Proposal of a New Methodology for Traffic Flows Estimation through the Optimization of the Device Location and the Route Enumeration

Fernando Álvarez-Bazo*
Santos Sánchez-Cambronero
Inmaculada Gallego
Department of Civil and Building Engineering, University of Castilla-La Mancha, 13071, Ciudad Real, Spain

ABSTRACT

In recent years, different techniques to address the problem of observability in traffic networks have been proposed in multiple research projects, being the technique based on the installation of automatic vehicle identification devices (AVI), one of the most successful in terms of results but to in turn, complex in terms of its combined use with other methods. Most of the current methods do not consider the possibility of installing a series of plate scanning devices in the elements of a network (nodes, links), such that they allow us to obtain a better definition of the O-D matrix and obtain a better set of data for the analysis and estimation of traffic flows for different scenarios. With these antecedents, a new methodology is proposed that jointly considers: 1) a device location model for a given traffic network according to criteria established by the analyst and, 2) a model that establish the best set of routes to be considered in the estimation step.
An example of the application of this methodology for a real study network in Ciudad Real is shown, where a sensitivity analysis is applied to test the influence of a set of relevant variables.

Keywords: Plate scanning; Sensor location problem; Traffic flow estimation

*Corresponding author: Fernando.AlvarezBazo@uclm.es

1. INTRODUCTION

The methods of defining travel demand or of the O-D matrix, whether static or dynamic dependent on time, are being approached from two different approaches (Toledo et al., 2015): direct methods of estimation based on surveys and indirect methods based on data obtained through instruments such as traffic counters or digital technologies such as mobile phone data and GPS.

In recent years, the technology of sensors or devices for identifying and counting vehicles in transport infrastructures has undergone significant advances that make them become useful tools in Intelligent Transport Systems (ITS). Current literature differs these devices into two large groups (Gentili and Mirchandani, 2012):

a) Passive sensors: Those who do not require vehicle information for their counting. It encompasses the most commonly used classic sensors such as loop detectors and detectors that are based on acoustic, infrared or shortwave signals or responses when passing a vehicle.

b) Active sensors: More sophisticated than the previous ones, since they require some information of the vehicle for its correct counting. These sensors are known as Automatic Vehicle Identification (AVI), and range from digital signal trackers and vehicle positioning to license plate readers.

The application of AVI devices in demand studies and monitoring of traffic networks is being widely used, especially for the quantification of travel times in linear corridors and, to a lesser extent, in urban traffic networks, relying on the use of other devices and existing techniques within the first group. Within the AVI devices we find the license plate scanning devices, which allow the identification and counting of vehicles through the reading of their license plates.

The main technical advantage of license plate scanning is that it allows to obtain better results of flow estimation compared to other techniques used, under the conditions of the modeling of the traffic network and the number of scanning devices available for carrying out such studies. In order to verify this and other advantages that involve the use of the data obtained by scanning the license plates, several studies have been carried out drawing the following conclusions: i) direct calculation of traffic flows through direct observation of the network (Castillo et al., 2008); ii) more information collected translated into a system with more flow equations; iii) possibility of total observability of the traffic network according to the available number of devices (Mínguez et al., 2010); iv) Combination with other counting techniques to specify the results (Castillo et al. 2012); and v) Possibility of quantifying travel times in traffic networks if the location of devices is adequate (Sánchez-Cambronero et al., 2017).

In spite of the advantages offered by this methodology, it is not yet fully adaptable to current traffic network modeling techniques, and many of them continue to base modeling on the use of centroids and connectors. Based on the latter, Sánchez-Cambronero et al. (2016) proposed a technique that minimizes the negative effects of the use of centroids and connectors in the network design, by replacing them with "origin nodes" and "destination nodes" in such a way that all trip origins and destinations are assigned to these nodes in accordance with the vehicles paths and the network shape. To this it is necessary to add the need for an exhaustive number of routes, a necessary input for a model based on the license plate scanning technique. About this, a route enumeration model is introduced in this methodology, so that the location of the devices in the network can be optimized by means of a location model and the subsequent estimation of traffic flows.

