Travel prediction methodology in medium-sized cities with GIS-T: maximum to minimum cost disaggregation

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Abstract

This paper describes the design of a traffic assignment model that predicts flows for each segment of an urban network with a higher resolution than a traditional four stage model, retaining the origins and destinations of travel. The research objectives are to determine the traffic intensity in specific areas of the network, and then to identify the origins and destinations of travel to predict changes in urban mobility. To achieve these objectives, relational databases and the geographic information system for transport environment are used (GIS-T), together with data from household and intercept interviews, to identify mobility patterns in the middle-sized city of Mérida, Spain. These application programs can detect changes in the mobility patterns and can locate problem areas. The results obtained show a high degree of adjustment between the predictions and the actual observations of the trips. In addition, the disaggregation levels in each midpoint section of the network combined with population data adjustment using population pyramids avoid bias in the travel samples.

Keywords: network analysis; origin/destination matrix; assignment models; GIS.

Resumen

Metodología de predicción de viajes en ciudades medias con GIS-T: desagregación máxima a coste mínimo

Este artículo describe el diseño de un modelo de asignación de tráfico que predice flujos para cada segmento de una red urbana, con una mayor exactitud que el modelo tradicional de cuatro etapas, conservando además los orígenes y destinos de viaje. Los objetivos de investigación son determinar la intensidad de tráfico en áreas específicas de la red, e identificar los orígenes y destinos de los viajes para predecir cambios en la movilidad urbana. Para lograr estos objetivos, se utilizan bases de datos relacionales y un sistema de información geográfico con los que analizar la oferta de transporte (GIS-T). Este entorno de trabajo se completa con datos de entrevistas a hogares y encuestas de intercepción, para identificar los patrones de movilidad en la ciudad de

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tamaño medio de Mérida, España. Estos programas de aplicación pueden detectar cambios en los patrones de movilidad y localizar áreas problemáticas. Los resultados obtenidos demuestran un alto grado de ajuste entre las predicciones y las observaciones de los viajes. Además, los niveles de desagregación en cada sección del punto medio de la red combinada con el ajuste de datos de población mediante pirámides de población, evitan sesgos en las muestras de viaje.

Palabras clave: análisis de redes; matriz origen/destino; modelos de asignación; GIS.

Résumé

Prédictions dans les villes moyennes de voyage avec environnement SIG pour le transport: ventilation maximale avec le minimum de coût

Cet article décrit la conception d'un modèle d'affectation de dynamiques de la circulation qui prédit les flux ventilées pour chaque segment d'un réseau urbain, tout en conservant les origines et les destinations de voyage. Les objectifs de recherche sont de déterminer l'intensité du trafic dans des zones spécifiques du réseau, puis d'identifier les origines et les destinations de voyage pour prévoir les changements dans la mobilité urbaine. Pour atteindre ces objectifs, bases de données relationnelles et le système d'information géographique pour l'environnement de transport sont utilisés (GIS-T), ainsi que les données tirées des entrevues de ménage et ordonnée à l'origine, pour identifier les modèles de mobilité dans la taille moyenne ville de Mérida, en Espagne. Ces programmes d'application peuvent détecter des changements dans les schémas de mobilité et peuvent localiser les zones à problèmes. Les résultats obtenus montrent un haut degré d'ajustement entre les prédictions et les observations réelles de l'accord sur les ADPIC. En outre, les niveaux de catégorisation dans chaque section du point médian du réseau combiné avec ajustement de données de population à l'aide de pyramides de population permet d'éviter les biais dans les échantillons de voyage.

Mots clés: Analyse réseau; matrice d'origine et de destination; modèles d'affectation; SIG.

1. Introduction

Urban traffic models are very useful for trip estimation, identification of travel routes and efficient management of urban mobility in middle-sized cities (which have populations of between 20,000 and 150,000 inhabitants, according to sources such as the European Middle Cities Network (CIUMED)). In addition, these models are intended to be used as tools to simulate traffic scenarios to determine how they influence certain specific changes in the traffic.

Also, with the gradual increase in the numbers of sustainable urban mobility plans (SUMPs) that have been designed in many European cities in this century as diagnostic tools, these models can identify mobility problems and can give more realistic results if they use fact-based modeling to manage the derived information.

Traditionally, this type of model design (whether the models are based on the classic four-stage model or on sub-models) has been addressed by traffic engineering using mathematical and statistical functions to estimate the demand (number of trips by each transport mode) or to offer the probability that a user chooses a route according to their departure time, mode of transport and motive of trip selected, depending on each case. This work has been associated with increasing specialization and the increasing numbers of application programs based on modeling (e.g.

TransCAD, EMME) that require a high degree of specialization and associated human costs, with license fees being equally important (Caliper, 2014; ESRI, 2014; gvSIG, 2014).

This level of human specialization is not important in generic geographic information system (GIS) environments. These applications were not used in transportation planning until the end of the twentieth century, despite their good network analysis tools (called GIS for Transport or GIS-T). When they were adopted, there was no preferred option in these model works for GIS applications. Nevertheless, GIS-T environments have been focused almost exclusively on the optimal location of facilities and calculating minimum cost routes or service areas for specific equipment (Murray and Tong, 2009; Lei and Church, 2010; Rybarczyk and Wu, 2010; Delmelle *et al.*, 2012). However, few studies have applied these generic GIS environments with relational databases to the design of models containing estimated trips (Cardozo *et al.*, 2012).

