfer trips: origin and destination airports, arrival and departure times to/from the airport.
- Passenger tours: characterization of the flight as a go or return trip, duration of the stay and purpose of the tour.
- Passenger profiling:
    - For Spanish passengers: age, gender, home location.
    - For foreign passengers: nationality.
- Workers and short-term visitors: presence volumes per day of the week, time of the day, home location, and location within the airport.

These aspects were analyzed for two different weeks corresponding to the summer and winter seasons: 7th-13th June 2018 and 14th-20th November 2018.

IV. Data and Methodology

A. Datasets

1) Mobile phone records. The authors have a data provision agreement with Orange Spain, through which continuous access to anonymized Call Detail Records (CDRs) is granted. Orange is currently the second lagest Mobile Network Operator (MNO) in Spain, with a market share of more than 27% and several Mobile Virtual Network Operators. The Orange group addresses different socioeconomic population groups, which together with the size of the sample, grants a good representativeness of the whole Spanish population. Call Detail Records are registers generated every time the mobile phone interacts with the mobile phone network due to voice calls, text messages, or data sessions, which are stored by the MNO for billing purposes. In addition, a number of passive events, such as changes between large coverage areas, refreshment of internet connections and pings from apps running in the background are also registered. The availability of these passive events in the dataset used grants an acceptable temporal granularity for determining long distance human mobility, as on average, a register is generated every 20 or 30 minutes for every user that has a data connection opened. For an average day, the dataset used contains more than 1 billion registers, distributed over 16 million of Orange Spain clients and 1 million of roaming-in users. Among other fields, they provide the following basic information:

- An anonymized identifier of the user
- The timestamp of the interaction with the network
- Location information

The mobile phone data used for the study do not provide the exact location of the users, but the cell to which the user is connected when the interaction with the network takes place. Therefore, the location accuracy depends on the density of the mobile network. This typically provides an accuracy of dozens or hundreds of meters in urban environments, and up to several kilometers in rural areas. To refine the estimation of the user position inside these estimated coverage areas, a layer of land use information has been used, which assigns users to different areas served by the same antenna through a probabilistic method that takes into account the type of land use (residential, commercial, industrial, etc.).

One of the innovative aspects of this work is the introduction of registers generated by the users during their stays abroad (roaming-out registers). Since the location of these registers cannot be provided by Orange, as they are generated in antennas that belong to other MNOs, we have used the OpenCellID database (https://opencellid.org/), an open database of mobile network towers. This has allowed us to overcome the inability to identify the origin or the destination of international trips, which was one of the main limitations of previous work conducted with CDRs.

2) Population and tourism official statistics

Census data and official tourism statistics available from the Spanish National Statistics Institute (INE) have been used for sample expansion purposes. Census data have been used as the sampling frame for expanding the sample of Orange customers, while tourism statistics on the total number of foreign visitors to Spain have been used to expand the sample of roaming-in users.

3) Transport supply data

In order to characterize ground access modes from the analysis of mobile phone registers, a set of auxiliary data on thr transport network and the supply of transport services has been used. This includes data on the road and rail networks, the timetables of scheduled transport services to/from the airport, and flight schedules.

4) Passenger surveys

The so-called Aerial Mode Mobility Surveys (EMMA), regularly conducted by AENA across its network, have allowed the extraction of characteristic behavioral patterns of leisure and business travelers, which have in turn been used to to inform the development of traveller classification algorithms. Passenger surveys have also been used to validate the indicators extracted from mobile phone records, by verifying that both data sources provide consistent information.

5) Passenger counts

AENA also provided data on the flights scheduled and operated in Adolfo Suárez Madrid-Barajas airport during the study periods. The dataset includes scheduled and actual operation times, operation status (e.g., cancelled flights), and number of seats and passengers of each flight. These data have been used to adjust the final results to match the total daily passenger volumes.

