Deriving origin–destination data from a mobile phone network

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Abstract: Acquiring high-quality origin–destination (OD) information for traffic in a geographic area is both time consuming and expensive while using conventional methods such as household surveys or roadside monitoring. These methods generally present only a snapshot of traffic situation at a certain point in time, and they are updated in time intervals of up to several years. A technique was developed that makes use of the global system for mobile communications (GSM) mobile phone network. Instead of monitoring the flow of vehicles in a transportation network, the flow of mobile phones in a cell-phone network is measured and correlated to traffic flow. This methodology is based on the fact that a mobile phone moving on a specific route always tends to change the base station nearly at the same position. For a first pilot study, a GSM network simulator has been designed, where network data can be simulated, which is then extracted from the phone network, correlated, processed mathematically and converted into an OD matrix. Primary results show that the method has great potential, and the results inferred are much more cost-effective than those generated with traditional techniques. This is due to the fact that no change has to be made in the GSM network, because the information that is needed can readily be extracted from the base station database, that is the entire infrastructure needed is already in place.

1 Introduction

Data on origin–destination (OD) mobility represent one of the most sought after sources of information with a view to strategic planning and management of terrestrial infrastructure networks. On the basis of this information, organised in the form of OD matrices, an estimate of the number of people moving between different points of a given network over a given period of time may be calculated and a ‘mobility map’ drawn up. A precise calculation of such mobility matrices for mechanised transport is an essential tool to enable administrative authorities to optimise the use of their transportation networks, not only for the benefit of users on their daily journeys but also with a view to the investment required to adapt these infrastructures to envisaged future needs.

However, the process involved in the calculation of an OD matrix, from the initial data-gathering to the exploitation of the first results, is lengthy and may take years. In addition to this limitation of time, the problems of the financial cost involved and the means necessary to create such matrices mean that the only customers likely to use them are governmental bodies.

Consequently, the possibility of creating an OD matrix automatically and, to a certain extent, immediately would represent a real revolution in the commissioning of mobility studies by administrative authorities. Furthermore, this possibility could help to provide an immediate response to problems derived from mobility and allow matters to which few resources have been allocated up to now, such as mobility at weekends, leisure-associated mobility and pedestrians, to be addressed.

It would also constitute an extremely valuable data-source for market surveys and user analysis by public transport operators. At the present time, these firms tend to use methods that are very narrowly focused on their own transport medium (counting passengers, customer surveys and so on), which fail to provide precise estimated figures for capture of new customers to their form of transport. Moreover, this kind of matrix would be capable of providing direct answers to individual passengers’ queries and questions of interest, such as information in real time on traffic flow, journey times and speeds and alternative routes.

This paper focuses on analysing a new technique for obtaining, immediately and automatically, data on traffic movements, such as OD matrices and traffic counts in given network links, by using data on location of cell-phones carried in vehicles.

The new methodology proposed in this paper uses information on the locations of mobile phones in order to supply a type of OD data. If a mobile phone is present in a vehicle, switched on and belonging to a certain cellular operator, that vehicle becomes a ‘probe vehicle’ (Fig. 1). A mobile network operator must be able to give its users coverage in any area, as the cell-phone could be moved anywhere. Also, because the cell-phone may be in movement, it is necessary to be able to track these in order to find the antenna (cell) to which the phone will connect. For this reason, a phone which is switched on, independent of whether it is using the network for a voice, data or simply it is in standby, notifies its position in terms of its actual cell or location area (LA) where it is currently located. This fact permits the cell-phone operator to continuously have all its subscribers located in order to give them all access to the services they have contracted as fast as possible and at the lowest signalling cost possible.

doi:10.1049/iet-its:20060020

Paper first received 11th April and in revised form 31st August 2006

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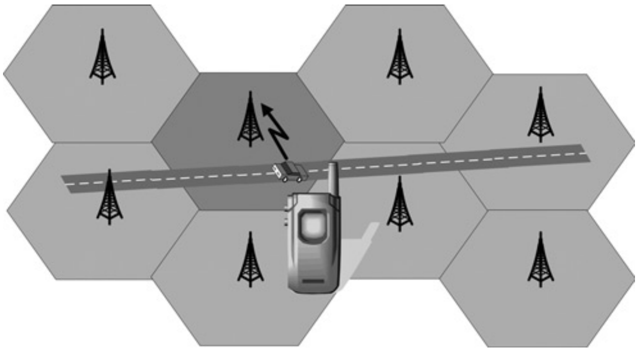

Fig. 1 *Schematic view of a car connected to a base station in a cellular network*

The method proposed in this paper exploits this characteristic, that is that an operator constantly has an updated database of the position of all cell-phones that are turned on. This fact, together with the extended use of cell-phones in the modern day society suggests that the location data of the phones, under the condition that they are turned on, may be used for traffic mobility studies. Obviously, the mobility data obtained are associated to the cell-phones of one operator and what is of interest are data related to mobility of vehicles. For this reason, an adjustment factor is introduced that transforms the data of phones to data of vehicles. The manner in which a given cell-phone is assumed to be related to a particular vehicle will be explained later in this paper. This way, mobility information will be obtained by analysing the location of mobile phones.

2 State of the art

As we have already mentioned, one of the main problems in traffic planning and management is how to obtain precise data practically in real time. Among such traffic data, OD matrices are especially important, as they are essential for the purposes of network management and scheduling. Historically, OD matrices have been calculated using different methodologies, principally by means of household questionnaires or road surveys (either directly on a sample of vehicles or by way of a chip supplied to drivers, or indirectly by recording vehicle registration numbers). Other methods have been based on theoretical models of distribution (the gravity model) or counting traffic (average traffic flow in the links of a road network model) for the purposes of updating a prior OD matrix. In certain cases, these methods are either relatively unreliable or very expensive in economic and/or social terms.

Another type of traffic data are obtained from traffic counts consisting of measuring vehicle flow through network links. This kind of information is gathered automatically in a group of points associated with links of the road network, and the data are therefore available in urban and inter-urban zones (metering on roads) at a very low cost. Consequently, the alternative for traffic counts has the advantage in financial terms of getting rid of surveys, data processing, monitoring and validation to a great extent. However, it also has the disadvantage of having to depend on an already existing metering infrastructure, which tends to be expensive to extend or modify (renewal or relocalisation of metering points).

On the other hand, the number of mobile phone users in the European Union now exceeds 90% of the total population. This growth is also reflected in our conduct, as the cell-phone has now become an essential element in our daily lives [1]. This fact gives rise to the consideration that mobile phones might well be used as 'monitors' of our behaviour, since we tend to carry them round with us all day.

Thus, a possible alternative method both for determining OD mobility matrices and for data metering at given points of terrestrial infrastructure networks (roads, highways and so on) would consist in the use of certain data on the positions of mobile phones, which are known to mobile phone operators for service administration purposes.

This new methodology would use such mobile phone location data to obtain information on traffic movements. Each vehicle could carry one on-board, whether belonging to the driver or to one of the passengers. The mobility data administered by the cell-phone networks would offer an estimation of the positions of their clients with reference to the zone in which they receive cover. This information might then be processed, without any need to reveal confidential subscriber data, in order to determine given data on vehicle movements by way of the cell-phones they happen to carry on-board.

The idea of using mobile phones to monitor traffic conditions is not new. Various countries have adopted new regulations requiring precision in the localisation of emergency calls (E-112, Europe 2002/22/EC), which has given rise to in-depth studies on new techniques for improving the localisation information provided by mobile phone operators. As a result of this investigation, new applications have arisen related to location data (LBS), many of which are of particular interest to the transport sector.

