A structural analysis method for the management of urban transportation infrastructure and its urban surroundings

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Abstract: Urban Transportation Infrastructure (UTI) is a key asset for any city as it affects economic growth and urban functioning; UTI is more valuable than ever due to the urbanization process that concentrates many people to the urban centers, generating a major mobility demand and car usage. Hence, an approach to UTI management is required, which would provide a greater significance to sustainable mobility. This paper’s objective is to structure in hierarchical manner UTI and urban surroundings indicators related to sustainable mobility in order to create a decision-making instrument related to UTI management in the form of a weighted index and to evaluate public policies-strategies associated to these indicators. This was accomplished through the structural analysis-MICMAC method; the results showed which indicators are the most important and the necessity to prioritize them in order certain public policies to be more effective conforming to their impact on the weighted index.

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The article’s information is important for the urban-transportation planning because it allows the development of neighborhoods that promote walking-cycling and public transport usage via a weighted index that considers the coverage and functionality of certain UTI-urban surroundings elements related to sustainable transportation modes.

PUBLIC INTEREST STATEMENT

Nowadays, the constant increase of automobiles usage has generated very important environmental, social and economic negative externalities, such as congestion, poor air quality, road accidents etc. Within this context, the Minister of Mexico’s City Mobility Department highlighted the necessity to implement strategic models of urban development aimed to prioritize the sustainable transportation modes (walking, cycling and public transport) in order to positively affect the quality of people’s life. Urban Transportation Infrastructure (UTI) is a key element to consider for the enhancement of sustainable mobility as it is able through its adequate coverage and functionality to establish neighborhoods that promote the safety and convenience of pedestrians-cyclists and public transport users. This work tries to reinforce sustainable mobility through the creation of a decision making instrument (weighted index) related to UTI-urban surroundings management and the evaluation of several public policies-strategies according to their impact upon the previously mentioned index.
1. Introduction
Appropriate transportation infrastructure is one of the most urging needs in most cities today. In recent decades, research shows that an investment in this sector causes a positive economic impact (Flores, Chatziioannou, Segura, & Hernández, 2013, p. 84). The analytical literature has shown studies using different approaches like production function (or cost), growth regressions, and different variants of these models with different data or methods. These studies found that transportation infrastructure has a positive effect on output, productivity and growth rate (Calderon & Serven, 2008, pp. 3–6).

One of the pioneer’s works in this area (Aschauer, 1991) provided evidence that transportation is an important determinant of economic performance. Alminas, Vasiliauskas, and Jakubauskas (2009) concluded that transportation has contributed to growth in the Baltic region. Another research concerning the Spanish plan to extend roads and railroads that connect Spain with other countries deduces that it has a positive impact in terms of Gross Domestic Product (Álvarez-Herranz & Martínez-Ruiz, 2012, pp. 414–427). In another direction, a study of the railroad network in the United States mentions that many economists believe that the project costs exceed the benefits (Balaker, 2006, p. 551).

In the traditional model of cost-benefit assessment the evaluation of the impact of transportation infrastructure on regional development is not included (De Rus, 2008, p. 23). A bias in these growth-focused studies is detected that favors economic impact rather than the social goals. Nowadays, it is important to emphasize the impact of transportation infrastructure on qualitative parameters such as development and not only on quantifiable ones such as growth in order to enhance the concept of sustainable mobility.

This paper focuses on the social aspects of transportation system and specifically of mobility and its implications for the management of urban infrastructure in Mexico City by resorting to the sustainable mobility paradigm (Banister, 2008; ITDP, 2012a). The above-mentioned paradigm prioritizes the change of the people’s displacement habits from the automobiles to efficient-sustainable transportation modes such as walking, cycling and public transport.

Hence, the actions of urban management need to reflect upon the establishment of an environment that promotes the security and convenience of the pedestrians, cyclists and users of public transport in order to cover their needs without using the car. A focal point in order to create such an environment is through the sufficient coverage and functionality of the UTI elements and its urban surroundings related to the sustainable transportation modes.

For that reason, a set of indicators related to pedestrians, cyclists and users of public transport is going to be constructed, by resorting to public information in form of shape files and tabular data. The above-mentioned information is available by the National Institute of Statistics and Geography (INEGI in Spanish), the National Statistical Directory of Economic Units (DENUE), the Ministry of
Urban Development and Housing (SEDUVI), the Ministry of Mobility (SEMOVI), the Ministry of Constructions and Services (SOBSE) among others.

As a case study, the indicators are determined for the most populated Census Tract (CT) in Iztapalapa County. Thus, it is possible to assess the actual situation at a CT level, in terms of coverage and functionality of the UTI and its urban surroundings elements related to sustainable mobility in order to generate a global index that is composed by the previously mentioned indicators and it has two parts.

The first part is the constant one (Table 1) depending on the opinion of the experts and results from the structural analysis method, the constant part is the same for every CT as is defined by the levels of each indicator’s dependency and influence. The second part of the index is the variable one; it depends on the level of equipment and the characteristics of each block in order to qualify the CT and results from the implementation of the indicators in a CT via a Geographic Information System (GIS) (Table 2).