B. Methodology

The main principles behind the identification of activities and trips through the analysis of anonymized mobile phone records are well documented in the transportation literature ([11],[12],[13],[14]). Based on these general principles, a number of improvements have been implemented to properly capture air transport trips. The main steps of the data analysis methodology are described below.

1) Generation of activity-travel diaries. In this step, the raw mobile phone registers generated by each user are transformed into a diary that contains information about all the trips and activities carried out by the user. In addition, for each trip of the user, the mode of transport and the different legs of the trip are identified. This is done through a two-step process: (i) first, stays are detected. Stays are understood as presence in a defined radius of a certain location for a given amount of time; (ii) then, semantical information is added to convert these stays into either activities or stops. An activity is defined as an interaction with the environment that motivates the displacement of the user (e.g., going to work, going back home, visiting friends), while a stop is defined as a stay that takes place between different legs of a trip (e.g., a stop to refuel during a car trip). More detailed information about the extraction of activity and trip diaries can be found in [15].

2) Selection of airport users sample. Once the activity-travel diaries have been calculated, two relevant sample groups are selected:

- Airport passengers' sample, which consists of all those users whose activity diary includes an air transport leg that starts or finishes in Madrid-Barajas Airport.
- Workers and short-term visitors sample, which consists of all those users whose activity diary has an activity in the airport but not an air transport leg based in Madrid-Barajas airport.

3) Characterisation of passenger trips. Many indicators can be directly extracted from the selected activity-travel diaries (e.g., domestic origin and destination, access and egress modes, D2D travel times…). In addition, a number of complementary analyses have been performed to extract additional features:

- **Analysis of international trips**. In the case of users that are clients of the MNO (typically users with residence in Spain), thanks to the availability of the registers produced during their stays abroad, it is possible to determine the country to/from which the trip has been produced. Additionally, the use of the OpenCellID database has made it possible to identify not only the country of origin/destination, but also the airport. An abroad origin or destination airport is considered as known if any of the abroad records before or after the flight takes place in the proximity of an airport. In the case of roaming-in users (i.e., visitors from outside Spain connecting to Orange network), these registers abroad are not available, so a naïve approach that assigns the trip abroad to the residence country of the mobile phone user has been adopted.

- **Transfer passenger analysis**. By analyzing the air trips detected in the activity diaries, it is possible to link air trips and infer transfers. The following conditions, in line with the definition used by the EMMA surveys for a transfer, were required in order to consider two air trips from the same user as a single trip with a connection in Madrid: (i) there are less than 24 hours of difference between the arrival of the incoming flight and the departure of the departure flight; (ii) the destination airport of the second leg is different from the origin airport of the first leg.
- **Passenger tour characterization**. A tour is defined as a sequence of a home-based trip to a given destination, a set of activities and trips performed at that destination, and a return trip from that destination to the traveler's home place. The activity-travel diaries of each user through several days or weeks allow us to extract, analyze and characterize air transport tours. To do this, trips need to be classified as 'go' or 'return'. This is done based on the following criteria: (1) for residents in Spain, 'go' trips are all outbound abroad trips, all trips to islands if they live in the peninsula, and all outbound intra-peninsular trips if they live in the proximity of the analyzed airport; (2) for foreign visitors, 'go' trips are all inbound abroad trips and those intra-peninsular trips that start in the region where they stay longer during their visit to the country. For both user groups, the remaining cases are labelled as 'return' trips. Once this has been done, 'go' and 'return' trips for the same mobile phone user can be linked together to create a tour, and therefore the duration of the tours can be obtained. Finally, a purpose was assigned to the tours detected depending on the combination of 'go' and 'return' weekdays and the stay duration. Two purposes were considered: business and leisure. The heuristics for labelling tours as 'business tours' have been derived from the survey results, and can be summarized as: (1) tours that start and finish within labor days of the same week, (2) tours that start on Sunday and finish before the following Thursday, (3) tours that start on a labor day and finish before the following Saturday at midday. All tours that do not meet any of these conditions are considered as 'leisure tours'.