A fair number of studies relating to this matter have been published in recent years. Bolla *et al.* [2] presented a model for estimating traffic by means of an algorithm that calculates traffic parameters on the basis of mobile phone location data. Lovell carried out various studies [3, 4] on the basis of anonymous data on the position of mobile phones with a view to transport applications such as journey times or speeds. We must also refer to the investigations by Sohn [5] and Akin and Sisiopiku [6] on OD matrix calculations using simulations of mobile phone data, as well as other studies focused on the efficacy of the technique, such as that by Cayford and Johnson [7], which analysed the main parameters to be taken into account, namely precision, metering frequency and the number of localisations necessary to achieve accurate traffic description.

Of all these factors, precision is the most important for achieving the desired results. The most focused level of precision provided by the global system for mobile communications (GSM) network without any modification either of the network itself or of the terminals is at the cell level, that is with the area covered by the base station the mobile terminal is connected to. The precision achieved will depend on the radius of the cell, which might be 200 m in a city or between 5 and 20 km in rural areas. Other models providing greater precision do however exist, but they either require modification of the network (installation of ancillary devices to measure the signal, reception angle, signal level and so on) or involve alteration of the terminals (GPS, clocks to record reception times and so on). In view of the costs involved in such supplementary modifications and the fact that the traffic data inferred need to be representative, that is to say the sample employed should be as large as possible (most users do not have modified terminals), this paper focuses on positioning provided by a typical unmodified GSM network. Although the level of precision achieved falls short of being optimal, it is sufficient to permit adequate estimation of traffic parameters.

At the present time, numerous pilot studies have been carried out in relation to this new method, and all of them have shown magnificent results with a view to possible implementation in practice. Nevertheless, although the method represents a source of real and reliable data allowing the daily activities of a city's inhabitants to be monitored, these aggregate location data are not used in a systematic manner to describe the planning of urban or inter-urban systems. The main reason for this is the difficulty of gaining access to these data in the possession of the mobile phone operating companies. Furthermore, the absence of regulations governing the use of such data together with growing concern relating to matters of confidentiality tend to impede rapid development of this methodology. However, a number of investigations [8–10] undertaken in the last few years show that the use of such data does not breach subscribers' rights and that, with the mobile operators' collaboration, it is possible to obtain new products that benefit not just the operators but society as a whole. They also show many advantages with respect to previous techniques, for example:

- Large data sample, proportional to the index of mobile phone use.
- Any area may be monitored, given the extent of mobile phone coverage.
- No installation of additional devices is required either in vehicles or in the network for them to be monitored.
- The data may be generated almost in real time.

2.1 Projects related to traffic data derived from mobile phones

Several pilot projects have been undertaken to study this technique, some of them using the actual localisation carried out by GSM operators when a cell-phone is simply switched on and others employing certain data associated with specific situations such as any type of call (billing data) or calls in the process of making handover (the process of transferring an ongoing call from one channel connected to the core network to another). There have even been projects that have developed their own software to capture mobile phone signals. We refer below to various projects related to this matter, all of which have focused on the use of location data associated with mobile phones to obtain information on vehicle movements, while respecting at all times the privacy of the mobile phone client.

The most recent investigation was carried out by Ratti at the MIT SENSEable City Laboratory [10, 11]. In this study, the researchers managed to map a city in real time, following thousands of people moving around with their cell-phones switched on. This achievement was possible, thanks to the mobile operator, the Austrian company A1/Mobilkom, handing over anonymous phone data, which enabled the MIT investigators to develop a project entitled 'Mobile Landscapes'. This involved the creation of digital maps showing phone use in the metropolitan area of the city of Graz in Austria, visualising the whole dynamic of the town in real time. The researchers brought together three types of data ceded by the operator: call density (measured in Erlang), the origins and destinations of calls (by way of 'handovers'), and the localisation at regular intervals of the phone users being followed.

In Europe, a traffic data system called MTS mobile traffic services has recently been developed. This system uses information from the GSM network on the movement of mobile phones (within vehicles) to monitor traffic circulation and thus assist traffic authorities in managing traffic flow and possible congestion. The pilot project was carried out in the province of Noord-Brabant in Holland in collaboration with LogicaCMG, Vodafone and the local government [12, 13]. The software base was developed by Applied Generics, whose RoDIN24 product monitors a mobile phone network to obtain anonymous localisations of a large number of phones in real time.

In the Flanders region in Belgium, the Belgian operator Proximus and the British company ITIS Holdings are also developing a pilot project using these techniques to monitor traffic on highways through localisation of mobile phones in moving vehicles and verify the speed of movement of each phone between one aerial and the next [14].

In 1999, TRL (the Transport Research Laboratory) took part in a project to update OD matrices with mobile phone data in the UK. This research found that it was possible to obtain OD matrix information through localisation of mobile phones along with other sources of traffic data such as journey times and speeds. The locations (at start and end of call) of the phones that are placing the call are recorded by the mobile operator along with the length of the call for billing purposes. TRL developed an algorithm to analyse anonymous phone data originating from billing data, which were supplied by the operator BTCellnet (now O2), and convert these data into traffic-related information [15, 16].

Another European project employing this technique is STRIP (System for Traffic Information and Positioning), which has studied and tested the use of mobile phone localisation to estimate journey times [17]. This research was carried out under the SERTI programme (Southern European Road Telematics Implementation) in collaboration with the French government and the mobile operator SFR. To obtain the mobile phone data, the localisation technique known as 'Abis Probing' was employed, which monitors the signalling data sent by the Abis and A radio interfaces. STRIP was divided into two base sub-systems, the first being a data-capture system that caught mobile phone messages in real time and calculated their position, and the other a processing and presentation sub-system that calculated journey times over given segments of the highway, showing direction of movement and position of calls.

In 2002, Finnra (Finnish Road Administration) and the mobile phone operator Radiolinja developed a system to capture data from a group of phones over a given stretch of highway so as to provide estimated journey times [18, 19]. In order to validate the technique, these estimates were then compared with others obtained from the license plate recognition (LPR) method. This new process produced more accurate results when traffic was monitored over relatively long stretches (around 10 km.) in which vehicles do not tend to join the highway, leave it or stop on it. Apart from this result, the new system was found not to be affected by adverse atmospheric conditions, as happened with the LPR technique. Insofar as data confidentiality is concerned, no data were stored after having been used, and in fact the numbers of the mobile phones involved were encrypted, so that it was impossible to tell which phone made the trip.

In Germany, Vodafone proposed to offer (within the ESGI 2004 programme) road traffic information services for its mobile phone subscribers, which were to be based on the generation of data on traffic flow and speed using the signalling information already created in the standard operations of its mobile phone network. The pilot project investigated the viability of the idea, analysing data collected from a motorway in Germany between July and September 2003, previously processed by Vodafone [20]. The event used in the project to infer the traffic information was the handover. Thus, the capture of anonymous data associated with each of the transferred calls (such as which cells were involved, the moment and duration of the handover or some other kind of signalling information) permitted the calculation of data such as speed and flow by means of the handovers between cells. Each cell previously had roads assigned to it and the positioning of borders between cells had been duly calculated [21].

The Israeli firm Decell Ltd. has developed a product known as AutoRoute-1, which carries out a periodical and random sampling of mobile phones travelling on-board moving vehicles within a given area. In accordance with these samples of cell-phones recorded in a network at a specified location, certain traffic parameters can be estimated (such as speed, density and flow) for each stretch of the road [22]. This system converts data that are being continuously generated within a mobile phone network into precise, real time information on traffic along a highway. In addition, it supplies drivers with recommended routes corresponding to the journey time envisaged to reach a given destination. Drivers can also receive instant warnings about significant factors affecting traffic, such as accidents, roadworks and so on. The AutoRoute-1 system produces information on traffic in real time, while at the same time respecting mobile users' privacy and anonymity.