Furthermore, logical connections between this set of indicators and public policies are going to be created so that the decision makers in the government to be able to identify key elements in order these policies to be more efficient according to their impact on the global index.

| Indicator                          | Influence (I) | Dependence (D) | Final value \( \frac{I+D}{2} = P(i) \) |
|------------------------------------|---------------|----------------|----------------------------------------|
| Public street lights               | 0.79          | 0.90           | 0.845                                  |
| Semi-fixed Merchant stands         | 0.63          | 0.51           | 0.57                                   |
| Roadside Merchant stands           | 0.63          | 0.51           | 0.57                                   |
| Pedestrian bridges                 | 0.79          | 0.75           | 0.77                                   |
| Sidewalks                          | 0.97          | 1              | 0.985                                  |
| Ramps                              | 0.76          | 0.93           | 0.845                                  |
| Sidewalk fittings                  | 0.52          | 0.70           | 0.61                                   |
| Road networks of motorized transit | 0.89          | 0.68           | 0.785                                  |
| Coverage of public transport       | 0.97          | 0.69           | 0.830                                  |
| Stations of public transport       | 1             | 0.99           | 0.995                                  |
| Population                         | 0.85          | 0.47           | 0.66                                   |
| Land use                           | 0.99          | 1              | 0.995                                  |
| Proximity to points of interest    | 0.93          | 0.36           | 0.645                                  |
| Block’s self sufficiency           | 0.81          | 0.87           | 0.84                                   |
| Bike lanes                         | 0.99          | 0.82           | 0.905                                  |
| Block’s size and form factor       | 0.88          | 0.39           | 0.635                                  |
| Trees                              | 0.72          | 0.09           | 0.405                                  |
2. Structural analysis literature review

The structural analysis along with the methods of scenarios is one of the most commonly used tools in prospective studies. It is likely that Jay Forrester, for his work with models of industrial and urban dynamics in 1961, is at the origin of the first structural analysis justifications. Meanwhile, the need to consider multiple, homogeneous, quantitative, and qualitative variables induced to the pioneers of structural analysis the use of other representation modes based primarily on tables and charts (Ballesteros Riveros & Ballesteros Silva, 2008, p. 194).

With this perspective, Wanty and Federwish (1969) applied the structural analysis approach to an iron-steel and to an air transportation company. Shortly after Teniere-Buchot, analyzed the “water” system and published an article about a model referred to the policy of water pollution (Arcade, Godet, & Roubekat, 1993). In the same period, Kane (1972) introduced the KSIM model that

| Table 2. Resume of the actual values of the established indicators in the examined CT |
|---------------------------------|---------------------------------|------------------------------------------------------------------------------------------------|
| Indicator                      | Actual values of CT = V(i)      | Description criterions in order to evaluate the CT according to each indicator                    |
| Streetlights                   | 13                              | Number of blocks that have streetlights in every front within the examined CT                      |
| Semi-fixed posts               | 11                              | Number of blocks that have semi-fixed posts in every front within the examined CT                  |
| Roadside stands                | 12                              | Number of blocks that have roadside stands in every front within the examined CT                  |
| Pedestrian bridges             | 2                               | Number of blocks that have pedestrian bridges in any of their fronts within the examined CT       |
| Sidewalks                      | 5                               | Number of blocks that have sidewalks in every front within the examined CT                         |
| Ramps                          | 5                               | Number of blocks that have ramps in every front within the examined CT                            |
| Sidewalk fittings              | 5                               | Number of blocks that count with sidewalk fittings in every front in the examined CT              |
| Road networks of motorized transit | 6                        | Number of blocks that have high or medium level of connectivity within the selected CT. It was chosen this kind of connectivity level because the principal roads of motorized transit facilitate the coverage of public transit because of their physical dimensions |
| Coverage of public transport   | 18                              | Number of blocks that have coverage of public transport in any of their fronts                    |
| Stations of public transport   | 2                               | Number of blocks that count with public transport stations in any of their fronts in the selected CT |
| Population’s concentration     | 15                              | Number of blocks that have population’s concentration greater than the average population’s concentration within the Iztapalapa County |
| Land use                       | 23                              | Number of blocks that count with mixed land use. Nevertheless, it is noteworthy to highlight that we decided to qualify all of the CT blocks as mixed, due to the existence of several points of interest around the blocks that cover human needs, transforming the area as a high candidate in terms of attraction and generation of trips. However, the officially registered land use type of the blocks with the examined CT is residential and possibly this discrepancy between the officially registered land use type and the one that we qualified the blocks is the result of the inexistence of the points of interest when has been officially registered the land use type |
| Proximity to points of interest| 23                              | Number of blocks that count with points of interest within an acceptable pedestrian distance (750 m) in the examined CT. All the blocks count with points of interest that cover distinct human necessities, qualifying the CT as complete neighborhood |
| Block’s self sufficiency       | 23                              | Number of blocks that count with points of interest that cover distinct human necessities such as security, survival, work, education, socialization, access to public transport etc., at an acceptable pedestrian distance, qualifying the blocks of the CT with high very high auto-sufficiency level. Equal to the case of the previous indicator the CT has the capacity to transform into a complete neighborhood |
| Bike lanes                     | 0                               | Number of blocks having bike lanes in any of their fronts within the selected CT. At the moment there are no bike lanes in the examined CT |
| Block’s size and form factor   | 7                               | Number of blocks that have regular form or close to regular form and small area in the examined CT |
| Trees                          | 0                               | Number of blocks that have sufficient coverage of trees (in every front of the block) within the selected CT |
although it is closely related to the industrial dynamics of Forrester, is nevertheless, a method of structural analysis.

For his part, Roberts (1971) led works for the United States National Foundation of Sciences in order to discover relationships among applications related to energy and pollution in the sector of transportation.

In a prospective study about nuclear power in France, Duperrin and Godet (1973) suggested a method to classify the elements of the system; this method was the structural analysis.

