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Evaluation of bus transit network: the case of CIM Ave

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ABSTRACT

Public Transport (PT) networks are complex system that are essential to promote population´s mobility. In Portugal, the new Legal Regime of the Public Transport Service of Passengers (RJSPTP, *Regime Jurídico de Serviços Públicos de Transporte de Passageiros*) is the legal framework of PT networks and addresses the European directives established in Regulation (EC) 1370/2007. This new legal regime profoundly changes the paradigm of the management of public passenger transport services, decentralizing skills and responsibilities, previously concentrated in the Institute of Mobility and Transportation (IMT). In this context, it is critical to understand how existing PT network performance can be assessed in order to identify flaws supporting the design of the future PT networks.

This project aims at developing a framework to support the performance evaluation of PT networks in the new RJSPTP.

A broad literature review allowed to identify main issues concerning the evaluation and improvement of bus public transport networks, as well as, the main techniques and methodologies associated. Based on the literature review a framework was developed to support the performance evaluation process, identifying key elements and key performance indicators

A case study of a PT network in the CIM Ave has been carried out and the framework has been explored to support the analysis and design stages of the construction of a new network. Results allowed to identify the main challenges associated to the redesign of a PT network, in particular, the difficulty in obtaining the relevant data to undertake a full assessment process.

After the case study, the performance of the framework was evaluated. It revealed the advantages, limitations and possible improvements of the proposed framework.

Keywords

Public transport, performance evaluation, transit accessibility, territorial coverage, school transportation.

Resumo

Redes de Transporte público (TP) são sistemas complexos que são essenciais para promover a mobilidade de população. Em Portugal, o novo Regime Jurídico de Serviços Públicos de Transporte de Passageiros (RJSPTP) elimina as diretivas Europeias estabelecidas no Regulamento n.º 1370/2007. Este novo regime jurídico muda profundamente o paradigma de gestão de serviços públicos de transporte de passageiros, a descentralização de competências e responsabilidades, anteriormente concentrada no Instituto da Mobilidade e dos Transportes (IMT). Novos Autoridades de Transporte, baseados em Municípios ou Comunidades Intermunicipais são agora responsáveis pela conceção e gestão de redes de transporte público. Neste contexto, é fundamental entender como o desempenho da rede existente de TP pode ser avaliado, a fim de identificar falhas e apoiar a conceção de redes de TP.

Este projeto inclui o desenvolvimento de um modelo para apoiar a avaliação de desempenho de redes de TP considerando o novo RJSPTP.

Uma ampla revisão da literatura permitiu identificar as principais questões relativas à avaliação e melhoria de redes de transportes públicos, bem como, as principais técnicas e metodologias associadas. Com base na revisão de literatura foi desenvolvido um modelo para apoiar o processo de avaliação do desempenho, identificação de elementos-chave e indicadores-chave.

O estudo de caso da rede TP da CIM do Ave foi realizado e o modelo foi explorado para apoiar a análise e o planeamento de uma nova rede. Os resultados permitiram identificar os principais desafios associados ao redesenho de uma rede TP, em particular, a dificuldade na obtenção de dados relevantes para realizar uma avaliação completa do processo.

No final, o modelo foi avaliado, tendo-se identificar as suas vantagens, limitações e possíveis melhorias.

Palavras-Chave

Transporte público, avaliação de desempenho, acessibilidade ao trânsito, cobertura territorial, transporte escolar.

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List of Acronyms

PT Public Transport

NUTS3 Nomenclature of Territorial Units, level 3 *(Nomenclatura de Unidades Territoriais)*

AMP Municipal Area of Porto *(Area Municipal do Porto)*

ST School Transportation

SC Special Circuits

INE National Statistics Institute *(Instituto Nacional de Estatística)*

1. INTRODUCTION

This dissertation is accomplished as a part of the technical report of Laboratório de Mobilidade. The purpose of this project is to carry out a study of public passenger transport networks and services in the Ave Intermunicipal Community (CIM), within the scope of the Legal System of Public Transport of Passengers (RJSPTP).

Cities across the world are involved in permanent developing processes. Demographic, economic and migration changes have an impact on the spatial distribution of population within regions. This influences the demand for public transport systems. Thus, current transit networks are not necessarily optimal and may need permanent evaluation.

According to the information from National Institute of Statistics (INE), almost 500 000 passengers were transported by road public transport in 2015. This number corresponds to 5% of all population of Portugal. From one hand, it is a significant number of passengers. On the other hand, this number may be increased, reducing the population's dependence from private cars and expenses on car infrastructure.

The development of new technologies facilitates the planners' job. Nowadays, an increasing amount of information about fare collection, passenger origins and destinations, real-time vehicle location, among others, is provided. Control tools are implemented in the majority of public transport systems. The availability and usage of this information allow planners and managers to design more efficient transit networks and have better performance control of operations.

Law 52/2015 approved the Legal Regime of the Public Transport Service of Passengers (RJSPTP). This legal regime profoundly changes the paradigm of the management of public passenger transport services, decentralizing skills, previously concentrated in the Institute of Mobility and Transportation (IMT). In addition, taking into account the European directives established in Regulation (EC) 1370/2007, it is necessary to carry out the proceedings until December 2019.

According to the RJSPTP, the management competencies of the public passenger transport service go to local authorities and to intermunicipal communities (CIM), depending on the type of service in question. In this way, the Municipalities will be the competent transport authorities with regard to municipal transport services. The CIM shall be the competent transport authorities with regard to inter-municipal and inter-regional transport services which are developed in their geographical area.

According to article 10 of the RJSPTP, there is the possibility of delegation and sharing of competences between the various transport authorities, so that municipalities may, under an inter-administrative agreement, delegate all or area of influence. In this sense, the CIM Ave assumes itself the responsible for the management of public intercity passenger services in this region. It should be noted that, in the beginning of this process, all municipalities that are included in the CIM Ave have assumed responsibility as transport authorities, being competent for transport services that are carried out exclusively within the respective geographical areas.

1.1 Objectives

This legal regime raises new and important challenges for newly created transport authorities. The need to know in detail all the services of its area of influence, characterizing and analyzing the existing reality, is the first step towards compulsory contracting until December 2019.

The objective of this study is to propose a framework for the evaluation of public transport networks. Additionally, this study uses the framework to assist CIM do Ave and its municipalities in characterizing, diagnosing and planning the mobility of their region, with a special focus on public passenger transport services, in the context of the new legal framework. Furthermore, the advantages and limitations of the evaluation framework are discussed as well as the main challenges of its application in a Portuguese case.

1.2 Methodology

The project is based on a case study of Intermunicipal Community Ave (CIM Ave). In order to accomplish the literature review for the theoretical basis of the project, international scientific databases were used to identify the most relevant academic contributions. The research only considered articles in English and the list of search keywords included (but was not limited to) the following: network evaluation; network assessment; public transport; public transit; network design; network frequencies; network timetabling; network scheduling; transfer evaluation; data collection; smart cards.

The overview is focused on papers connected with the bus networks and includes some researches based on other transit modes.

Based on the literature review, a framework has been developed identifying key performance indicators to support the characterization and analysis of existing bus network. The framework was then applied to the case of the CIM Ave.

1.3 Structure of the Dissertation

This project includes the theoretical part and the case study. Chapter 2 presents the literature review of the best practices of public transport evaluation. Chapter 3 summarizes these findings into a conceptual framework and compares it with the law requisites in order to propose the adjusted framework for the evaluation of network in CIM Ave. Chapter 4 provides the description of CIM Ave region, based on statistical information. Chapter 5 includes the evaluation of the public transport network in CIM Ave, based on the adjusted framework, and discussion of the results. Conclusions are presented in Chapter 6.

2. State of Art

This chapter presents a systematic literature review concerning the articles in English language, allowing to identify the main issues to take into account in the design, evaluation and redesign of public transport networks.

2.1 Transit planning process – an overview

Evaluation and improvement of Public Transport (PT) network begin with an understanding of the basic principles of its creation process. The whole planning process is divided into a set of problems. Different names for the same PT network planning problem are used across the articles. In this review, we consider the terminology of Guihaire and Hao (2008):

- *Transit Network Design Problem (TNDP):* definition of the set of bus lines and stops, considering road network topology and spatial distribution of customer's required origin and destination points. It has an impact on network accessibility.
- *Transit Network Frequency Setting Problem (TNFSP):* determination of service frequency for each bus line. Calculations are based on time distribution of customer's demand, considering daily, weekly end seasonal variations. It has an impact on network accessibility.
- *Transit Network Timetabling Problem (TNTP):* determination of bus arrival (or arrival and departure) times for each stop during the operational period. It has an impact on network transfer synchronization.
- *Vehicle Scheduling Problem:* assignment of buses to services with the objective of executing all planned trips with minimum operator's costs.
- *Driver Scheduling Problem:* determination of necessary staff (bus crews) with the objective of executing all planned trips with minimum operator's costs.
- *Driver Rostering Problem:* personnel assignment in order to cover all necessary duties.

All these steps are presented in Figure 1. Scheduling and rostering issues are usually dealt with by transit operators. In this work, the focus is on the first three of the abovementioned PT planning problems, which are normally solved by transport authorities.

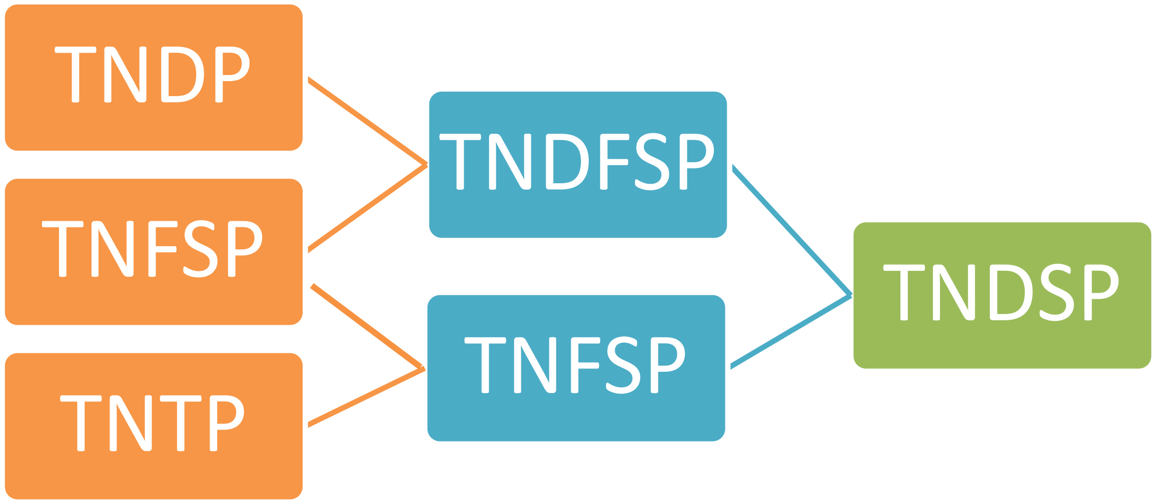


Figure 1 - Structure of Transit Network Design and Scheduling Problem

When TNDP and TNFSP are considered simultaneously, they are called Transit Network Design and Frequency Setting Problem (TNDFSP). Furthermore, TNFSP and TNTP form Transit Network Scheduling Problem (TNSP). Finally, TNDP, TNFSP, and TNTP together comprise the Transit Network Design and Scheduling Problem (TNDSP).

2.2 Input data collection

In this section, the data that is required for an efficient PT network planning and evaluation as well as for the methods of its collection, are considered. Some information can be obtained from authorities or PT operators, such as road network, possible bus stop locations, current PT routes, stops, and schedules. Other data is variable and should be sought in other sources. This information includes:

1. *OD data*. Includes information about the trip origin and destination points and times of trip demand. Usual sources of OD data:
    a. mobility surveys on bus stops, by telephone or internet (Badia Rodríguez, 2016; El-Geneidy, Tétreault, & Surprenant-Legault, 2009);
    b. Smart-cards/tickets (Agard, Morency, & Trépanier, 2006; Bagchi & White, 2005; Jang, 2010; Morency, Trépanier, & Agard, 2007; Munizaga & Palma, 2012; Yang, Chen, Cao, Li, & Li, 2017);

c. Mobile phones positioning (Ahas, Aasa, Silm, & Tiru, 2010; Reades, Calabrese, Sevtsuk, & Ratti, 2007). Active and Passive data collection from a mobile phone can be considered (Saini, Sinha, & Srikanth, 2015);

2. *Service levels*. The majority of researchers use input data from customer's surveys obtained by telephone (van Lierop & El-Geneidy, 2016) or internet (Tsami & Nathanail, 2017). Some information can be provided by PT operators (Hassan, Hawas, & Ahmed, 2013).
3. *Bus stop accessibility.* Household spatial distribution and land topography (pedestrian infrastructure) can be obtained from local authorities (Kittelson and Associates, Parsons Brinckerhoff, KFH Group, Texas A&M Transportation Institute, & Arup, 2013; Murray, 2003) and customer surveys (Hawas, Hassan, & Abulibdeh, 2016).
4. *Travel times.* Data is usually provided by PT operators or estimated by open source software (John, 2016).

2.3 Network planning methods

Improvement of existing PT networks involves their revising by using advanced planning methods. It starts with solving the transit network design, frequency setting, and timetabling problems. Then, the obtained solution is refined by various operating strategies.

This step provides a new set of bus routes, stops and arrival/departure times for each stop.

Solution methods can be classified into four big groups:

1. Analytical approaches;
2. Mathematical approaches. This category also includes hybrid simulation-mathematical methods;
3. Heuristic approaches, including neighborhood searches such as simulated annealing and tabu search;
4. Metaheuristic approaches. Evolutionary search such as genetic algorithms.

The evolution of planning methods for each transit network problem is presented in Table 1. When a mathematical model is proposed together with a solution method within the same paper, it is categorized according to the solution method employed.

The second column of the table exhibits whether application of the solution is the real case ("R") or theoretical example ("T"). The third column corresponds to the planning problem reviewed in the article. The fourth column presents the objectives considering during network improvement. The fifth column exhibits the solution approach – analytical (A), mathematical (M), heuristic (H) or metaheuristic (MH).

Table 1 - Literature review for the Transit Network Planning Problem.

Article	App.	Problem	Objectives	Solution
Mandl (1979)	R	TNDP	Travel time, Number of transfers	H
Ceder & Wilson (1986)	T	TNDFSP	Operator's costs, Travel and Transfer time	H
Baaj & Mahmassani (1991)	R	TNDP	Transfer time, Number of transfers	H
Murray (2003)	R	TNDP	Operator's costs, Bus stop accessibility	M
Zhao & Gan (2003)	R	TNDP	Trip coverage, Number of transfers	M
Fan & Machemehl (2004)	T	TNDP	Operator's costs, Bus stop accessibility, Travel time, Transfer time	H
Borndörfer, Grötschel, & Pfetsch (2005)	R	TNDFSP	Operator's costs, Travel time	M
Fernández L., de Cea Ch., & Malbran (2008)	R	TNDP	Operator's costs, Travel time	H
Shimamoto, Murayama, Fujiwara, & Zhang (2010)	R	TNDFSP	Operator's costs, Travel time	MH
Ibeas, Dell'olio, Alonso, & Sainz (2010)	R	TNDP	Operator's costs, Bus stop accessibility, Travel time, Transfer time	H

Article	App.	Problem	Objectives	Solution
Asadi Bagloee & Ceder (2011)	R	TNDP	Operator's costs, Service level	H, MH
Cipriani, Gori, & Petrelli (2012)	R	TNDFSP	Operator's costs, Travel time	MH
Chew, Lee, & Seow (2013)	T	TNDP	Operator's costs, Travel time	MH
Mumford (2013)	T	TNDP	Operator's costs, Travel time	H, MH
Nikolić & Teodorović (2013)	T	TNDFSP	Travel time, Number of transfers	MH
Nayeem, Rahman, & Rahman (2014)	R	TNDP	Trip coverage, Travel time, Nº transfers	MH
Nikolić & Teodorović (2014)		TNDFSP	Operator's costs, Travel time, Transfer time	MH
I. Ö. Verbas, Frei, Mahmassani, & Chan (2014)	R	TNFSP	Operator's costs, Travel time	M
İ. Ö. Verbas & Mahmassani (2015)	R	TNFSP	Operator's costs, Travel time	M
Ibarra-Rojas, López-Irarragorri, & Rios-Solis (2015)	R	TNTP	Nº transfers	M
Cancela, Mauttone, & Urquhart (2015)	R, T	TNDFSP	Operator's costs, Travel time, Nº transfers	M
Arbex & da Cunha (2015)	T	TNDFSP	Costs, Coverage, Travel time, Nº transfers	MH

Continuation of Table 1

Article	App.	Problem	Objectives	Solution
Pternea, Kepaptsoglou, & Karlaftis (2015)	R	TNDP	Environment sustainability, Nº transfers	MH
John (2016)	T	TNDFSP	Operator's costs, Travel time, Nº transfers	MH
Zaourar-Michel (2016)	R	TNFSP	Transfer time	H
Badia Rodríguez (2016)	R	TNDP	Operator's costs, Nº transfers	A
Ceder (2016)	R, T	TNDSP	Operator's costs, Service level, Trip coverage, Travel time, Transfer time	M, H, MH
Laporte, Ortega, Pozo, & Puerto (2017)	T	TNTP	Operator's costs, Travel time	M
Liu & Ceder (2017)	T	TNTP	Operator's costs, Transfer time	M

The list of software packages used in PT network improvement IVU.SUITE (Borndörfer et al., 2005), Emme (Cipriani et al., 2012), TransCAD (Zhao & Gan, 2003), SUMO (Saini et al., 2015).

Matlab (Chen, Liu, Zhu, & Wang, 2015; Ibeas et al., 2010), C++ program codes (Fan & Machemehl, 2008), ESTRAUS (Ibeas et al., 2010) and Java Genetic Algorithms Package (Saini et al., 2015) are used to deploy Genetic Algorithms and plot Pareto frontiers.

Moreover, almost every PT research requires a geographic information system tool (software) – ex. open-source QGIS, GRASS, etc. or proprietary ArcGIS, MapInfo, etc. – in order to visualize transit lines on maps and perform some spatial statistical analyses.

2.4 Network Evaluation

The literature review reveals the four main aspects of PT network evaluation. The importance of their impact on customers' interests are (on a decreasing order) as follows:

- Evaluation of PT necessity.
- Evaluation of Accessibility to PT network.
- Evaluation of Transfers.
- Multicriteria evaluation of network performance.

This aspects are discussed in the following sections.

2.4.1 Evaluation of PT necessity

The whole area is divided into Transportation Analysis Zones (TAZ). The TAZ is a district with homogeneous properties (Yan-yan et al., 2016). Methods of TAZ evaluation are based on a household density or proximity to primary facilities.

Each transportation analysis zone (TAZ) is evaluated to determine whether it has the necessity for public transport. Evaluation is based on the minimum household density of 3 households or more per acre or a job density of 4 jobs or more per acre. Ideally, transit service will be provided within a normal walking distance of one's origin and destination. Alternatively, transport on demand could be implemented. Other options are driving to a park-and-ride lot or riding a bicycle to transit service. (Kittelson and Associates et al., 2013)

Index of public transport needs (IPTN) (Fransen et al., 2015) for the evaluation of public transport in TAZ is based on three components. The first component is the number of primary facilities within walking and biking distance. If a person has neither a car nor the financial resources to buy one but nevertheless lives in the proximity (walking or biking distance) of primary facilities such as jobs or health care, then this person is not considered dependent on public transport. If the distance from TAZ centroid to the primary facilities is less than 1.0 or 2.5 km, the facility is considered available on foot or by bicycle, respectively. These distances correspond with an average travel time of 15 min, which is the maximum travel time standard in Europe aimed at for more than 90% of the population (Doerner, Focke, & Gutjahr, 2007).