In the USA, various projects relating to this technique are under way. Most of them are being carried out by the Departments of Transport of different States in collaboration with private corporations and/or mobile phone operators. An interesting one is that being developed by Virginia Department of Transportation (VDOT) in collaboration with AirSage with a view to showing the feasibility of using phone data for traffic monitoring [23]. For this project, AirSage created a software programme to collect signalling data (sent automatically) associated with localisation of anonymous phones either in use or simply switched on, in order to monitor their movements. This information enables the position of anonymous phones to be known from time to time and, once processed and reproduced on a map, the data show the speed of traffic fluctuation on any given road for vehicles with mobile phones on-board [24].

Another project developed in Maryland in collaboration with Delcan Corp. used phone movements to create a map in real time showing the traffic moving along its main highways [25]. The basic aim of this project is to show the state of roads with a view to detecting traffic events (congestion, accidents and so on) without having to use sensors, cameras or other devices that have to be installed as supplementary apparatuses along highways. Drivers's mobile phones are used instead of such ancillary devices, and data can be obtained from any point in the road network where there is a mobile phone, as mobile operators need to know the locations of their subscribers in order to route their calls. The mobile phone data, which belong to handover signals, are treated as anonymous, thus avoiding the possibility of following a particular person on their journey to a given destination. Consequently, with this information and the corresponding road maps in hand, the position of phones and their velocity can be calculated. The data are supplied by the mobile operator ITIS Holdings [26].

3 Services based on LBS localisation

Services based on localisation, commonly known as LBS, refer to the group of possible value-added applications that use the position of mobile terminals to produce a given result. At present, phone operators offer their subscribers certain applications on the basis of their location. One of the key applications of these services arose as a result of the regulations requiring precision in the localisation of emergency calls. These regulations required a certain level of precision in the process of localising phones making emergency calls (in Europe this is regulated by Directive 2002/22/EC).

3.1 Applications directed towards mobile phone users

This group of applications comprises those whose main beneficiary is the owner of a mobile phone. The phone acts as an intermediate tool to access data on its location and will position it on a map. Some of the possible applications are as follows:

- interactive information service,
- traffic services,
- advertisements and news services,
- navigations aids.

3.2 Applications directed towards others

This series of applications consists of those whose main beneficiary is not the owner of a mobile phone but rather other bodies, generally public authorities. This group of applications includes the services that this paper is concerned with, and some of them are listed here:

- emergency call services (Europe 112, USA 911),
- fleet management,
- family safety,
- real time traffic systems.

These applications represent one of the sectors with greatest market potential in the context of mobile telecommunications systems. In future, these services will become one of the principal sources of income for phone operators. In addition, non-operator corporations may well think up new applications and/or modify existing ones, thanks to the possibilities offered by localisation processes, which will help add value to their products, boost sales and open up fresh opportunities in new markets.

4 Mobility management in cellular networks

One of the main features of cellular networks is the fact that phones have no permanent connection to the network. Moreover, the network has to deal with moving users. The network has to track the location of each phone in order to provide service to its user with short delays and a low signalling cost and must be able to find the cell in which each phone is currently registered. First, the concepts of LAs and cells will be explained roughly. In a GSM network, a service coverage area is divided into smaller areas of hexagonal shape, referred to as cells. Each cell is defined as the area in which one can communicate with a certain base station. In other words, a cell is served by a base station. An LA is a geographic area covered by base stations belonging to the same group (Fig. 2). The identifier of the LA they belong to is called the location area identifier (LAI) and identifies distinctively an LA in the network.

Another identifier is the cell identity (CI), which uniquely identifies a cell in an LA, that is to say, a cell into a group with the same LAI. A cell within a GSM network is

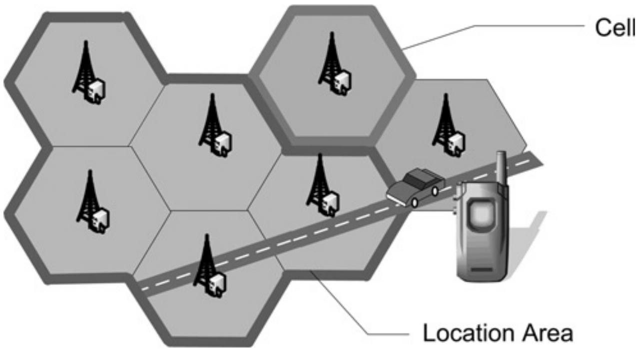

Fig. 2 *Schematic view of several LAs sub-divided into cells*

identified by the cell global identifier (CGI) made up of the LAI and the CI.

To store the locations, a GSM network makes use of a two-level database hierarchy, which is formed by the home location register (HLR) and the visitor location register (VLR) (Fig. 3).

Mobility management is the set of processes used to allow users to be reached wherever they are in the network coverage area. The two basic operations involved with mobility management are: location updating and paging.

4.1 Location updating

This procedure can be divided into two steps. The first one consists in sending a signal to a mobile phone in order to update its location. Secondly, the record of the location in the system database is updated by the message sent by the mobile phone. This is recorded in the HLR and the VLRs. These records are triggered by one of the following events:

1. A mobile phone connects to the cellular network, that is to say, in the moment in which a MS is switched on.
2. A mobile phone moves into a cell which belongs to a new LA.
3. A timer associated with a location process comes to an end. The mobile phone has to poll, although it is in the same area.

Some of the values which are updated in this procedure are the LAI and CI. These identifiers correspond to the location of the base station (cell) where the phone has been registered.

4.2 Paging

The paging operation is performed by the cellular network. When an incoming call arrives for a mobile phone, the cellular network will search for the mobile terminal in all possible cells by sending paging messages. This procedure tries to find the cell in which the mobile phone is located so that the incoming call can be routed to the corresponding base station.

5 Traffic data via mobile phones

The coverage of a cellular network is usually very good in cities and along the major elements of the transport infrastructure, for example railway lines, major roads and so on. In the case of highways, the presence of mobile phones on-board vehicles may be used to estimate traffic conditions. As mentioned earlier, the GSM network produces an estimation of a phone's position when it is switched on within the network's coverage. If we transfer this to the ambit of cell-phones on-board vehicles in movement, a terminal which is connected to the network (via a call) can provide fairly continuous data on its journey in terms of the cell and area of localisation through which it is passing. Even if the phone is not in use but only switched on, it can still provide reliable route data, as the LA in which it is situated at any moment is continuously known. In this case, routes can still be constructed even though the information is less accurate and frequent.

By combining data on the cells and LAs in which a mobile phone has been registered, it is possible to construct journeys from which OD data may be inferred. It must be pointed out, however, that the interest of this technique lies in the journey itself, not in who made it. Accordingly, the identity data relating to the mobile phone concerned would be encoded, either by way of an encrypting algorithm or using a false identifier.

5.1 Technical factors

The efficacy of obtaining data on traffic from mobile phones depends on various different factors. One of these is the accuracy of the location data, which depends on the cell's range of coverage (Fig. 4).

This information on position used in GSM networks is based on identification of the cell that is providing coverage to a mobile phone, with approximate information as to the geographical zone in which the mobile phone is located rather than its precise position. Consequently, there is always a margin of error, which will depend on the cell's range. This range may vary between 100 m and 1 km in built-up areas and in rural areas, depending on aerial density, it may vary between 5 and 20 km.