More recently, Qureshi, Kumar, and Kumar (2008) employed the structural analysis method to measure the key guidelines of 3PL provider’s services. Arya and Abbasi (2001) applied it for purposes of environmental analysis. Furthermore, Kanungo, Duda, and Srinivas (1999) used the structural analysis in order to evaluate the effectiveness of information systems. Sharma and Gupta (1995) in turn, considered waste management with structural analysis. Moreover, the structural analysis has been used in order to understand, describe and predict the structure of international conflict with existing international relations theories (Kim & Barnett, 2007, pp. 135–165).

3. Method’s objectives and stages
The structural analysis is a tool designed to link ideas. It allows the description of the explored system thanks to a matrix that connects all of its components. By analyzing these relationships, the method makes it possible to highlight the variables that are essential to the evolution of the system. The structural analysis comprises three stages (Arcade et al., 1993):

1. The inventory of variables-factors.
2. The description of the relationships between variables-factors.
3. The identification of essential variables-factors.

It is worth mentioning, that we decided to use the word “indicator” instead of variable or factor within the process of structural analysis because of the OECD definition. According to this definition, an indicator is a quantitative or qualitative factor or variable that provides simple and reliable means to measure achievement, to reflect the changes connected to an intervention or to help assess the performance of a development actor (OECD, 2010, p. 25). Hence, being an indicator a quantitative or qualitative factor-variable that is used for evaluation purposes permit us to use it in structural analysis.

Furthermore, it is noteworthy that the structural analysis is based on the cross impact method that was originally developed by Gordon and Helmer in 1966, in fact the structural analysis method (MICMAC) is a variant of the original cross impact method taking into account not only the direct relations but also the indirect ones (Cabrera, Cobacho, & Lund, 2002).

The behaviour and functionality of structural analysis will remain intact either by the use of variables or by the use of indicators, because the analogy between the systems of performance indicators described by Cabrera (2001) and the ones described by Godet are clear, because Godet’s variables are related just the same way performance indicators are. This is why the concepts of structural analysis can be used to the selection of indicators (Cabrera et al., 2002). Thus, for the reasons mentioned before, we decided to use the term indicator within the process of structural analysis presented in the following lines.

3.1. The inventory of indicators for the case study
At this stage, it is helpful to create a list that includes all the indicators that we have considered and constructed as part of the system in order to reinforce the sustainable mobility paradigm. Table 3
## Table 3. The indicators related to UTI and urban surroundings

| I(i) | Name                          | Domain (codification)                                                                 | Description of the indicator at a block’s level                                                                 |
|------|-------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| I(1) | Streetlights                  | (1) Sufficient coverage  
(2) Insufficient coverage  
(3) Without streetlights            | Indicates if every, some or any fronts have streetlights                                                                 |
| I(2) | Semi-fixed posts              | (1) The whole block has semi-fixed posts  
(2) Some fronts of the block have semi-fixed posts  
(3) The block does not have semi-fixed posts | Signals if every, some or any fronts have semi-fixed posts. The semi-fixed posts along with the roadside stands belong to the category of merchant stands |
| I(3) | Roadside stands               | (1) The whole block has roadside stands.  
(2) Some fronts of the block have roadside stands  
(3) The block does not have roadside stands | Signals if every, some or any fronts count with roadside stands                                                                                   |
| I(4) | Pedestrian bridges            | (1) Pedestrian bridge with accessibility elements  
(2) Pedestrian bridge without accessibility elements  
(3) Block without pedestrian bridge | Indicates if there is a pedestrian bridge and if that bridge counts with accessibility elements                                                   |
| I(5) | Sidewalks                     | (1) Sufficient coverage  
(2) Insufficient coverage  
(3) Without sidewalks            | Signals if every, some or any fronts have sidewalks                                                                                        |
| I(6) | Ramps                         | (1) Sufficient coverage  
(2) Insufficient coverage  
(3) Without ramps               | Represents every, some or any fronts have ramps                                                                                             |
| I(7) | Sidewalk fittings             | (1) Sufficient coverage  
(2) Insufficient coverage  
(3) Without sidewalks fittings      | Indicates if every, some or any fronts have sidewalk fittings                                                                      |
| I(8) | Road network of motorized transit | (1) High connectivity  
(2) Medium connectivity  
(3) Low connectivity             | Qualifies the value of connectivity (1, 2, 3) in blocks that present more than one road types (e.g. roads of continuous circulation, principal arteries, secondary avenues, local streets) the qualification logic is to give preference to the combination of major hierarchy |
| I(9) | Public transport coverage      | (1) Flow of public transport from every block’s front  
(2) Flow of public transport from some block’s front  
(3) Without public transport coverage | Indicates the coverage of public transport in terms of public transport flow from every, some or any front of the block |
| I(10)| Stations                      | (1) High capacity  
(2) Medium capacity  
(3) Low capacity              | Represents the capacity of public transport mode that the station offers                                                                    |
| I(11)| Population’s concentration    | (1) Very High population concentration >276  
(2) 138 < High population concentration ≤276  
(3) 69 ≤ Medium population concentration ≤138  
(4) Low population concentration <69 | Shows the population in a block in order to reveal the points of major demand for mobility according to the number of inhabitants per block |
| I(12)| Land use                      | (1) Mixed  
(2) Housing  
(3) Industrial              | Indicates the dominant type of land use related to the demand of mobility (trips generation schedule)                          |

(Continued)
reveals the list of the considered indicators for this case study, and the theoretical construction of them in order each block to be qualified according to the possible values that an indicator related to the UTI-urban surroundings may have in terms of coverage and functionality.

Since the 17 indicators have been theoretically constructed, we are able to implement them in the most populated CT within Iztapalapa County via a geotechnology tool such as a GIS, the software that has been used is QGIS because it is license pay free, more specifically is the version 12 of the QGIS project with the code name “Lyon”. The actual characteristics of the selected CT are seen in Table 4 in order the lector to be more familiarized with it, while in Table 2 are appreciated the current performance values of the CT in terms of coverage and functionality of the indicators established previously.