The second component is based on the percentage of the population aged 65 or older, the percentage of the population that is unemployed and the percentage of families without a car, which represent the inability to own and/or use a car. The third component has a high positive factor loading for children. TAZs with a high IPTN index are considered to be relatively disadvantaged.

2.4.2 Evaluation of Accessibility to PT network

There is no common list of accessibility measures for public transport; each author has his own point of view. The compilation of the most popular measures consists of:

1. Bus stops availability, based on distance or walking time;
2. Temporal availability and service frequency – service is available at the times of travel demand;
3. Trip coverage – customers' Origin-Destination (OD) connectivity;
4. Space-time accessibility (destination point can be reached during the limited time).

The list of less popular accessibility measures includes:

1. Information availability – a customer can easily obtain bus schedules, stop locations data, operators' policy, etc. (Hess, 2009; Kittelson and Associates et al., 2013).
2. Capacity availability – there is enough space inside the buses and at supporting facilities such as park-and-ride lots. (Kittelson and Associates et al., 2013);
3. Utility-based accessibility – simultaneous evaluation of the socioeconomic variables (household income, private transport availability), environmental impact, and bus stop accessibility, taking into account the travel purposes and motivations (Foth, Manaugh, & El-Geneidy, 2013)
4. Relative accessibility – comparison between different modes of transport, usually between PT and private cars (Benenson, Martens, & Rofé, 2010; Benenson, Martens, Rofe, & Kwartler, 2011; Chapleau & Morency, 2005; Golub & Martens, 2014; Yang et al., 2017).
5. Location-based (contour, cumulative opportunities) accessibility – the number of opportunities (jobs, hospitals, shops, etc.) within the pre-definite travel time contour from customers' origin (C. do C. F. da Silva, 2008; C. Silva & Pinho, 2010). Kaza (2015) estimate the number of opportunities for each 10 min interval during the weekdays and weekend.

6. Person-based accessibility – customers' possibility to participate in his personal activities during the time limits, traveling by PT network. Requires detailed OD surveys (Dong, Ben-Akiva, Bowman, & Walker, 2006).
7. Perceived accessibility – customers' perception of network accessibility. The measure is based on public surveys (Lattman, Olsson, & Friman, 2016).

Bus Stop availability

Most studies of bus stop availability focus on distance from the origin point to the first bus stop and from alighting stop to customer's destination. Another method considers walking time instead of distance. A variety of methods to measure the spatial area served by a PT network includes:

- Corridors along each bus line (Chapleau, Lavigueur, & Baass, 1987; Wirasinghe & Vandebona, 1987) – simple method, that usually overestimates access coverage;
- Euclidian metric – circle around each bus stop. Does not consider any physical barriers (Bruno, Ghiani, & Improta, 1998; Dufourd, Gendreau, & Laporte, 1996);
- Manhattan metric – the diamond-shaped area around a bus stop. Well-suited for cities with the perfect grid of streets (El-Geneidy et al., 2009; Horner & Murray, 2004);
- Street Network analysis – the most precise method. Access to PT network is calculated on the base of real streets topography around each bus stop and barriers to walking such as rivers, lakes, walls and freeways (Zhao, Chow, Li, Ubaka, & Gan, 2003). Also may include terrain, population characteristics (medium age, etc.), and pedestrian crossing difficulty (Kittelson and Associates et al., 2013). Hilly areas have a negative impact on acceptable walking distance, due to the effort involved. The analysis is usually made by means of GIS software.

There are different opinions about the distance that people may walk to get to a stop. Researchers typically use walking distances of 400 m (0.25 mile) for bus stops (El-Geneidy et al., 2009; Hess, 2009; Hsiao, Lu, Sterling, & Weatherford, 1997; Kimpel, Dueker, & El-Geneidy, 2007; Kittelson and Associates et al., 2013; Lovett, Haynes, Sunnerberg, & Gate, 2002; Mamun, Lownes, Osleeb, & Bertolaccini, 2013). This distance is an equivalent of five minutes walking time, assuming an average walking speed of 80 m/min (about 5 km/h).

Another distances, e.g. 300 m (Mondou, 2001) and 500 m (Chapleau & Morency, 2005), have also been used. Enlarged walking distance to transit stops can be considered for rural areas. In

Columbus, Ohio walking distances of 400 meters, or 800 meters in low-density areas, are accepted (Central Ohio Transit Authority, 1999) (Murray, 2003).

Sometimes PT network coverage may be applied only for the majority of the population. The policy goal of providing 90% of the total population access within 400 m of a bus, rail or ferry stop in the South East Queensland region is actually a common transportation planning objective in Australia, as shown by Murray, Davis, Stimson, & Ferreira (1998).

Some investigations compare theoretical walking distances with real ones. Burke & Brown (2007b, 2007a) show that for Brisbane, Australia, the trip distances walked to destinations are generally much greater than the distance conventions commonly used by planners – 600m in average to reach origin stop and 470 m from destination stop.

Murray et al. (1998) analyze the sensitivity of the threshold distance in evaluating access to bus stop. The coverage trade-off for threshold distances: to measure the distance when the 90% goal is achieved, and compare it with the stated distance (400 m). Then population (%) with access to the bus stop is calculated for different walking distances.

Temporal availability and Service frequency

Temporal availability of PT service is based on the periods of network functioning – time intervals for each day of the week. Service frequency reflects the headways – waiting time between two consecutive buses. These intervals may have a significant difference between peak and non-peak commuting times.

Methods of temporal availability and service frequency evaluation include:

- Mondou (2001), Yigitcanlar, Sipe, Evans, & Pitot (2007) categorize transit service frequency by headway intervals - at least every 15 min, at least every 30 min, and 30 min and more;
- Lovett et al. (2002) focus on return bus services. They estimate the percentage of the population with access to a certain number of return bus trips per weekday;
- Polzin, Pendyala, & Navari (2002) calculate time-of-day travel demand distribution and provide the relative accessibility of transit service for each time period. Spatial coverage of 400 meters alongside transit routes is considered;

- Jones et al. (2008) identify sections of the road network with a headway 1 hour in the daytime from Monday to Saturday simultaneously with estimation of the number of customers who lived within 800 m of these routes;
- Curtis & Scheurer (2010) adopts a minimum service frequency standard (headway) of 30 min during weekday inter-peak periods;
- Currie (2010) counts the number of trips per week for each stop;
- Saghapour, Moridpour, & Thompson (2016) develop a public transport accessibility index (PTAI) that combines the data of PT service frequency and population density in metropolitan Melbourne, Australia.

Trip coverage and Space-time accessibility

The trip coverage reflects the physical possibility of reaching a destination from a given location, using PT. Space-time accessibility estimates the possibility to do the same during the limited time budget, taking into account the walking, waiting, transfer and onboard times.

These two different aspects of PT accessibility are strongly connected with each other, so frequently the researchers tackle them simultaneously. Methods of trip coverage evaluation and space-time accessibility include:

- Miller (1991) introduce the concept of the space-time prism to estimate an individual access to an environment. Miller (2006) makes some comments to this research;
- Kwan (1999) measures the gender difference in space-time accessibility;
- O'Sullivan, Morrison, & Shearer (2000) focus on isochrone analysis (constant time budget) and generates maps of areas accessible by the PT network. Developing of the approach is continued by Lei & Church (2010);
- Huang & Wei (2002) calculate access via transit to business and industrial activities, classified into 11 sectors. Authors focus on the distance between census tracts and destinations. Number of bus runs per day is also included in the model;
- Kim & Kwan (2003) take into account the properties of activity (operating hours, minimum activity participation time) and PT network features such as one-way streets and turn restrictions. The number of accessible opportunities is estimated;

- Yigitcanlar et al. (2007) propose a GIS-based Land Use and Public Transport Accessibility Index (LUPTAI). The LUPTAI estimates the accessibility of the major activity locations considering walking distances, PT travel time, and transit service frequencies;
- Burns & Inglis (2007) estimate access to supermarkets and fast food outlets. Authors calculate the travel cost (time) for the car, bus and walking travel modes, based on the road type and service frequency of buses;
- Curtis & Scheurer (2010) provide spatial network analysis for multimodal urban transport systems (SNAMUTS). Authors estimate connectivity and centrality - the spatial proximity to the various activity nodes. Another accessibility measure is the average travel time along a route segment divided by the frequency of service – departures per hour;
- Cheng & Agrawal (2010) estimate complete travel time from origin to destination, including walking, waiting and traveling times. The Time-Based Transit Service Area Tool (TTSAT) is proposed to visualize and analyze transit service coverage by generating the transit service area maps;
- Benenson et al. (2011) propose an Urban.Access extension of ArcGIS to evaluate an accessibility of transport network in Israel. Impact of travel speed and traffic congestion on travel time is estimated;
- Mavoa, Witten, McCreanor, & O'Sullivan (2012) calculate a Public Transit and Walking Accessibility Index (PTWAI) to estimate access by PT (buses, trains, and ferries) and walking mode. The PTWAI calculates access to disaggregate destinations on the base of travel time and a standard waiting time at each transit stop;
- Mamun et al. (2013) propose the Transit Opportunity Index (TOI) to measure OD connectivity and connectivity decay with increasing travel time. The TOI also permits the evaluation of bus stop availability and temporal availability of the PT network;
- Fransen et al. (2015) evaluate the time-continuous PT accessibility to key destinations. Estimation is made at regular time intervals for various peak and off-peak time windows during weekdays and weekends. The obtained results are compared to a public transport needs index;

- Kaza (2015) analyses space-time accessibility considering the diurnal and seasonal changes in service frequency;
- Hawas et al. (2016) estimate transit coverage and transit and route diversity. The districts are evaluated using the TOPSIS method and categorized into five groups applying a K-clustering method;
- Yan-yan et al. (2016) calculate the PT accessibility by means of Area Public Transit Accessibility (APTA). Authors define accessibility as a convenient transportation from a particular traffic zone to surrounding regions. APTA takes into account the bus stop accessibility and number of transfers required to reach the destination. This method was applied in Beijing Chaoyang district, China;
- Fayyaz, Liu, & Porter (2017) take into account the variations of the PT schedule during the day. Travel times between transit stops at multiple departure times throughout the day are calculated.

2.4.3 Evaluation and improvement of transfers

The main criteria of transfers' evaluation are the number of transfers and transfer waiting time. Guo & Wilson (2011) analyze the other aspects of transfer evaluation - transfer walking and estimation of the transit facility (bus stop convenience).

Each transfer has an associated psychological penalty, that is typically considered as 5 minutes time penalty (Chew et al., 2013; Nikolić & Teodorović, 2014). Han (1987) estimates that the disutility of 1 transfer is roughly equal to 5 min of walking time, 10 min of waiting time, or 30 min of in-bus traveling time. Nevertheless, customers in Taipei (China) prefer to board on the first available bus even if it requires an additional transfer.

The monetary equivalent of transfers in customers' perception is estimated by Guo & Wilson (2011), Han (1987), Leiva, Muñoz, Giesen, & Larrain (2010). It means that the customers are willing to pay more for direct trips. So, transfers optimization can generate profit to bus operators. The additional fare for each transfer trip can be included into equation alongside with perceptible transfer cost.

It is assumed that a customer will not use PT if it is necessary to make more than two transfers to reach the destination (Chakroborty, 2003; Yu, Cheng, Yang, & Liu, 2005). Public opinion surveys confirm this assumption (Yan-yan et al., 2016). Thus, a majority of researchers aim to minimize the number of transfers. Recent methods of transfers' coordination permit to obtain

85-95% of direct trips, 5-15% of trips with 1 transfer and 0-1% of trips with 2 transfers (they can be totally avoided) on theoretical examples.

Evaluation of the number of transfers and transfer time is normally made by comparison of the existing transfers' structure with proposed one. The proposed solution is obtained by solving the PT network planning problems with the objective of transfer optimization. Hence, this section is related to network evaluation and improvement methods at the same time.

The most successful methods of transfer evaluation and optimization:

- Nikolić & Teodorović (2013) solve TNDP minimizing the number of transfers and the total travel time (including transfer time) of all served customers applying the Bee Colony Optimization (BCO) metaheuristics;
- Nayeem et al. (2014) solve TNDP proposing the genetic algorithm with elitism (GAWE) and more sophisticated genetic algorithm with increasing population (GAWIP). The objectives of optimization are the same as ones used by Nikolić & Teodorović (2013). Applying to the same benchmark, this method outperforms the previous one in terms of both number of transfers and total travel time;
- Nikolić & Teodorović (2014) solve TNDFSP by improved BCO method, considering two options: customers' objectives of direct trips and travel time minimization, and PT operators' objective of fleet size reduction;
- Arbex & da Cunha (2015) solve TNDFSP and consider customers' and operators' objectives simultaneously by using an alternating objective genetic algorithm (AOGA). Pareto frontier provides the whole specter of solutions and permits to estimate the impact of fleet size on customers' satisfaction. GA proposed by (Chew et al., 2013) showed the weaker result in the majority of examples;
- Liu & Ceder (2017) focus on TNTP considering both customers' objective (minimal waiting time) and operators' objective (minimal costs). A set of Pareto-efficient solutions is obtained applying a deficit function (DF)-based sequential search method.

The list of other popular, but currently outperformed optimization methods includes researches of Asadi Bagloee & Ceder (2011), Baaj & Mahmassani (1991), Chakroborty & Wivedi (2002), Fan & Machemehl (2008), Shih, Mahmassani, & Baaj (1998).

The most common benchmarks for performance evaluation of the new transfer optimization methods are the small PT network (15 bus stops) proposed by Mandl (1979) and four models, including two based on real cities, proposed by Mumford (2013).

However, some researches do not consider transfers as a negative aspect, if the additional fare is not required. Badia Rodríguez (2016) examines the new bus network of Barcelona, Spain, that increase the percentage of non-direct trips from 11% up to 44%. In the middle of implementation (26% of trips with transfers) it was found that the number of PT customers raised.

Transfers synchronization can also be improved by different operational and control strategies. For example, Nesheli, Ceder, & Liu (2015) combine holding, skip-stops, and short-turn actions with the objective to minimize transfer time and total travel time. A 4.7% reduction in total travel time is achieved in the case study of Auckland, New Zealand.

2.4.4 Multicriteria evaluation of network performance

Multicriteria evaluation is the evaluation of bus operators from the perspective of different stakeholders. For example, the bus company would focus on operational efficiency. The passenger is more interested in service quality and safety. The government may have other criteria such as social duty and environmental sustainability. The range of indicators varies in different research articles. This level of evaluation usually doesn't measure the real accessibility of the transit network and the interaction of different transit lines.

Performance evaluation articles reveal the most important criteria of service level and estimate real PT network. Such estimation is usually based on customer survey data, input from operator and authority (economic and environmental aspects). Articles that focus only on the classification of service level criteria (survey data processing) are considered theoretical applications.

Yeh, Deng, & Chang (2000) present a fuzzy multicriteria analysis (MA) approach to performance evaluation for urban public transport systems involving multiple criteria of multilevel hierarchies and subjective assessments of decision alternatives. The concept of the degree of optimality of each alternative with respect to each criterion is used to transform a weighted fuzzy performance matrix into a fuzzy singleton matrix. A wide range of indicators such as safety, comfort, cost efficiency, average vehicle age, air pollution level is considered. A case study on 10 bus companies of an urban public transport system in Taiwan is conducted.

Lao & Liu (2009) combine Data Envelopment Analysis (DEA) and GIS to evaluate the performance of bus lines within a public transit system, considering both the operations and operational environment. GIS is used to create demographic profiles within the service corridor of each bus line. Then the DEA method is applied to compute each bus line's operational efficiency and spatial effectiveness scores. Authors focus on seven census variables: total population, population density, median household income, commuters who use buses, population 65 and older, people with disabilities, and automobile ownership.

De Oña, De Oña, Eboli, & Mazzulla (2013) proposes a methodology for evaluating the quality of service perceived by users of a bus transit service. A Structural Equation Model (SEM) approach is used to reveal the unobserved latent aspects describing the service and the relationships between these aspects with the Overall Service Quality (OSQ). The results emphasize the influence of *Service* and *Comfor*t levels, including the behavior of the staff. Proximity and Fare have the lowest weight.

Li, Chen, Li, & Guo (2013) present method on evaluating the performance of 3 bus routes within a public transportation system using revised DEA method and sensitivity analysis of indexes. A virtual index is used as input from the operators' and passengers' perspective. Passenger load rate, service reliability, average dwell time and average running speed are chosen as output indexes. The results show that the operation in the off-peak period is better than that in the peak period, and average running time and service reliability are the key factors influencing performance.

Georgiadis, Politis, & Papaioannou (2014) use DEA to evaluate the performance of individual bus lines in Thessaloniki, Greece. DEA results enable to perform clustering of bus lines based on the derived piecewise production functions. It is found that scheduling of buses with fewer seats would be a more successful performance improvement measure than reducing the span of service.

Garrido, De Oña, & De Oña (2014) represent Artificial Neural Networks (ANN) analysis and note its high capability for prediction because it does not require a pre-defined model. The study shows the almost equal importance of all service factors, including frequency of service, stop proximity, bus temperature, cleanliness, safety, etc. – all of them receive high priority.

Zhang, Juan, Luo, & Xiao (2016) evaluate the performance of public transit systems based on a combined evaluation method (CEM) consisting of information entropy theory and super-efficiency data envelopment analysis (SE-DEA). They integrate the public transit industry regulations, transit operation, and passenger requirements to construct an evaluation indicator system based on satisfaction and efficiency. The CEM is used to evaluate the performance. The results show that CEM can reduce the risks of SE-DEA affected by the dimensions of indicators, and improve its discrimination capability.

Van Lierop & El-Geneidy (2016) apply high priority to cleanliness, availability of the information on-board and driver's behavior.

Guirao, García-Pastor, & López-Lambas (2016) develop a survey technique based on hierarchy processes to estimate the stated importance of quality attributes. Research reveals punctuality, frequency and driving security as the most important attributes for customers.

Morton, Caulfield, & Anable (2016) suggest that attitudes regarding quality of bus service vary significantly across passenger groups, with females having a tendency to exhibit relatively negative opinions regarding the quality of the cabin environment with a similar finding observed in the case of passengers who are looking after the home and family. Research empathize the role of convenience, cabin environment and ease of use on perceived quality of service. The most important issue is a convenience, which is related to service frequency, availability, and reliability.

De Oña, de Oña, Eboli, & Mazzulla (2016) use the index numbers usually applied in the economic and industrial field for continuous monitoring of service quality based on users' opinions. It permits to evaluate the effect of new policies in public transportation.

Stelzer, Englert, Horold, & Mayas (2016) analyze the necessity for standardized automated information exchange between travelers and transportation company and introduce TRIAS, a standard for bidirectional mobility information.

Aydin (2017) proposes a service quality evaluation of public transport on the example of rail transit lines in Istanbul. Performance is evaluated via passenger satisfaction surveys. The proposed method combines statistical analysis, fuzzy trapezoidal numbers and TOPSIS method for multi periods (2012-2014). The author determines the factors need to be improved and provides recommendations to enhance the operation for specific lines and guidelines for future investments.