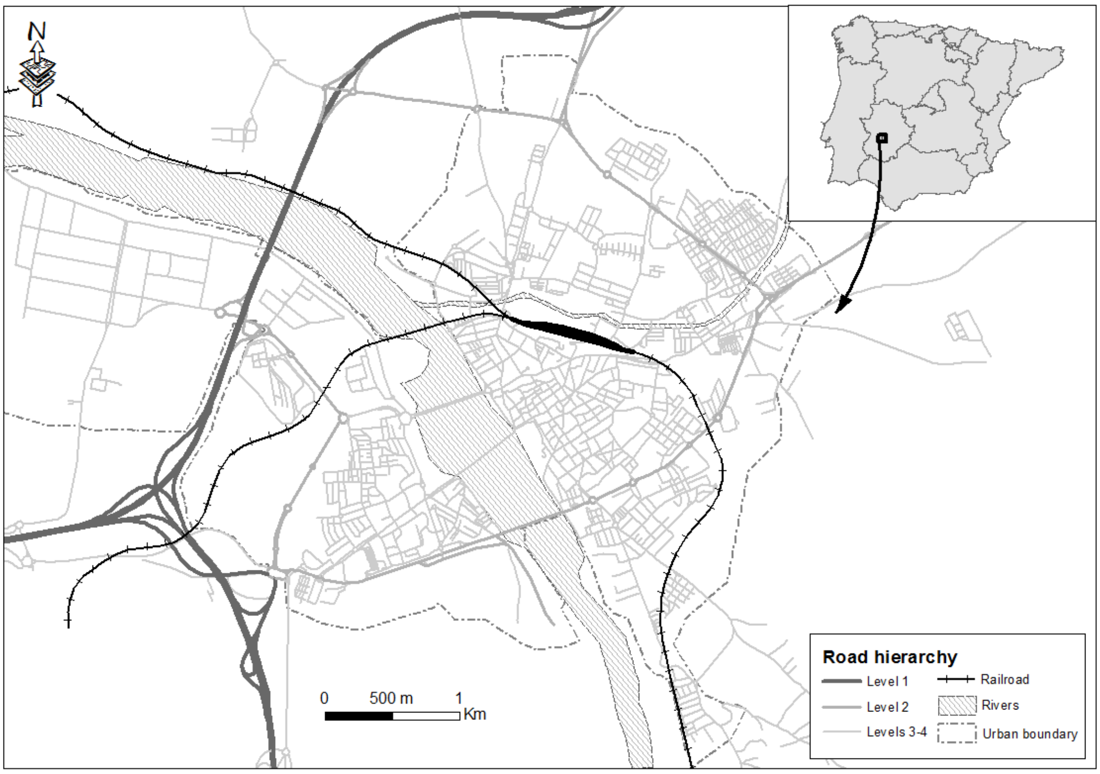
Planners and decision makers must be able to easily understand the limitations of the data derived from a SUMP, which will provide a simpler and less expensive design methodology to estimate the travel patterns (or assignments) offered in this article. This technique helps the users to manage all the information and offers real alternatives to the specific cases of congestion that are detected in medium-sized cities. The proposed system is based on the use of generic GIS environments and relational databases, which will greatly reduce the economic and human costs associated with maintaining accurate results. In addition, these issues must be highlighted in terms of the level of information disaggregation; while other assignment models are based on a centroid disaggregation level, this study is carried out at the midpoint level of each road section, which greatly increases the accuracy of its predictions. Another interesting contribution of this model is the simplified route selection process; it changes the tree route design that is used in traditional planning to obtain optimal routes (including mapping) using the GIS networks.

The proposed model is implemented in the study area of Mérida. Helpful local information has been used for the development of the model, including the volumes of movement patterns at the household level and multiple traffic count points that were strategically located around the city on two sample trips to provide *a municipal pilot project to promote sustainable mobility in Mérida* (Mérida's SUMP). Specifically, the study has focused only on the period when the highest traffic intensity is detected (i.e., the peak hour between 14:00 and 15:00) and the most problematic mode of transport used in the city, which is the owner-driven car (Gutiérrez, 2011).

Mérida is a middle-sized city located in the south-central region of Extremadura, Spain. It has a population of 57,173 inhabitants, according to the Spanish National Statistics Institute (INE, 2011) and the city's public parking lots have 42,194 spaces compared with the population's 28,475 private vehicles (Statistical Yearbook of La Caixa, 2011). This represents an urban motorization rate with respect to private vehicles of 0.50 vehicles per inhabitant (veh/inhab) that is slightly above the European average of 0.48 veh/inhab (EMTA, 2012). This rate indicates that Mérida, in terms of its urban area and population, has a volume of private vehicles that is similar to that of other European cities, based on the analysis of information in European reports.

As shown in Map 1, this city has certain barriers that make normal mobility difficult for its users: its geographical location between the Guadiana and Albarregas rivers have restricted urban growth tremendously and has influenced its urban morphology. Thus, a large part of its network morphology (which is a legacy of Roman, Visigoth and Arabian cultures) causes a reduction in high traffic flows, depending on the means of transportation used (narrow roads and unidirectional pathways are the dominant trends in this environment, with the consequence that there is a high degree of circulatory guidance in the network). Finally, the role of the city as a regional and tourist capital attracts large numbers of visitors (according to SUMP studies, the daily floating population is approximately 5,000 people), which causes further circulatory traffic congestion problems, parking problems, noise and environmental pollution, and stress.

Map 1. Location map of Mérida



Source: The authors.

To solve and anticipate these types of problems, this research describes a deterministic assignment model, in which the following objectives have been proposed: 1) determination of the number of shifts that run through each of the sections (a segment of way that is bounded by two intersections) that belong to Mérida's urban network; (2) determination of the origin and destination of each of these movements; and (3) an ability to predict changes in urban mobility to enable timely modifications to be offered.

These objectives are achieved by applying a methodology that is based on the classification of the modeling tasks in different phases by following a scheme that is similar to the traditional *four-stage-model* or FSM (Willumsen *et al.*, 2008). The purpose of this classification methodology is not to generate a simulated global transport model, but to provide a sub-model for mapping and estimation of travel that also allows the information with regard to the travel origins and destinations to be retained (the traditional model is only used to organize the tasks of the process). The last two phases of the four stages of physical modeling, generation/attraction, distribution and allocation of travel stand out in this work: the distribution, by trying to determine travel from the midway point of each section, substantially improves the accuracy of the determination of the matrix of trips (the origin-destination matrix, O/D) and that of the model in question (this matrix is composed from the results of household surveys in each of the neighborhoods), while the significance of the allocation of travel lies in the fact that the allocation of these trips to the network is carried out using the minimum cost routes calculated using the GIS environment. In addition, the relational database allows the total number of sample trips to be expanded in a simple way by linking with the sample population that was obtained from the National Institute of Statistics (NIS). Finally, the proposed travel estimation model offers results that are close to the observed traffic flows, as shown in the adjustment method section of this paper.

In Section 2, after we describe the general specifications of the proposed model, a brief state of the art overview gives an explanation of how this model relates to urban modeling and its applications in Mérida. Then, Section 3 describes the methodology for each of the processes carried out in the design. This section is divided into several sections, including physical modeling, the distribution of urban flows and the mapping of these flows to the network. Finally, the results, discussion and conclusions about the methodological design are given in Sections 4, 5 and 6, respectively.

2. State of the art

Over the last 30 years, medium-sized European cities have copied the Anglo-Saxon urban growth model, which are mainly characterized by increasing expansion into fringes of the city, away from the original town center. This leads to decentralization of the services and specializations (e.g., industrial, recreational, residential) that are located in environments near main roads (Brueckner, 2000; Dombriz, 2009). This trend has been further matched by changes in the mobility patterns of the users of these services (Seguí and Martinez, 2004; Pozueta and Gurovich, 2007; Monzón, 2009): an exponential increase in the numbers of trips and distances traveled (Steg and Gifford, 2005; Ortúzar and Willumsen, 2008) was detected, together with abusive use patterns for private vehicles with occupation levels close to 1.2 passengers per vehicle (Dombriz *et al.*, 2008).

These new mobility patterns cause specific problems that must be addressed by planners and decision-makers: traffic congestion (Camagni *et al.*, 2002; Cameron *et al.*, 2003), acoustic and atmospheric pollution (Lyons *et al.*, 2003; Barr and Prillwitz, 2012), reduced security during trips (Hadayeghi *et al.*, 2003), parking problems (Dijk and Montalvo, 2011) and increasing health problems and need for access to social services (Bocarejo and Oviedo, 2012), which coexist with the need to offer different transport modes to users who do not have private vehicles (Boschmann and Brady, 2013). To mitigate these problems and achieve more sustainable mobility, the European Union (EU), since the late 20th century, has been urging all public agents to implement actions to effect changes in urban mobility for the benefit of the residential population (CEC, 1996, 2006 and 2011; Kenworthy and Laube, 1999; EC, 2007; CEC, 2007; Directive 34CE, 2007; Mora *et al.*, 2010). The aim is to provide a more equitable travel distribution between the transportation modes offered, giving greater weight to collection and sustainability (mainly for pedestrian and collective modes), to reduce atmospheric and noise pollution, and to increase social equity in terms of universal access to all goods and services that are offered.