### Table 3. (Continued)

| I(i) | Name | Domain (codification) | Description of the indicator at a block's level |
|------|------|-----------------------|-----------------------------------------------|
| I(13) | Proximity to the points of interest (POIs) | (1) Number of POIs in a short distance (0–250 m)  
(2) Number of POIs in a medium distance (251–500 m)  
(3) Number of POIs in a long but acceptable distance (501–750 m) | Shows the proximity of population within the blocks to the POIs |
| I(14) | Block's self-sufficiency according to the presence of POIs | (1) Very high self-sufficiency  
(2) High self-sufficiency  
(3) Medium self-sufficiency  
(4) Low self-sufficiency | Represents the combination of the existing POIs within the area of influence of the inspected block |
| I(15) | Bike lanes | (1) Separated-Exclusive  
(2) Confined-Shared  
(3) Without bike lanes | Indicates the type of bike lanes that a block has or the inexistence of bike lanes |
| I(16) | Type of block and form factor (area/perimeter) | (1) Area/perimeter <5.5  
(2) 5.5 ≤ Area/perimeter <11  
(3) 11 ≤ Area/perimeter ≤22  
(4) Area/perimeter >22 | Relates the perimeter and area of each block within the inspected census tract with the purpose to demonstrate the easiness to walk, in the sense that the bigger the area and the more irregular the form factor the more distance needs to be covered by the people. The measurement unit is meters |
| I(17) | Trees | (1) High coverage of trees  
(2) Medium coverage of trees  
(3) Without trees | Represents if every, some or any fronts have trees |

### Table 4. Actual features of the selected CT

| CT features | Resume |
|-------------|--------|
| Relation between CT and blocks | The examined CT consists of 23 blocks |
| Total population | The selected CT is the most populated within the geographic borders of Iztapalapa County. Thus, it generates a very high demand of mobility and at the same time demands the existence of sufficient-adequate UTI and urban surroundings in order to cover the different human needs of its inhabitants |
| High concentration of POIs | The selected CT has a very high concentration of various points of interest, which can cover several human needs, making as a result the area of study a high candidate in relation to generation and attraction of travels |
| Low level of urban planning | The blocks within the examined CT do not have a regular form, their form factor in majority is very different from the normal one (square form factor). For that reason, the blocks look like labyrinths, do not permit easy connectivity between different blocks, make the orientation of pedestrians difficult and more importantly the blocks due to their form factor do not offer the opportunity to the people to be connected with public transportation modes and to pass from hierarchical networks to well organized ones |
The summary of our findings by concluding the implementation process is very interesting because it shows that the current situation in terms of coverage and functionality of UTI and its urban surroundings in the examined CT needs to be changed. There is insufficient coverage in terms of streetlights, sidewalks, ramps, sidewalk fittings, and trees. There are many merchant stands, which could potentially cause problems in terms of pedestrian and cyclist mobility; there are no bike lanes within the examined CT and the pedestrian bridges do not count with elements of accessibility. The geometry of the blocks within the examined CT are not the result of an intelligent planning, they do not have the regular square form, they do not connect with each other, making them look like labyrinths and making them difficult for walking.

On the other hand, there are good conditions in terms of public transportation coverage, proximity to the POIs, level of self-sufficiency and land-use. Something that allows the promotion of the necessary counter-measures that need to be part of an Integral Plan of Mobility (IPM), concerning subjects like Transit Oriented Development (TOD), the creation of complete streets, and neighborhoods that in general, prioritize the convenience and security of pedestrians, cyclists and users of public transport.

3.2. Description of the relations between the indicators

The objective of this stage is to link the indicators in a structural analysis matrix of double entry (Figure 1) prepared for this study. The square matrix expresses at the level of each row the influence that an indicator exerts on the others, while at the column level expresses by which indicators each one of them is influenced (Romero Perea, 2012).

For each pair of indicators, the following questions arise: is there a relationship of direct influence between the indicators i and j? If it does not exist, record 0; otherwise, we need to evaluate whether this relationship of direct influence is weak (1), medium (2), strong (3) or potential (P) (Ballesteros Riveros & Ballesteros Silva, 2008, p. 195). It is noteworthy, that only two values will be taken into account in our case for reasons of simplicity, the first will be zero (“0”) when there is no relationship and the second will be one (“1”) when there is a relationship between indicators.

![Figure 1. Matrix of direct influences-dependencies.](image)