4) Sample expansion and adjustment. Mobile phone records provide information about a population sample, and therefore in order to extract meaningful insights it is necessary to expand the sample to the total population. In the case of Orange clients, a longitudinal analysis is carried out to detect the place where the user sleeps more oftern, which is assumed to be their residence place; then, a ratio between the number of mobile phone users with residence in a certain census tract and the number of residents according to official statistics is calculated for every census tract; finally, the ratio is used to replicate the activty-travel diaries of those users, thus expanding the sample to the total Spanish population. A more detailed description of this process can be found in [15] and [16]. This procedure allows us to correct the spatial heterogeneity of Orange's market share. In the case of roaming-in users, a similar procedure is carried out. In this case, the expansion is made by country of residence and traveller type (excursionist or tourist). The traveller type is also obtained from a longitudinal analysis of the user, while the country of residence is assumed to be the same as that of the MNO. Official statistics on the total number of tourists and excursionists per country of origin are used as sampling framework. Finally, the results are adjusted to be compatible with daily passenger inbound and outbound volumes. In the case of domestic relations, the values are adjusted at airport level. In the case of international relations, the values are adjusted at country level.

V. RESULTS AND DISCUSSION

In this section, the main results obtained from mobile phone records are presented and validated against the results from the EMMA surveys carried out for the same period of study.

A. Sample and analysis of abroad trips

In Madrid-Barajas Airport, international flights account for more than 70% of the passenger volume. This makes the analysis of trips to/from abroad crucial for the viability of mobile phone records as primary data source for passenger behavior characterization and analysis. Thanks to the use of abroad registers in the analysis, it was possible to identify the origin/destination country of around 30% of the trips to/from Madrid airport. Given the large initial sample size of mobile phone records, after removing those trips that did not have registers abroad, the sample of mobile phone users was still 81% larger than the sample captured by passenger surveys. From these users, it was possible to determine not only the origin/destination country, but also the airport in 91% of the cases. This is particularly relevant, as according to EMMA surveys, up to 75% of the passengers taking international flights in Madrid-Barajas Airport have as origin or destination a country that is connected with Madrid through more than one airport.

The results of the origin/destination airport identification were validated with the survey data, in terms of distribution of abroad trips by countries and airports. As the survey is only conducted to outbound passengers, the validation was conducted for trips with abroad destination. The correlation at country level shows satisfactory results, with an R^2 above 0.9, revealing that the obtained sample is well-distributed at this level (Figure 1). In addition, the sample for the top 10 destination countries is 127% larger than the one captured by the passenger surveys.

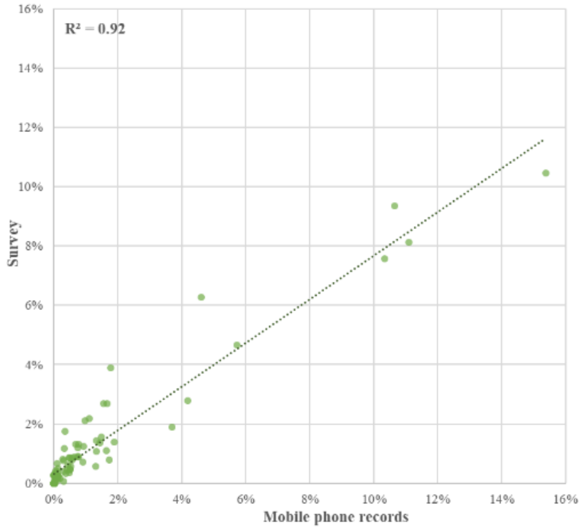

Figure 1. Distribution of observed abroad trips of passengers residing in Spain by destination country

If we look at the correlation at airport level, it decreases (Figure 2). This can be explained by the fact that the quality of the open source cell database used to estimate the position of travelers abroad is lower than the cell plans provided by the MNOs, and in metropolitan areas with more than one airport it does not always provide the level of detail required to accurately determine the airport. As an example, if the airports serving the metropolitan areas of Rome and Milan are aggregated in two groups, the correlation of Italian destinations from Madrid rises from 0.20 to 0.81.