This paper describes an innovative methodology that integrates the estimation of traffic flows from the data from the license plate scan, considering an efficient modeling of the traffic network and the use of a route enumeration model that conditions the best location of scanning devices.

It is organized as follows: in Section 2, the proposed methodology is presented, described and analyzed; explaining the integration of the network modeling technique and the route enumeration model with the localization and flow estimation models. Section 3 is dedicated to studying the application of this methodology in an example of a traffic network, using actual data and characteristics, along with the observation of the results obtained by a brief analysis of the sensitivity of the model parameters in the solution; and finally, some conclusions are provided in the last section.

2. METHODOLOGY

To explain the methodology in this paper, consider a traffic network ($\boldsymbol{N}, \boldsymbol{A}$), where $\boldsymbol{N}$ is the set of nodes and $\boldsymbol{A}$ is the set of links. For the set of links, its capacity and cost characteristics are established, in addition to an O-D trip matrix. This matrix defines the number of trips per network zone $\hat{T}_{ZiZj}$, where each zone Z contains a certain set of nodes. All this information is considered as inputs of the model that will be developed below, which also have the purpose of defining the travel matrix by nodes and the exhaustive set of reference routes $\boldsymbol{R}$.

2.1 Characterization of origin-destination nodes.

In this step, is used the technique proposed by Sánchez-Cambronero et al. (2016), which considers that every node of the network will generate or attract trips depending on the characteristics of the adjacent links, i.e, depending on the capability of the adjacent links to attract and generate trips (i.e, number of on-street parking spaces, number of private parking spaces, etc.). This capability is quantified in terms of the capacity of link a to attract and/or generate trips CG_a. Then, according to these capacity values, is possible to determine the proportion of total trips attracted PA_i and generated PG_i in the zone Z, that begin or end at node i.

Finally, the relationship between the number of trips made between the origin and destination nodes and the number of trips made between the zones to which these nodes belong can be established as follows:

$$T_{ij} = \hat{T}_{ZiZj} PA_i PG_j \quad (1)$$

where T_{ij} is the number of trips from node i to node j, $\hat{T}_{ZiZj}$ is the number of trips obtained through an out of date O-D matrix, PA_i is the proportion of attracted trips at node i, and PG_j is the proportion of generated trips at node j. The completion of this step entails the definition of a new O-D matrix defined by trips between nodes rather than a matrix defined by trips between zones.

2.2 The definition of set of routes with a route enumeration model

Another necessary input for the model is the set of reference routes $\boldsymbol{R}$ with their reference flow values f_r^0, determined from a route enumeration method. In this work, a route enumeration algorithm, based on Yen´s k-shortest path algorithm (Yen, 1971), was used to check the effect of considering k routes on each O-D pair. This algorithm introduces into the model an initial route set $\boldsymbol{R}$ that varies in size according to the value of k. There are usually certain discrepancies between transportation analysts and planners about the optimal value of k, since values equal to or greater than 4 are usually rare to find in the literature due to the high computational cost that it would entail. For the analysis and study of the example network that will be shown in the next section, we have chosen to select reasonable values of k equal to 2 and 3. Similarly, for this study a sensitivity analysis has been carried out by varying the value of the maximum relative cost per route C_{thres} so that it can be considered as such.

2.3 Network simplification

In order to have a model more similar to reality and without involving excessively high computing times due to the amount of introduced data, a criterion of network simplification is introduced. The simplification criterion is the same as that developed by Sánchez-Cambronero et al. (2016), which states that an attracted or generated node demand have to be below a threshold value F_{thres} established by the analyst.

When checking this, the studied node would lose its origin/destination condition, also implying that none route could begin or end on that node. For this reason, it will be necessary to transmit these flow routes to other nodes belonging to another implied route, as long as it would be possible. This flow transmission must meet the "transmission criteria": transmit node demand to another node, which must have the same condition. Transmission will be made provided that the node which will receive demand would be at a shorter distance than an established threshold C_{thres}. If it is not possible to transmit demand, the implied node as well as the mentioned demand will disappear on the model.