| 1 : Street lig | 2 : Semi-fixed | 3 : Roadside | 4 : Pededridge | 5 : Sidewalks | 6 : Ramps | 7 : Sidelitn | 8 : RolNeMoTr | 9 : PubTraCov | 10 : Stations | 11 : PopuConce | 12 : Land use | 13 : ProxiPOIs | 14 : Self-suffi | 15 : Bike lanes | 16 : Tybifo | 17 : Trees |
|----------------|--------------|-------------|---------------|-------------|---------|-----------|-------------|-------------|-------------|-------------|-------------|--------------|------------|-------------|----------|-------|
| 1 : Street lig | 0 1 1 1 1 1 1 0 1 0 1 0 1 1 0 0 |
| 2 : Semi-fixed | 1 0 0 1 1 1 1 0 0 1 0 1 0 1 0 0 |
| 3 : Roadside | 1 0 0 1 1 1 1 0 0 1 0 1 0 1 0 0 |
| 4 : Pededridge | 1 1 1 0 1 1 0 1 0 1 0 1 0 1 1 0 |
| 5 : Sidewalks | 1 1 1 1 0 1 1 1 1 1 0 1 0 1 0 1 1 |
| 6 : Ramps | 1 0 0 1 1 0 0 1 1 1 0 1 0 1 1 0 0 |
| 7 : Sidelitn | 0 0 0 0 1 0 0 1 1 1 0 1 0 1 0 0 0 |
| 8 : RolNeMoTr | 1 0 0 1 1 1 1 0 1 1 0 1 0 1 1 1 0 |
| 9 : PubTraCov | 1 0 0 0 1 1 1 1 0 1 1 1 1 1 0 0 0 0 |
| 10 : Stations | 1 1 1 0 1 1 1 1 0 0 1 1 1 1 1 0 0 0 0 |
| 11 : PopuConce | 1 1 1 1 1 1 0 1 1 0 1 0 1 0 0 0 0 0 0 |
| 12 : Land use | 1 1 1 1 1 1 0 1 1 0 1 0 1 1 1 0 0 0 0 |
| 13 : ProxiPOIs | 0 1 1 1 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 0 |
| 14 : Self-suffi | 1 0 0 1 1 1 1 0 1 1 1 1 0 0 0 0 0 0 0 0 |
| 15 : Bike lanes | 1 0 0 1 1 1 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 |
| 16 : Tybifo | 1 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 |
| 17 : Trees | 1 0 0 0 1 1 1 1 1 0 0 1 0 1 1 0 0 0 0 0 0 0 0
Moreover, in order to enrich the structural analysis method, some criterions of Sussman, Dodder, McConnel, Mostashari, and Sgouridis (2007) have been used such as the direction of relation. Also, it is noticeable that others have been added like the type of relation (if it is topological, functional or a relation of territorial polarity) and more importantly the impact of the relation, since in structural analysis we are able only to identify the existence of relations between the indicators without knowing if they are positive or negative. In Figure 1, the “1” with red colour define a relation of negative impact while the “1” with black colour a positive impact. Finally, in order to avoid the leader’s phenomenon we made use along with structural analysis, a heuristics method like Delphi, where through interviews each expert were consulted in private in order to discover: the relations and the direction of influence-dependence between the considered indicators, what type of relations are, upon which criterion each relation is based, etc. Afterwards, the results were exposed to the group of experts so that to have a consensus.

Nevertheless, it is worth mentioning that the matrix of direct relations is the product of a consulting process with various experts through which we were able to discover relations between indicators that at first were not obvious. We tried to keep the group of experts consulted as interdisciplinary and as independent as possible, firstly, because of the sustainable mobility paradigm’s nature that demands interdisciplinary approaches and secondly in order to avoid the phenomenon of leaders.

Thus, the experts consulted come from various fields, such as transportation and sustainable transportation experts, geographers, experts in matters of energy consumption, experts in urban planning and territorial organization, experts in public policies-strategies related to the sustainable mobility paradigm as well as decision makers within the institutions responsible to manage the UTI and its urban surroundings. The consulting process followed in order we to be able to validate our methodology through the expert’s opinion is seen in Figure 2.

### 3.3. Identification of the essentials indicators

The objective of this step is to detect the indicators of greater importance. They are detected in terms of influence upon other indicators, as well as in terms of dependence (Colodni, 1987, p. 3).
In order to achieve it we need not only to measure the direct relationships between the indicators but also the indirect relationships that occur through chains of influences and feedback, this is achieved through the MICMAC method (Arcade et al., 1993).

The direct qualification is easy, as it means simple sums of values of influence and dependence for each of the considered indicators, while the indirect classification is obtained after the power elevation of the matrix of direct relations. The elevation of the matrix to the square shows the relations of order 2 between two indicators; the elevation of the matrix to cube reveals the relations of order 3 and so on (Romero Perea, 2012). However, the question is what matrix of indirect relationships should be used in order to analyze the indirect influence and dependence of the system’s indicators?

It is necessary to raise the direct relationship matrix as many times as necessary until the results stabilize; that is until the influence and dependence of the matrix’s indirect relations to the next elevation does not alter in relative terms and thus, we can set the hierarchy between the selected indicators (Guzmán Vazquez, Malaver Rojas, & Rivera Rodríguez, 2005, p. 27). In Figure 3 is seen a flow diagram with the process of finding the matrix stability criterion.

**Figure 3.** Flow diagram with the structural analysis process in order to reach stability.

1) Experts consulting
2) Discover the direct relations between the indicators
3) Fill the matrix with “0” and “1”
4) Classify the indicators according to the sum of influence that an indicator exerts on the others and the sum of dependence that an indicator receives from the others.
5) Represent graphically the matrix of direct relations
6) Elevate the matrix to the square in order to find the indirect relations of second order.
7) Classify the indicators according to the sum of influence that an indicator exerts on the others and the sum of dependence that an indicator receives from the others.
8) Compare the ranking of influence and dependence of each indicator between the matrix of direct relations and the matrix of indirect relations of second order.
9) Is the ranking equal?
   - Yes
   - No
10) It is not necessary to continue elevate the matrix because has been stabilized
11) Elevate the matrix to successive powers until the ranking of each indicator in terms of influence and dependence between power n and n-1 is equal

Finish
When the stability of the matrix has been achieved, the hierarchy of each indicator in terms of influence and dependence is set. In order to establish such a hierarchy there is the need to sum the elements within the matrix that result from each iteration in terms of row and column, the sum in row indicates the influence of an indicator i upon the other indicators. The sum in column highlights the number of times an indicator j is influenced by other indicators (Romero Perea, 2012). From the obtained results, each indicator is classified according to its level of influence and dependence and is located to the following hierarchy sectors (Figure 4).