Chica-Olmo, Gachs-Sanchez, & Lizarraga (2017) focus their attention on the difference in service levels on different transit lines. They apply a combined method using nonlinear principal component analysis (NLPCA) and a logit multilevel model (LMLM) to a satisfaction survey.

Tsami & Nathanail (2017) develop a decision tree, which linked user perceptions and expectations with the overall service quality assessment for a case study in Greece. The J48 algorithm is used. Findings showed that the performance indicator “Availability of information by phone, mail” was the most crucial parameter for the overall assessment of the service, while both performance and importance variables participated in the tree formulation.

Echaniz, Dell’Olio, & Ibeas (2017) analyze such parameters as travel time, service frequency, network coverage, the possibility of carrying large objects, driver’s kindness, etc. Researchers conclude that the effort required to obtain the data to feed the models with increasing complexity may not be time worthy.

Evaluation of access to a network and transfers quality is usually based on public opinion and does not consider precise calculations. This level of network assessment can be more accurate if it is based on the results of accessibility and transfers evaluation.

Some authors focus on the economic evaluation of bus operators. (Hensher, 1992) analyze performance measures considering average numbers over seven financial periods. He uses detailed metrics based on fleet characteristics (size, mean age), labor (number of drivers/mechanics/all employees), revenue, distance, and costs. The author combines all these metrics to calculate indicators such as Nº of buses per labor unit/driver/mechanic, Passenger kilometers per labor unit/driver mechanic, revenue per each employee category, cost per seat x km, etc. However, such a detailed analysis is not a common practice in researches.

Wang, Feng, & Wang (2000) emphasize that financial performance might directly influence the survival of an operator. Thus, the financial indicators, such as Short-term liquidation, Long-term solvency, Profitability and Return on Investment, must be considered alongside with an operational performance. Authors conclude that transportation indicators are more suitable to measure the production efficiency, and financial ratios are the best indicators for the execution efficiency.

Yeh et al. (2000) divide such operation indicators as cost efficiency, cost-effectiveness, and service efficiency. Author measure them by the total vehicle-km run per employee, the total number of passenger trips served per employee, and the total number of passenger trips carried per vehicle-km.

Hassan et al. (2013) focus on user’s satisfaction and economic evaluation: vehicle utilization, revenue per day or per km, etc. The TOPSIS model is selected for the route performance evaluation. The route analysis level is based on a multi-criteria evaluation procedure that involves weighted scoring techniques. A case study on a transit system of 12 operating routes in Abu Dhabi city is conducted to illustrate the framework.

Ayadi & Hammami (2015) assess the efficiency cost of the Tunisian public bus transport system using six stochastic frontier models. Input data includes labor and energy costs and network length. The output is a dependent variable “variable cost” and an independent variable “seats per kilometer”. The results show that the reviewed bus companies are economically inefficient, what is explained by the outdated wage policy where financial risk is incurred by the authorities and not by the company.

Venkatesh & Kushwaha (2016) examine short and long-term efficiencies of bus companies under high levels of regulatory constraints in India. The cost variant of DEA is used when market price data is available. Also, variable cost efficiency is determined in the short run when some inputs cannot be varied. Such inputs are referred to as “quasi-fixed” inputs. It is found that by adopting efficiency enhancing practices, operators can significantly reduce their operating costs.

As a summary, there is a lot of researches related to the multicriteria evaluation of public transport, but each author may focus on different set of performance indicators.

3. Framework for public transport evaluation

This chapter represents the conceptual framework based on the literature review, the analysis of the RJSPTP law requisites, and the adjustment of the conceptual framework to the case study of CIM Ave.

3.1 Conceptual framework

A framework for evaluation and improvement of the public transport network, elaborated during this project, is presented in Figure 2. The framework is based on the knowledge obtained during the literature review.

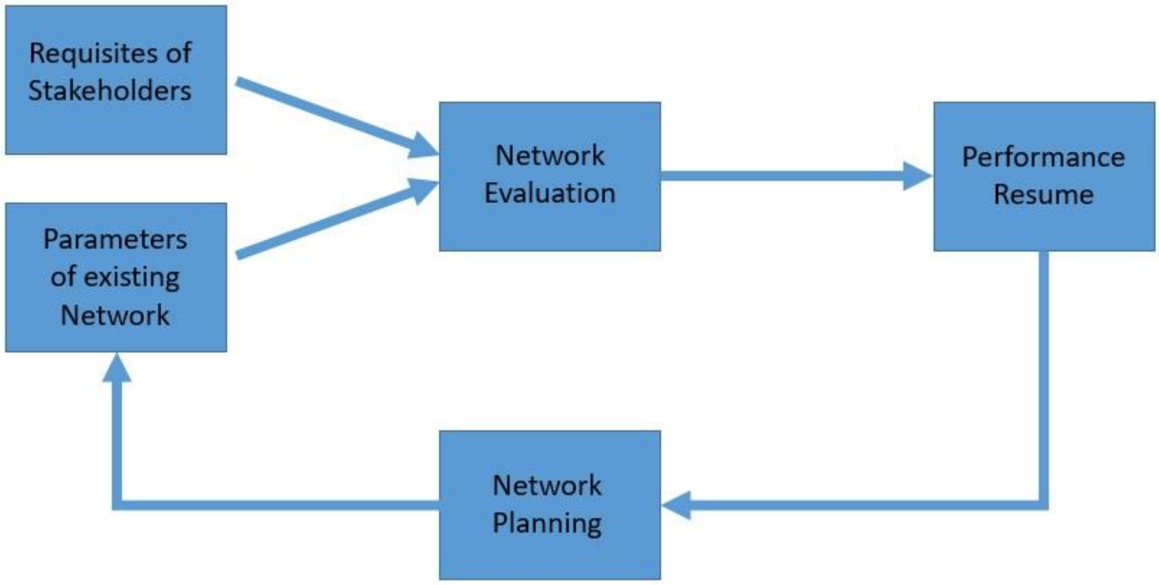


Figure 2 - Framework for network evaluation and improvement

The first step is to identify the requisites of all stakeholders:

- Passengers – travel demand (origin, destination, days of the week, time) and ticket prices;
- Transit operators - financial information (operation costs);
- Authorities - Law requirements, ecological sustainability, the number of jobs in the transport sector, etc.

The second step of a network evaluation process is to obtain the parameters of the actual network. The list of parameters is strongly connected with the requisites of stakeholders. It includes road network, bus stops location, transit operators, fleet number and capacity, fuel consumption, number of employees.

Then, requisites of stakeholders and parameters of existing network are compared – this step corresponds to network evaluation. This process requires the utilization of software packages – Geographic information systems and data analysis tools, such as ArcGIS and Excel.

The result of network evaluation is summarized in Performance Resume, which includes all relevant indicators.

Performance Resume may reveal a necessity to make changes in the actual transit network. In this case, the new Transit Network Planning process should be executed. This is a very complexed process, which is shown in 2.1. Thus, sometimes it is not necessary to perform the whole planning process - the right part of it should be chosen, based on Performance Resume.

After this, parameters of improved transit network should be compared with the requisites of stakeholders in order to check the results of the improvement. If new Performance Resume shows positive results, the network evaluation, and improvement process if finished.

Anyway, cities are constantly changing, and passengers demand may change. Thus, the periodical analysis should be repeated with a certain frequency – for example, every 3-5 years.

Indicators of network performance

The literature review revealed the list of commonly used performance indicators for evaluation of public transport. All these indicators can be divided into 5 groups – Accessibility, Vehicle evaluation, Outside the vehicle, Operational performance and Financial performance (Figure 3). First, three groups of indicators are related to Passengers' and Authority's interests. Operational and financial performance is more important for transit operators. Nevertheless, Authorities should also control these parameters to evaluate the efficiency of operators and their ability to fulfill a contract for public transportation.

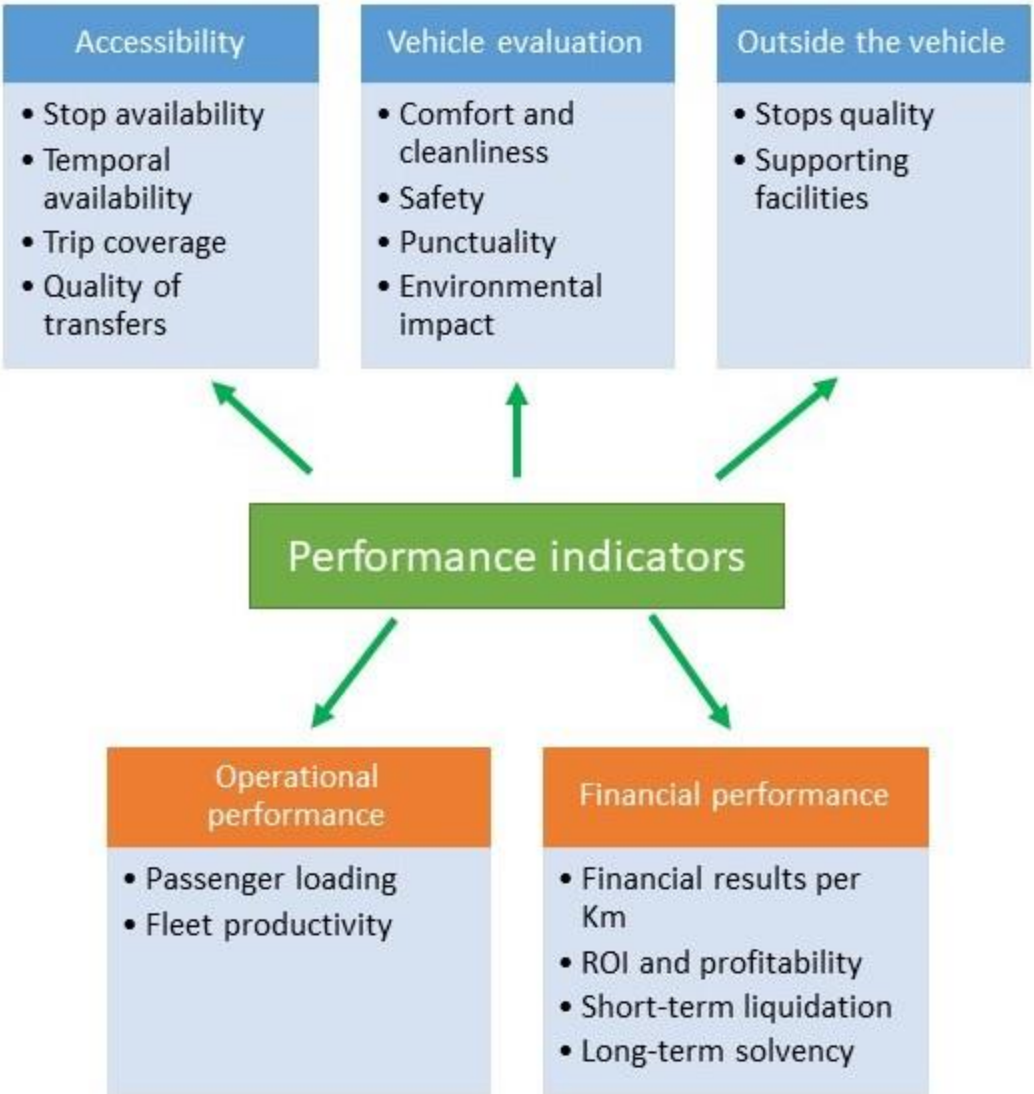


Figure 3 - Main indicators of public transport performance

A complete list of performance indicators is presented below.

1. Accessibility
   1.1. Stop availability;
   1.2. Temporal availability and service frequency;
   1.3. Trip coverage and Space-time accessibility;
   1.4. Quality of Transfers;
2. Vehicle evaluation (**Levels:** route/operator/network)
   2.1. Onboard comfort and cleanliness

2.1.1. Boarding/landing comfort;

2.1.2. Seat comfort;

2.1.3. Overcrowding rate;

2.1.4. Cleanliness;

2.1.5. Air temperature on-board;

2.1.6. Driver's driving skills;

2.1.7. Driver's appearance and friendliness;

2.1.8. The convenience of travel with a baby carriage or wheelchair;

2.1.9. The possibility of bicycle transportation;

2.1.10. The convenience of fare collection (option: fare collection on the bus stop);

2.2. Safety on board;

2.2.1. Safety from crime;

2.2.2. Safety from road accidents;

2.3. Punctuality

2.4. Environmental impact

2.4.1. Vehicle air pollution level;

2.4.2. Vehicle noise level.

3. Outside the vehicle

3.1. Stops/terminals quality

3.1.1. Safety on stops/terminals;

3.1.2. Information availability;

3.1.3. Comfort;

3.2. Supporting facilities

3.2.1. Park-and-ride lots;

3.2.2. Bicycle parking or renting facilities;

3.3. Information available on the internet, newspapers and other sources;

3.4. Convenience of ticket purchasing;

4. Operational performance (Levels: route/operator/network)

4.1. Annual Nº of operating days;

4.2. Passenger loading

4.2.1. Average Nº of passengers per day;

4.2.2. Average Nº of passengers*km traveled per day;

4.2.3. The average distance of 1 passenger's trip;

4.3. Fleet productivity

4.3.1. Fleet size;

4.3.2. Average distance traveled per vehicle per day;

4.3.3. Operating time utilization;

4.3.4. Average Nº of passengers carried per vehicle per day;

4.3.5. Average Nº of trips per day per vehicle;

4.3.6. Average Nº of seats in the vehicle;

4.3.7. Average vehicle capacity utilization;

4.3.8. Average vehicle's speed at rush hour and out of rush hour;

4.4. Labor productivity

4.4.1. Average Nº of bus trips per employee;

4.4.2. Average operation distance per employee;

4.4.3. Average Nº of passenger trips per employee;

5. Economic performance (Levels: route/operator/network)

5.1. Financial results per km

5.1.1. Average fare per km traveled;

5.1.2. Average operator's cost per km;

5.1.3. Average profit per km;

5.2. Return on investment and Profitability

5.2.1. Return on vehicle costs;

5.2.2. Return on total assets;

5.2.3. Operation cost ratio;

5.3. Short-term liquidation and Long-term solvency

5.3.1. Current ratio;

5.3.2. Current liabilities turnover;

5.3.3. Debt ratio;

5.3.4. Long-term liabilities turnover;

5.3.5. Total liabilities turnover;

5.3.6. Interest expense ratio.

The analysis of some of these performance indicators requires very detailed information about the public transport network, vehicles, supporting facilities, and operators' financial data. It is difficult to obtain all relevant information in the context of this research: it is partly classified (e.g. detailed financial report), and sometimes does not exist and requires additional surveys (e.g. passengers' opinion on seat comfort and cleanliness inside a vehicle). Thus, the undertaken analysis of public transport network in CIM Ave considers only the part of performance indicators – mostly based on law requisites.

3.2 RJSPTP: Law requisites

Law Nº 52/2015 (RJSPTP – Regime Jurídico de Serviços Públicos de Transporte de Passageiros) defines the minimum levels of public transport service.

For the purposes of specification and monitoring, minimum levels of public passenger transport service are defined by the following criteria:

1. Territorial coverage;
2. Temporary coverage;
3. Comfort;
4. Sizing of the service;
5. Information to the public.

All of these criteria are explained below.

3.2.1 Territorial coverage

The territorial coverage criteria are related to the geographic amplitude and connectivity offered by public transport services passengers. These criteria are intended to specify to what extent the network allows connections between the various geographical area served under appropriate conditions, in particular in terms of total travel time. For the purpose of setting the minimum level of public passenger transport service must be following territorial coverage criteria:

a) All locals with a resident population higher than 40 inhabitants must have access to a public transport;

b) All the municipality centers must have a public transport service, ensuring that they are connected to remaining municipalities of the intermunicipal community or metropolitan area in which they are inserted, without prejudice to the sizing of service.

3.2.2 Temporal coverage

The criteria for temporal coverage are related to with the hourly range and operating rhythm of public passenger transport services. The minimum level of public transport service is defined by the following criteria:

a) The schedules practiced must be adjusted to the needs population and the period of operation of the public equipment and services, trade and employment;

b) Links between a local and the respective municipality center, at least three days a week, to ensure:

    i) one trip to the municipality center in the morning;

    ii) one trip from the municipality center in the afternoon;

c) Links between municipality centers which ensure:

    i) one trip in each direction in the morning;

    ii) one trip in each direction in the afternoon.

d) Trips within an urban perimeter with more than 50 000 inhabitants, to ensure:

    i) two trips per hour in morning and afternoon peak periods;

    ii) one trip per hour during the day.

The mentioned time coverage criteria shall be valid for each working day of the year.

3.2.3 Convenience

These criteria are intended to specify to what extent:

a) The network allows direct connections between the areas, minimizing the need to transfers between different means and modes of transport;

b) The network coordinates the different services provided, in particular in terms of schedules.

For the purpose of setting the minimum level of service public passenger transport services, the following numbers and maximum duration of transfers must be ensured:

a) Movements between an area and a municipality center:

   (i) number of transfers not exceeding one transfer;

   (ii) Average waiting time at transfer not exceeding 15 minutes;

b) Displacements between municipality centers:

   (i) number of transfers not exceeding one transfer;

   (ii) Average waiting time at transfer not exceeding 30 minutes;

c) Movements within an urban perimeter:

   (i) The criterion of maximum number of transfers shall not apply;

   (ii) Average waiting time at transfer not exceeding 15 minutes.

3.2.4 Sizing of service

The sizing criteria for the service are related to the adequacy of the capacity offered by the public transport service to the demand. For the purpose of setting the minimum level of public transport service must be ensured that occupancy rates are the same or lower than the approved number of seats and in standing places available in the vehicle.

It is allowed to transport passengers through of standing places in the following situations:

a) The vehicle is approved to transport standing passengers;

b) The speed limit is 70 km/h.

3.2.5 Information to the public

These criteria are related to the access to clear and adequate information at any stop point and on the internet. The following information should be disclosed:

a) routes,

b) stops

c) schedules;

d) tariffs, including possible bonuses and discounts;

e) rights and duties of passengers and operators.

3.3 Adjustment of a conceptual framework to Case study

Considering the foremost importance of compliance with RJTPSP law, the framework for the public transport network in CIM Ave is adapted to incorporate law requisites. However, it is not possible to evaluate all aspects mentioned in law during this Master of Science dissertation due to lack of information in municipalities. It requires additional research with interviewing of local authorities, bus operators and passengers.

Thus, the research evaluates territorial coverage (RJSPTP, paragraph 1, requisites "a" and "b") and temporal coverage (RJSPTP, paragraph 2, requisites "b", "c", and "d"[1]) of public transport in all municipalities of CIM Ave. Part "a" in paragraph 1 is qualitative, and can not be measured.

In order to compare the transport network in the region with the best practices, the analysis is not limited by verification of compliance with law requisites, but also evaluates additional aspects based on the literature review. Performance indicators for a case study in CIM Ave are summarized in Table 2.

Definition of the time periods mentioned above: morning hours – from 07.30 to 09.30; afternoon hours – from 17.30 to 19.30; morning peak hours – from 07.30 to 09.30; afternoon peak hours – from 17.30 to 19.30.