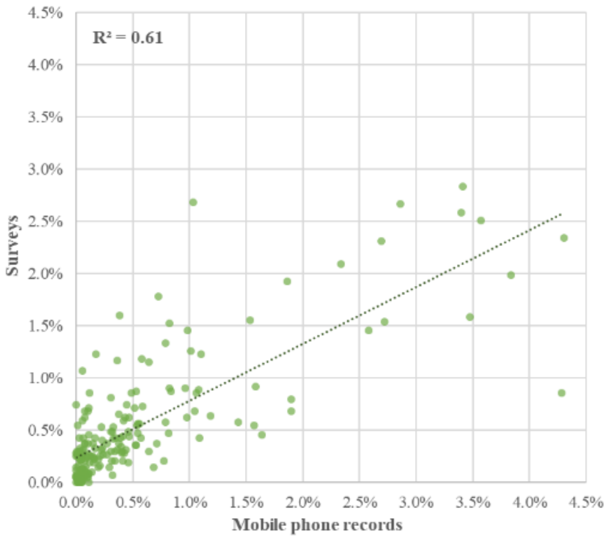

Figure 2. Distribution of observed abroad trips of passengers residing in Spain by destination airport

B. Analysis of catchment areas

Although mobile phone records have already been used to characterize airport catchment areas [4], in this work we take advantage of the availability of the EMMA surveys data to perform a validation of the results. In Figure 3 we present the percentage of Spanish national passengers coming from each NUTS-3 region of Spain obtained from both data sources, showing the consistency between them.

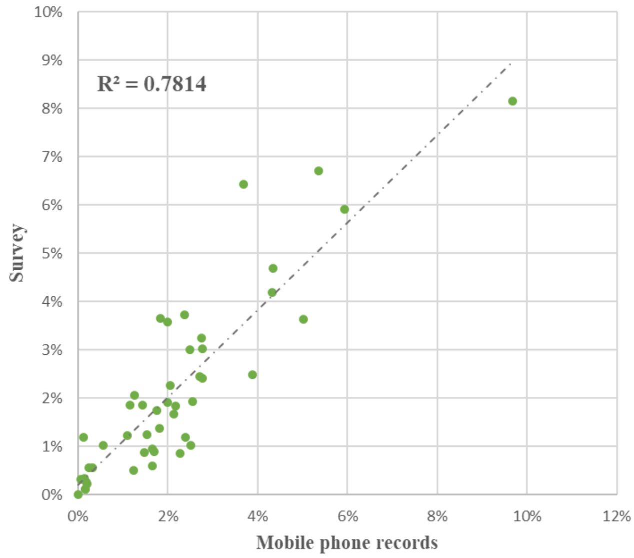

Figure 3. Distribution of origins for the trips that depart from Madrid airport

C. Transfer passenger analysis

In this section we analyze the number of passengers that have made a connection at the Madrid Barajas Airport. In Table I we present the percentage of Spanish passengers departing from Madrid that have taken a domestic connection, differentiating those who come from the Canary/Balearic Islands from those who come from the rest of the Peninsula. In general, the results from the analysis of mobile phone records are consistent with the observations from the surveys, although the results from mobile phone data seem to underestimate the percentage of connecting passengers.