Another type of action that is intended to improve and optimize mobility in cities is the design of traffic management models (Gentile *et al.*, 2007; Sundaram *et al.*, 2011; Watling *et al.*, 2012; Peer *et al.*, 2012). These models involve simulation of the global dynamics of urban traffic through mathematical functions to obtain the volume of trips that traverse a particular area. These functions are related to the service level of each network segment, the generalized costs associated with daily trips in one or more modes of transport, and the potential demand to carry out these movements, which in turn refers to the behavior patterns with regard to the choice of route related to the demand (Cameron *et al.*, 2003; Ortúzar and Roman, 2003). The benefit of this type of model is that, based on these simulations, mobility managers can accurately predict the mobility guidelines that are followed by the users of an urban system, meaning that they can anticipate potential problems arising from a change in supply point (Fernández *et al.*, 2003; Ben-Akiva *et al.*, 2012).

This greatly improves the decision-making processes and adjusts the mobility demand to match the existing transport offered, thus rationalizing the urban system and making it more sustainable. Some clear examples in this respect have been shown in European cities such as Grenoble, Genoa and Tarrasa, where the implementation of rationalization methods in mobility have been represented by a 28% reduction in road accidents, 20–50% reduction in the private traffic in central urban areas, and an 8–10% reduction in air pollution levels (Velázquez and Estebaranz, 2011). Economically, the costs that result from deficient optimization of the traffic in a city can exceed 3 million dollars per minute of delay in private transport modes and 34 million dollars per minute of delay in the case of public transport modes (Robles *et al.*, 2009).

Transport engineering has traditionally been responsible for the design and implementation of different modeling processes, which in many cases are based on the FSM (Ortúzar and Willumsen, 2008). However, in recent years, an increasing number of studies aimed to unify the various stages of the FSM into a single step through the generation of an objective function that minimizes the usefulness of the trip (Zargari *et al.*, 2009; Pel *et al.*, 2012; Pohlmann and Friedrich, 2013). In addition, there is also a tendency to generate sub-models for transportation that treat the problems of each of these phases in a discreet manner, i.e. without contemplating the sequential FSM design (Wen-Long, 2007; Yim *et al.*, 2011; Lu *et al.*, 2013). Among these sub-models, several are related to dynamic traffic assignment (DTA), which is based on a simulation that allows mobility patterns to be represented over a certain period of time by assignment of an array of trips to a route group with widespread travel costs that are lower than the remaining alternatives (Peeta and Ziliaskopoulos, 2001; Szeto and Lo, 2006; Juran *et al.*, 2009).

Simulation-based models represent a highly appropriate technique for travel estimation on the various tracks of an urban network, because they take the experience gained by users in their usual travels and the characteristics of the network (e.g. level of service, speed limit) into account. The level of adjustment between the predictions of these models and the observed results is usually high. Within this type of technique, consideration of how different individuals travel requires the inclusion of dynamic models. These results demonstrate in more accurate estimates if it is possible to identify the user behavior when a particular event occurs in the network, such as a restriction to one-way traffic (Cascetta and Cantarella, 1993; Long *et al.*, 2011). However, DTA models still have some limitations (Ran *et al.*, 1992; Nie, 2010; Ben-Akiva *et al.*, 2012); the implementation of these models in traffic assignment is not as efficient as the use of other techniques and it is difficult to replicate the network congestion realistically.

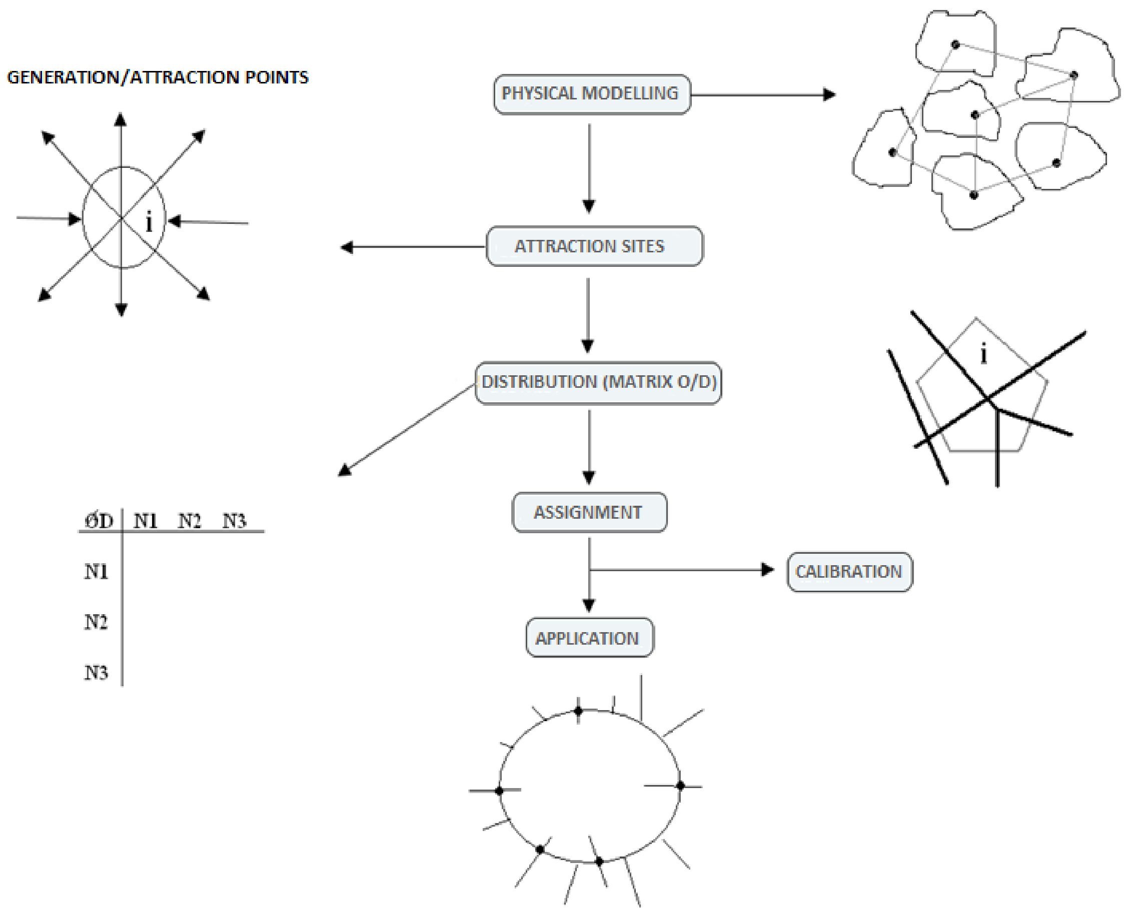
One issue that is attracting increasing interest among researchers is the fact that GIS applications and relational databases have not been used together to design models that determine traffic flows and travel times for each O/D pair. This kind of application can accelerate some design tasks, making them more understandable and intuitive (Chen *et al.*, 2011). Another highlight of the use of these applications is that they allow users to work with external information from the modeling process to improve decision-making and enable follow-up on actions arising from projects such as SUMP.