Table 2 - Performance indicators for a case study in CIM Ave

What is evaluated	Has associated law requisites?	Benchmarks / Law requisites
Network accessibility	Yes (1.Territorial coverage, part "a")	All locals with a resident population higher than 40 inhabitants must have access to a public transport.
Accessibility of primary facilities	No	The maximum travel time of 15 min from residence to primary facilities.
Connections to municipality center	Yes (2.Temporal coverage, part "b")	One trip from local to the municipality center in the morning and one return trip in the afternoon, at least three days a week.
Connections between municipality centers	Yes (1.Territorial coverage, part "b"; 2.Temporal coverage, part "c")	Each municipality center in CIM must be connected to remaining municipalities. One trip in the morning and one trip in the afternoon in each direction between municipality centers.
Circulations in urban perimeters	Yes (2.Temporal coverage, part "d")	Two trips per hour at morning and afternoon peak periods, and one trip per hour during the day within an urban perimeter with more than 50 000 inhabitants.
Scholar transportation system	No	At least 90% of pupils use public transport, OR Costs per passenger in special circuits do not surpass the costs in public transport.

4. CASE STUDY CIM AVE. DESCRIPTION OF THE REGION

This chapter aims to provide a framework and a characterization of the area of study, in particular, the issues related to the territory, its population, road infrastructure, pendular mobility, travel modes and time, and operators of public transport in order to identify the factors that can condition the design of solutions of a system for the region.

4.1 Geographical description

The Intermunicipal Community of Ave (CIM Ave) is an association of municipalities, whose purpose is the management of intermunicipal projects on NUT3 Ave. It is composed of eight municipalities, Cabeceiras de Basto, Fafe, Guimarães, Mondim de Basto, Póvoa de Lanhoso, Vieira do Minho, Vila Nova de Famalicão and Vizela, in a total of 169 parishes. It has a territorial area of 1.451,31 km2, corresponding to 6.81% of the North region (Figure 4).

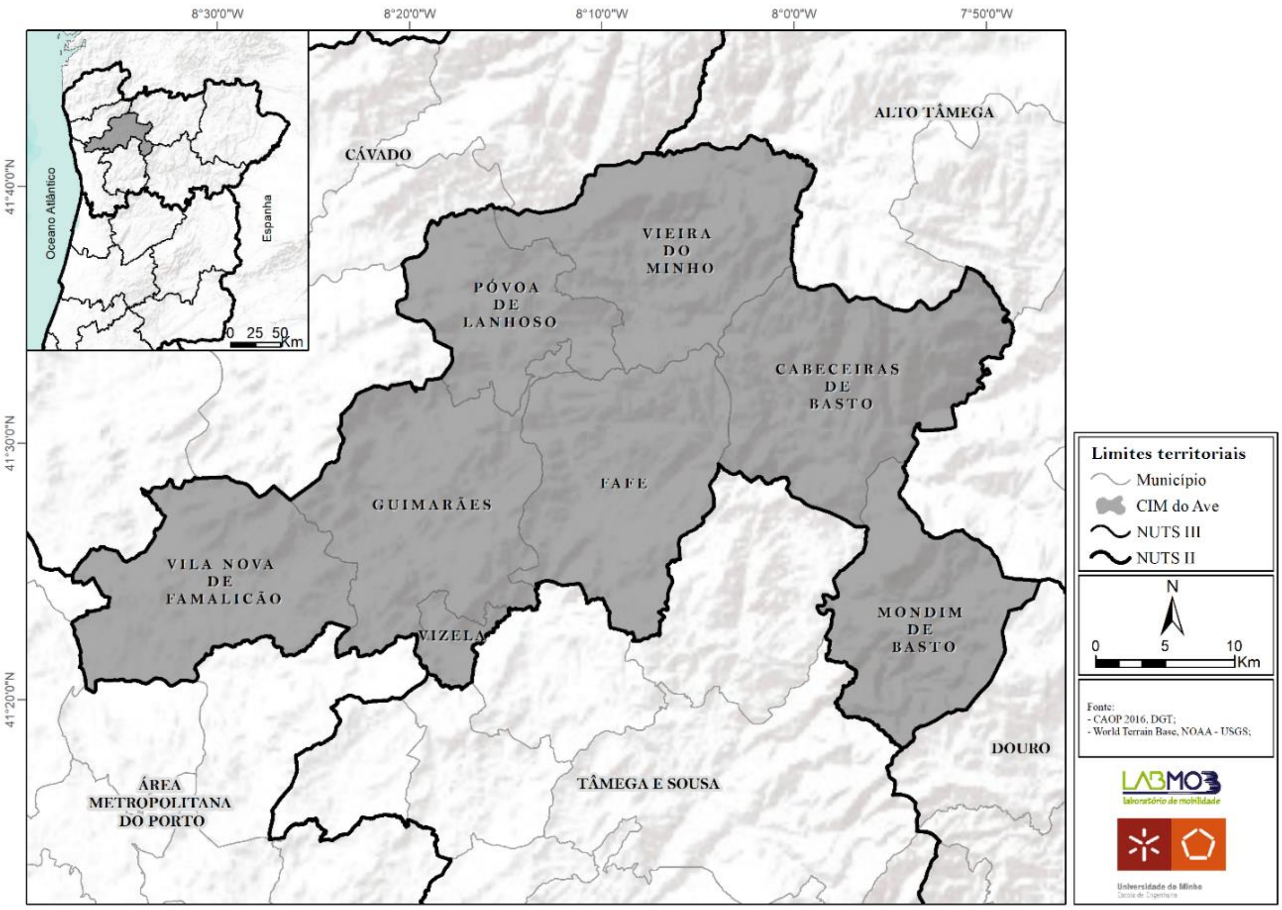


Figure 4 - Geographical description of CIM Ave

CIM Ave is located in the NUT2 North region. It is bordered by the NUT3 regions of the Intercommunal Communities of Cavado and Alto Tamega in the north, with the Intermunicipal Community of the Douro to the east and with the Metropolitan Area of Porto (AMT) and the Intermunicipal Community of Tamega and Sousa in the south.

4.2 Demographic description

According to data from the Census – 2011, 425,411 inhabitants live in the CIM of Ave (1,451.31 km2), which translates into an average population density of 293 inhabitants per square kilometer (pop./km^2). It is higher than the national average (114.5 pop./km^2). This density is not homogeneous among the 8 counties (Table 3).

Table 3 - Area and population of CIM Ave (INE, 2011)

Municipality	Area (km^2)	Number of parishes	% Area (CIM Ave)	Population	Population density (pop./km^2)	% Population
Cabeceiras de Basto	241,8	12	16,5	16 710	69	3,9
Fafe	219,1	26	15,0	50 633	231	11,9
Guimarães	240,9	48	16,7	158 124	656	37,2
Mondim de Basto	172,1	6	11,9	7 493	44	1,8
Póvoa de Lanhoso	134,6	22	9,2	21 886	163	5,1
Vieira do Minho	216,4	16	15,1	12 997	60	3,1
Vila Nova de Famalicão	201,6	34	14,0	133 832	664	31,5
Vizela	24,7	5	5,6	23 736	961	5,6
CIM Ave	**1451,3**	**169**		**425 411**	**293**	

An analysis of the distribution of the resident population in the CIM Ave shows that the municipalities of Guimarães and Vila Nova de Famalicão stand out. Together they make up about 70% of the total resident population in the study area. The territory of the CIM Ave is thus bipolar, where, on the one hand, there are the largest urban centers and, on the other, the municipalities with the highest rurality.

These numbers reflect a disparate reality in CIM Ave, with municipalities with population densities lower than 44 pop./km2 (Mondim de Basto) and others with densities of 961 pop./km2 (Vizela).

Figure 5 shows the distribution of the resident population by local and identifies areas where the number of residents is less than 40 inhabitants per place, lower limit from which the new Legal Regime of the Public Transport Service of Passengers (RJSPTP) provides the existence of minimum transport services.

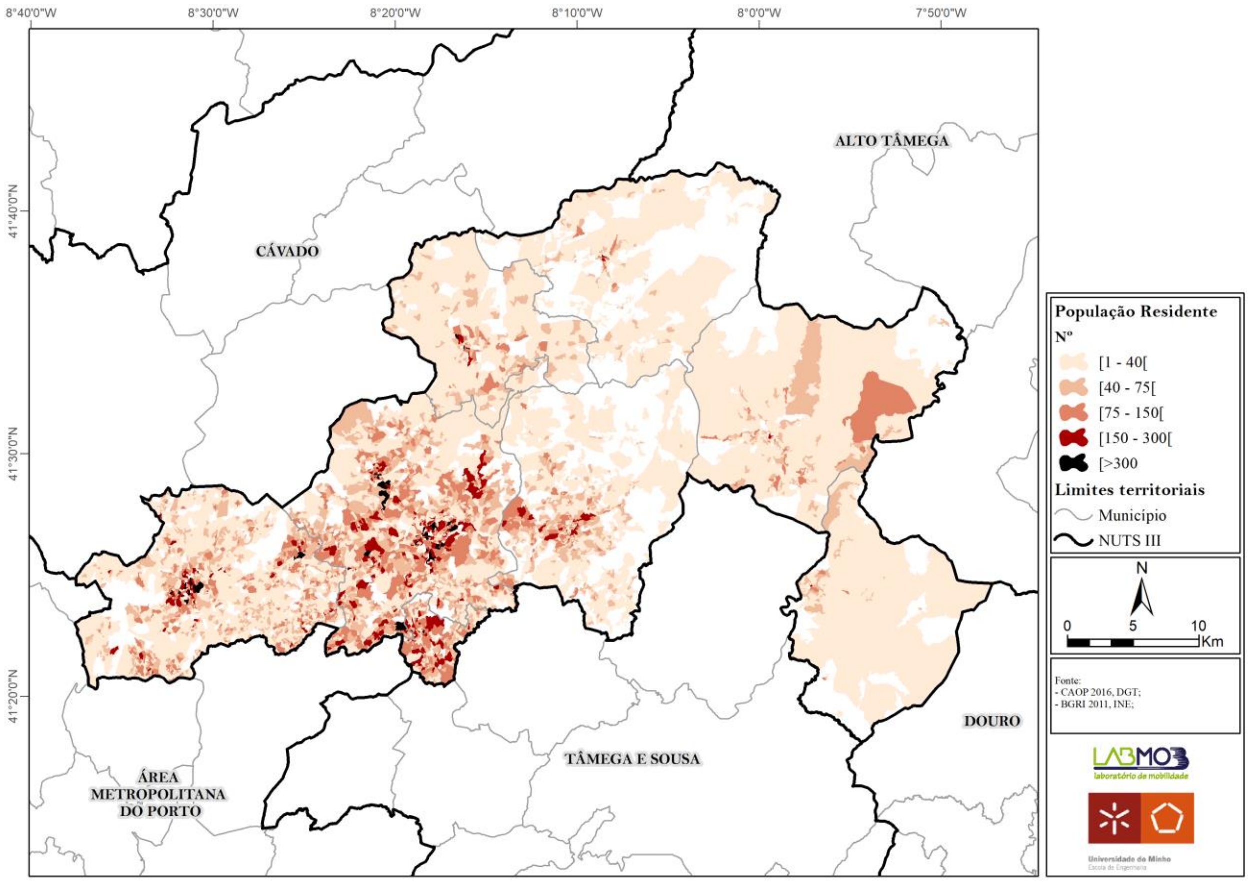


Figure 5 - Resident population per local (INE, 2011)

Figure 6 shows the demographic variations occurred in the census periods 1991-2001 and 2001-2011, with a significant decrease in the municipalities of Mondim de Basto and Vieira do Minho and increase in the municipalities of Vila Nova de Famalicão and Vizela. The municipality of Guimarães, as well as the CIM Ave (as a whole), recorded a significant increase in the first decade, followed by stagnation in the most recent decade. The remaining municipalities oscillated between significant percentage increases (1991-2001) and significant percentage decreases (2001-2011).

Figure 6 also shows the increasing trends in the Cávado and Metropolitan Area of Porto (AMP) territories, contrasting with the losses in the interior territories (Alto Tâmega, Douro and Terras de Trás-os-Montes).

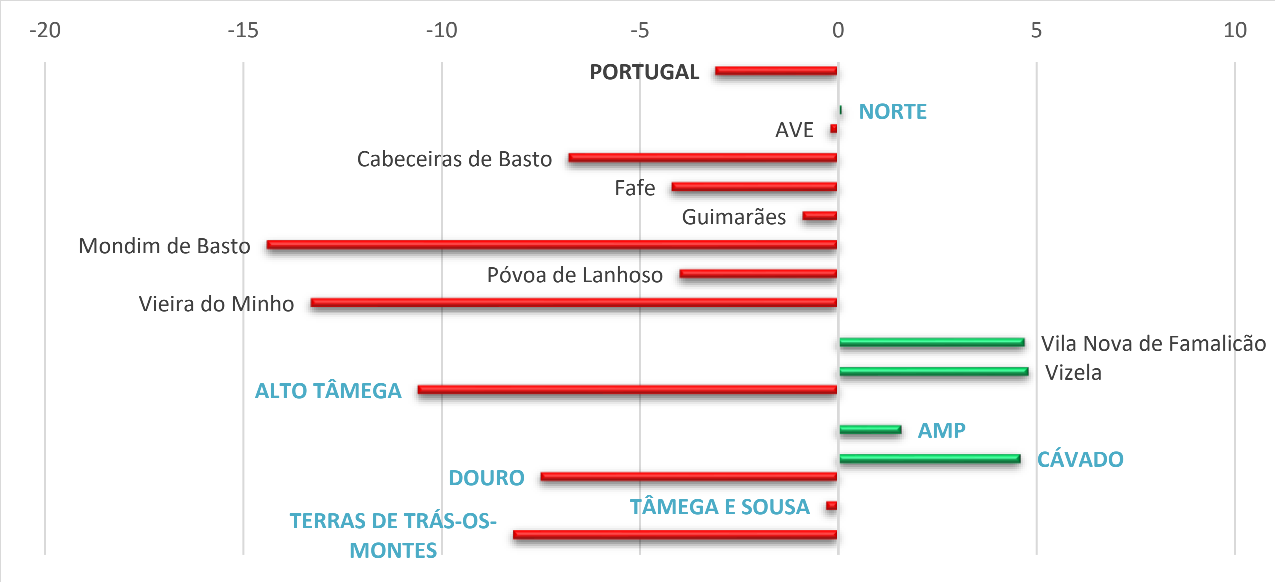


Figure 6 - Variation (%) of the resident population in 2001 and 2011 (INE; NUTS3)

After registering a population increase of 9.5% between 1991 and 2001, which is well above the national average and the North Region, the CIM Ave presents a stagnation in the variation of the resident population (similar to the rest of the North Region). With the exception of Cávado and AMP, which maintained a positive variation, hence with a decreasing trend, the remaining CIMs showed a decrease in population, with special emphasis on the Alto Tâmega, Trás-os-Montes, and Douro, with losses reaching 10,6%, 8,2%, and 7,5%, respectively.

Age structure

Significant oscillations in the age composition of the population have also occurred in recent years.

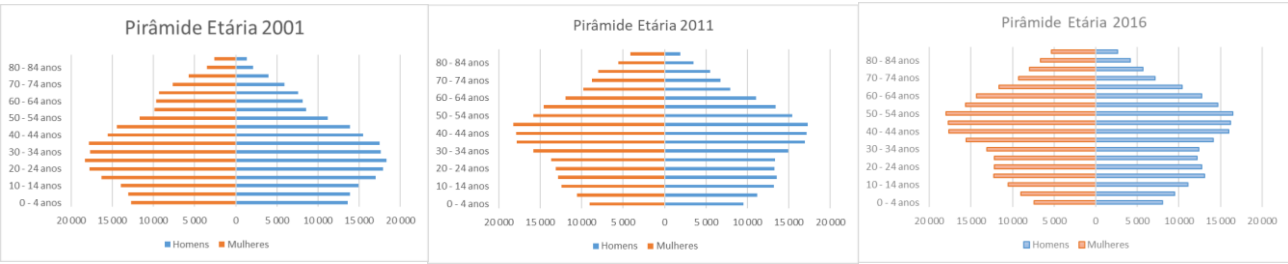


Figure 7 - Variations of age structure between 1991, 2001 and 2011 (INE, Censes)

From the reading of Figure 7, an aging population is observed in the periods in question, resulting in an evident narrowing of the pyramids at their base with the evolution of time. It is possible to observe that there is a fall in the birth rate, and there is no renewal of the lower echelons of the age structure.

4.3 Road infrastructure

In this section, we present the main infrastructures that support transport in the Intermunicipal Community of Ave (CIM Ave), namely at the road and rail level (Figure 8).

As for rail transportation, CIM Ave is served by a rail service, the Minho line (dual electrified track), which connects Porto to Valença, crosses Vila Nova de Famalicão. The dual electrified track to Braga is connected to Minho line in Nine. Vizela and Guimarães are served by the Guimarães Line (single electrified track) that originates in Lousado (Vila Nova de Famalicão) and crosses Santo Tirso (outside CIM Ave), Vizela and Guimarães.

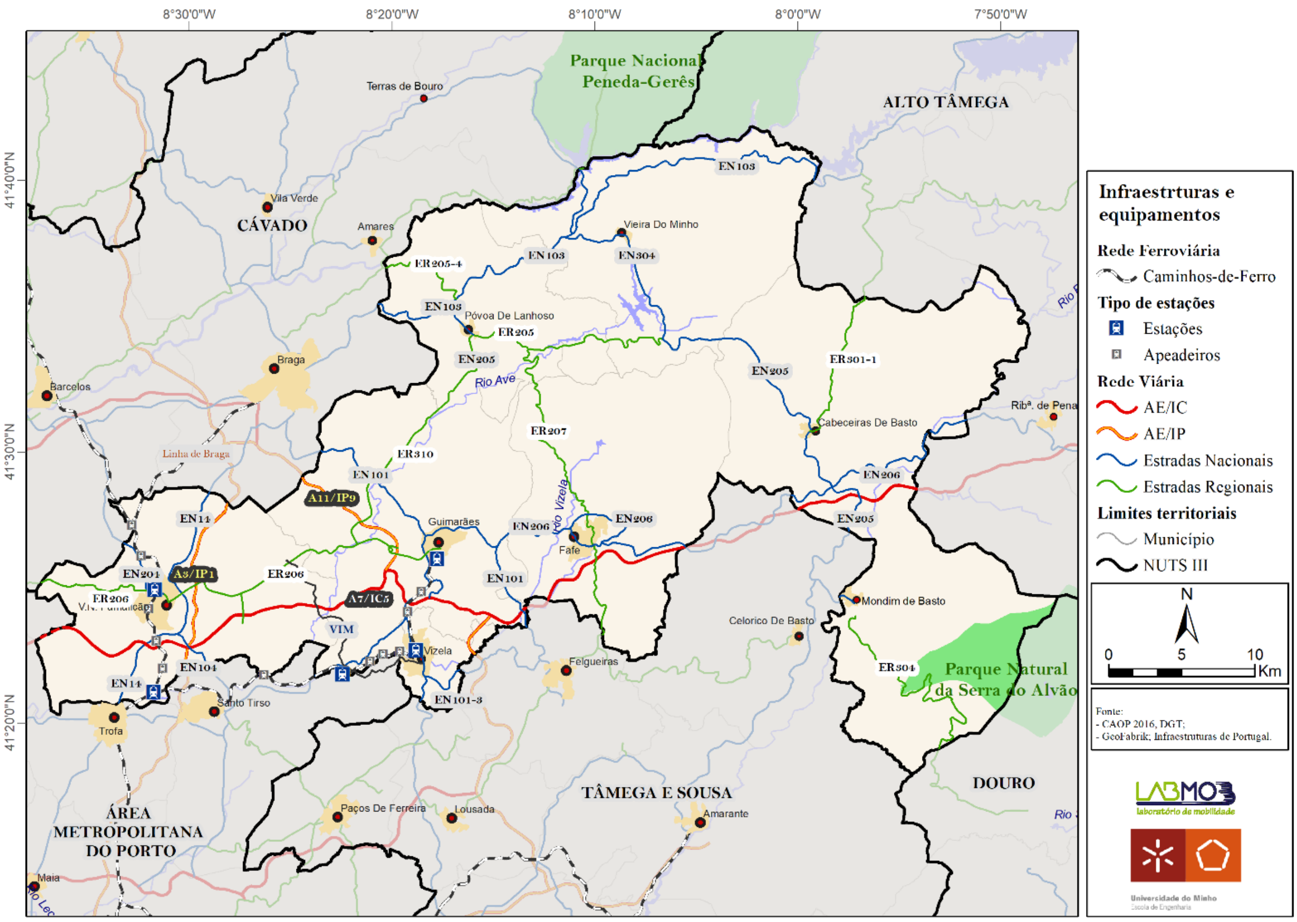


Figure 8 - Road and railway network

The road network serving the municipalities of CIM Ave has very diverse characteristics, guaranteeing different levels of accessibility to the populations and producing imbalances in terms of the opportunities of movement. It should be noted that there are variations in the density of the road network between values over 5.5 km / km2 (Vila Nova de Famalicão and Vizela) and 0.9 km / km2 in Mondim de Basto. These inequalities are also reflected in the number of residents per kilometer of the network, with municipalities far above the CIM Ave average (Guimarães, Vila Nova de Famalicão, and Vizela) and others far below the average (Cabeceiras de Basto, Mondim de Basto, and Vieira do Minho).