At the time that flow transmission is made, routes would be remade in a new set $\boldsymbol{Q}$ of them with an associated flow f_q^0.

2.4 Sensor location and estimation models

From the network information, the set of routes $\boldsymbol{Q}$ and the associated flows f_q^0 to them, a location model of plate scanning devices in the links of the traffic network is used. The main purpose of applying this model is to determine the optimal set of links SL to be scanned to obtain the best possible estimation of the remaining flows of the network. That sensor location model is formulated with the following set of equations:

$$\max_{z_a;y_q} M = \sum_{q\in\boldsymbol{Q}} f_q^0 y_q \tag{2}$$

subjected to:

$$\sum_{a\in\boldsymbol{A}} P_a z_a \leq B \quad \forall a \in \boldsymbol{A} \tag{3}$$

$$\sum_{a\in\boldsymbol{A}} \delta_a^q z_a \geq y_q \quad \forall q \in \boldsymbol{Q} \tag{4}$$

$$\sum_{a\in\boldsymbol{A}|\delta_a^q+\delta_a^{q1}=1} z_a \geq y_q \quad \forall (q,q1) \in \boldsymbol{Q}^2 |\, q > q1 \tag{5}$$

$$z_a = 0 \quad \forall a \in NSL \tag{6}$$

$$\sum_{a\in\boldsymbol{A}} S_a^{iter} z_a \leq \sum_{a\in\boldsymbol{A}} S_a^{iter} \quad \forall iter \in \boldsymbol{I} \tag{7}$$

The objective function (2) maximizes the observed route flow in terms of f_q^0; y_q is a binary variable equal to 1 if a route can be distinguished from others and 0 otherwise. Constraint (3) satisfies the budget requirement, where z_a is a binary variable that equals 1 if link a is scanned and 0 otherwise. This constraint guarantees that we will have a number of scanned links with a cost P_a for link a that does not exceed the established limited budget B.

Constraint (4) ensures that any distinguished route contains at least one scanned link. This constraint is indicated by the parameter δ_a^q, which is the element of the incidence matrix. Constraint (5) is related to the previous constraint since it indicates the exclusivity of routes: a route q must be distinguished from the other routes in at least one scanned link a. If $\delta_a^q + \delta_a^{q1}$ = 1, this means that the scanned link a only belongs to route q or route $q1$. If $\sum z_a \geq y_q$ and y_q = 1, then at least one scanned link has this property; on the other hand, if y_q = 0, then the constraint always holds. Constraint (6) ensure us that certain links belonging to a set NSL cannot be scanned and therefore, the value of binary variable z_a is equal to 0. The applicability of this constraint will be discussed in detail in *section 3.1*.

Finally, since this model is part of an iteration process, we propose an additional constraint (7), which allows us to obtain different solutions of SL sets for each iteration performed through the definition of S_a^{iter}, which is a matrix that grows with the number of iterations $\boldsymbol{I}$, in which each row reflects the set SL resulting from each iteration carried out up to then by the model (S_a^{iter} is 1 if link a was proposed to be scanned in the solution provided on iteration $iter$ and 0 otherwise). Each iteration keeps the previous solutions and does not permit the process to repeat a solution in future iterations. That is, each iteration carried out by the algorithm is forced to search for a different solution with the same objective function (2). Another main feature introduced in the model is the possibility of working with a set of routes not fixed. Until now, the sensor location and flow estimation models have been formulated considering a set of existing fixed and non-changing routes. In the proposed model, each SL set allows to obtain a set of new routes observed as a result of the location of the devices, being some of routes compatible with those of the set $\boldsymbol{R}$, and which add to a new global set $\boldsymbol{C}$ that encompasses the routes in $\boldsymbol{Q}$ and the new ones observed.