Through the MICMAC software, we were able to raise the matrix to successive powers (1, 2, 3 etc.). The matrix has been raised to 3 because at that iteration was stabilized and the indirect relationships were obtained. At the end of the process, we have the matrix of indirect relations, which is represented graphically in Figure 5.

The most important indicators are the ones placed in sector 2 (they are called “key” indicators) because they are by nature factors of instability since any action upon them has consequences to the other indicators. For that reason and because of the fact that within a sustainable mobility paradigm the most important user is the pedestrian, we find in this sector three elements that form part of the pedestrian network such as sidewalks, pedestrian bridges and ramps.

Moreover, a very important element for sustainable mobility is the cyclist; hence, the bike lanes are located in the same sector. Nevertheless, pedestrian and cyclists are not able to cover long distances, thus, they need public transportation elements in order to compete with motorized transportation modes, consequently the coverage and stations of public transport are assigned with great importance.

The streetlights indicator is a very important element considering sustainable mobility, since they can enhance the security of pedestrians, cyclists and users of public transport. The land use indicator is also located in sector 2 because not only it can create greater mobility demand affecting the principal components of sustainable mobility but also, is an essential element for the promotion of TOD type policies.
The road network of motorized transit is as well as the previous ones a very important indicator because it sets the basis for the existence of other indicators, for example, the road networks determine where the sidewalks, streetlights, pedestrian bridges, sidewalk fittings, coverage of public transport, stations of public transport should be placed.

Finally, at the same sector is located the indicator of block’s self-sufficiency, because is an important factor for the creation of complete neighborhoods (neighborhoods with low car dependence), where the people are able to cover their needs by using the principal components of pedestrian, cyclist and public transportation user network due to the small distance separating from the POIs.

Nevertheless, the indicators located in sector 1 (influential indicators) are also important, because they determine the system’s behaviour. In this sector are located indicators, such as proximity to POIs, since the closer to a reasonable walking distance there are POIs that meet various human needs, the smaller will be the use of the car in order for the people to perform their daily activities.

The indicator of total population within a block is important to consider in the context of TOD type policies, this kind of policies propose the necessity to count with coverage of public transportation in geographical areas that have a high population concentration. In addition, a greater number of people mean a greater mobility demand, which in turn means greater use of the main, pedestrian, cyclists and public transportation user components.

The block’s size and form factor is in the same sector because according to its shape it can contribute to the orientation of pedestrians and the facilitation of the passage from hierarchical networks to well-connected networks that not only reduce the distance, but offer more alternatives for people to reach their destination.
Then according to their importance follow the indicators located in sector 3, they are highly dependent indicators that is not preferable to be addressed directly, but through the indicators from which they depend. In this sector is located the indicator of sidewalk fittings that it is an important indicator for the purposes of pedestrian mobility but it is better to manage it through the indicator that principally influences it, that is the sidewalks.

In the sector 4 near the origin of influence and dependence axes, are located the so called autonomous indicators such as merchant stands and trees that have low level of dependency and low level of influence.

It is noteworthy, that the majority of influence that the indicators in sector 4 have upon the others is negative, however, in the case of merchant stands this influence is negative a priori, while in the case of trees is negative under certain conditions. For example, the merchant stands reduce the designated space that the people have to walk; they hinder the free flow of people around stations of public transport and pedestrian bridges etc. The trees on the other hand, may cause problems upon the road networks of motorized transit, streetlights, sidewalks, ramps, sidewalk fittings, bike lanes etc., only when there is no proper maintenance, and when the authorities chose the type of trees poorly.

Meanwhile, the trees are not only useful in order to make people’s travel more enjoyable in terms of aesthetic, but also are able to protect the people from rain and sun, therefore, the trees can help a sustainable mobility through facilities offered to pedestrians and cyclists, nevertheless, they pose a certain risk factor if not given the proper maintenance. For the reasons explained above in the sum process of the global index (Equation (3)) the merchant stands are going to be subtracted as a negative, while the trees are going to be summed as a positive factor for the sustainable mobility. In the following lines we are able to see the location of each indicator at the four sectors, as well as their abbreviations in order to be more easily understood by the lector (Table 5).

Now that the selected indicators have been located at the four quadrants according to their level of influence and dependence, a normalization process is going to be applied through the formulas (1) and (2) in order to be able to weight up each indicator (seen in Table 1) according to the distance separating it from the two axes of dependency and influence.

| Table 5. The location of the selected indicators at the four sectors |
|---------------------------------------------------------------|
| **Sector 1** | **Sector 2** |
| * Proximity to the points of interest (ProxiPOIs) | * Sidewalks (Sidewalks) |
| * Size and form factor of the block (Tyblfofa) | * The road networks of motorized transit (RoNeMoTr) |
| * Total population within the block (Popuconce) | * Bike lanes (Bike lanes) |
| | * Pedestrian bridges (Pedebridge). |
| | * Stations of public transport (Stations) |
| | * Land Use (Land use) |
| | * Block’s self-sufficiency (Self-suffi) |
| | * Street lights (Street lig) |
| | * Coverage of public transport (PubTraCov) |
| | * Ramps (Ramps) |

| Sector 3 | Sector 4 |
|-----------------|-----------------|
| * Sidewalks fittings (Sidefittin) | * Semi-fixed posts (Semi-fixed) |
| | * Roadside stands (Roadside) |
| | * Trees (Trees) |
where $a_i$ and $a_d$ are the actual values of influence and dependence for each indicator after the third elevation of the matrix where the stability was achieved, while $a_{i \text{ max}}$ and $a_{d \text{ max}}$ is the maximum value of influence and dependence respectively.