TABLE I. ANALYSIS OF CONNECTION FLIGHTS

	Connection		Point to point	
	Survey	Mobile phone	Survey	Mobile phone
Island	20	14	80	86
Peninsula	39	25	61	75
Total	30	20	70	80

The access mode to Madrid Barajas Airport for all the domestic passengers was also extracted from mobile phone records and validated with the results from the survey. Due to the characteristics of mobile phone records, trip mode could only be determined for medium and long distance trips. For validation purposes, the mode of access to Madrid Barajas was analyzed only for those trips that were originated in a NUTS-3 region different than Madrid and that had an airport connected by air to Madrid. In Figure 4, we present the correlation for the shares of road access obtained from mobile phone records with that observed from the surveys.

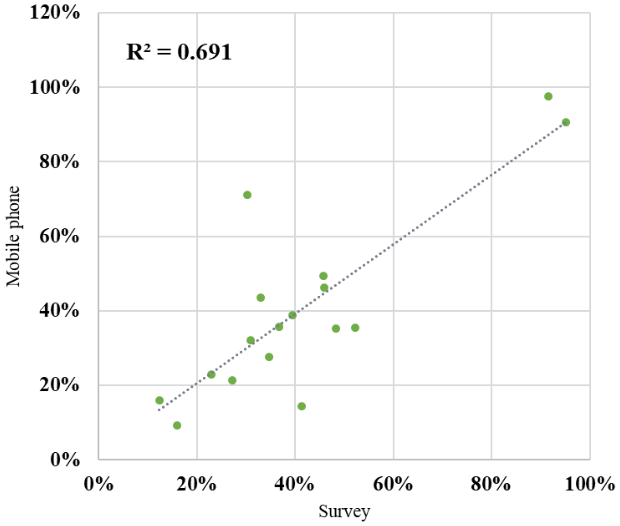

Figure 4. Distribution of the share of road access to the airport for trips that started in other NUTS-3 region than Madrid

The results show that, in most cases, mobile phone records are able to replicate the results provided by the survey, capturing the share of modes for the access to the airport legs, with R2 values of around 0.7. It is interesting to note that road access is one of the most difficult modes to characterize through other data sources as, unlike in the case of air and rail connections, there is no ticketing data that can be used for this purpose.

D. Passenger tour characterization

The first validation carried out related to passenger tour characterization was the share of 'go' trips for different days of the week. This is presented in Figure 5. In general, the results show a very good agreement between both data sources, albeit there are some slight discrepancies for Wednesdays and Sundays, where mobile phone suggests that the share of 'go' trips is a little higher than the results shown by the surveys. In the case of Sundays, both sources show consistency: they present the lowest share of 'go' trips for Sundays. It is for Wednesdays where both data sources show a difference in the trends observed: for mobile phone data it keeps consistency with Tuesday and Thursday values, while for surveys it drops considerably.

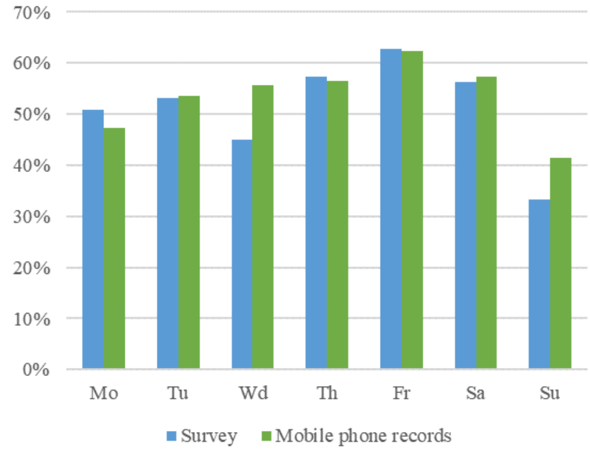

Figure 5. Rate of 'go' trips among domestic flights depending on the weekday

Once the methodology used to characterize trips as 'go' or 'return' was validated, trips were joined to construct tours, and then, their purpose was determined according to the heuristics presented in section IV.3. Once tours were classified as business or leisure, some additional insights were obtained from mobile phone data. As an example, in Figure 6 it is shown, for all the trips departing from Madrid, the hourly distributions of business/leisure trips per hour of passenger arrival to the Madrid airport terminal. The shape of the curve corresponding to business trips has two peaks, one at early morning, corresponding to business trips that need to attend an early meeting, and a second peak at 17-18 in the afternoon, corresponding to the return trips of those business passengers that came to Madrid for a meeting. In the case of leisure passengers, the shape of the curve is much flatter, which means that leisure passengers are distributed almost evenly throughout the day. The fact that the methodology is able to capture these hourly patterns, which has not been used for calibration, is interpreted as an indication of the validity of the approach.