Another factor is the renewal frequency of these location data, which will depend on whether the terminal is merely switched on (in which case updating will take place on termination of a timer or change of LA) or the network is being used in some way (e.g. a call), in which case updating is instantaneous and continuous.

However, in terms of cost and benefits offered in achieving the required localisation quality, the positioning

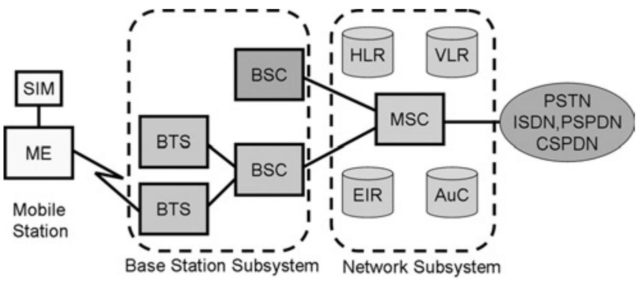

Fig. 3 *Schematic view of the GSM system*

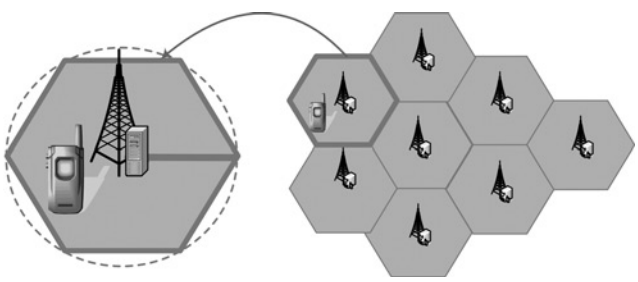

Fig. 4 *Localisation via CGI*

information supplied by an unmodified GSM network allows reliable data to be obtained for the purposes of monitoring the movements of phones and, consequently, vehicles without the need for setting up any ancillary infrastructure. Additionally, it is a significantly cheaper system, since it takes advantage of GSM networks to obtain the location of mobile phones. Furthermore, any mobile terminal however simple can be used as long as it is switched on.

5.2 Legal aspects

It must be made clear that these techniques for estimating traffic parameters by way of mobile phones do not infringe the privacy of phone users. The data analysed would be treated as an aggregate and anonymously in compliance with European regulations, so that it would be impossible to associate these location data with actual cell-phone users. The aim of this methodology and of this project, in particular, is to demonstrate its viability for improving methods of calculating traffic parameters.

The main worry arising from the use of these LBS services is the fact that phone users' movements are continuously monitored, particularly in cases where such personal location data are made available to applications whose beneficiaries are third parties. Nevertheless, all these services are within the law as they are governed by regulations controlling the protection of privacy. Specifically, European Directive 2002/58/EC regulates the treatment of personal data and protection of intimacy in the electronic communications sector. Article 14 of this Directive includes a description of location data, stating that: 'Location data may refer [. . .] to the identification of the cell in the network in which the mobile terminal is located at a given moment or to the time at which the localization information has been registered.' Article 9 of this Directive also supplies regulations covering location data, as follows: 'In the event that location data can be processed [. .] such data may only be processed if they are made anonymous, or with the prior consent of the users or clients, to the extent and for the time necessary to provide a value-added service.'

It is therefore clear that such services require prior agreement and the protection of privacy is the basic factor in relation to any of them. It must be pointed out that the provision of the service does not violate the law on privacy protection, because it uses anonymous data so as to avoid the association of particular movements to specific individuals. The only information sought is data relating to the localisation of a phone terminal, considered as an anonymous element in the network, moving through it, irrespective of the user's characteristics or any other kind of information associated with it.

6 Feasibility study

The objective of the pilot study is to show the feasibility of obtaining traffic data to be used to update an OD matrix. The information is deduced from the movements of anonymous mobile phones correlated to vehicle displacements. For this feasibility study, a simulator tool has been used.

6.1 GSM network simulator

A cellular network records the current location of mobile phones over time in a database. The mobile operator needs to know the location of all mobile phones at any given time in order to provide an optimal service to its clients. However, the only data currently stored by mobile operators is billing data which refers to the locations of the phones when they either place or receive calls. Thus, the billing data provide information on only a fraction of all mobile phones moving through the network, and the information obtained will be biased.

If the data corresponding to mobile phones which are switched on throughout the day could be known, then it would be possible to evaluate traffic flow. Unfortunately, continuous data is not stored because it is not useful for billing purposes; moreover, the size of the data files would be exceptionally large. Nevertheless, it would be possible to retrieve this continuous information by collecting the data directly from the base stations, for instance by downloading the data to a portable computer or jump drive.

Since a GSM network has a database that records the current location of mobile phones systematically, a simulator tool that generates a synthetic database with the location data of mobile phones that are switched on during a 24-h period and travel along a road section is used which emulates a real GSM network database. Specifically, the simulator tool emulates a corridor in an inter-urban area covered by a cellular network. This corridor has a set of cells and LAs, which are spread along the road. Each cell covers a road link, along which the simulated vehicle types are travelling. For simplicity, the traffic in each direction is analysed independently. The simulator creates a set of vehicles with mobile phones on-board travelling along the studied highway. The input data required by the simulator tool are a simulation scenario and a set of simulation parameters that define the experiment. The scenario is composed of different types of data: road network description, LAs and cells (GSM network description) and traffic demand data. The simulation parameters are fixed values that describe the experiment (simulation time, vehicle occupancy, statistical data and so on) and some parameters used to manage the mobile phones and GSM network (mobile phone penetration, operator market share, calls rate and so on).

In this case, the trunk road between the Spanish cities of Huelva and Seville has been used as simulation scenario (Fig. 5). The region is divided into a number of zones represented by centroids. A centroid is a node, corresponding to a zone, where trips either originate or terminate. These centroids are defined based on loop detectors on the studied trunk road. In this case the centroid is defined by traffic counts from seven loop detectors. Finally, the scenario needs a traffic demand that will simulate, that is to say, the trips between centroids. This traffic demand data is estimated using historical data from traffic counts on the highway concerned.

This simulator implements a microscopic simulation approach based on emulating individual vehicles (Fig. 6). This means that the behaviour of each vehicle in the network is continuously modelled throughout the simulation time period while it travels through the traffic network. Along with that, the simulator manages the activities which are related to the mobile phones on-board of the vehicles, for instance phones turned on and off, calls placed or received and SMS messages. It also manages the 'location updating' procedure when some register event is produced, for example a mobile station moves into a cell which belongs to a new LA. Each vehicle has an assigned trip to carry out over the corridor, an instant to start its trip and a number of on-board mobile phones according to its occupants. So that, mobile phones present in vehicles will be moved within the cells that provide the coverage to the corridor. If some register event is produced while a phone is within a cell, the mobile phone location will be