Taking the premises above into account, while designs that use GIS applications linked to these tasks are currently beginning to appear, it is not easy to find references to this aspect in the literature (Mora *et al.*, 2003; Gutierrez *et al.*, 2008 and 2011; Chen *et al.*, 2011; Scott and He, 2012; Garcia-Palomares *et al.*, 2012). The efforts of these researchers are usually related to user demand to access various services and facilities, such as metro stations or bicycle rental (Suárez-Vega *et al.*, 2012). The most outstanding aspect of these studies is that they are based on information obtained from field surveys and traffic assessments (Ibeas, 2007), which are then used to design a model that relates the variables that were previously collected through the relational databases.

3. Materials and methods

The assignment model proposed in this paper is deterministic and its spatial predictions are higher than the traditional four stage model. It includes only private vehicle trips made by the residents of Mérida in the peak hour period between 14:00 and 15:00.

Picture 1. Methodological assignment of model design scheme



Source: The authors.

To achieve the objectives outlined in this paper, it is necessary to perform several different tasks, as mentioned above. These tasks are divided into several groups based on a scheme similar to that of the FSM. However, it should be again clarified that the authors do not intend to claim that this could be a global transport model; the sole purpose of these phases is logical organization of the design tasks, which will be the final assignment process.

As shown in the diagram in Picture 1, all stages that lead into the modeling process are described in the following sections.

3.1. Physical modeling process

In this first stage, we carried out the work to obtain the cartographic base upon which the assignment model and the removal of the existing demand in the urban network are overlaid. The latter was obtained through field intensity measurements carried out in two different seasons (July and September 2009) to take the seasonality of urban movements into account.

For the traffic intensity, the average numbers of trips made by the resident population from the various possible origins to the available destinations were calculated. We also analyzed the main points of external access to the city and the intersections, which occupy strategic positions and regulate most urban flows. All this information was stored in a relational database for use in subsequent stages to validate and calibrate the assignment model.

To implement the previous capacity on the proposed model and identify the minimum cost routes for each origin-destination pair, it is necessary to have an urban map that represents the real road network under study. In this case, we have a ramified road network, and must consider topological information and movement directions for subsequent calculation of the minimum cost route. With regard to the disaggregation of the travel, treatment is performed at the individual level, while the origin-destination location process is at the level of the midpoints of each section network in the case of travel related to homes and at specific locations in the cases of services and facilities. This mapping is also used to present the final results of the model, comparing the predicted travel with the observations made in field (i.e. traffic intensity). The cartographic format used is *shapefile* (.shp), which is very common in GIS applications.

The model mapping base consists initially of an urban road network. This information layer includes data relating to the directions of the roads, the maximum speeds and impedances, and the resistance that is offered by every stretch of road to be crossed by users during their trips. For physical corrections, digital ortho-imagery provided by the Extremadura Government (2007) was taken into account.

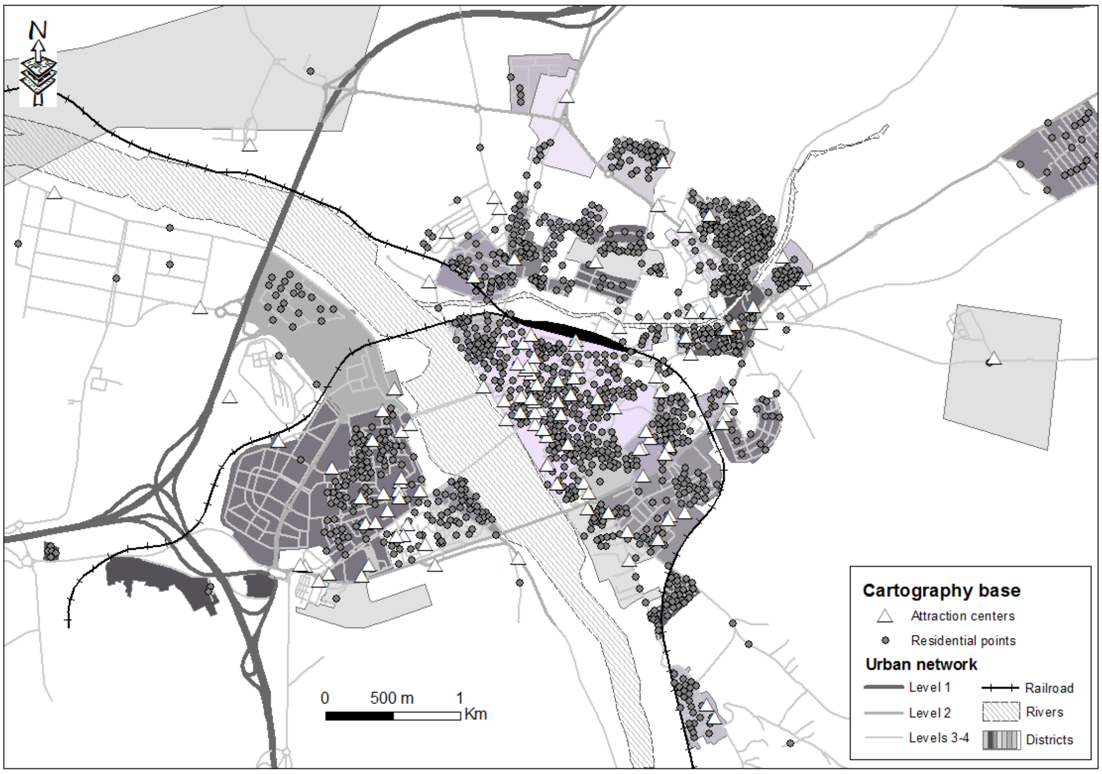
The model also provides cartographic information related to the locations of the residential population, where information related to the numbers of inhabitants residing in each track section and the numbers of portals existing in the same section is stored. These data are derived from the municipal register of the Council of Mérida, while adjusting the total population to match the number given by the annual official register of the NIS, relative to the year 2009. Then, the model generates a point-type mapping, which is grouped in the central points of each section for the inhabitants living in that section. In this way, the model reduces calculation costs and simplifies the information, assuming an acceptable level of miscalculation. At each point in a section, the model includes both the sum of the resident population and the number of existing portals (however, the initial locations of the residents in terms of the portals are stored because this information is useful when obtaining the O/D matrix).

The classification of the city into neighborhoods is another fundamental aspect that is taken into account in the mapping base. Each zone will have a name, a surface and a resident population. This layer allows the model to aggregate results and to adjust the samples obtained in the field.