4.4 Pendular mobility

The understanding of the pendular movements of the population residing in the study area is fundamental for the process of analysis of a transport system, with the identification of gaps and solutions.

According to the census of 2011 (INE), a little more than 216 thousand individuals in CIM Ave perform pendular movements Home-School or Home-Work (Table 4). The great percentage (74%) of the population residing in the CIM Ave studies or works within the municipality where it resides and, on average, 6% in other municipalities of Ave (for the student population, 83% study in the municipality of residence). The total number of inbound traffic to CIM Ave represents 9% of the total pendular movements, slightly lower than the 11% outbound traffic. In terms of the student population, the number of exits from Ave (8%) is slightly higher than that of entrances (5%). The home-employment movements are balanced (11% and 12%, respectively).

Table 4 - Pendular movements Home - School and Home – Work

	Total		Home - School		Home - Work	
	2011		2011		2011	
Inside CIM Ave	216 106	80%	74 206	87%	141 900	77%
Cross municipality borders	199 184	74%	70 533	83%	128 651	70%
Inside one municipality	16 922	6%	3 673	4%	13 249	7%
Traffic to CIM Ave (*)	24 124	9%	4 000	5%	20 124	11%
Traffic from CIM Ave (*)	29 624	11%	7 210	8%	22 414	12%
Total	269 854		85 416		184 438	

**Only adjacent to CIM Ave Intermunicipal Communities are considered*

Table 5 illustrates a summary of pendular movements by directions (inbound and outbound traffic). On average, more than 80% of the movements are inside the municipalities (81% of the outbound and 85% of the inbound). Thus, on average, only about 20% of the trips in each municipality are generated externally, both in the CIM Ave and in the exterior. Vizela has a lower than average rate of intra-municipal movements: about 30% of trips originated outside the municipality (in particular Guimarães) and account for 23% of trips origin (11% outside CIM, in particular, Tâmega and Sousa and the Metropolitan Area of Porto.

Table 5 - Inbound and outbound pendular movements by the municipality

	Outbound traffic			Inbound traffic			Total		Variation
	CIM Ave	Out of CIM Ave	%	CIM Ave	Out of CIM Ave	%	From CIM Ave	To CIM Ave	
Cabeceiras de Basto	359	658	2%	232	363	1%	1 017	595	- 422
Fafe	2 485	2 378	10%	1 342	1 039	6%	4 863	2 381	-2 482
Guimarães	7 079	7 756	32%	8 041	8 074	39%	14 835	16 115	1 280
Mondim de Basto	102	417	1%	49	407	1%	519	456	- 63
Póvoa de Lanhoso	911	1 789	6%	1 126	1 222	6%	2 700	2 348	- 352
Vieira do Minho	364	652	2%	245	373	2%	1 016	618	- 398
Vila Nova de Famalicão	3 300	13 958	37%	4 267	11 170	38%	17 258	15 437	-1 821
Vizela	2 322	2 016	9%	1 620	1 476	8%	4 338	3 096	-1 242
CIM	**16 922**	**29 624**	**46 546**	**16 922**	**24 124**	**41 046**	**46 546**	**40 146**	**-6 400**

The pendular movements of the resident population in CIM Ave show which municipalities have the greater attractive capacity. The municipalities of Vila Nova de Famalicão and Guimarães are the main generators of mobility since they present the highest absolute number of entries.

Four municipalities (Fafe, Póvoa de Lanhoso, Vila Nova de Famalicão, and Vizela) have their greatest interaction of pendular movements with the municipality of Guimarães. The municipalities of Vizela and Fafe also present a significant weight in the pendular movements within the CIM Ave, representing the third and fourth municipalities, respectively, with importance in the total pendular movements within the CIM.

Guimarães and Vila Nova de Famalicão are municipalities with a strong attractiveness of employment and schools, mainly by the textile industry, and by universities. However, the municipality of Guimarães is the main destination of the workers' movements in the CIM Ave.

The municipalities of CIM Ave have a dynamic in pendular movements with municipalities not belonging to the CIM Ave, generally with bordering municipalities, but also with municipalities with higher attractiveness, such as Porto and Maia. These municipalities represent a great pendular interaction of workers and students with the CIM Ave municipalities, and the number of exits from the municipalities of the CIM AVE (about 30,000) is much higher than the entrances (about 24,000).

The pendular movements between CIM Ave and other external municipalities occur mainly with the municipalities of Vila Nova de Famalicão and Guimarães. These two municipalities stand out as the main attractors of CIM Ave, for their attractiveness and equipment, and create a flow of workers and students, forming a "west axis" of travel.

The eastern municipalities (Vieira do Minho, Cabeceiras de Basto, and Mondim) have the lowest values of pendular movements.

In terms of employment, although it is possible to observe a relative attractiveness by all municipalities in the study area (between 12% and 30%), Vizela and Póvoa de Lanhoso stand out because of their greater attractiveness in relation to the resident population. These two municipalities also have the highest rates of repulsion.

In terms of student repulsion rates, the distribution is more homogeneous among CIM Ave municipalities (losing between 10% and 16%), with the exception of Cabeceiras de Basto, which has the lowest student repulsion rate (8.5%).

4.5 Travel modes and average travel time

Increased mobility of people and goods is a hallmark of recent decades because of greater access to motorized means of transport. The following municipalities stand out by modes of the pendular movements Home – Work and Home – School (Figure 9):

- Pedestrian mode - Vizela has the highest proportion (about 26%), and Vieira do Minho and Vila Nova de Famalicão have the lowest proportions (about 15%);
- Car - Vila Nova de Famalicão has the highest proportion (around 68%), and Mondim de Basto has the lowest (around 49%);
- Bus - Mondim de Basto has the highest proportion (around 19%), and Vila Nova de Famalicão and Vizela have the lowest proportions (8.5%);
- Transport of the company or school - Fafe, Mondim de Basto, Póvoa de Lanhoso and Vieira do Minho have the highest proportions (between 8.1 and 8.9%), and Vila Nova de Famalicão and Guimarães have the lowest proportions (4.4% and 4.8%, respectively).

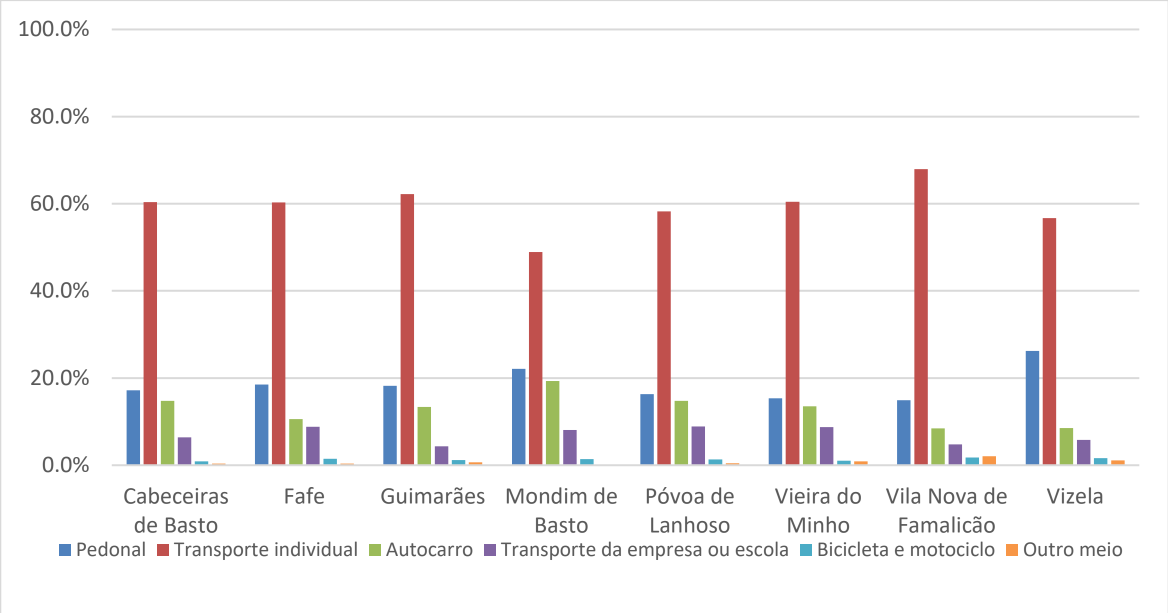


Figure 9 - Distribution of pendular movements Home - Work and Home - School by transport mode

Figure 10 indicates the average duration of pendular movements (minutes) of the resident employed population or students using the individual mode of transportation and the public transportation by the municipality (based on 2011 Census).

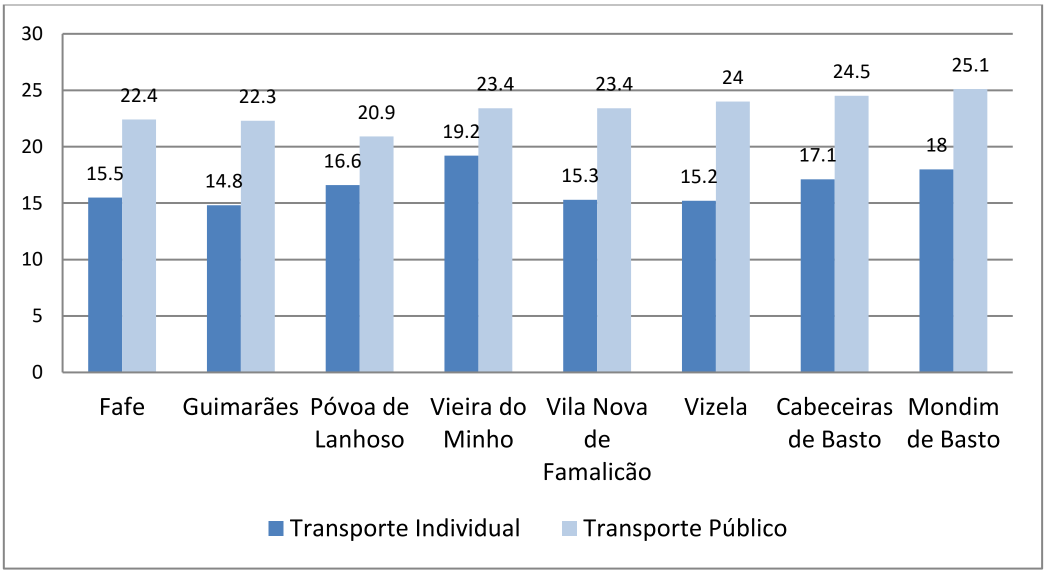


Figure 10 - Average duration of pendular trips (min)

It is possible to observe differences in the average travel times in various municipalities, in particular for the automobile and public transport modes. Average trip duration by individual transport is between 14.8 (Guimarães) and 19.2 (Vieira do Minho) minutes, and by public transport, it is between 20.9 (Póvoa de Lanhoso) and 25.1 (Mondim de Basto) minutes. In both cases, the difference between the inner and upper results is about 20%. Generally, the travel time is higher in rural municipalities (Vieira do Minho, Cabeceiras de Basto, Mondim de Basto).

4.6 Operators of public transport

The public road transport services in CIM Ave are carried out by the following operators: Arriva Portugal (ARRIVA), Auto Viação Landim (LANDIM), Auto Viação Pacense, Giromundo, Rodoviária D'Entre Douro e Minho (REDM), Transurbanos de Guimarães (TUG) and Transdev Norte (TRANSDEV).

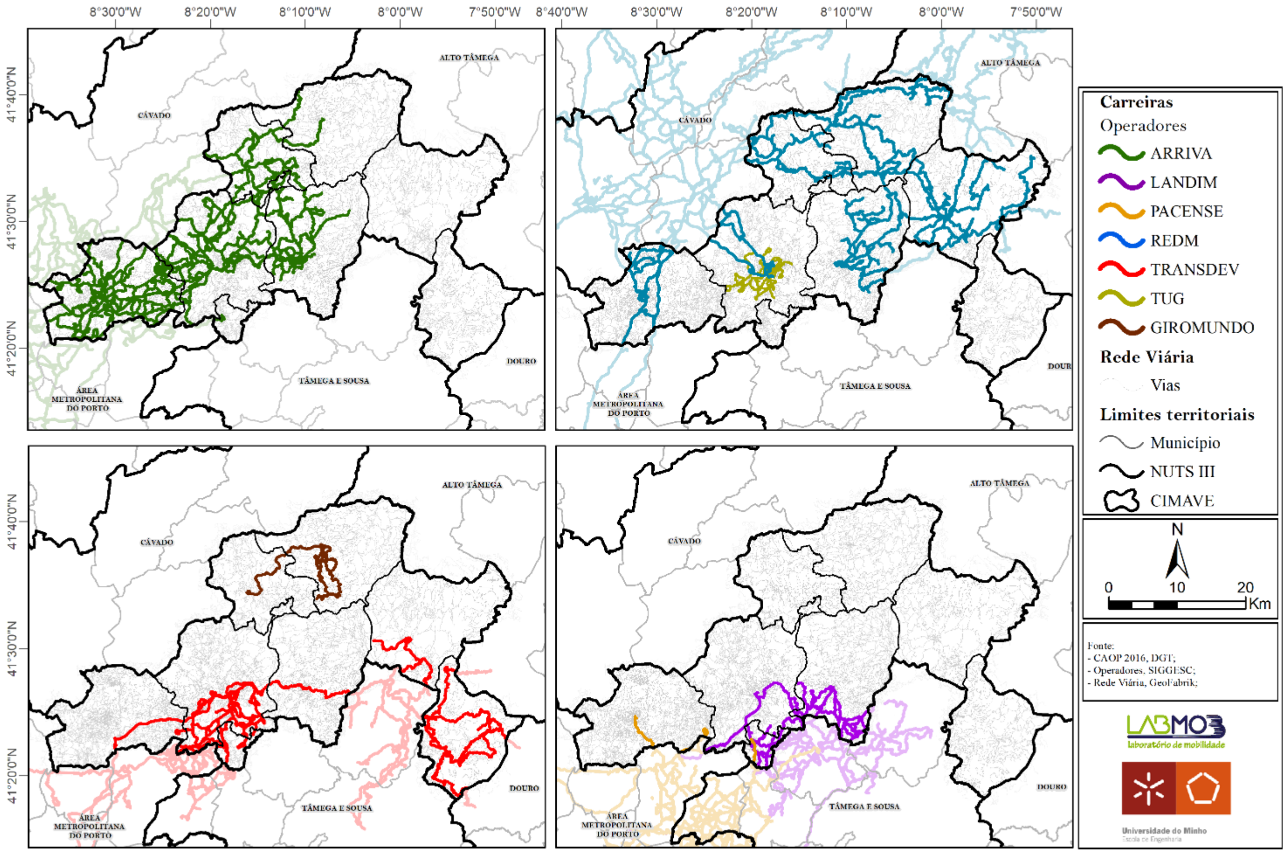


Figure 11 - Public transport network in CIM Ave

Figure 11 shows the public transport network served by each of the operators in the CIM Ave.

There is a higher density of territorial coverage of the public road transport network associated in more populated municipalities to the west of CIM Ave and a greater dispersion in municipalities in the eastern part of the region.

Operator ARRIVA assures the exploitation of about 50% of all 1,900 services existing in the CIM Ave, followed by companies REDM (18%), TRANSDEV (16%) and LANDIM (11%). The company TUG (3%) has exclusively urban services in Guimarães.

It is important to highlight the importance of the operators in each municipality: REDM in Vieira do Minho (90%) and Cabeceiras de Basto (78%), ARRIVA in Vila Nova de Famalicão (86%), Póvoa de Lanhoso (61%) and Guimarães (55%), TRANSDEV in Mondim de Basto (100%) and Vizela (49%). There are two main operators in Fafe - LANDIM (35%) and ARRIVA (33%).

Data analysis by operator highlights the main municipalities for each company: around 50% of TRANSDEV services are concentrated in Guimarães. LANDIM operates mostly in Fafe (40%), and ARRIVA in Vila Nova de Famalicão (41%) and Guimarães (37%).

Considering the information presented in this chapter, we can make a conclusion that the CIM Ave region is appropriate for the implementation of the framework of the public transport network evaluation. This region is big enough to represent a significant percentage of territory and population of Portugal, it has both urban and rural areas, and the information quantity and quality permits to obtain the reliable results of evaluation.

5. Case Study CIM Ave. Analysis and discussion of the results

This chapter provides the analysis of all indicators considered in the evaluation framework, including the accessibility of the public transport network in CIM Ave, connections to municipality centers, circulations in urban perimeters and scholar transport system. Discussion of the results is presented in the end of the section.

5.1 Metodology

The case study of CIM Ave was undertaken by LabMob *(Laboratório de Mobilidade)* during the project of complex evaluation of the public transport network in the region. The project team was multidisciplinary and included specialists in logistics, geography, economics, IT and data analysis. My functions during the project were related to the systematization and analysis of information about the number of passengers and costs of service.

The input data was received from the local authorities, public transport operators, and open sources such as the statistical institute INE.

Sources of information:

- Bus lines, stops and schedules – information from local Authorities and bus operators, consolidated in the Portuguese public transport database SIGGESC;
- Resident population per per local – *Instituto Nacional de Estatística* (INE), 2011;
- Household map – *Direção-Geral do Território* (DGT). The map contains the areas of continuous housing;
- Roadmap – Open Street Map (OSE);
- Number of passengers, costs, routes and other information related to the Scholar transportation system – local Authorities (in form of spreadsheets, text reports, and digital copies of documents).

It should be noted that each local authority keeps information in different formats, that makes the analysis much more difficult – at first, it is necessary to transform all information into standardized form. Bus lines, stops, and schedules kept in SIGGESC do not have this flaw, but this information is not reliable: it is partly obsolete, partly repeated, and does not include some new data. Thus, it was necessary to find possible problems in the SIGGESC database, and to verify them with the local Authorities.