The estimation of remaining flows in routes and links from reference flow values can be done through classical methods such as generalized minimum squares (Mínguez et al., 2010; Castillo et al., 2013). Once the estimation problem has been resolved, the quality of the solution in absolute terms, can be quantified as follows:

$$RMARE = \frac{1}{n}\sum_{a\in \boldsymbol{A}} \frac{|v_a^{est} - v_a^{real}|}{v_a^{real}} \qquad (8)$$

where $RMARE$ is the root mean absolute value relative error; n is the number of links in the network; v_a^{est} and v_a^{real} are the estimated flow and (assumed) real flow for link a. Such error is calculated over the link flows since the number of them remain constant regardless of the network simplification. Each value of $RMARE$ is associated with a specific set of scanned links SL, and it indicates the quality of the estimation by using the set SL for the traffic network. However, due to the complexity of the problem, it has not a unique solution and it is necessary evaluate a great amount of combined solutions. The best solution or set SL, for the established conditions, will be that provide the low $RMARE$ value.

3. CASE STUDY OF CIUDAD REAL CAMPUS NETWORK

The methodology explained in the previous section is now applied to an example of a real traffic network, using an O-D matrix of real trips and with the configuration shown in Fig. 1. The network that serves as an example is the idealized traffic network of the University campus of Ciudad Real (Spain). It is a network consisting of 75 nodes and 175 links. The definition of the O-D trip matrix has been elaborated by zones, according to the correlation between the different nodes and the different neighborhoods/districts that exist. For this studied example, we have chosen to carry out a sensitivity analysis by varying some of the parameters of the model, specifically those related to the information that is introduced in it.

In the first place, as mentioned in *section 2.2*, it is usual to find in the literature that the parameter k is equal to 2 or 3. Here it has been decided to consider these two values to verify the effect that it would have on the estimation to consider a greater or lesser number of routes between O-D pairs. Having considered 4 routes per O-D pair would have involved high computational costs and, for this example of network and concrete situation, it would have been unrealistic. Therefore, a first analysis of the effect on the estimation of flows is performed when considering different k values.

Fig. 1 – Representation of the traffic network of the Ciudad Real campus.

A second analysis consists in varying the value of the threshold flow F_{thres} that is used in the simplification algorithm, described in *section 2.3*. Depending on the value of this threshold value, the degree of simplification of the network will be greater or lesser, affecting the number of routes considered and therefore the amount of needed information for the estimation step.

Finally, a third analysis has been carried out where the variable parameter is the maximum relative cost C_{thres}. This parameter would affect the assignment of the routes that the enumeration model considers for each O-D pair. It is interesting to see how this can affect the estimation results. For all the analyzes described, it has been considered to start from a situation close to real tests carried out in the same network considering a quantity of 30 scanning devices. Based on this, and considering that each device has a unit cost P_a, it has been decided to consider a constant budget B equal to 30.

3.1 Effect of varying the k parameter.

Varying the k parameter means considering more or smaller number of existing routes in the traffic network, or otherwise, information and data with which the model must work. The consideration of such a parameter in this work has been through the use of a route enumeration algorithm, selecting values of 2 and 3 for the example presented, as described in *section 2.2*. For this first analysis, it has been considered to analyze a very simplified network scenario, considering a F_{thres} equal to 10.

An important aspect that has been studied in this first analysis is that related to the consideration of a set of links $NSL \in \boldsymbol{A}$, where the cost and difficulties of installing a scanning device is greater than with respect to other links in the network. Based on this, it has been considered to include one more restriction (6) that specifies that certain links $a \in NSL$ are not candidates to install a scanning device and therefore, the value of the variable z_a must be 0.