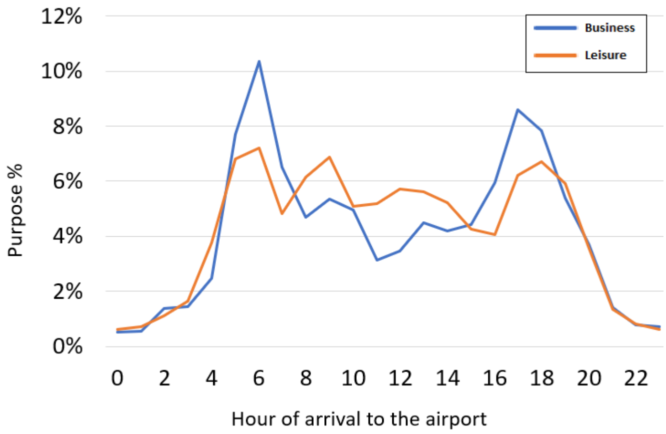

Figure 6. Hourly distribution of business/leisure trips

One of the assumptions of [5] was that the time spent in airports depends on the type of passengers, with business

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passengers spending less time than leisure passengers (probably due to the fact that business passengers often do not check-in luggage). The times spent at the airport were measured from the mobile phone data, and, as it can be seen in Figure 7, this assumption has been confirmed and quantified: business passengers spend shorter times both at origin airports when compared to leisure passengers. This conclusion can also be obtained by looking at the statistical properties of the distribution of the time spent in departure airport for both types of passengers (Table II). Both distributions have a similar average, but the standard deviation of the business distribution is higher and presents a considerably higher skewness towards small duration values.

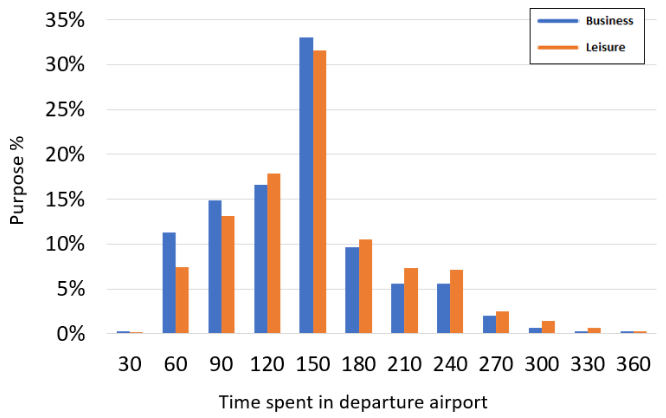

Figure 7. Histogram of the times spent in departure airport for business/leisure trips

TABLE II. STATISTICS OF THE TIME SPENT AT THE AIRPORT DISTRIBUTION

	Business	Leisure
Avg (min)	148	144
Std (min)	78	66
Skewness	1.78	1.31

E. Workers and visitors volumes

As an example of the type of information that can be extracted only from mobile phone records, it is presented the comparison between the volumes of passengers, workers and visitors for an average between Monday, Tuesday and Wednesday. There it can be seen that workers and visitors (i.e. companions to travelers) represent a non-trivial amount of people that airport facilities need to take into account for their operations (e.g. ensuring accessibility for workers, parking facilities, etc.).