Information was processed with ESRI ArcGIS and MS Excel software, the main processing steps are presented below.

5.2 Network accessibility

This chapter evaluates the existence of public transport stops near the residence of the population. The number of locals (land use units) and population with an access to public transport (PT) network is analyzed.

Public transport network in CIM Ave does not have the same design during the whole year – a part of routes takes part only on school season (September – June). In this project, we consider the worst scenario – summer season with a lower number of services available. In order to compare it with a better scenario, the tables below also reflect the additional services provided from September to June.

Table 6 presents the number and percentage of locals in CIM Ave with and without access to the public transport network. According to the law, "every local with a resident population higher than 40 inhabitants must have access to a public transport". Thus, the law does not define the maximum acceptable walking distance from someone's residence to the bus stop, and if the bus stop could be situated outside the local but close enough to the frontier. The common practice is the walking distance of 500 meters. However, considering the relatively low population density in CIM Ave, we use the walking distance of 600 meters in this project. We consider that the local has an access to PT network if at least one person lives in this local in the maximum walking distance from the nearest bus stop, even if this stop is situated outside the local. In addition, a bus must pass through that stop at least once a week.

According to the law, public transport operators do not have the necessity to provide regular or flexible public transport in locals with the population less than 40 inhabitants. Thus, the definition of the necessity of PT in the local is based on this information. Similarly, the population without the necessity of public transport is the number of people who live in areas with less than 40 people per local.

Table 6 - Locals CIM Ave with access to PT network

Municipality	Total number of Locals	% of Locals with the fulfilled necessity of PT	% of Locals without the necessity of PT	% of Locals with the unfulfilled necessity of PT	Nº of Locals with the unfulfilled necessity of PT	Additional coverage during school season: Nº of Locals
Cabeceiras de Basto	130	66.9%	26.9%	6.2%	8	2
Fafe	338	69.2%	20.7%	10.1%	34	13
Guimarães	540	83.7%	12.2%	4.1%	22	5
Mondim de Basto	59	57.6%	32.2%	10.2%	6	0
Póvoa de Lanhoso	244	61.9%	32.8%	5.3%	13	3
Vieira do Minho	138	55.8%	30.4%	13.8%	19	7
Vila Nova de Famalicão	562	80.1%	11.7%	8.2%	46	15
Vizela	71	91.5%	2.8%	5.6%	4	0
Total	2082	74.4%	18.3%	7.3%	152	45

Table 6 shows that every municipality in CIM Ave has locals with a population of more than 40 inhabitants and lack of public transport coverage. Thus, no one municipality meets the law requisites of territorial coverage.

Information was processed with ESRI ArcGIS software. Main steps:

1. Set up bus stops on the roadmap;
2. Assign the population of the local to the household area in that local. Information about each house is not available, uniform distribution of population inside the household area is considered;
3. Design a buffer around each bus stop, considering roadmap and the walking distance of 600 meters;
4. Calculate the resident population inside the buffers.

Table 7 shows the necessity of residents in public transport. Percentage of the population without the necessity of public transport reflects the main land use type – high percentage indicates a rural region with low population density.

Table 7 - Population CIM Ave with the necessity of public transport

Municipality	Total Population	Population with the necessity of PT	Population without the necessity of PT	Population without the necessity of PT (%)
Cabeceiras de Basto	15730	14794	936	6.0%
Fafe	50269	48280	1989	4.0%
Guimarães	157022	155134	1888	1.2%
Mondim de Basto	7096	6624	472	6.7%
Póvoa de Lanhoso	21157	19129	2028	9.6%
Vieira do Minho	12287	11207	1080	8.8%
Vila Nova de Famalicão	132941	130841	2100	1.6%
Vizela	23544	23493	51	0.2%
Total	420046	409502	10544	2.5%

Table 6 shows that 18.3% locals do not have necessity in public transport access. Only 2.5% of the population (10 544 residents) lives there. In fact, sometimes a local have the necessity of PT but does not have any bus stop available. Sometimes the opposite situation happens – a local does not have confirmed necessity in PT, but has a bus stop. These situations are analyzed in Table 8.

Table 8 - Necessity of PT and access to network per municipality

Municipality	Population with access to PT and confirmed necessity	Population with access to PT and without confirmed necessity	Population with neither access to PT, nor necessity	Population with necessity in PT, but without access	Population with necessity in PT, but without access[1] (%)	Increase of population covered by PT during school season	Increase of population covered by PT during school season[1] (%)
Cabeceiras de Basto	9 271	212	724	5 523	37.3%	80	0.54%
Fafe	33 103	1 228	761	15 177	31.4%	639	1.32%
Guimarães	107 375	1 167	721	47 759	30.8%	180	0.12%
Mondim de Basto	3 243	187	285	3 381	51.0%	0	0.00%
Póvoa de Lanhoso	12 346	1 062	966	6 783	35.5%	80	0.42%
Vieira do Minho	5 249	416	664	5 958	53.2%	389	3.47%
Vila Nova de Famalicão	90 910	1 632	468	39 931	30.5%	1984	1.52%
Vizela	15 700	26	25	7 793	33.2%	0	0.00%
Total	277 197	5 930	4 614	132 305	32.3%	3352	0.82%

[1] *In relation to the population with the necessity of public transport.*

Two municipalities with the biggest population, Guimarães, and Vila Nova de Famalicão, represent the best accessibility of PT network. However, even in these municipalities, more than 30% of the population with the confirmed necessity of PT does not have an access to the network. This number corresponds to 87 690 inhabitants. In worst cases (Vieira do Minho, Mondim de Basto), more than 50% of the population have lack of access to PT network.

Table 9 presents the resume of necessity in PT and an access to it, considering all the population of CIM Ave. Almost one third (31.5%, that corresponds to 132 305 inhabitants) have a lack of access to public transport, granted by law. Every municipality has problems with compliance with this indicator.

Table 9 - Resume of necessity in PT and access to the network

	Does not have necessity in PT	Have a necessity in PT
Have access to PT network	1.4%	66.0%
Does not have Access to PT network	1.1%	**31.5%**

Considering possible ways of cost-reducing, attention could be paid to locals with an access to PT network, but without necessity in it. These locals should be investigated one by one because sometimes a bus line just passes through a local on the way to more populated parts of the municipality. Thus, in this case, there are no additional costs in having a bus stop in that local.

5.3 Accessibility of primary facilities

The average distance from parish to primary facility, which can be in the municipality center, is an important indicator in the context of accessibility. We consider the maximum acceptable travel time of 15 minutes from residence to the nearest primary facilities, based on a literature review (Doerner, Focke, & Gutjahr, 2007).

In this analysis, we measure the travel time by bus, considering the road network and the average travel speed according to road type. The bus schedule is not taken into account. Hence, the analysis is based on the assumption of walking and waiting time equal to zero minutes.

In theory, the waiting time of zero minutes can be achieved, if a passenger is aware of the bus schedule, and the bus service is working according to this schedule. In the chapter “Network accessibility” we mentioned that the maximum walking distance for the analysis is 600 meters, that corresponds to 7.5 minutes of walking time. Considering the plain distribution of population around a bus stop, the medium walking distance is 300 meters, and the average walking time is about 4 minutes.

Thus, even considering the average waiting time of 6 minutes, the maximum duration of the trip to the primary facility is about 25 minutes, which is quite reasonable.

Figure 12 shows the average distance, in minutes, from the territory to the municipality center. The highest values are found in the innermost areas of CIM Ave, in the municipalities of Vieira do Minho, Cabeceiras de Basto, and Mondim de Basto. This analysis is not directly connected to the accessibility of primary facilities, but it shows the similar problem zones with a low access.

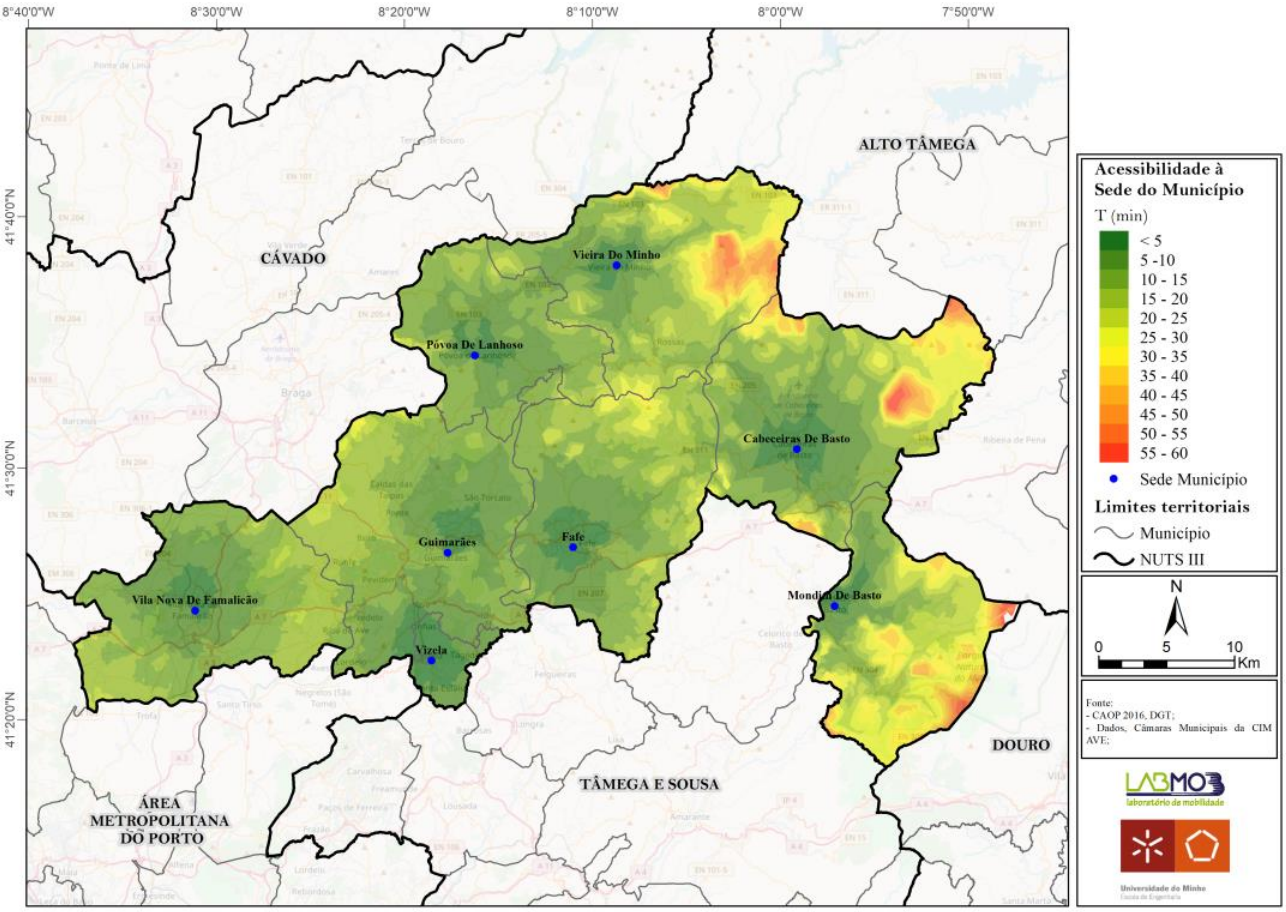


Figure 12 - Accessibility (minutes) to municipality centers

Analysis of an access to the main hospitals in the region (Figure 13) allows us to highlight again the same three municipalities, observing that the residents of these areas will seek the hospital services outside the CIM Ave (for example, Amarante and Vila Real).

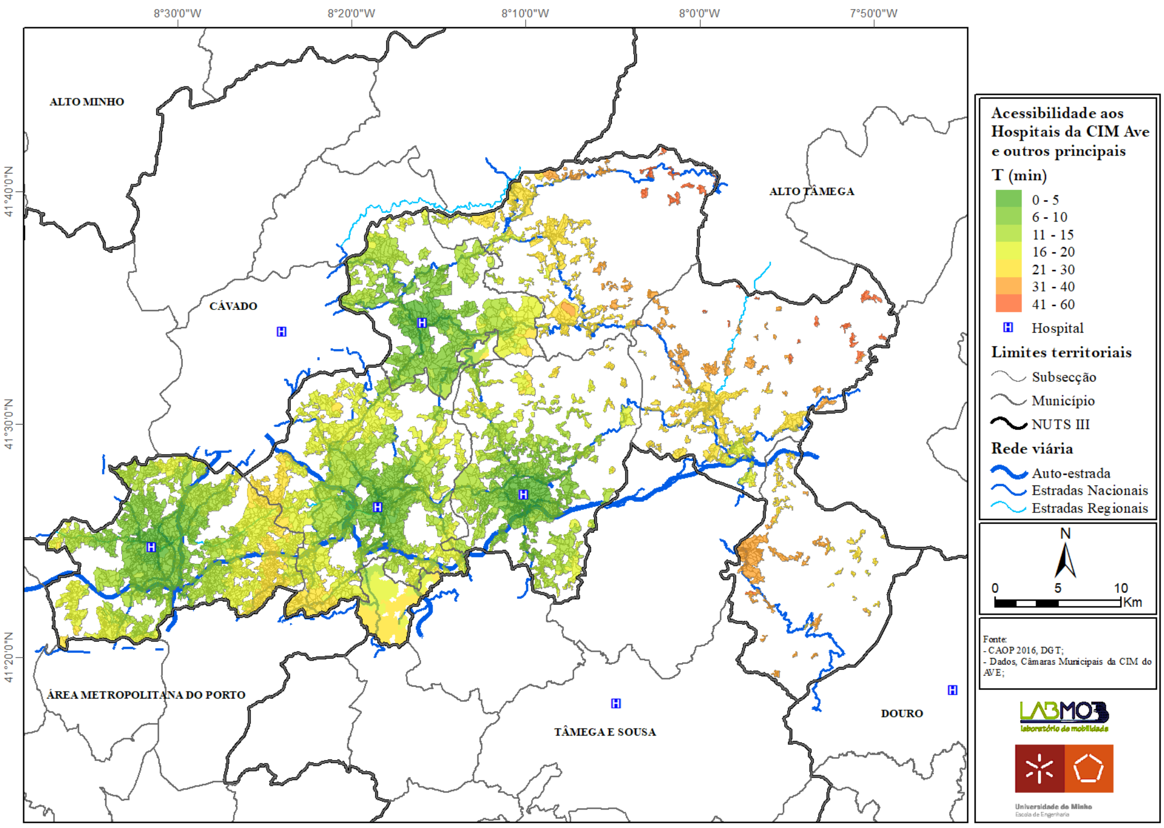


Figure 13 - Accessibility (minutes) to the main hospitals of CIM Ave and neighboring CIMs

Globally, access to basic health care (Figure 14) is uniform throughout the territory, except in the more peripheral places (CIM's eastern border) of the municipalities of Cabeceiras de Basto and Mondim de Basto. However, this analysis does not include extensions of Healthcare Centers, but only their headquarters. A similar pattern is recorded in the access to education facilities of different levels - kindergartens (Figure 15), basic schools of 1st stage (Figure 16), 2nd stage and 3rd stage (Figure 17), and secondary schools (Figure 18).