Since the actual values of the examined CT and the associated weights for each one of these indicators are known via the structural analysis method, we are able to measure the quality of mobility according to the functionality and coverage of UTI and its urban surroundings elements by taking into consideration the opinion of the experts. Furthermore, it is noteworthy that our methodology has the capacity to escalate to different geographic “entities” because for each CT that exists in the city there are “$m$” number of blocks. It is remarkable, that each CT is formed from a distinct number of blocks depending on its size. Moreover, the blocks that are part of a certain CT cannot be part of another CT. With other words, there is no block belonging to two distinct CT.

Consequently, if we know the actual situation through certain established indicators at a block level we can produce a synthesized indicator (a global index) at a higher geographic level (CT) (Equation (3)) that will provide to the public authorities synthesized information about the quality of sustainable mobility in terms of UTI and urban surroundings coverage and functionality. Furthermore, if we have available information at a CT level we can move on to the next geographic level and calculate a synthesized indicator at a County level (Equation (4)) and so on.

\[
I(\text{ct}) = \sum_{i=1}^{n} \frac{V(i) \times P(i)}{k}
\]

where $i$ is the value of each one of the 17 indicators with its associated weight, $n$ is the number of indicators (in our case they are 17) and $k$ is the number of blocks that belong to the examined Census Tract $\text{ct}$. Because the CT and the County are interrelated geographical entities (a County consists of a set of CT), we also define a sustainable mobility quality indicator for the County $\text{C}$,

\[
C(\text{P}) = \frac{\sum_{i=1}^{n} I(\text{ct})}{n}
\]

where $n$ is the number of CT within the County $\text{p}$ and $\text{ct}$ is each CT within the County $\text{p}$.

Nevertheless, it needs to be stated that for the purposes of the first author’s PhD thesis the indicators were implemented only within the most populated CT of the Iztapalapa County. Furthermore, a mathematical formula has been created, showing how to calculate the quality of mobility via UTI and its urban surroundings at a county level; however, the Equation (4) is going to remain for the moment only at a theoretical level due to the fact that its quantification greatly surpasses the time limitations of the first author’s postgraduate program. Thus, in the following lines we are able to see the actual performance value of the examined CT according to the Equation (3).

\[
I(i) = \frac{104.615}{23} = 4.54
\]

This performance value can be greatly improved if there are upgrades in terms of coverage of certain UTI elements and urban surroundings elements, such as an increase of sidewalks, sidewalks fittings, ramps, bike lanes, coverage of public transport, streetlights, trees etc. Nevertheless, these lines of actions need to be part of a comprehensive plan with its strategies-public policies rather than a number of partial implemented countermeasures. Hence, in the following section of the
paper we are going to establish (according to the experts opinion) logical relationships between the selected indicators and public policies with its corresponding lines of action in order to see their impact on the actual performance value of the examined CT.

4. Logical connections between strategies-public policies and the selected indicators

Transportation is a fundamental activity for the modern economies, nevertheless there are also some negative externalities related to transportation, for example the private cars are responsible for generating the majority of greenhouse emissions and several distinct pollutants, these emissions contribute to climate changes which could have serious consequences in terms of health and environmental costs (Galindo, Heres, & Sánchez, 2006, p. 124).

The losses only for negative externalities generated by the excessive use of private cars represent 5,379 pesos per capita, or the equivalent to 4% of the total GDP of five large metropolitan areas that concentrate 40% of the national urban population (Medina, 2012a, pp. 36–37). The future prospect in Mexico is that this situation will get worse if the use of cars continues to grow.

In order to, successfully boost a federal policy related to the reduction of automobiles and the reduction of the negative externalities associated to this mode of transportation it is essential to change the way in which the problems of transportation in the cities are conceptualized (Medina, 2012b, p. 37).

The traditional transportation paradigm related to greater supply of road infrastructure in order to improve the flow of vehicles has expired. Nowadays, it is important to change the habits of displacement and encourage the efficient use of transportation modes. By that way, it will be easier to achieve public policy objectives associated to the idea of push & pull travels. Since the ideal is to push travels away from the private transportation modes (automobiles) and pull them close to the sustainable transportation modes (walking, cycling, public transportation) (Medina, 2012b, p. 37).

For the reasons mentioned before SEMOVI in 2014 decided to establish an IPM which is based on the sustainable transportation paradigm in order to change the habits of displacement and encourage the efficient use of transportation modes.

The above-mentioned paradigm consists of its associated strategies that in turn consist of public policies. In this part of the paper, we are going to create logical relations between the indicators considered for this study and certain strategies-public policies with their associated lines of action that belong to the IPM and are related to sustainable transportation. By that way, we are able through a simple example to conclude which lines of action must be implemented first (next to each line of action we see the order to implement them) and consequently structure in a hierarchical manner the public policies and strategies according to their impact on the global index.

The following (Figures 6–10) contain the IPM with its respective strategies and public policies (Gaceta Oficial de Distrito Federal, 2014), they also contain a description of the policies as well as the
Figure 6. General scheme of the relations between plan, strategy, policies and lines of action.

![Diagram of the relations between plan, strategy, policies, and lines of action.]

Figure 7. Policies, indicators and lines of action oriented to pedestrians, belonging to “Complete streets” strategy.