With respect to the network used as an example, the greatest flows usually occur in the southeast and northweast corridor, where the roads have greater capacity. However, they are roads with physical conditions not suitable for the installation of devices and identification of vehicles. With respect to the latter, the higher speed and the overlapping flow on two lanes make identification of the license plates difficult, in addition to the possible identification of vehicles that circulate in the opposite direction as there are no barriers or other elements that separate the flow in a more defined way (see Fig. 2(a) to (c)). The remaining links have physical characteristics or elements that allow to identify without confusion the flows in their sense of correct circulation and without inducing the failure to capture data (see Fig. 2(d) to (f)). For the joint study of the k parameter and of the latter, it has been considered to study a scenario (Model A) where all the links have the same opportunity of being observable, and another (Model B) where a certain set of links are not suitable to locate the devices due to their characteristics.

Fig. 3 shows the effects of these considerations on the results of the model. There are four well-differentiated graphs in pairs, one assigning a k equal to 2 and another with equal to 3. Each jump in the graph means that the location model has found an optimal set of scanned links SL that improves the solution in terms of error, and the horizontal sections mean that in that iteration, the model has not been able to find a solution that improves on the previous one.

It is observed that considering a higher value of k, the results of the model are better in terms of the error in the estimation of traffic flows. We clearly see how a $k = 3$ obtains quite better results than considering a $k = 2$ due to the existence of a greater number of routes for each O-D pair.

Another interesting observation is to verify the effect of considering a certain series of links as not valid to locate the scanning device, since it has a higher installation cost than usual.

Despite this inconvenience and considering the rest of the conditions equal in both situations, Model B has been able to locate certain links, of which none belongs to $\{a_u\}$, so that the error with respect to Model A is of the smallest possible difference, also reaching a certain convergence after a number of iterations performed. We therefore see how, in this particular case, considering or not certain links to install the devices does not produce a relevant difference in the estimation error to be obtained. In view of this, for the following analyzes will consider the possibility of not scanning certain links of the network since, due to their physical conditions, they would prevent us to install properly the device and that, for qualitative purpose in the estimation, it would not have a significant importance.

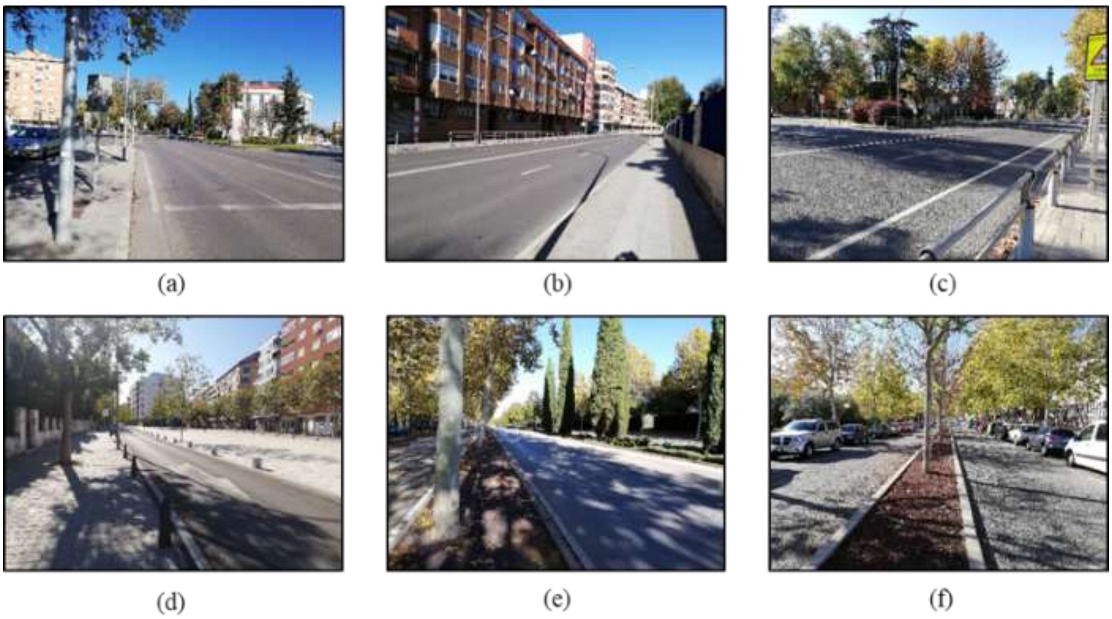

Fig. 2 – Examples of existing links in the Ciudad Real campus network. Upper pictures (a, b and c) show links belonging to the southwest and northeast corridor of the network, not suitable for locating a device. Lower images (d, e and f) show suitable links for locating scanning devices.