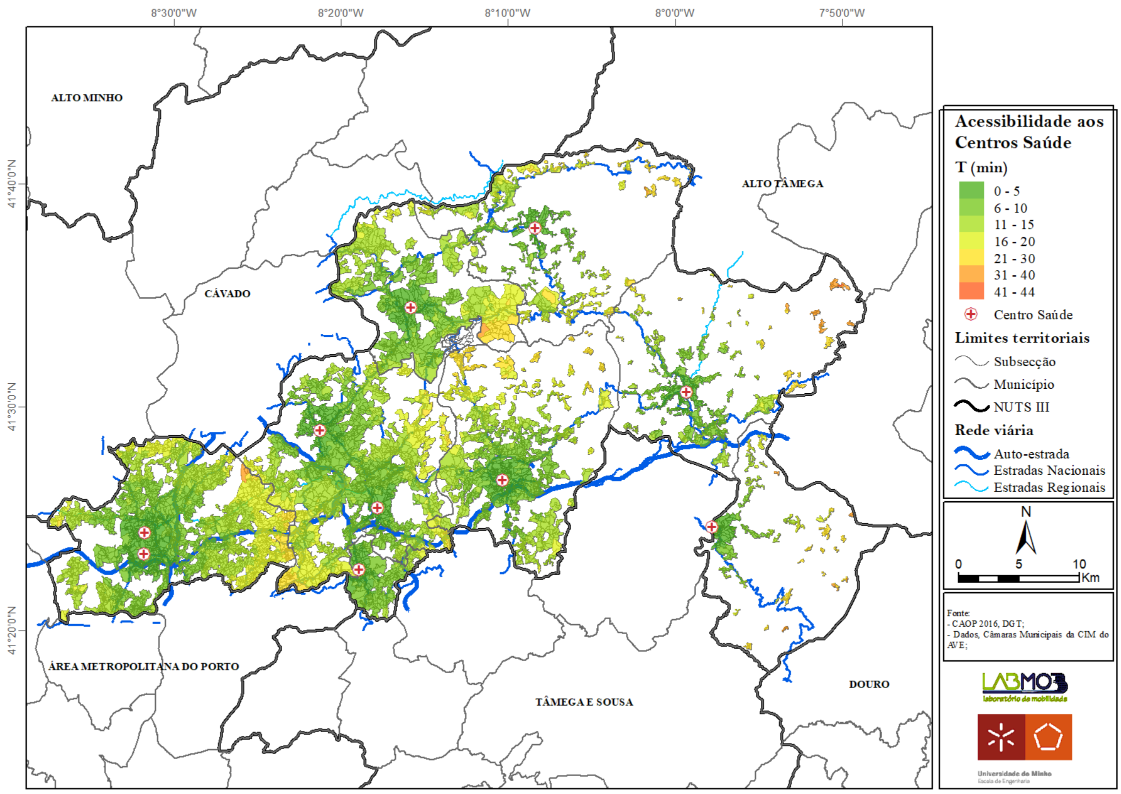


Figure 14 - Accessibility (minutes) to Healthcare Centers in CIM Ave

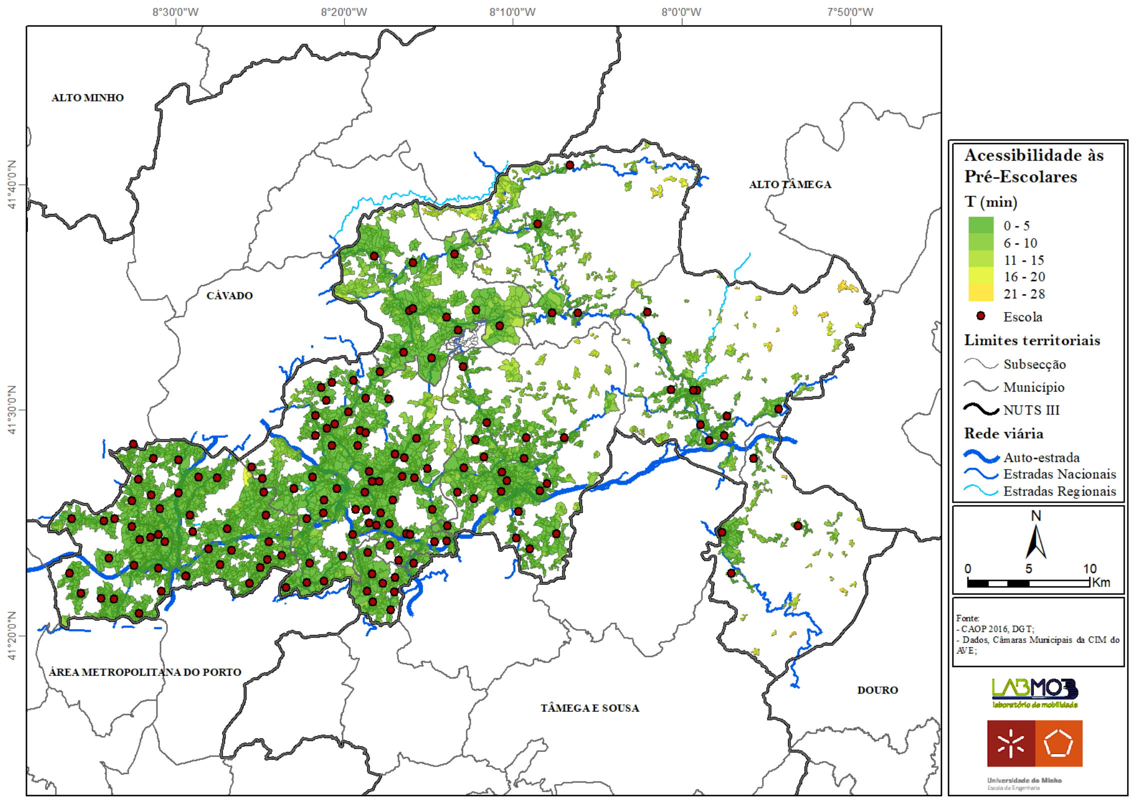


Figure 15 - Accessibility (minutes) to the public and private kindergartens

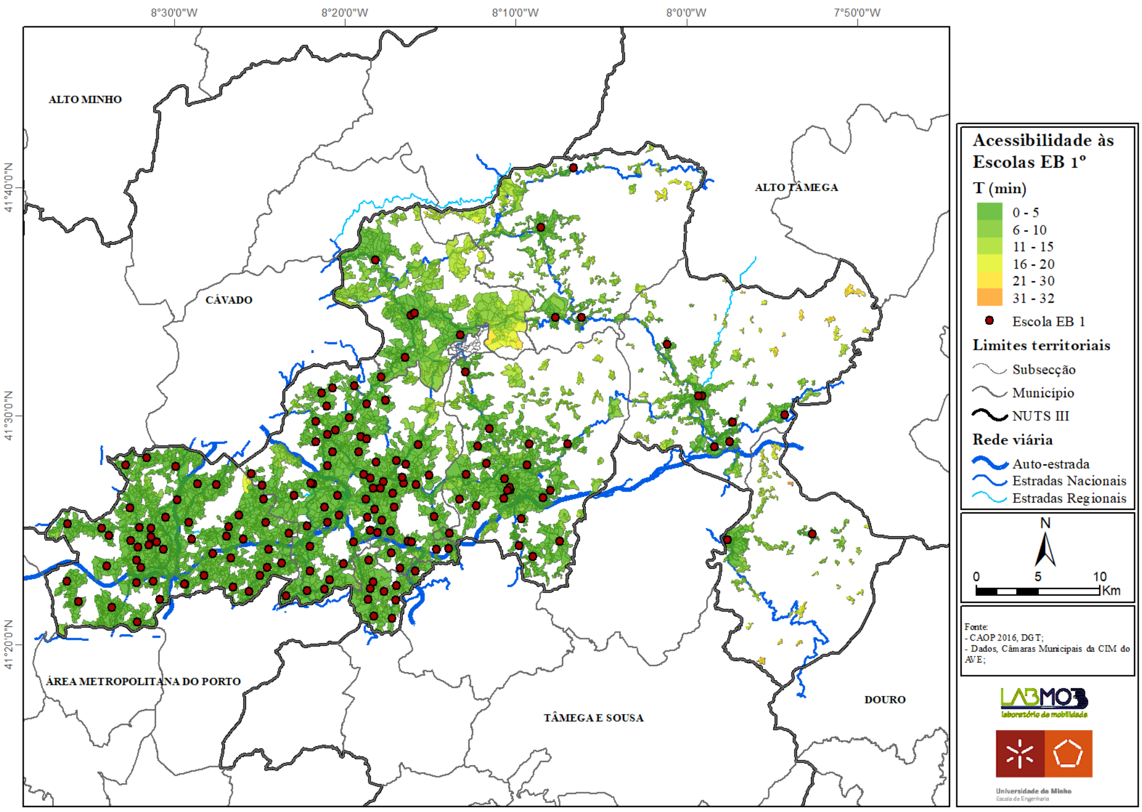


Figure 16 - Accessibility (minutes) to Basic Schools of 1st stage (1-4 year groups)

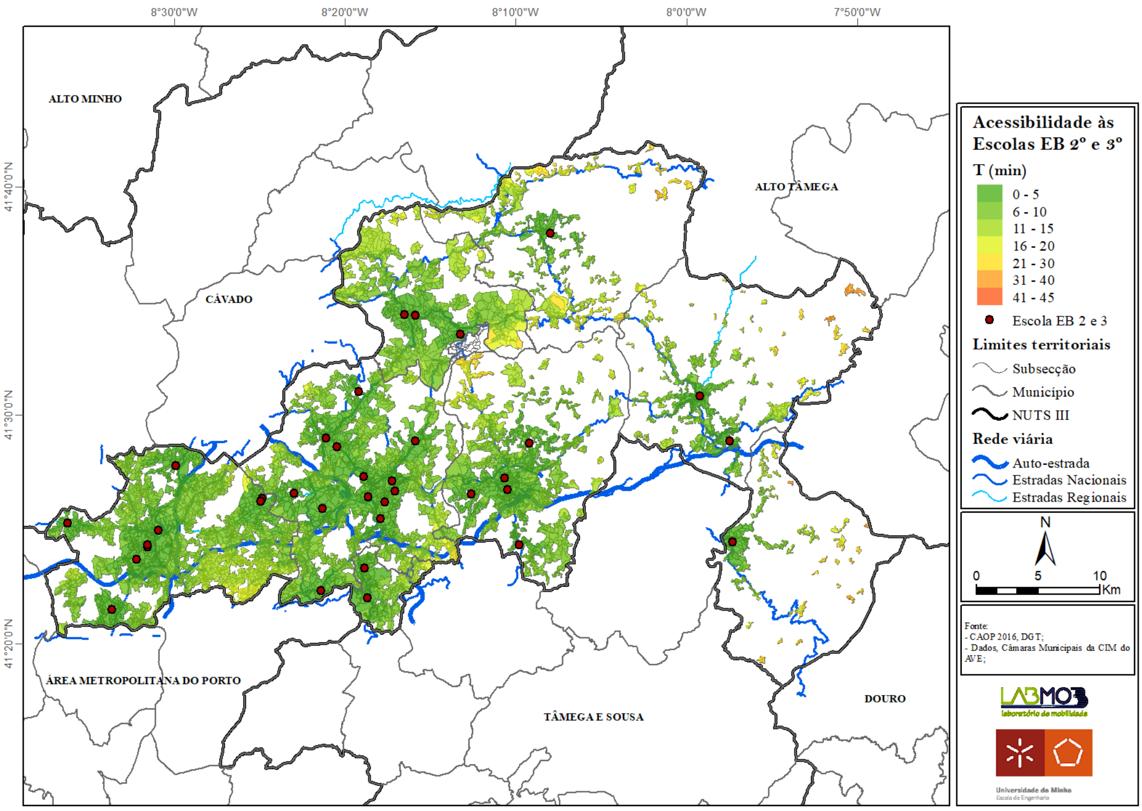


Figure 17 - Accessibility (minutes) to Basic Schools of 2nd and 3rd stage (5-9 year groups)

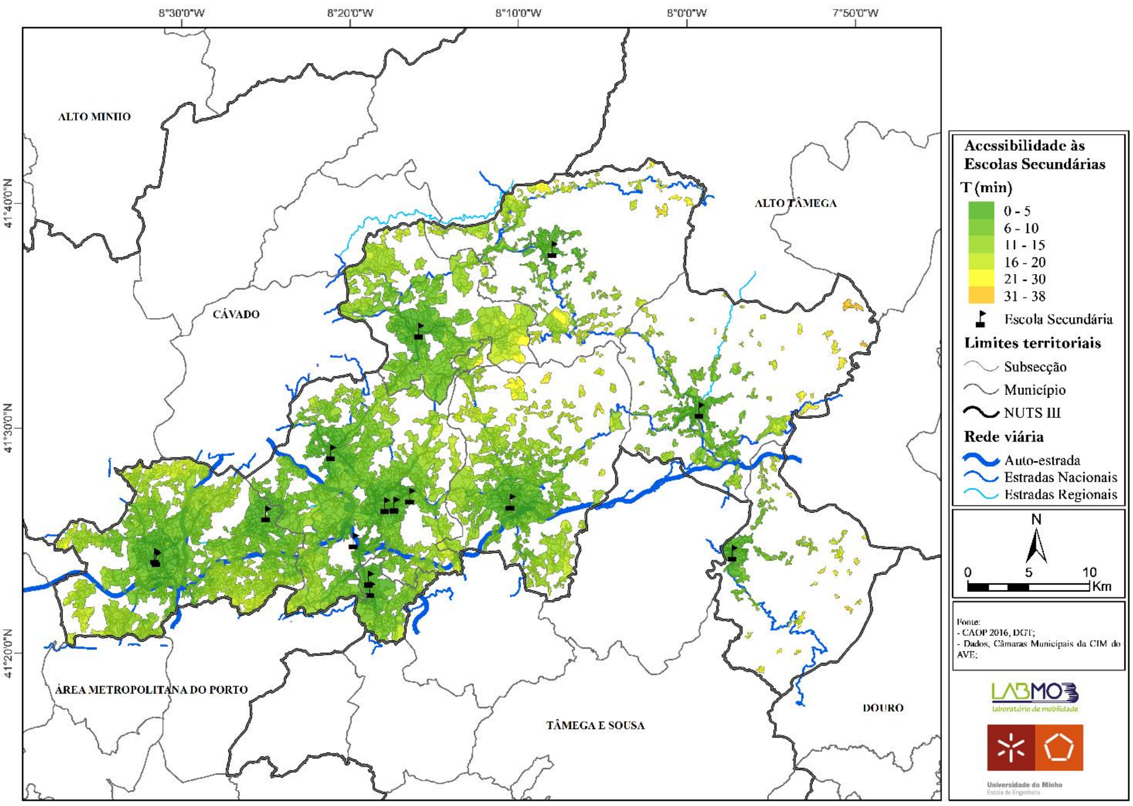


Figure 18 - Accessibility (minutes) to Secondary Schools (11-12 year groups)

We can observe that the southeast part of Fafe municipality and eastern part of Vieira do Minho, Mondim de Basto, and Cabeceiras de Basto municipalities have significant problems with an access to all types of the primary facilities.

Speaking about the access to health care centers and hospitals, we can add the frontier area of Vila Nova de Famalicão and Guimarães to the list of problem territories.

5.4 Connections to municipality center

According to the law, a parish fulfills the requisites of temporal coverage if it has circulations with respective municipality center, at least three days a week during the whole year, to ensure:

1. one trip to the municipality center in the morning;
2. one trip from the municipality center in the afternoon.

Table 10 indicates the number of parishes without connection to the municipality centers, during school periods, outside of school periods, on Saturdays and Sundays.

Table 10 - Connections between parishes and municipality centers

Municipality	Nº of parishes	School period: Nº of parishes without connections (2 directions)	Holiday period: Nº of parishes without connections (2 directions)	Saturday: Nº of parishes without connections (2 directions)	Sunday: Nº of parishes without connections (2 directions)
Cabeceiras de Basto	12			5	3
Fafe	25				
Guimarães	48	1	1	6	6
Mondim de Basto	6			4	4
Póvoa de Lanhoso	22	2	2	7	7
Vieira do Minho	16		2	10	10
Vila Nova de Famalicão	34	1		5	9
Vizela	5				1
Total	**168**	**4**	**5**	**37**	**40**
Total (%)		**2.38%**	**2.98%**	**22.02%**	**23.81%**

We highlight the municipalities of Cabeceiras de Basto, Mondim de Basto and Vieira do Minho without public transport services at the weekend in most of the parishes (Figure 19).

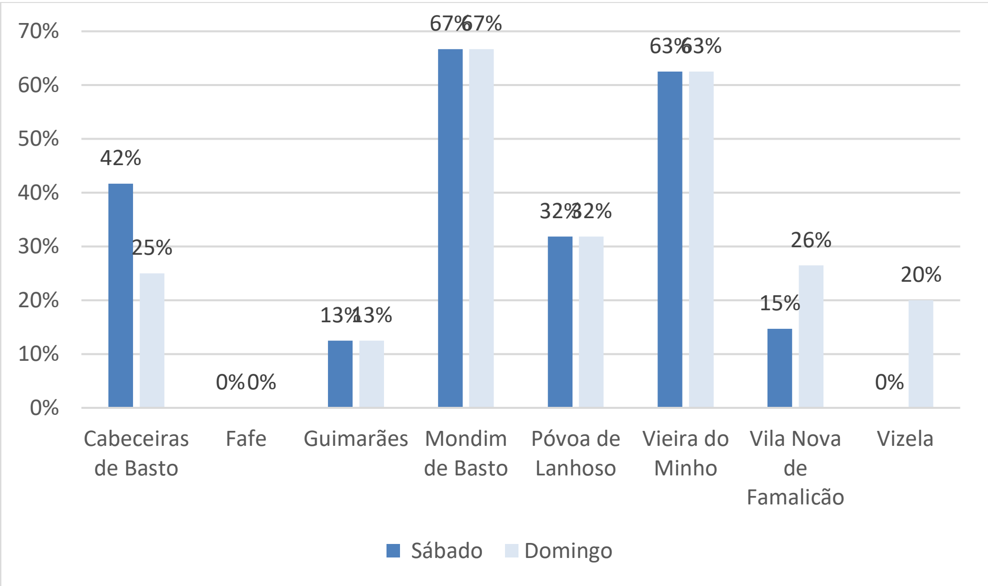


Figure 19 - Reducing of the number of circulations to municipality center on the weekend

Figure 20 shows the percentage of parishes in CIM Ave without connection to the municipality center by public transport. We can observe that the service coverage during weekdays is almost equal in School period (TA – tempo de aulas) and Holiday period (FTA – for a de tempo de aulas) –

about 2.5% of parishes do not have an access to municipality center. During the weekend the service level is much lower – 22% of parishes do not have connections to the municipality center on Saturday (Sabado) and 24% on Sunday (Domingo).

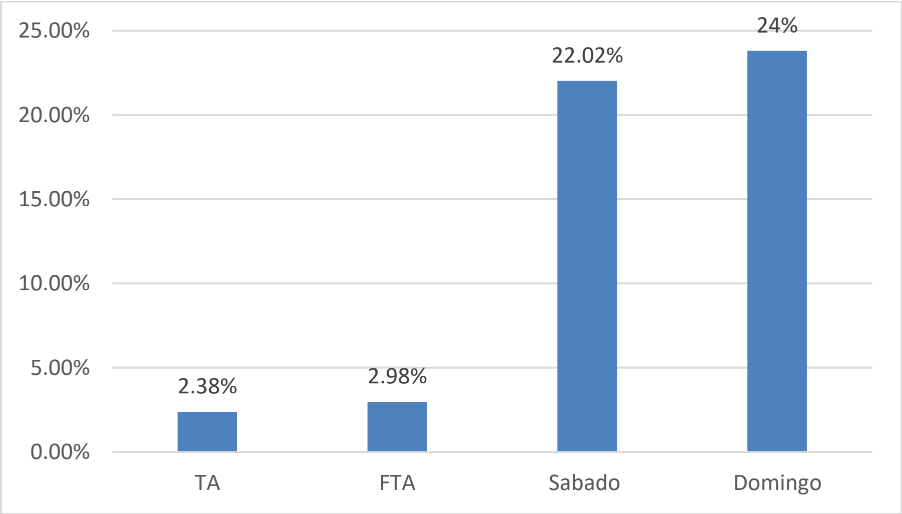


Figure 20 - Percentage of parishes without public transport services

Appendix 1 includes load maps by the municipality, representing the available circulations during a working day (School period and Holiday period) and weekend.

An analysis of these maps reveals the weight of PT in different municipalities and allows us to identify municipalities where a significant proportion of the territory does not have a PT network coverage throughout the year. These areas should receive special attention in the context of the new legal framework. The list of municipalities and parishes with lack of access to PT includes:

- Municipality of Guimarães: Longos;
- Municipality of Póvoa de Lanhoso: São João de Rei, Verim, Friande, and Ajuda;
- Municipality of Vila Nova de Famalicão: Mogege.

This situation is aggravated in other parishes at the weekends.

5.5 Connections between municipality centers

Table 11 shows the weekly number of circulations (Monday through Friday, direct connections, excluding expresses) between the municipality centers in CIM Ave and surrounding municipalities. The analysis of the table allows highlighting the number of circulations between Guimarães and Fafe and between Vila Nova de Famalicão and Guimarães.

Thus, Guimarães is the center of the western zone of CIM Ave with frequent connections between Vila Nova de Famalicão, Fafe and Vizela. Following are the connections to Póvoa de Lanhoso. This distribution is in agreement with the distribution of the pendular movements in the CIM Ave.

The main findings about external and internal connections of municipalities of CIM Ave:

- Vila Nova de Famalicão has strong connections with municipalities of the Metropolitan Area of Porto (Trofa, Porto, Santo Tirso, and Póvoa de Varzim) and Braga;
- Cabeceiras de Basto is connected only with Fafe and Guimarães in CIM Ave, and with Amarante, Celorico de Basto, Porto, Ribeira de Pena, and Amarante out of CIM Ave;
- Mondim de Basto is connected only with Fafe and Guimarães in CIM Ave, and with Amarante, Celorico de Basto, Santo Tirso, and Porto out of CIM Ave;
- Vieira do Minho is very isolated, with direct connections only to Póvoa de Lanhoso (CIM Ave).