The layer of external displacement points aggregates all information related to the numbers of visitors to Mérida for various reasons, e.g. work, leisure, health, or studies. In this case, for each point, the model brings together the population that access Mérida by each of the access routes, based on the location of the core population and the minimum cost path used to reach the city in the case study.

The final mapping element that is considered in this model is the facilities centers, where information is stored on the fixed volume of workers/users that access each service and the location of that service in the city. This is an essential layer used to address the facilities that attract the majority of urban movements within the city. This layer brings together different types of centers: residential population and external population attraction centers (Map 2). For this mapping, a pre-selection process is carried out for centers with outstanding attraction potential and which therefore causes high volumes of travel within the city (e.g. basic services such as shopping centers, regional and local administration offices, and health, educational and leisure centers).

Map 2. Cartographic base used to design the urban assignment model



Source: The authors.

The next stage is to design and calculate all required parameters for the proposed assignment model, using its own GIS applications and relational databases (Microsoft Access database, 2007 version), as an alternative to the traditional approaches based on the use of statistical programming applications.

3.2. Trip distribution

To calculate the existing trip distribution in Mérida, it is necessary to design a household interview method, which allows us to obtain a statistically representative sample of the daily travels for each O/D pair in the city (i.e., the O/D matrix). In this work, the minimum sample size is determined by considering the distribution of the existing population throughout the city and the number of portals (entrance hall or main entry) that are located in each neighborhood. Because it would be excessively expensive to consider the residents on an individual level for this sample, we opted to work with the portals, surveying all autonomous mobile residents in each randomly selected portal (from which the volume of movement patterns used in the model are obtained). In this study, the term «autonomous mobility» refers to a resident that uses his/her own means and modes of transport without anyone else in the family unit who would move together (in this way, young children are not taken into account when conducting the survey because analysis shows that these children are transported by their parents and, in such a case, their movements are made later).

In parallel with the sampling work, a template is designed to interview the resident members of each selected household. Basically, a group of questions is provided to be completed by each interviewee on a questionnaire sheet. Subsequently, we implement and save all surveys in a database (Microsoft Access database, 2007 version) and, when the entire survey process is complete, the final O/D matrix is generated. This matrix contains all O/D pairs with recorded travels in the estimated time period (peak hour). The final travel sample obtained included 8,472 daily trips, from interviews with 2,220 inhabitants in 1,278 portals of the city.

3.2.1. Method to obtain the initial O/D matrix

To obtain the previous O/D sample matrix (the initial matrix), all origins and destinations in the zones of Mérida are considered, along with their equipment highlights from the viewpoint of mobility and all access points. In addition, the existing displacements in each O/D pair are analyzed for a single peak hour period (from 14:00 to 15:00), in which a higher volume of traffic on the network with larger numbers of trips is observed for obligatory reasons (work or study-related trips).

When a displacement sample was collected, we selected all O/D pairs with a volume of movement that was higher than or equal to 1, which significantly reduced the sample size and accelerated subsequent calculations. After this reduction, a series of validation and expansion tasks for the total population sample of trips were conducted to consider an adjusted estimate of the global flows in the proposed model for the analysis period.

3.2.2. Expansion of trips

The first validation process consists of correcting the bias detected in the sample, which was related to the age and gender of the residents. These two bias sources are related to the hours used in the survey (from 10:00 to 13:30 and from 16:00 to 21:00) because, at those times, the majority of the resident population is quite restricted (e.g. women of middle or old age who are dedicated exclusively to household activities). In these cases, it is very common practice to extrapolate travel based on the income level per household or the number of residents in each household. Alternatively, in this study, our procedure was to compare the interviewed sample population (Table 1) with the total population in terms of age group and gender using population pyramids (i.e., a sample pyramid vs. the population pyramid from the NIS for the same year, 2009). This procedure is followed to correct the two biases and also calculates expansion factors to convert the sample trips into total travels.

Table 1. Trip distribution sample by car at peak hour according to gender and age group

Age group	Male	Female	Total
15 to 19	4	3	7
20 to 24	8	10	18
25 to 29	10	14	24
30 to 34	16	26	42
35 to 39	32	30	62
40 to 44	30	36	66
45 to 49	18	26	44
50 to 54	29	10	39
55 to 59	25	9	34
60 to 64	16	2	18
65 to 69	6	0	6
70 to 74	2	0	2
Total	196	166	362

Source: The authors.

Thus, the adjustment procedure consists of following a series of steps. First, the total volume of trips in the peak hour is estimated by extrapolating the number of trips obtained in the sample to the whole population of Mérida. This step is performed using Eq. (1):

Equation 1.

$$Tot._{trips} = \frac{P_{Tot.} * v_{HP}}{P_{survey}}$$

where *Tot.trips* is the total number of trips made by the inhabitants of Mérida in the peak hour; *PTot* is the total population from the population pyramid of 2009; *vHP* is the number of trips taken in the peak hour from the household interviews; and *Psurvey* is the sample population that was interviewed.

Using the data extracted from the O/D matrix relative to the volume of trips (2,220), the volume for the same point is realized for the peak hour (362) and, by taking into account the resident population, which was estimated to be 56,395 inhabitants, a first approximation of the total number of trips in the peak hour (9,196) is obtained, which will be helpful for the next step.

In the second step, the sample trips are adjusted by taking the population pyramids (age groups and gender) into account. The volume of travel calculated using the previous expression (*Tot. trips*) is a gross value and must be adjusted by taking the age groups and gender from the population pyramid extracted from the NIS (2009) into account.

Table 2 shows the trip distribution when adjusted based on age and gender group, considering that only certain age groups can drive a private vehicle through the city.

Table 2. Trip distribution adjustments at peak hour by gender and age group

Age group	Male	Female	Total
15 to 19	110	96	206
20 to 24	233	343	576
25 to 29	378	462	840
30 to 34	490	583	1,072
35 to 39	724	595	1,319
40 to 44	706	711	1,417
45 to 49	363	419	782
50 to 54	478	167	645
55 to 59	422	175	596
60 to 64	234	19	252
65 to 69	94		94
70 to 74	39		39
Total	4,270	3,569	7,838

Source: The authors.

When the total number of trips in the peak hour has been adjusted (7,838), the estimate of the number of trips made for each specific O/D pair must be calculated using Eq. (2):

Equation 2.

$$v_{ij} = \frac{Tot._{trips} * vs_{ij}}{Tot._{trips}^{PHM}}$$

where *vij* is the trip distribution calculated for each origin *i* and destination *j* pair; *vsij* is the displacement volume sample detected for each origin *i* and destination *j* pair; and is the total number of trips made in the peak hour using a specific transport mode (in this case, in a private car).

The final result is an O/D matrix where the sample trips have been extrapolated to the population volume. This is the matrix from which travel will be assigned to the minimum cost paths, which are to be identified in the GIS environment, as will be described in the next section.

3.3. Assignment and calibration method

Tasks related to the assignment of trips on the different paths of the urban network refer mainly to implementation of the total travel identified in each O/D pair. Together with a number of the network segments, they form each of the routes where the cost of movement in private mode is minimal.