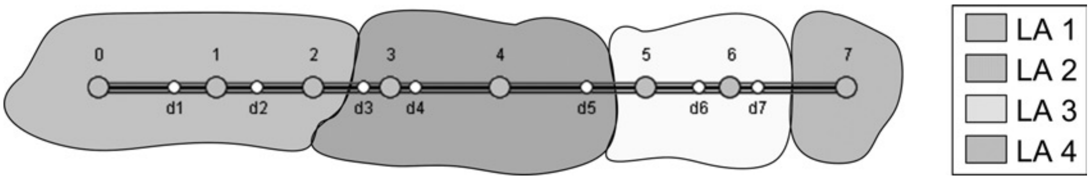

Fig. 5 *Eight centroids, seven detectors and four LAs in the scenario*

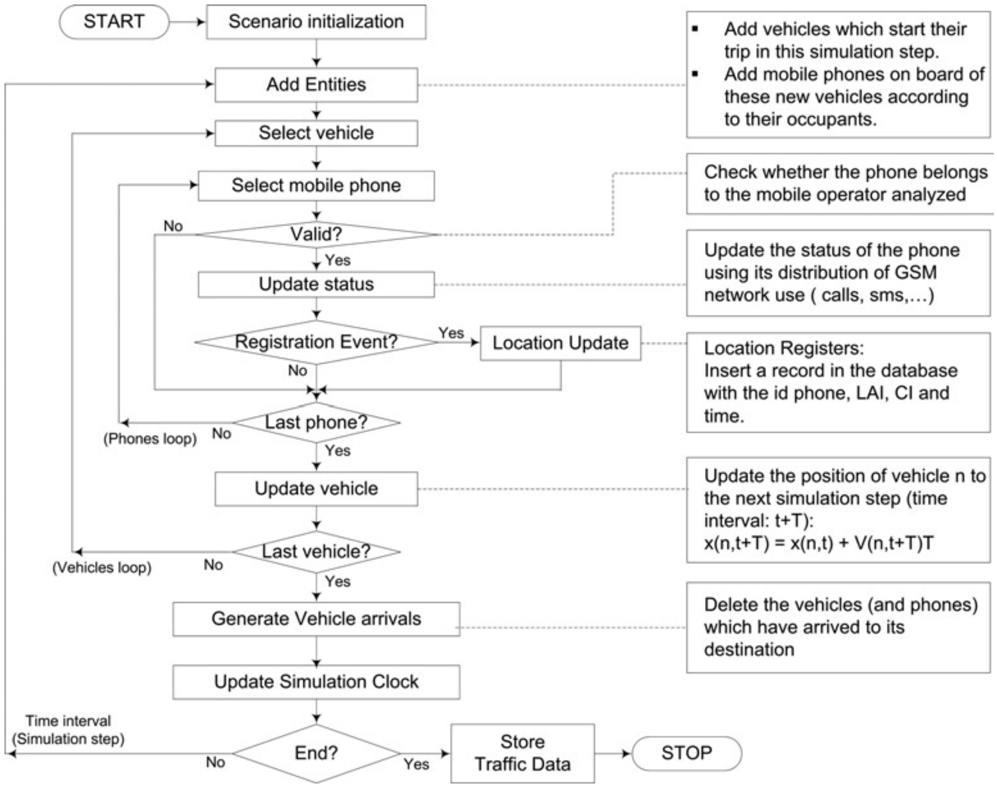

Fig. 6 *Basic flow chart of the simulation process*

recorded in the synthetic database to update its location, such as real GSM 'location updating' procedure. Finally, the database will have stored the location of all phones on-board of simulated vehicles during a day. This location data is related to the cell and location area in which a mobile phone has been registered, such as real GSM networks.

The simulation divides the time period into sample instances where creation and analysis of the entities are effectuated. Once the scene is defined, the simulation process begins. When a vehicle is created, attributes are associated to it such as the centroid of origin and destination, number of occupants and the number of mobile phones on-board. A series of attributes such as for instance the operator it belongs to, the kind of the network used (i.e. voice, data or sms) will be associated to every telephone throughout a 24-h period. Each analysed vehicle makes a trip according to the assigned centroid of origin and destination and will have on-board a number of cell-phones depending on the number of occupants. At every sample time, the vehicle moves along its trajectory and updates its position for the following iteration. Additionally, the properties of each one of the phones that are transported are examined in each step, that is any event that updates the position is verified (such as calls, change of LA, SMS and end of timer). If positive, the nearest base station to the position where the vehicle is at that certain time will be consulted. By taking the associated values LAI and CI to that base station the appropriate identifiers for a 'location update' will be known. Whenever an event takes place, the updated information will be inserted in a database, simulating the location register that is made by a real GSM network. Table 1 shows examples of such registers.

When the simulation ends, the synthetic database with location registers of phones which have travelled along the scenario is generated. This database will be analysed to generate the traffic data inferred with the methodology proposed later. Besides, the simulator tool also provides as output, traffic data measures such as trips between LAs. So, the tool offers the opportunity to evaluate the inference accuracy, since the inferred traffic data using mobile phone location data can be validated by means of the real data provided by the simulator.

6.2 OD matrix inference

Traditionally, the areas that constitute the origins and destination in the study of OD matrices are defined by socioeconomic criteria or population clusters called 'census areas' grouped forming the 'transport area', that is areas that could have a causal relation with the transport movements occurring among them. In the proposed methodology, the areas of origins and destination (i.e. where the trips begin and finish) are established by the design of the cell-phone network, since the OD areas coincide with the LAs which are used for the management of the GSM network services. The factor that causes the use of those LAs resides in the inherent characteristic of the management of mobility of a network GSM. This makes the phone to notify the system

Table 1: Example of 'location register' generated by the simulator

Time	Encrypted ID phone	LAI	CI
2006-05-12 17:38:00	6130 81	2140 1551 02	4875 1
2006-05-12 17:57:00	9214 69	2140 1560 21	4983 3
2006-05-12 18:10:00	1534 34	2140 1559 01	4930 1

its present position when it enters a new LA. For this reason, a turned-on cellular phone will provide real information of the LAs along which it has travelled during a trip.

It is necessary to bear in mind that neither the phone numbers nor the subscriber names are used to carry out the analysis. All that is required is an identifier to distinguish between all mobile phones. All phone numbers in the database are therefore encrypted to avoid infringing public liberties. Then the use of mobile phone location data is anonymity.

To develop this method, a database with the location records during a day is used. If this database is the one held by the mobile operator, it is necessary to distinguish users of the cells covering the road of interest from other users. On the other hand, if the database used is the one generated by the GSM network simulator, the records are already filtered as they are coming from phones on-board the vehicles travelling on the virtual road.

On analysing the data generated by the simulator, we can discover which of the 'anonymous' mobile phones have been moved into the cells that cover the road in question. By combining the cells and LAs where each 'anonymous' mobile terminal has been registered, it is possible to construct a journey from which the origin and destination may be inferred. Specifically, the initial and final registers recorded for each phone over one of the LAs of the pilot 'scenario' are sought. In this way, if they were produced in different areas, a journey for that pair of OD LAs is detected, which started at the moment when the first register was recorded and terminated with the last register.

Additionally, the analysis of the location registers allows distinguishing between trips that really are associated to origins and destination (LA) inside the OD matrix under study from the rest of the trips. These are trips that began or finished in other origins or destination different from the ones being studied. Initially, it is necessary to define the time window of the analysis. Once this is defined, the first register that is carried out by a telephone included in the databases in this time interval is considered as beginning of a trip. Furthermore, the end of a trip is defined as the last register carried out during a time interval. Once the initial and final registers are known, and hence the origin (first register) and destination (last register), it is verified that these areas belong to the LAs defined by the surveyed area, that is the OD trip of interest. Obviously, there are losses due to trips that began or finished outside the time interval. However, the results demonstrated that this error was insignificant taking a 24-h interval.

The estimation of an OD matrix with traditional methods as surveys is very time consuming. In addition, sometimes those methodologies are less trustworthy and in comparison expensive from a budgetary and/or social point of view. Normally, such a survey process requires working with a representative sample of the population. On the other hand, it is assumed that the use of data from cell-phones uses an extensive sample of the population, since the rates of penetration of mobile phones is above 90% of the population. Also, it is important to emphasise the low cost of implantation because it is not necessary to change neither hardware nor software of the cell-phones in use today. The only condition for this method to work is that the phone is turned on. It is fair to say the results obtained by using this methodology as a serious complement to traditional methods.