![Diagram showing policies, indicators, and lines of action related to pedestrians within the “Complete streets” strategy.]

| Key indicators as determined through MICMAC method | Corresponding lines of action |
|-----------------------------------------------------|------------------------------|
| Public streetlights                                 | Install public street lights in every block’s front. (4) |
| Sidewalks                                           | Construct sidewalks in every block’s front. (3) |
| Proximity to POIS, block’s self sufficiency         | Enhance the densification of land use through the establishment of proximity to points of interest at a reasonable pedestrian distance, as well as the establishment of block’s self-sufficiency to a high-very high level. (2) |
| Ramps                                               | Construct ramps in every block’s front. (5) |
| Pedestrian bridges                                  | Secure sufficient illumination in every pedestrian bridge within the county of Itapalapa and when is possible, equip the bridges with features of integral accessibility. (6) |
| Coverage of public transport, stations of public transport, block’s size and form factor, bike lanes. | Establish alternatives of sustainable mobility at a reasonable pedestrian distance in order for the people to be able to perform their daily activities without the obligation to use the car (for example, bike lanes, elements of public transport) through an intelligent urban planning. (3) |
Figure 8. Policies, indicators and lines of action oriented to cyclists, belonging to “Complete streets” strategy.

| Strategy 1: Complete streets | Policies oriented to cyclists | Key indicators as determined through MICMAC method | Corresponding lines of action |
|-----------------------------|------------------------------|---------------------------------|-----------------------------|
| Objective                   |                              | Public street lights            | Install public street lights in every block’s front. (4) |
|                             |                              | Coverage of public transport, stations of public transport, bike lanes. | Construct bike lanes that preferably are close to routes and stations of public transportation. (1) |
|                             |                              | Bike lanes                      | Construct new bike lanes. (3) |
|                             |                              | Ramps                           | Construct ramps in every block’s front. (5) |
|                             |                              | Bike lanes, population           | Establish bike lanes where there is a high population’s concentration. (2) |

Figure 9. Policies, indicators and lines of action oriented to public transport, belonging to “Complete streets” strategy.

| Strategy 1: Complete streets | Policies oriented to public transport | Key indicators as determined through MICMAC method | Corresponding lines of action |
|-----------------------------|--------------------------------------|---------------------------------|-----------------------------|
| Objective                   |                                      | Road networks of motorized transit, coverage of public transportation, stations of public transport, population. | Locate stations of public transport of medium-high capacity in the blocks that have a high or medium level of connectivity, as well as a high population concentration. (1) |
|                             |                                      | Coverage of public transport.    | Increase the public transportation coverage in the blocks that do not count with public transportation modes (expand the public transportation service, develop BRT, confined lanes etc.). (3) |
|                             |                                      | Sidewalks, ramps, public street lights, sidewalk fittings. | Secure the existence of pedestrians UTI that is necessary for the ascending and descending of people to the transportation mode. (2) |
key indicators identified by the MICMAC method related to the policy-strategy presented. Furthermore, we can see with more detail, the logical connections between the lines of action and each indicator as well as the ranking of each line of action according to each indicator’s weight up value (seen in Table 1).

5. Conclusions

The objective of this paper has been the hierarchical structure of UTI-urban surroundings indicators connected to sustainable mobility, in order to create a weighted index related to UTI management and to evaluate public policies-strategies associated to these indicators.

The soundest part of this survey is the construction of a synthesized index that not only is capable of measuring the quality of sustainable mobility through the coverage and functionality of certain constructed UTI-urban surroundings indicators but within the measurement process is capable to integrate the perception of experts through the structural analysis. Moreover, the index has the capacity to escalate to different geographic entities. Additionally, through the previously mentioned index, and via the establishment of logical relationships between the indicators and public transportation policies, we are able to identify the key indicators in the context of the policies, identifying which strategies-public policies with their associated lines of actions are the most effective in accordance to their impact on the synthesized index.

It should be mentioned that the selected indicators are indeed related to the sustainable mobility paradigm but they are not the only one, there are several others indicators that could be used such as traffic lights, road signals etc. However, we selected the above mentioned indicators due to their relationship with the mobility of pedestrians, cyclists and users of public transport and due to information’s availability.

The summary of our findings is very interesting because it demonstrates through the MICMAC software that the most important indicators are the proximity to POIs, size and form factor of the block, coverage of public transport, total population of the block, land use, block’s self-sufficiency, public streetlights, sidewalks, road networks of motorized transit and stations. Consequently the
most important strategy is the urban development one and more specifically the TOD public policy because includes the majority of the identified “key” indicators. Then we have the complete streets strategy with its associated public policies and indicators, where of first importance in terms of effectiveness upon the global index is the policy oriented to pedestrians, then follow the one associated to public transport and finally the one associated to cyclists.

Moreover, it is noteworthy that the following characteristics should be considered within an IPM in order to successfully establish the new mobility paradigm in Mexico City (ITDP, 2012b):

- Quantifiable Objectives: that needs to be easily understood, evaluated and monitored by the government and the majority of the people.
- Integration: this will encourage the cooperation between the environmental, land use and transportation sectors in order to create a sustainable urban development.
- Participation: it will be fundamental to promote the communication of the government with the civil society, with the purpose of considering the people as an important part of the urban management process, and this will generate the process of co-management.
- Long-term vision: the plan must count with the instruments and public institutions that are able to assure the continuity of plan in long-term.
- Sustainability: the plan needs to consider a balance between economic development, social equity and environmental quality of the cities.

The next step will be to consider each one of these characteristics and analyze each project from these points of view not only for Mexico City but also for other cities of the world. Moreover, in relation to the synthesized index, there is the need to find efficient ways to complement this set of indicators, in order to help the assessment of mobility and enrich the proposed global index.

Furthermore, it would be interesting to see how the final results of the indicators weighting process (structural analysis) would have been if we would have taken into account the intensity of the direct relations within the matrix, or how would have been the final quantitative results if the importance of dependency and influence levels were not equal. Nevertheless, the above-mentioned future investigation has not been taken into account due to time limitations of the first author’s PhD program and because of the scope of his investigation according to his tutor’s opinion.

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