The assignment technique selected in this case is «all or nothing,» based on the large circulatory orientation in the urban network, which was inherited from the geographical location environment of the Albarregas and Guadiana rivers and the morphology of the original old town. This technique consists of assigning all movements of an O/D pair to a single path (i.e., the path where the travel costs are minimal), which is defined by a number of attributes of the road network (mainly the distance and the speed limit allowed for each section). The GIS environments and the «impedance» attribute that is assigned to each segment of the network are used to calculate the paths. The impedance means the minimum time taken to cross a section by any user in a specific transport mode (in the case of a private vehicle). This attribute allows a set of optimal routes (one per O/D pair) formed by a union of different network sections to be generated quickly and easily.

In this case, the impedance or displacement cost is calculated using a typical expression for straight and uniform movement, which is related to the maximum speed of passage through each section of the same length, as shown in Eq. (3):

Equation 3.

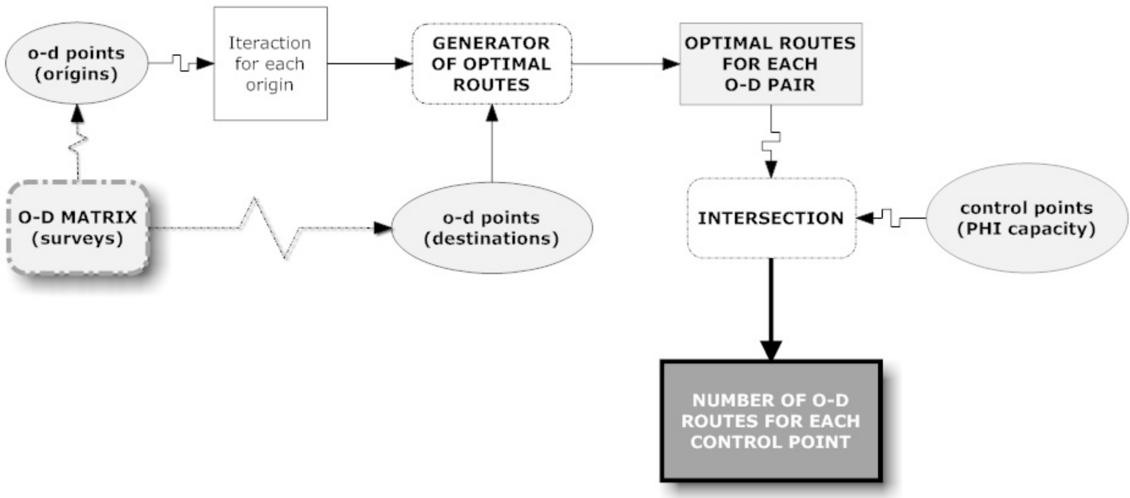
$$t_{(min.)} = \frac{l_{(km)}}{s_{(km/_{min.})}}$$

where *t(min.)* is the time in minutes taken to cross a specific segment of the network; *l(km)* is the length of each segment (in km); and *s(km/min.)* is the maximum speed allowed in this segment (measured in km/min).

In the route generation process, there is a characteristic that must be specified: in the case of residential areas or neighborhoods, they are taken to be origins and destinations in the neighborhood in themselves (i.e., classifying all origins to their specific zones). This process speeds up the model calculations in terms of routing.

In addition, with regard to the origin and destination points considered in the model, a number of affordable points that are strategically distributed by the city are considered. A series of traffic counts and classifications conducted by modes were performed during the analysis period to obtain the actual traffic volume of private vehicles crossing each area at the city control points. These control points are taken into account at the assignment stage for identification of the number of routes through each point. For this purpose, the GIS environment has its own tool, *Model Builder*, which begins from a set of input data (O/D matrix and road network) and allows different processes to be grouped together in the same time period.

Picture 2. Model Builder tool used to obtain the optimal routes



Source: The authors.

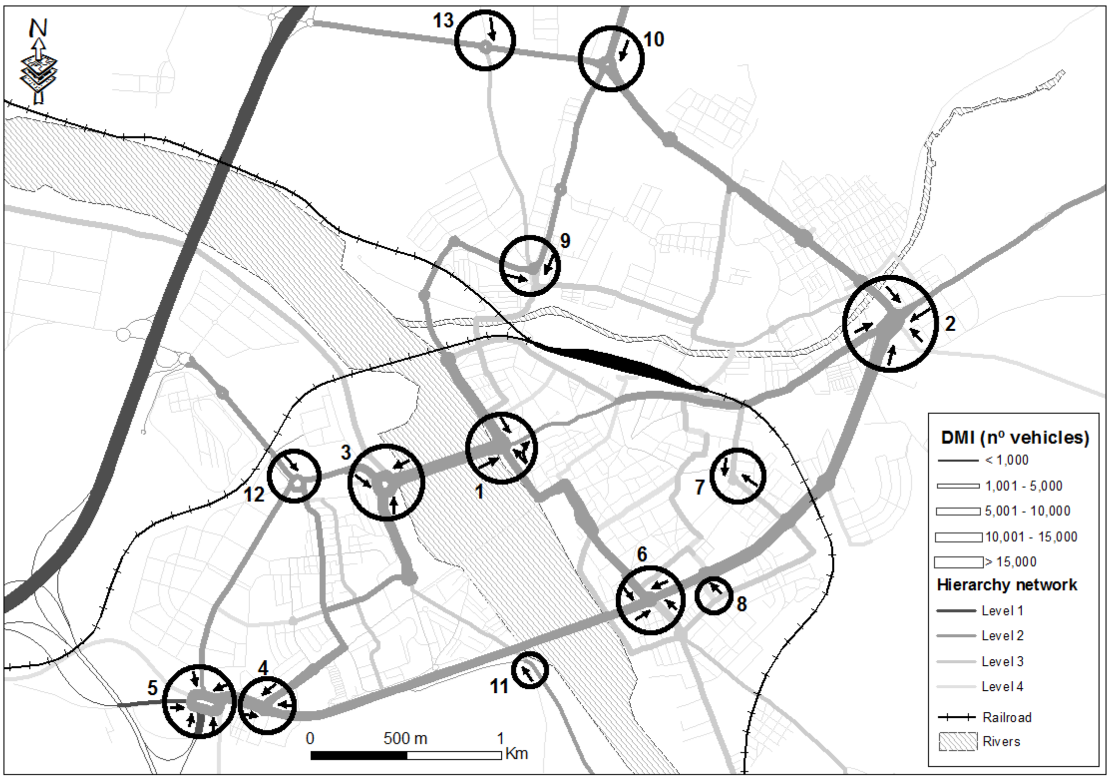
The *Model Builder* calculation process (Picture 2) basically identifies and counts the different routes that pass through each control point. In this process, *Model Builder* performs iterations to calculate routes that face towards each origin with their corresponding destinations. The preferred routes crossing each of the control points are counted in seconds. The benefit of this tool is that it performs all calculations simultaneously, thus reducing the model estimation time. It also dispenses with the intermediate generated information and prevents unnecessary storage.