6.3 Traffic counts

A traffic count measures the amount of vehicles that travel past a certain point of the roadway. Traditionally, these traffic counts are a type of information that is sampled automatically as a set of points associated to arcs on the roadway which is why the calculation of this parameter of traffic makes it necessary to install additional elements on the road (inductive loops, cameras and so on). With the proposed methodology presented in this research, it is not necessary to install elements on the roadway. Instead, virtual or fictitious counts will be used which are located on the borders between the LAs of a GSM network.

For the purposes of determining traffic flow, the process is based fundamentally on the fact that mobile terminals perform the whole 'location updating' procedure (registration) when they enter an LA with an identifier distinct from the one they had previously recorded. For this reason, irrespective of whether the terminal is recorded in the network due to any other event, registration data for a given phone will always be available when it enters a new LA, as long as it is switched on (Fig. 7).

Estimations of traffic volumes passing through these borders are carried out by looking for the moments in databases for each mobile phone in which registrations take place due to changes of LA, that is to say moments in time when the first registration of each mobile phone occurs with an LAI different from that previously recorded for the same phone. In this way, passage between areas is monitored as a 'virtual' traffic count. Analysing the topology of the network and the distribution of the LAs, the location of the borders can be assigned to zones of the roadway. Whenever a phone enters a new LA, it notifies its new position to the GSM network (location update). When this happens, it is considered to have passed the virtual count located at the border between LAs. This will be possible analysing the records stored in the database, looking for every phone with its first record in a location area with an identifier (LAI) different from the previously stored. Knowing this record, and observing whether it belongs to borders among the LAs of interest, the time of

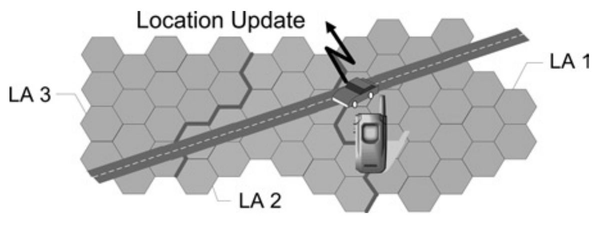

Fig. 7 *Example of location updating on entering a new LA*

crossing the associate border will be known and the virtual count of a phone will be calculated.

Obviously, the topology of the road network can be more complex and different road links can coexist on the borders of LAs. To be able to associate a count with a border in these cases, the procedure should look for the first record in the databases with an LAI different from the previous one, as well as the cell identifier in that new LA. When a mobile phone carries out the process of 'location update', it updates in the system databases the LA and the cell. Due to this, it is possible to detect the route the phone has taken, and also therefore calculate the crossing of this phone over the appropriate virtual count. In Fig. 8, the above-mentioned situation can be observed. Knowing both the identity of the LA and the cell, it is possible to know the route of the phone within the new LA.

The use of phones in vehicles like anonymous measurement sensors, which allows inferring information of traffic presents multiple advantages with regard to the traditional methods. Primarily, the treatment of this information supposes handling a very extensive sample of the population as already it has been commented in the section about the OD matrices. Likewise, in contrast with fixed sensors (loop detector, road tubes, image detection and so on), the mobile phones provide information with regard to behaviour of the traffic of any zone wherein GSM coverage exists and without the need of additional infrastructure. It even allows for detecting the direction of travel. As with the OD matrices, the information obtained is associated to phones of one operator only and not to the complete set of vehicles, and therefore an adjustment factor should be applied. Consequently, the methodology does not need a penetration of mobile telephony of 100%. It will obtain information of a certain sample (only turned-on phones of one operator) and transforms this information into equivalent number of vehicles according to the adjustment factor.

6.4 Adjustment factor (mobile phones per vehicle equivalents)

It is important to bear in mind that this technique generates data associated with mobile phones switched on for a particular mobile operator. However, the main interest is obtaining vehicle traffic data, not mobile phone data. Consequently, an adjustment factor that relates vehicles to mobile phones is used. This factor (f_{MPV}) is used in the GSM data analysis to convert phone data into equivalent vehicle data. It is defined as

$$\mathrm{CellPhones}_{\mathrm{ON\ Op}} = \mathrm{CellPhones}_{\mathrm{ON\ Op}}|_{\mathrm{vehicle}} \cdot \mathrm{Vehicles} \\ \Rightarrow f_{\mathrm{CPV}} = \frac{1}{\mathrm{CellPhones}_{\mathrm{ON\ Op}}|_{\mathrm{vehicle}}} \tag{1}$$

The concept of estimating cell-phones per vehicle equivalent (CPVE) is to calculate approximately the number of mobile phones, which are switched on and belong to a specific mobile operator, displaced on-board of each vehicle under a specified area ($\mathrm{CellPhones}_{\mathrm{ON\ Op|vehicle}}$). This value of mobile phones per vehicle is defined using statistical parameters of a mobile phone market from annual studies published by the Telecommunications Market Commission in Spain (Mobile Phone Penetration, Operator Market Share by Number of Subscribers and so on), together with other traffic vehicular parameters (vehicle occupancy, proportion of vehicle types and so on). The value of $\mathrm{CellPhones}_{\mathrm{ON\ Op|vehicle}}$ is defined as

$$\mathrm{CellPhones}_{\mathrm{ON\ Op}}|_{\mathrm{vehicle}} = \mathrm{MarketShare}|_{\mathrm{operator}} \\ * \mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{vehicle}} \tag{2}$$

where

$$\mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{vehicle}} = \mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{driver}} + \mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{occupants}}$$

$$\mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{driver}} = 1 * T_{\mathrm{ON}}|_{\mathrm{driver}} * \mathrm{Penetration}|_{\mathrm{driver}}$$

$$\mathrm{CellPhones}_{\mathrm{ON}}|_{\mathrm{occupants}} = (\mathrm{OccupancyAverage}|_{\mathrm{vehicle}} - 1) * T_{\mathrm{ON}}|_{\mathrm{occupants}} * \mathrm{Penetration}|_{\mathrm{occupants}}$$

To estimate the number of phones on-board, a particular vehicle property of the driver ($\mathrm{CellPhones}_{\mathrm{ON|driver}}$), the probability of which the driver has a cell-phone ($\mathrm{Penetration}|_{\mathrm{driver}}$) and the probability that this is turned on ($T_{\mathrm{ON|driver}}$) are used. For the rest of occupants the same procedure applies, with the exception that in this case the average occupation of the vehicle does not include the driver. In the case of the occupants, the parameter $T_{\mathrm{ON|occupants}}$ defaults to '1' since passengers normally do not turn off their telephone. Nevertheless, for a driver the situation is different, and the values are taken from previous studies carried out and published (just like the other parameters) by the Spanish Dirección General de Trafico. The value, $\mathrm{f}_{\mathrm{CPV}}$, derived from (1) and (2) allows transformation of the information obtained of a sample set of phones from one operator, to be transformed to an equivalent set of vehicles.

7 Results

The aim of this report is to assess the feasibility of using mobile phone location databases to infer OD matrices by means of phones that are switched on all the time. This approach provides much more information than other techniques using billing data or active localisation. In this project, the highway between the Spanish cities of Huelva and Seville has been used as simulation scenario. This road is covered by four LAs (three borders) (Fig. 9).