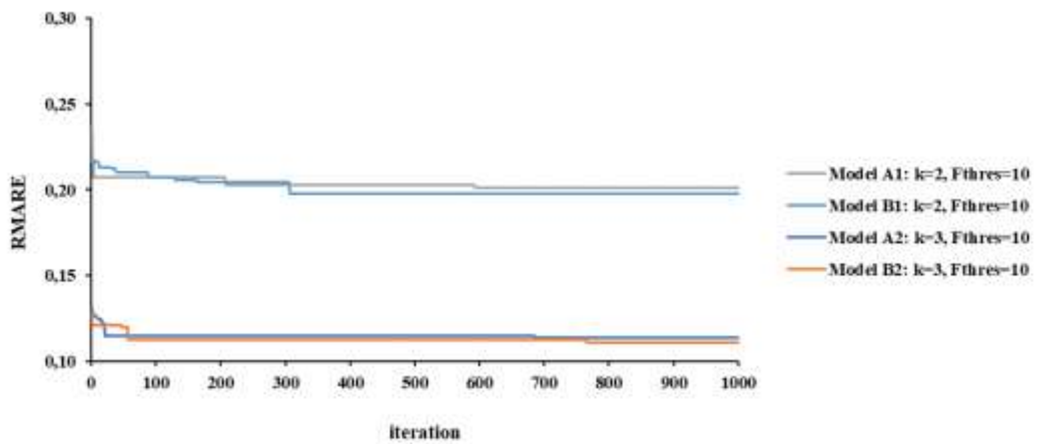

Fig. 3 – Evolution of $RMARE$ value for the different cases varying the k parameter and the threshold flow.

3.2 Effect of the simplification network.

If the value of F_{thres} is small, the proposed methodology will do a smaller simplification of the network and therefore, will lead to a lower error in the estimation of traffic flows since it is being considered a greater number of existing routes and flows. As F_{thres} increases, there will be a greater degree of simplification and therefore, greater error in the estimation. Fig. 4 shows this effect regardless of the value of parameter k. It is observed that lower F_{thres} values, and therefore less simplification, tend to smaller error values, also reaching a certain convergence after having performed multiple iterations with the proposed location model.

For this specific network case, we see how an optimal solution is achieved with a minimum error difference when considering a F_{thres} equal to 10 or 15, with k = 3. For other values of F_{thres}, there is a greater difference in error but it can be assumed according to the analyst's criteria.

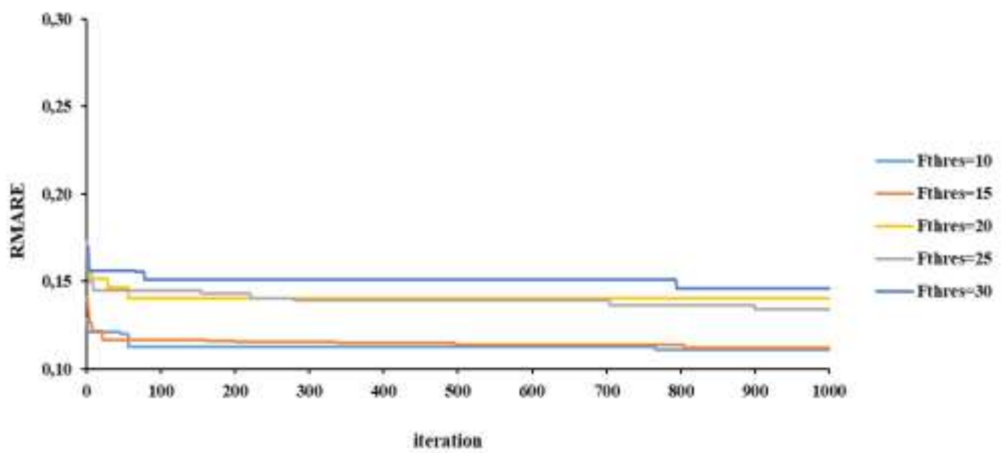

Fig. 4 – Evolution of $RMARE$ value for the different cases varying the threshold flow.