The resulting information will be useful to relate the model to the trips O/D matrix calculated in Section 3.2.2 and to expand the travel. This relationship is based on a database, which is used to calculate the following: the travel adjustment of the initial O/D matrix; the distributions of the residential trips between the different midpoints of each zone (the disaggregation process); and the number of trips that cross each control point, while storing their origins and destinations.

With regard to the process of disaggregation of residential trips, it is important to mention the proportional distribution of the travel when both origin and destination are in the same neighborhood, which depends on the number of existing midpoints in each neighborhood and the resident population in the same volume.

The next step is to identify the proportion of the urban trips that have origin or destination areas outside the city, because a percentage of the daily flows are linked to the visitor population. Therefore, the intercept survey method is used for screening, involving selection of control points for the intercept network where the location is important for external detection (Map 3). This method also allows the validation of the routes.

Map 3. Identification of the control points selected for the intersection survey



Source: The authors.

In a similar manner to a household survey sample, a representative sample is calculated to intercept, in this case, the traffic volume experienced at the control points, relative to the two seasons cited at the beginning of this section (see Tables 3, 4 and 5).

Table 3. Diary means intensity from zone to poll

Access point	2.1	2.3	2.4	2.5	2.6	2.7	2.9	2.13	3.2	3.3	3.6	A2	P13
A	547	146	406	394	1,019	381	421	192	302	958	190	128	99
B	514	297	11	331	278	333	254	452	275	6	99		
C	576	293	628	105	828	887	494	263	85	1,145	447		
D	348	335	787	449	205	956	256	300	651	717	278		
E		164					248		779	340	35		
F		1,349								278	211		
G											104		
Total	1,985	2,584	1,832	1,279	2,330	2,557	1,673	1,207	2,092	3,444	1,364	128	99

Source: The authors.

From the data given in Table 3, the total number of surveys saved in each database is calculated.

Table 4. Number of surveys made in each intercept zone

Access point	2.1	2.3	2.4	2.5	2.6	2.7	2.9	2.13	3.2	3.3	3.6	A2	P13
N. of Surveys	92	93	91	89	92	93	91	89	92	93	90	55	49

Source: The authors.

Using the total number of surveys made at each interception point (Table 4), the number of surveys was proportionally distributed by taking the traffic detected at these points into account (Table 5).

Table 5. Distribution of surveys on basis of access points

Access point	2.1	2.3	2.4	2.5	2.6	2.7	2.9	2.13	3.2	3.3	3.6	A2	P13
A	25	5	20	28	40	14	23	14	13	26	12	55	49
B	24	11	1	23	11	12	14	33	12		7		
C	27	10	31	7	33	32	27	19	4	31	29		
D	16	12	39	31	8	35	14	22	29	19	18		
E		6					13		34	9	2		
F										8	14		
G											7		
Total	92	93	91	89	92	93	91	89	92	93	90	55	49

Source: The authors.

The final interception sample is 5% of the total traffic intensity, allowing for a 10% maximum error and assuming the worst case in the interception (p=0.5). When the field data has been taken, all the information is saved in a database and the external percentage of travels for each interview access can be obtained. This percentage is used to calibrate the model and determine the final volume of trips that is predicted by the assignment model.

The results that link the residential and external movements that cross each control point are exported to the GIS application using a common identifier. In this way, areas with prediction

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deficiencies are identified through visual inspections that provide us with a first approximation of the degree of reliability detected in the model.

4. Results

In this section, the main results obtained are shown after application of the previously described methodology for the case of Mérida. In one hand, if the trips predicted by the model are extended from the control points to the rest of the network analyzed, the routes obtained are more similar than real routes used by the inhabitants (Map 4 was compared with observed routes of Map 3). This confirms the right use of the assignment model in this research ('all or nothing' method). In the other hand, the interception of particular points allows us to calibrate these routes and obtain good results in this issue.

Map 4. Routes predicted by the model

Source: The authors.

The most important result for the prediction derived from the model is shown in Map 5. Although the prediction is performed throughout the city and values that have been adjusted at all control points are obtained, it is interesting to focus the analysis on the central town area, which recorded the biggest mobility problems for private vehicles.

Here, we can confirm that the degree of adjustment of the model is acceptable relative to the actual traffic intensity measured in the field (Table 6), because the total standard deviation for the trips is 36 (i.e. the average difference between the predictions and the actual capacities), with a coefficient of variation of 0.079. The average number of trips detected throughout the city during the peak hour between 14:00 and 15:00 is 450.

Map 5. Number of vehicles predicted in the peak hour by the model (veh/hr)

Source: The authors.

Table 6. Number of trips predicted in the peak hour by the model

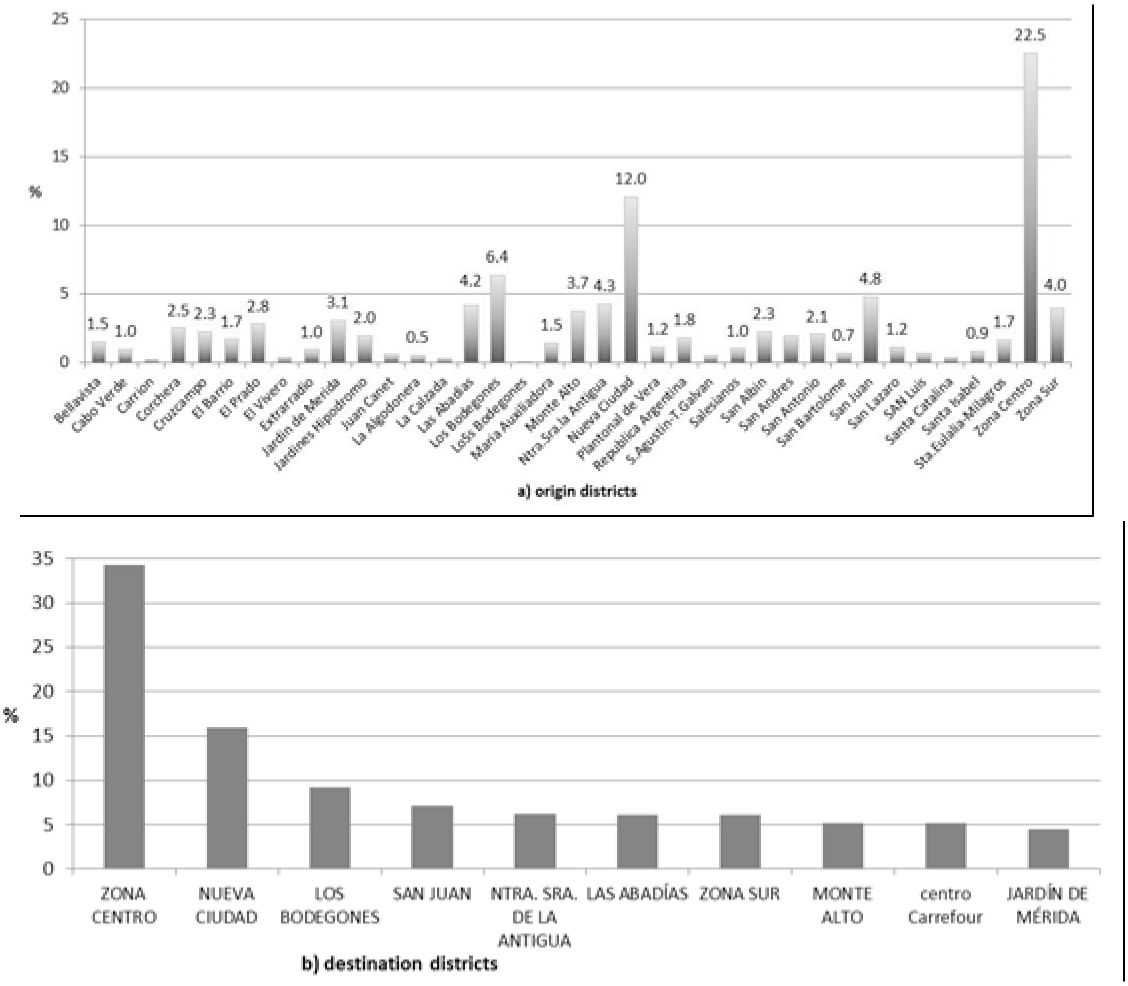
ID	Count	Predicted N. by model (residents)	External users %	Adjusted N. by model	Dif. of Trips
…	…	…	…	…	…
1	152	38	76.46	161	-9
2	764	613	20.62	772	-8
3	756	592	22.38	762	-6
4	434	271	38.38	439	-5
5	231	188	20.54	236	-5
6	852	605	29.39	856	-4
7	512	274	46.71	514	-2
8	394	625	26.78	396	-2
9	442	204	53.51	438	4
10	424	95	77.24	417	7
11	472	261	43.58	462	10
12	242	37	83.89	229	13
13	862	660	22.35	849	13
14	140	301	36.57	127	13
15	866	565	33.69	852	14
16	620	334	44.87	605	15
17	354	406	16.50	325	29
…	…	…	…	…	…
Mean of trips: 450		Standard deviation of error: 36 trips		Coef. of variation: 0.079	