The first step for the purposes of evaluating this technique is to obtain the synthetic database containing the location registers using the simulator. Accordingly, a simulation is created with a sample rate (simulation step) of 1 min over an average working day, generating a set of vehicles (with their mobile phones) travelling along the stretch of highway being studied during that time, as shown in Fig. 10.

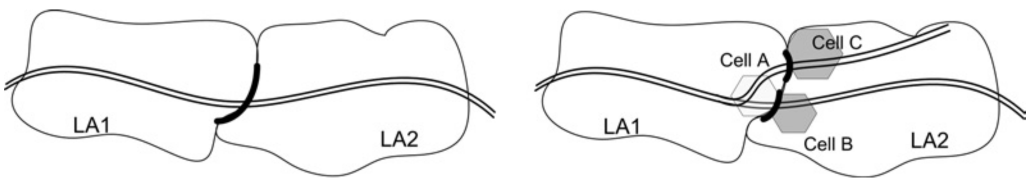

Fig. 8 *Examples of traffic count location*

Fig. 9 *Pilot section*

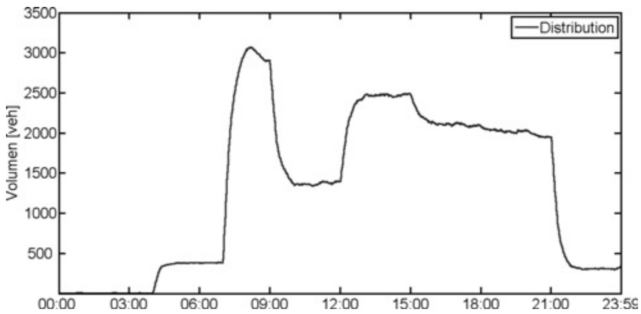

Fig. 10 *Vehicle distribution per hour over a 24-h period*

The results obtained from analysis of the synthetic database provide an estimate of the number of phones travelling between points in a network over a given period of time. With the adjustment factor, the traffic data associated with phones in movement transform into vehicle data. In order to evaluate the efficiency of the estimation of the method, a comparison will be made between this information of estimated vehicle movements (OD matrices and counts related to LAs) and data of traffic stored by the simulation tool. This is possible, thanks to the double functionality of the simulator. On the one hand, this manages and generates the records of location of a zone in an analogous manner to a real GSM network. Also, the simulator captures the real mobility data of the vehicles that have been simulated. With this, it will be possible to obtain data of traffic in order to compare with calculated data obtained the registers of mobile phones, previously transformed to data of vehicles through the adjustment factor. The error measurement of the used estimation is defined as the relative error comparing the real value and the estimated number of vehicles as seen in the following

$$\text{Error} = \left| \frac{X_{\text{real}} - \hat{X}_{\text{estimated}}}{X_{\text{real}}} \right| \tag{3}$$

Values $\hat{X}_{\text{estimated}}$ (OD trip matrix between LAs and counts in the borders) are obtained as explained in previous sections, after being transformed to data associated to vehicles. Values X_{real} are taken from the data of traffic generated and stored by the simulator during the movement of the vehicles. In this latter case, the OD trip matrix between LAs is derived from the calculation of trips of the simulated vehicles whose origin centroid is in an LA different from the location of the destination centroid. For the case of the counts, a detector was located in each border so that the data is gathered of vehicles that have crossed the border during the simulation. From multiple simulations and analysis, it has been demonstrated that it is possible to obtain traffic information from mobile phone data to infer data such as (i) OD trip matrix between different LAs and (ii) traffic counts with the number of vehicles that have passed through each border between LAs. For instance, in Fig. 11 the estimation error of these traffic data from a simulation over a 24-h period is depicted.

Fig. 11 samples different representation error from estimation of matrices OD, that is the difference between the real number of vehicles that include each one of the OD trips against the estimated ones. In this case, the matrix is defined as the trips between the different existing LAs in the zone under study. In particular, Fig. 11*a* shows the evolution of the average relative error of estimation of all the trips of the matrix in different periods from observation. Fig. 11*b* shows the errors in detail for each one of the trips of the matrix, over a 24-h period.

Fig. 12 shows the evolution of the relative errors of estimation throughout 24 h in each one of the borders, evaluating the estimation of vehicle flow volumes crossing each of the borders between the LAs of the zone of study. It also shows a line with the evolution of the average relative error of estimation (average over the three borders) in every time period.

In the cases of both OD matrices and traffic counts, it can be seen that estimation errors tend to decrease as observation intervals increase. This effect is principally due to the adjustment factor transforming mobile phone data into vehicle data. This alternative approach detects data associated with mobile phones, while what we are interested in are traffic data relating to vehicles. Accordingly, a factor is introduced that associates vehicles with phones. This factor is estimated using average statistical figures evaluated in 1 day. As the observation interval for the estimation of traffic data nears the evaluation interval for these parameters, the adjustment factor that transforms mobile phone data into vehicle data produces a high accuracy.

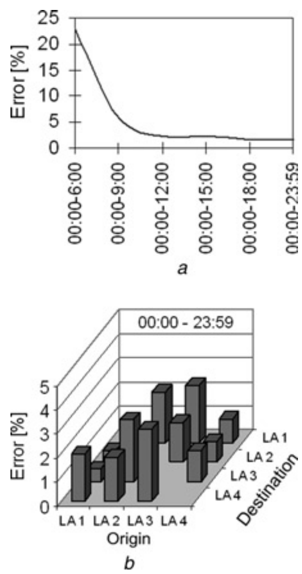

Fig. 11 *OD matrix estimation error from simulation over different periods*

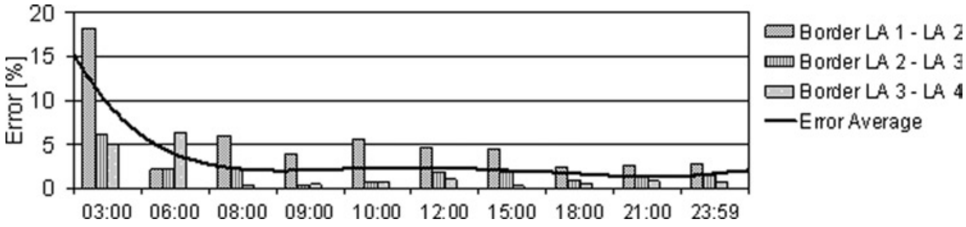

Fig. 12 *Traffic counts estimation error from simulation over each period*

However, there are other loss factors in addition to those already referred to, which do not depend on the time interval analysed and which cannot be avoided (either with simulated or real data). For example, a phone terminal that is switched off throughout the whole journey provides erroneous data, since this journey is not then detected; on the other hand, if it is switched on during the journey, a journey that does not correspond with the real one is detected.

Despite this, it can be seen that the correction adjustment is almost perfect, producing significantly reduced levels of error. Logically, this depends on the factor employed, which is calculated using the same average values as those used to define the statistical distributions modelling the simulator's vehicles and phones. Obviously, calculation of the correction factor will not be so trivial when real data are used, enabling more complex analysis to be undertaken. Nevertheless, the aim is to point out the opportunities offered by mobile phone network systems for the calculation of traffic data 'almost' in real time, and it has been shown that this technique constitutes a feasible method for obtaining such information. The complete contents of this research project are available in Caceres *et al.* [27].

8 Conclusions

The methods currently available for monitoring traffic tend to require the installation of ancillary devices along roadways (loop detectors, cameras and so on), which, along with the costs of installation and maintenance, render alternative techniques more attractive. This research project has demonstrated a new methodology to infer traffic data, such as journey OD matrices or traffic counts at given points in the road network. The technique involves analysis of anonymous phone location data in a mobile phone network, and preliminary results have shown that the method has great potential, having produced reasonably precise estimation results.