3.3 Effect of varying the maximum relative cost.

The maximum relative cost C_{thres} is related to the value of k parameter, since by applying the route enumeration algorithm, we will obtain for each O-D pair, k routes that have a relative cost less than or equal to C_{thres}. This relative cost is defined as the ratio of the maximum and minimum costs of the k routes considered. If we relate a real traffic analysis with a reference value C_{thres}, we can observe how by varying this value, we move away from one situation from real to another with more uncertainty where the treated data leads to greater uncertainty and therefore to greater error. This is the case observed in Fig. 5, where a reference cost value equal to 1.50 has been considered with k equal to 3. If we analyze different situations where we operate the algorithm of enumeration of routes with lower C_{thres} value, we move away from the reference and this leads to higher error values. Approaching C_{thres} = 1, we are considering that all routes have the same and minimal cost, something little true for this type of analysis.

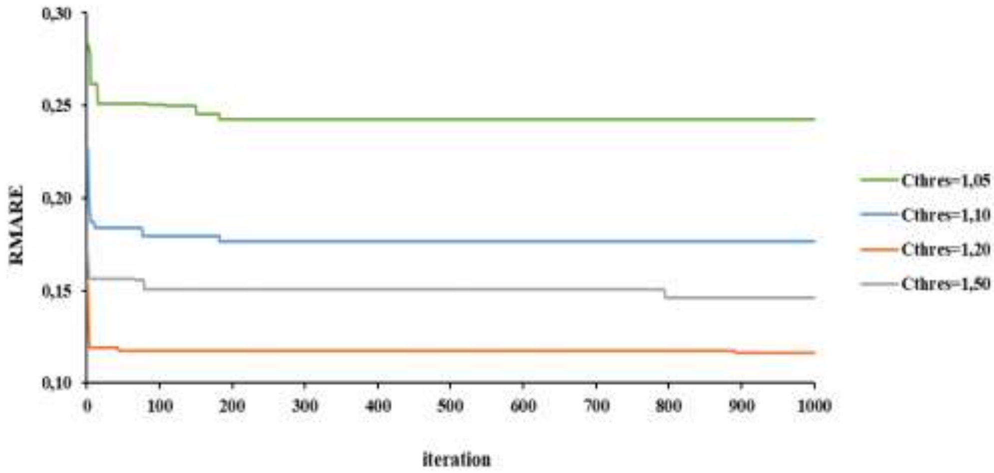

Fig. 5 – Evolution of $RMARE$ value for the different cases varying the maximum relative cost with respect a reference value.

4. CONCLUSIONS

This paper presents a brief summary and application of a methodology that jointly uses a model of location of license plate scanning devices and a model of route enumeration, that determines the best sets of these for the subsequent estimation of the traffic flows. Such methodology is applied to an example of a real network.

From the analyzes carried out, it is deduced that considering a greater number of existing routes, represented by means of the parameter k, leads to a better estimation of flows in terms of achieving a smaller $RMARE$. However, a high value for k would entail working with a network with a high number of routes, which would have a high computational cost. From the analysis carried out with the example network and in accordance with other works carried out, we can affirm that a value of k = 3 is acceptable for studies with plate scanning devices. In reference to network simplification, a low-medium degree of network simplification leads to a good performance of the methodology in terms of the error obtained in the estimation step.

Finally, it is important to adopt an appropriate value of the maximum relative cost C_{thres}, that defines the reality of the routes to be considered for each O-D pair. Values around unity bring us closer to unrealistic situations that lead to an erroneous estimation of flows.

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