Source: The authors.

For the specific case of the central urban area (Table 6), the average error barely admitted reaches 4 trips, with a standard deviation of 10.69 units. Three values were observed where the model overestimated the trips (the IDs are 8, 14 and 17); these three anomalous flows referred to Almendralejo Street via an urban road that crosses from the west to the east of the central urban area.

With regard to the main origins and destinations detected in the city (Graphics 1a and 1b), it should be noted that, after the household survey and the subsequent expansion to the total population, greater volumes were detected in the Center and New City Zones (the central and west regions of the town, respectively).

Graphic 1. Detected percentage ranges of origin and destination trips in the districts



Source: The authors.

Between the two main neighborhoods (i.e. the Center and the New City), the movements are divided into 34% of the trips at origin and 50% of the trips at the destination (these movements represent approximately 42% of the total trips in the city during the peak hour).

5. Discussion

Based on the results obtained in this paper, the proposed model clearly offers the possibility of predicting changes in the global dynamics of mobility. In addition, this model can analyze paths

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to and from a particular facility in the city or can determine areas of potential demand (an example of this is the generation of educational assignment areas by considering the number of available places in the schools and the residential locations of the potential students in the city).

The use of relational databases and generic GIS environments enables parts of the calculations used in the modeling processes, such as route generation or determination of the generalized cost of a trip, to be performed quickly and easily. These applications therefore offer the possibility of implementing external information from different areas to model mobility in the prediction process (e.g., environmental pollution data or accessibility indicators). All these processes offer the possibility of enriching the decision-making process and help to identify problems in which the spatial component is crucial to the understanding of the problem. In addition, it should not be forgotten that the use of this type of application is quite widespread in the specific programs of the Traffic Engineering Society (e.g., TransCAD, Transportation Planning Software by Calipe Corporation, or EMME version 4.1 by INRO). Thus, these GIS environments can be used by technicians and local mobility managers who may require this type of tool to carry out effective procedures to follow up on actions taken following implementation of SUMPs in middle-sized cities, similar to Mérida.

Apart from the simplicity of the design and of the interpretation of the results, the level of detail achieved in the treatment of the flows stands as another original contribution of this work. Considering the midpoints of each network segment as the sources and destinations of the residential movements greatly improves the calculation of the generalized travel costs and favors the detection of problem points on the routes. This feature in our deterministic and mesoscopic model has considerably improved the degree of accuracy with which each problem site is located. If we apply a number of models similar to the one proposed in this paper, they can be used as the origins and destinations of travel from the centroids of the different areas into which the city is divided.

In addition, the method of adjustment and expansion of the travels using the population pyramid of Mérida (NIS, 2009) is highlighted in this study. The expansion of the travels based on a comparison between population pyramids (i.e. with the sample with the population pyramid) ensures the validity of this process, regardless of the data available on household income levels that are usually used in these cases (in Mérida, the data collected from household incomes had a extremely low degree of acceptance among the members of the population that were interviewed, with null and void responses forming more than 70% of the sample). In addition to deriving the travel expansion factors, this procedure corrects any biases related to the gender and age of the respondents, making it a more representative sample of the overall travel. An added benefit of this method is that it identifies anomalous values in the sample to be eliminated during the adjustment calculations, which further improves the final results.

A new consideration to be highlighted in this study is related to the way in which we visualized and compared the predictions of the model with the observations made in the field. The spatial union of graphical information about the GIS environment outcomes eases the flow visualization and the detection of possible mismatches next to the location of the site in the network. In most cases, the mismatches between reality and the model are caused by differences between the optimum paths and the paths that were actually chosen by the users. These disagreements were mainly caused in Mérida by habitual behavior acquired in each user's travels.

For future research, the need to address intermodality as an element of the design of this type of model is evident, along with the need to reduce the execution costs, based on the GIS environment approach. In addition, it is possible to implement the level of service of each network segment indicated in the model. This would enable detection of sections that are congested at certain times, would offer alternative routes in this regard, and would thus ease the mobility problems of medium-sized towns.

6. Conclusions

Based on the results obtained here, we concluded that the proposed methodology was successful in its analysis of the mobility in a medium-sized city as a key study for SUMP design. This statement is justified from two points of view: on one hand, the degree of adjustment between actual and predicted values is high (the average difference between observations and predictions is 36 travels, and the coefficient of variation is 0.079); and on the other hand, the union between the attributive and geographical information through databases and the GIS environments enables successful predictions to be carried out. We can therefore say that the proposed model could successfully predict changes in the mobility patterns of users in a medium-sized urban system, with specific changes in the data offered.

Another peculiarity to highlight in this proposal is that, in the simulations, it is possible to store the origins and destinations of each of the analyzed urban movements, which is not allowed in any other traditional application modeling processes. This would be an important factor in more specific studies, where analysis of the impact of a problem could generate a timely change in a particular area of the city for the users that reside therein.

With regard to the origins and destinations of the trips made in the city, it was found that most of the trips are distributed between the Central and New Town neighborhoods (the central and west regions of the map, respectively). This is because these are the areas where the majority of the urban facilities (Central Zone) and the residential areas with the greatest volumes of population (New Town Zone) are concentrated.

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