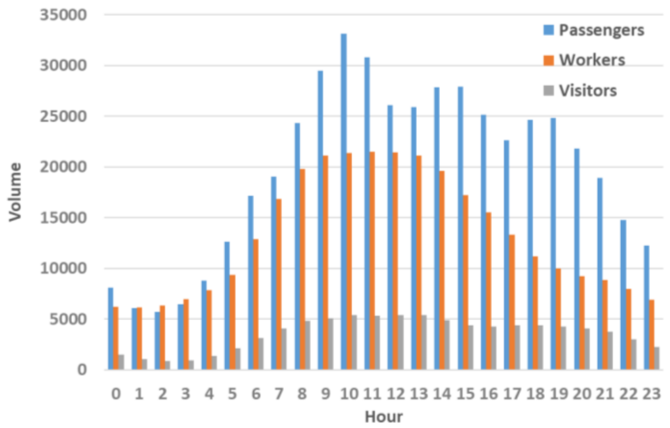

Figure 8. Volumes of passengers, workers and visitors for different hours of the day at the airport

VI. CONCLUSIONS AND FUTURE DIRECTIONS

The main conclusions of the study are summarized below:

- Mobile phone registers have proven to be a valid source of information on air transport passenger behavior. Results offered by mobile phone data do not show any major inconsistencies with the insights extracted from the EMMA surveys. This successful validation exercise is the first step towards the future development of a hybrid survey & mobile phone-based passenger characterization methodology.
- Thanks to the availability and analysis of mobile phone registers produced while the user is in roaming, the geographical scope of the studies based on mobile phone data can be extended to cover international flights.
- The analysis of the ground transport access mode shows that a high percentage of passengers that depart from Madrid but start their trip in other Spanish region perform short-haul flights to reach Madrid. This suggests the possibility of replacing certain short-haul flights with more efficient and environmentally friendly solutions, in particular high-speed train.
- A methodology that characterizes air transport tours as business or leisure tours, based on mobile phone data and calibrated through the information from the EMMA surveys, has been developed. This tour characterization was used to extract information about the durations of the stays at the airport, allowing us to measure the duration of the stays at the airport for different types of passengers.
- In order to have a more comprehensive characterization of passenger flows, a hybrid methodology based on the fusion of mobile phone records with surveys has been employed, which can be used to take advantage of the strengths of each data source. As an example, due to their low costs of extraction and analysis, mobile phone records could be used to produce regular updates of some of the

indicators extracted from surveys. Also, mobile phone records allow the analysis of past events (e.g., heavy disruptions caused by strikes or weather), which is not possible with surveys. In addition, mobile phone records can be used to determine the volume of workers and visitors at the airport for different times of the day. Finally, the fact that some pieces of information can be obtained from both mobile phone data and surveys could be used to reduce the response burden for passengers, both making the surveys focus on those aspects that cannot be obtained from other sources and increasing the probability of being completed.

Future research avenues include the following:

- Mobile phone data open the possibility of analyzing other airports and periods where nowadays surveys are not carried out due to budgetary issues. Cross comparisons of passenger mobility patterns between peak and off-peak seasons at different types of airport (seasonal, hub, low traffic, etc.) could be conducted, leading to a better knowledge of passenger behavior, which would in turn result into better, more adjusted to passenger needs, intermodal solutions and concepts.
- The availability of mobile phone registers abroad could be used to extract information not only about the destination of the flight that the passenger is taking, but also to find out if that flight is a connection and which is the final destination. This way, a better understanding of international connection flows can be developed, which could be useful for airport marketing purposes.
- In order to study and develop efficient and sustainable intermodality concepts, all long-distance transport modes need to be characterized. Mobile phone records provide an excellent opportunity to provide this kind of information. The availability of huge samples of fine-grained mobility data unlocks the possibility of developing transport simulation models that represent annual long-distance travel, enabling the evaluation of the effect of different intermodal solutions and the resulting impact on multimodal KPIs with a level of realism that does not exist today.

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