The estimation of traffic data has been carried out using non-real data generated by a simulator of vehicular traffic and phones along a stretch of the road network. These simulated data comprise phone location data, which form the source for the development of this new technique. However, the use of real data instead of simulated data would give even greater relevance to this methodology. Real data use would require the collaboration of one of the mobile phone operators in supplying the location data needed. This kind of co-operation will be crucial for the future development of this technique. Cell-phone operators know the location of their clients at any time so as to provide them with a proper service. If one of the operators were to offer to provide such data, this would constitute a very important source of information for the purposes of extracting traffic data, since it would represent complete and real information on phone movements.

Latest published statistics indicate that 89.4% of the Spanish population has access to a mobile phone. Although the use of cell-phones while driving is unacceptable, the mere presence of a switched-on phone on-board a vehicle is sufficient to convert it into a research 'probe' for capturing traffic data. In fact, the idea that all vehicles carrying mobile phones on-board can form efficient traffic monitors is surprising, as this would significantly improve traditional methods of data collection.

The fundamental advantage of this new technique lies in the possibility of estimating traffic data with a certain degree of automaticity and immediacy and avoiding the need for installing ancillary devices along the road network or the use of other costly methods such as traffic surveys. The employment of mobile phone data is a potentially inexpensive solution for the collection of traffic data. For instance, as each vehicle is likely to have a cell-phone on-board belonging to one or other of its occupants, the cost of equipping the cars involved is minimal. Furthermore, unlike the use of fixed sensor networks, mobile phones provide data on traffic behaviour in any zone with GSM coverage, without the need for mounting additional infrastructure along the various stretches of roadway. In addition, the supply of traffic data via mobile phones is not impaired by low-visibility weather conditions (as is the case with other methods such as licence-plate reading), nor does it suffer from the deterioration of sensor equipment (loop detectors, cameras and so on) installed along highways.

Consequently, and bearing in mind the fact that the process is automatic and, to a certain extent, immediate, this technique based on cell-phone data represents a major revolution in traffic mobility research, with the further possibility of providing an immediate response to such problems as may arise.

9 Acknowledgments

This project has been financed by the Ministry for Public Works (Ministerio de Fomento) through the programme 'Aid for I + D Projects in the Transport Sector' (Ayudas a la Realización de Proyectos I + D en el Área de Transportes FOM/486/2003).

10 References

1 Townsend, A.M.: 'Mobile Communications in the 21st Century City' in Brown, B., Green, N., and Harper, R. (Eds.): 'The wireless world: social and interactional aspects of the mobile age' (Springer-Verlag, Berlin, 2001)
2 Bolla, R., Davoli, F., and Giordano, F.: 'Estimating road traffic parameters from mobile communications'. 7th World Congress on ITS, Torino, Italy, 2000
3 Lovell, D.J.: 'Accuracy of speed measurements from cellular phone vehicle location systems', *ITS J.*, 2001, **6**, (4), pp. 303–325
4 Smith, B.L., Pack, M.L., Lovell, D.J., and Sermons, M.W.: 'Transportation management applications of anonymous mobile call sampling'. Proc 11th Annual Meeting of ITS America, Miami, FL, 2001
5 Sohn, K.: 'Dynamic estimation of origin–destination flows using cell phones as probes' SDI 2004-R-04, Department of Urban Transportation, Seoul Development Institute, Korea, 2004

6 Akin, D., and Sisiopiku, V.P.: 'Estimating origin–destination matrices using location information from cell phones,'. Proc. 49th Annual North American Meetings of The Regional Science Association Int, Puerto Rico, 2002

7 Cayford, R., and Johnson, T.: 'Operational parameters affecting use of anonymous cell phone tracking for generating traffic information'. Proc. Transportation Research Board 82nd Annual Meeting, Washington, DC, 2003

8 Ahas, R., and Ülar, M.: 'Location based services – new challenges for planning and public administration?', *Futures*, 2005, **37**, (6), pp. 547–561

9 Rose, G.: 'Mobile phones as traffic probes' (Institute of Transport Studies, Department of Civil Engineering, Monash University, Australia, 2004)

10 Ratti, C., Pulselli, R.M., Williams, S., and Frenchman, D.: 'Mobile landscapes: using location data from cell-phones for urban analysis', *Environ. Plan. B – Plan. Des.*, **33**, (5), pp. 727–748

11 (SENSEable City Laboratory, MIT: 'Mobile landscape, Graz in real time', Available at: http://senseable.mit.edu/graz/

12 (LogicaCMG – Mobile Traffic Service (MTS): Available at: http://www.mts-live.com

13 Vodafone Group – Features: 'Case study: relieving traffic congestion in Portugal and the Netherlands, May 2004. Available at: http://www.vodafone.com/article/0,3029,OPCO%253D40000%2526CATEGORY_ID%253D213%2526MT_ID%253Dfa%2526LANGUAGE_ID%253D0%2526CONTENT_ID%253D233430,00.html

14 ITIS Holdings – Press Releases. Available at: http://www.itisholdings.com/pdf/itisproximus.pdf http://www.itisholdings.com/pdf/,Interim_Results_24th_November_2005.pdf

15 White, J.K., and Gower, P. 'Collecting origin-destination information from cellular phone location data' Transport Research Laboratory, 1999, unpublished report

16 White, J., and Wells, I.: 'Extracting origin destination information from mobile phone data'. 11th Int. Conf. on Road Transport Information and Control (Conf. Publ. No. 486), London, March, 2002, pp. 30–34

17 Ygnace, J.-L. 'Travel time/speed estimates on the French rhone corridor network using cellular phones as probes': Final report of the SERTI V program, INSERTS, Lyon, France, 2001

18 Kummala, J. 'Travel time service utilising mobile phones': Finnish Road Administration Finnra Report 55/2002 Helsinki, 2002, p. 67

19 Virtanen, J. 'Mobile phones as probes in travel time monitoring', Finnish Road Administration, 2002

20 Alger, M.: 'Smith institute: real-time traffic monitoring using mobile phone data' 2004, Available at: http://www.smithinst.ac.uk/Projects/ESGI49/ESGI49-Vodafone

21 Thiessenhusen, K.-U., Schäfer, R.-P., and Lang, T. 'Traffic data from cell phones: a comparison with loops and probe vehicle data', Institute of Transport Research, German Aerospace Center, Germany, 2003

22 Decell Technologies Ltd: 'AutoRoute1: real-time route guidance' Decell Ltd, Israel. Available at: http://www.decell.com/autoroute1/real_time.htm

23 Airsage – Press Releases: 'Using cellular technology to provide an intelligent traffic roadmap', Available at: www.airsage.com/assets/AirSageExecutiveSummary.pdf

24 Airsage – Press Releases: 'Cell phones could keep you out of traffic jams', Available at: www.airsage.com/assets/Virginian_Pilot_4_27_05.pdf

25 Delcan Corporation – Press releases: 'Delcan.NET and ITIS holdings in partnership', Available at: http://www.delcan.com/prod/index.php?id=291

26 Delcan Corporation – Press releases: 'Traveler information derived from cell phones begins to flow from innovative public–private partnership in baltimore', April 2005. Available at: http://www.delcan.com/prod/index.php?id=295

27 Caceres, N., *et al.*: 'Herramienta para la Inferencia y Actualización de Matrices OD de Movilidad a través de datos de Telefonía Celular,' (Ingeniería e Infraestructura de los Transportes, Escuela Superior de Ingenieros, Sevilla, 2005), ISBN: 84-88783-77-9