Table 11 - Weekly number of circulations (Monday through Friday, direct connections, excluding expresses) between the municipality centers

Weekly Nº of circulations	Cabeceiras de Basto		Fafe		Guimarães		Mondim de Basto		Póvoa de Lanhoso		Vieira do Minho		Vila Nova de Famalicão		Vizela	
Municipality	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From
CABECEIRAS DE BASTO			70	61	40	40	0	0	20	15	0	0	0	0	0	0
FAFE	61	70			625	645	60	35	80	105	0	0	45	45	5	5
GUIMARÃES	40	40	**645**	**625**			50	35	110	130	0	0	383	379	190	215
MONDIM DE BASTO	0	0	35	60	35	50			0	0	0	0	0	0	0	0
PÓVOA DE LANHOSO	15	20	105	80	130	110	0	0			45	40	0	0	0	0
VIEIRA DO MINHO	0	0	0	0	0	0	0	0	40	45			0	0	0	0
VILA NOVA DE FAMALICÃO	0	0	45	45	**379**	**383**	0	0	0	0	0	0			0	0
VIZELA	0	0	5	5	215	190	0	0	0	0	0	0	0	0		
RIBEIRA DE PENA	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BARCELOS	0	0	0	0	0	0	0	0	0	0	0	0	60	45	0	0
BRAGA	15	20	0	0	340	360	0	0	110	105	0	0	265	254	0	0
CELORICO DE BASTO	40	35	15	15	15	15	5	10	0	0	0	0	0	0	0	0
AMARANTE	15	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FELGUEIRAS	0	0	30	25	120	145	0	0	0	0	0	0	0	0	121	116
MAIA	0	0	0	0	0	0	0	0	0	0	0	0	90	105	0	0
PORTO	40	40	145	140	205	210	10	15	0	0	0	0	165	185	115	125
PÓVOA DE VARZIM	0	0	0	0	140	130	0	0	0	0	0	0	180	155	0	0
SANTO TIRSO	5	5	60	65	75	75	40	35	0	0	0	0	110	130	150	140
VILA DO CONDE	0	0	0	0	0	0	0	0	0	0	0	0	65	60	0	0
TROFA	0	0	0	0	0	0	0	0	0	0	0	0	305	300	0	0

Table 12 - Minimal number of PT trips in connection of municipality centers

	Cabeceiras de Basto	Fafe	Guimarães	Mondim de Basto	Póvoa de Lanhoso	Vieira do Minho	Vila Nova Famalicão	Vizela
Cabeceiras de Basto	-	1	1	2	1	2	2	2
Fafe		-	1	1	1	2	1	1
Guimarães			-	1	1	2	1	1
Mondim de Basto				-	2	**3**	2	2
Póvoa de Lanhoso					-	1	1	2
Vieira do Minho						-	2	2
Vila Nova de Famalicão							-	2
Vizela								-

Table 12 shows the minimal number of circulations (separate trips) required to establish the connection between the municipality centers in CIM Ave. Stands out the connection between Vieira do Minho and Mondim de Basto, which involves three separate bus trips (requires two transfers).

5.6 Circulations in urban perimeters

This requirement applies to urban perimeters with a population more than 50 000 inhabitants. There are only two such urban perimeters in CIM Ave – Guimarães and Vila Nova de Famalicão. These cities are the centers of their municipalities.

Table 13 shows the number of circulations made in between each of the parishes and their municipality centers, during school periods, outside of school periods, on Saturdays and Sundays. A total number of circulations in CIM Ave is less than a sum of circulations in every municipality because some circulations pass through different municipalities.

The law requires two trips per hour at morning and afternoon peak periods and one trip per hour during the day. It means 22 circulations per day, considering operation hours from 06.00 to 00.00, morning peak hours 07.30-09.30 and afternoon peak hours 17.30-19.30. Even on Saturdays, municipality of Guimarães has 1912 circulations per day (Table 13), and the municipality of Vila Nova de Famalicão has 298 circulations.

Table 13 - Number of circulations per municipality

Municipality	Weekday, Scholar period	Weekday, Holiday period	Reduction (Scholar period / Holidays)	Saturday	Sunday
Cabeceiras de Basto	1060	843	20.47%	30	24
Fafe	5771	5225	9.46%	378	278
Guimarães	21211	20106	5.21%	2190	1912
Mondim de Basto	635	551	13.23%	25	18
Póvoa de Lanhoso	2661	2211	16.91%	138	122
Vieira do Minho	1231	893	27.46%	12	14
Vila Nova de Famalicão	8253	7436	9.90%	436	298
Vizela	2664	2549	4.32%	176	102
Total	33921	30669	9.59%	2488	2056

Considering this information, we can assure that this law requisite is fulfilled in all relevant urban perimeters in CIM Ave.

5.7 Scholar transportation system

5.7.1 Population covered by Scholar transportation system

Scholar Transportation (ST) is the provision of transportation service between the residence of students and the educational establishment, where the residence is more than a certain distance from the establishment. It applies to pupils of kindergartens (KG), basic schools of 1st, 2nd and 3rd levels (BS1, BS2, and BS3), secondary schools (SS) and Professional schools (Prof.). For basic school pupils, ST is obligatorily free. Pupils of Secondary schools usually contribute to the cost of ST.

The organization of Scholar Transportation involves the local authorities, schools and the central administration. Due to its relevance in the context of population mobility, an analysis of the existing ST system was undertaken in the municipalities of the CIM Ave.

Table 14 - Number of pupils covered by Scholar Transportation system, 2017/18

Municipality	KG	BS1	BS2	BS3	SS	Prof	Total
Cabeceiras de Basto	64	214	190	329	366	59	1 222
Fafe	23	68	272	495	400	0	1 258
Guimarães	3	325	1 121	2 191	1 841	0	5 481
Mondim de Basto	n.d.*	n.d.	n.d.	n.d.	n.d.	n.d.	579
Póvoa de Lanhoso	0	86	0	574	291	0	951
Vieira do Minho	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Vila Nova de Famalicão	0	262	1 112	1 591	1 495	0	4 460
Vizela	0	8	171	356	157	0	692
Total							14 643

**n.d. – no data provided by local authorities*

Table 14 shows the number of pupils covered by Scholar Transportation system in 2017/18 school year. Normally, kindergartens and Basic schools of 1st level (1-4 scholar years) are situated close to every neighborhood, and pupils can go there on foot. Basic schools of 3rd level (7-9 scholar years) and Secondary schools (10-12 scholar years), which usually are joined in one establishment, are rather rare. Thus, these schools are situated longer from residence than maximum walking distance, and more pupils are included in the Scholar Transportation plan.

5.7.2 Distribution by transportation mode

Table 15 summarizes the situation regarding to the distribution of pupils by type of service in CIM Ave in the 2017/18 school year: Public Transport (PT) - included in the regular collective passenger transport; and Special Circuits (SC) - transport provided by the municipality, with own resources or subcontracted to other entities (taxis, ambulances, or even buses).

Table 15 - Distribution of pupils by travel mode in Scholar Transportation system, 2017/18

Municipality	PT	Subcontracted SC (buses)	Subcontracted SC (cars)	SC by Local Authorities (buses)	SC by Local Authorities (cars)
Cabeceiras de Basto	85,4%	1,2%		13,4%	
Fafe	92,8%	7,2%			
Guimarães	94,1%	0,3%	0,3%	5,3%	
Mondim de Basto	41,5%	30,7%	4,1%	23,7%	
Póvoa de Lanhoso	69,1%		0,1%	7,8%	23,1%
Vieira do Minho	n.d.*	n.d.	n.d.	n.d.	n.d.
Vila Nova de Famalicão	97,2%	1,4%	0,6%	0,8%	
Vizela	96,7%			3,3%	

**n.d. – no data provided by local authorities*

According to the data provided by the municipalities, at the time of this report, about 90% of school transportation is done in existing public transport services. The municipality of Mondim de Basto stands out with almost 60% of school transport done in subcontracted circuits and in the transport owned by the municipality.

5.7.3 Costs by transportation mode

In the following sections, we present some indicators related to costs of scholar transport, namely: costs by transportation mode, and costs per passenger. Table 16 shows the annual costs of each municipality by transportation mode in 2017/18.

Table 16 - Annual costs of Scholar transport by transportation mode, 2017/18

Municipality	Duration of ST (months)	PT	SC of Local Authorities	Subcontracted SC	Total
Cabeceiras de Basto[1]		n.d.	n.d.	n.d.	n.d.
Fafe[1]	10	486 880,30 €[1]	- €	62 790,00 €	549 670,30 €
Guimarães	11	2 035 263,45 €	- €	350 573,38 €	2 385 836,83 €
Mondim de Basto	10	91,751.04 €	19 406,70 €	73 678,26 €	184,836.00 €
Póvoa de Lanhoso[1]	10	335 620,09 €	115 567,00 €[1]	57 779,30 €	508 975,39 €
Vieira do Minho	n.d.	n.d.	n.d.	n.d.	134 479,80 €
Vila Nova de Famalicão	10	1 557 488,50 €	16 000,00 €	72 970,00 €	1 664 458,50 €
Vizela[1]	10	214 572,52 €	n.d.	- €	214 572,52 €

[1] *Total cost does not include some information, that was not provided.*

According to the data provided so far, Guimarães is the municipality that supports the highest transport costs (values much higher than Vila Nova Famalicão that comes in second place). Guimarães also is the municipality with the largest number of students. The values reported by the Authorities of Guimarães point to a longer school period (11 months) than any other municipality. Usually, the duration of the school period is 10 months. During this period, the local Authorities support the costs of service.

The comparison between the academic year 2016/17 and the year 2017/18 shows the following results:

- Guimarães: an increase in costs for each type of service (+ 17.4%);
- Vila Nova de Famalicão: a decrease in costs in PT (-10.4%) and subcontracted vehicles (-16.5%), and a decrease in total cost (-9.6%);

- Vizela: subcontracted vehicles are no longer used and have been replaced by the transport belonging to the local authority; total cost decreased slightly (-0.6%);
- Other municipalities: it is not possible to make a cost comparison due to lack of information.

Considering the transportation provided by vehicles belonging to Local Authorities, the cost structure (for example, fuel costs, drivers, depreciation, maintenance, etc.) has not been provided. It explains some possible disparities in comparison of costs between municipalities or transportation modes.

5.7.4 Costs per passenger

The following section reports the transportation costs per student.

Table 17 shows the annual costs per pupil per transportation mode in CIM Ave in 2017/18.

Table 17 - Average annual costs per pupil in Scholar transportation system, 2017/18

Municipality	Total pupils	% pupils in ST	PT	SC of Local Authorities	Subcontracted SC	Average annual cost per passenger
Cabeceiras de Basto	1 222	85.4%	n.d.	n.d.	n.d.	n.d.
Fafe[1]	1 263	92.8%	415.40 €	- €	690.00 €	435.21 €
Guimarães	5 481	94.1%	394.51 €	- €	1 088.74 €	435.29 €
Mondim de Basto	579	41.5%	382.30 €	141.65 €	364.74 €	319.23 €
Póvoa de Lanhoso[2]	1375	69.1%	353.28 €	364.59 €	n.d.	n.d. €
Vieira do Minho	n.d.	n.d.	- €	- €	- €	- €
Vila Nova de Famalicão	4 460	97.2%	359.20 €	470.59 €	810.78 €	369.16 €
Vizela[2]	692	96.7%	320.74 €	n.d.	- €	320.74 €
	14 643					

[1] *School period of 10 months is assumed;*

[2] *Total cost does not include some information, that was not provided.*

Stands out the costs subcontracted transport in Guimarães, that is particularly high when compared to other municipalities (once again, the cost structure of own transport is unknown). Despite these disparities, the average annual value per pupil ranges from a minimum in Mondim de Basto of € 319 to a maximum in Fafe and Guimarães of € 435.

The average annual cost per pupil in Guimarães increased by 15.3% in 2017/18 due to the change in the duration of service from 10 to 11 months per year, among other factors. The increase of 8.8% in the average annual cost per pupil in Vila Nova de Famalicão in 2017/18 happened due to the following main factors:

1. Increasing of costs of public transport service provided by ARRIVA by 8.8%, apparently due to the increase in the average travel distance from 5.4 km to 6.0 km;
2. The increase of average cost per student for subcontracted vehicles and transport belonging to local Authorities because of a lower rate of vehicle occupation.

It should be noted that the municipality of Guimarães has the highest cost in any type of service. The biggest difference is for circuits covered by local authorities. In the academic year 2017/18, the cost per student of this type of service in Guimarães increased by 53% compared to the year 2016/17. The total cost of transportation by local authorities in Guimarães increased by 63% in the same period.

5.7.5 Summary

Evaluation of scholar transportation system in CIM Ave is based on two metrics:

1. Public transport coverage – at least 90% of pupils should have access to school by public transport. It means that the public transport network is wide enough to provide connections between a residence of pupils and their schools;
2. Cost of service – cost per passenger in special circuits (transportation by subcontracted vehicles or vehicles belonging to local authorities) should not surpass the cost of public transport. This metric is especially important for municipalities that do not meet the first criteria.

The scholar transportation system in the municipality is considered effective if it meets at least one of the requisites mentioned above. The results of the evaluation are presented in Table 18.

Table 18 - Evaluation of scholar transportation system

Municipality	Public transport coverage	Cost of service	Resume
Cabeceiras de Basto	Do not match	n.d.	Do not match
Fafe	Match	Match	Match
Guimarães	Match	Match	Match
Mondim de Basto	Do not match	Match	Match
Póvoa de Lanhoso	Do not match	n.d.	Do not match
Vieira do Minho	n.d.	n.d.	n.d.
Vila Nova de Famalicão	Match	Match	Match
Vizela	Match	Match	Match

Scholar transportation system in the municipalities of Fafe, Guimarães, Vila Nova de Famalicão and Vizela matches all performance indicators.

Municipalities of Cabeceiras de Basto, Mondim de Basto, and Póvoa de Lanhoso do not match the criteria of public transport coverage. Nevertheless, the cost of other transportation modes in Mondim de Basto is low enough to consider that its scholar transportation system is well balanced and effective.

Municipalities of Cabeceiras de Basto and Póvoa de Lanhoso did not provide complete information about the costs of service. Thus, the scholar transportation system in these municipalities is considered ineffective and requires adjustment.

The municipality of Vieira do Minho did not provide enough information for any level of performance evaluation.

5.8 Discussion of the results: public transport in CIM Ave

The results of public transport evaluation in CIM Ave are summarized in Table 19. We can observe that no one municipality meets all requirements of the Law 52/2015. Moreover, no one municipality fulfills the requisites of Network accessibility and Connections between municipality centers. Vizela shows the best result, but even this municipality does not meet two law requisites.

Table 19 - Resume of public transport evaluation in CIM Ave

Municipality	Network accessibility	Accessibility of primary facilities	Connections to municipality center	Connections between municipality centers	Circulations in urban perimeter	Scholar transport system	Overall result
Cabeceiras de Basto	-	-	+	-	N/A[1]	-	-
Fafe	-	-	+	-	N/A	+	-
Guimarães	-	+	-	-	+	+	-
Mondim de Basto	-	-	+	-	N/A	+	-
Póvoa de Lanhoso	-	+	-	-	N/A	-	-
Vieira do Minho	-	-	+	-	N/A	n.d.[2]	-
Vila Nova de Famalicão	-	+	-	-	+	+	-
Vizela	-	+	+	-	N/A	+	-

[1] Criterion does not apply to the municipality.

[2] No data provided by local authorities.

Possible improvements of the network may start by providing new transit routes to directly connect every municipality center with others in CIM Ave. This step requires just a few new bus lines between major cities of the region (even if they are rather small, in fact).

The tremendous number of 31.5% of all resident population of CIM Ave (that corresponds to 132 305 resident) have do not have an access to public transport, although they should have it. To improve network accessibility, new bus stops and routes should be designed. Flexible transport and transport on demand can significantly reduce this problem without huge associated costs of service.

It is important to notice that the law does not define the maximum acceptable walking distance from a bus stop to the residence. Thus, the law should be refined in order to eliminate this gap. Newer statistic information and actual distribution of population inside the household area, instead of the uniform distribution, also may change the results of network evaluation.

There are two ways to improve the accessibility of primary facilities – the first is to improve the bus lines and road network (reducing travel time), and the second is to open new facilities closer to the customers (residents). The second option is unlikely in the eastern part of Vieira do Minho, Mondim de Basto and Cabeceiras de Basto due to low population density in these areas. But some areas, like the southeast part of Fafe municipality, have enough population to consider the opening of new primary facilities.

5.9 Discussion of the results: Framework performance

In this section we discuss the performance of the proposed framework for public transport network evaluation, considering the case study of CIM Ave. This project shows that the framework provides reliable results even in the regions with the problems in quality of information and is suitable for both urban and rural regions.

Difficulties in utilization

The main difficulties of every evaluation framework are usually related to the quality and quantity of input data. Supposedly, the existence of the official database of the Portuguese public transport, SIGGESC, should guarantee the high level of information. In fact, it was revealed that the information about the bus lines, stops, and schedules in SIGGESC is not reliable: it is partly obsolete, partly repeated, and does not include some new data. Thus, it was necessary to find there the possible problems, and to verify the information with the local Authorities.

Moreover, some information that is necessary for the framework functioning is not included in the SIGGESC database. For example, the demand, costs and routes of the scholar transportation system are kept by local authorities and bus operators. Problem is that each of them uses information in different formats and quantities, that makes the analysis much more difficult – at first, it is necessary to transform all data into standardized form.

As a result, the implementation of the framework requires a multidisciplinary team of specialists in logistic, geography, economy, IT and data analysis. Low response speed of some local Authorities and bus operators requires the projects with long duration, that also increase the costs. The literature review reveals the same difficulties in different regions and countries.

The accuracy of evaluation can be improved by public surveys about trip origins, destinations, frequencies, etc. The literature review confirms that some of the researchers choose this way. Sometimes, the surveys are undertaken by the local Authorities each 5 or 10 years. In Portugal, it is still difficult to obtain this information.

Advantages

The framework successfully combines the law requisites for public transport networks (RJSPTP) and additional indicators revealed during the literature review. The law requisites represent the minimal acceptable level of service. By adding the indicators from the literature review, we match the framework for network evaluation with the real expectations of public transport passengers and consider the best international practices.

Thus, the framework confirms its effectiveness and can be applied on other public transport networks, and the emerging methods of data collection and analysis will provide its further improvement.

6. Conclusions

During this project, the framework for the evaluation of public transport network was proposed. At first, a conceptual framework was constructed on the base of the overview of the best practices. Then, the requisites of the law 52/2015 were analyzed, and the framework for public transport network evaluation was proposed on the base of these requisites and literature review.

The framework was applied to the case study of public transport in Intermunicipal Community of Ave (CIM Ave) in the North of Portugal. Finally, we analyzed the performance of the framework and revealed its advantages, limitations and possible improvements.

The case study of CIM Ave showed that none of the municipalities meets the requisites of an effective network. During the analysis, some gaps in law definitions were identified.

Future work may focus on the following steps:

- Evaluation of law requisites related to convenience, sizing of service and information to the public;
- Sensitivity analysis of walking distance to the bus stop;
- Evaluation of public transport in other regions of Portugal.

The main contribution of this research is the framework for the evaluation of public transport, that combines the best world practices and the requisites of Portuguese law. Thus, it is adapted to local features and tested in a real environment.

References

Agard, B., Morency, C., & Trépanier, M. (2006). Mining public transport user behaviour from smart card data. *IFAC Proceedings Volumes*, *39*(3), 399–404. https://doi.org/10.3182/20060517-3-FR-2903.00211

Ahas, R., Aasa, A., Silm, S., & Tiru, M. (2010). Daily rhythms of suburban commuters' movements in the Tallinn metropolitan area: Case study with mobile positioning data. *Transportation Research Part C*, *18*, 45–54. https://doi.org/10.1016/j.trc.2009.04.011

Arbex, R. O., & da Cunha, C. B. (2015). Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm. *Transportation Research Part B: Methodological*, *81*, 355–376. https://doi.org/10.1016/j.trb.2015.06.014

Asadi Bagloee, S., & Ceder, A. (2011). Transit-network design methodology for actual-size road networks. *Transportation Research Part B: Methodological*, *45*(10), 1787–1804. https://doi.org/10.1016/j.trb.2011.07.005

Ayadi, A., & Hammami, S. (2015). An analysis of the performance of public bus transport in Tunisian cities. *Transportation Research Part A: Policy and Practice*, *75*, 51–60. https://doi.org/10.1016/j.tra.2015.03.009

Aydin, N. (2017). A fuzzy-based multi-dimensional and multi-period service quality evaluation outline for rail transit systems. *Transport Policy*, *55*(February), 87–98. https://doi.org/10.1016/j.tranpol.2017.02.001

Baaj, M. H., & Mahmassani, H. S. (1991). An AI-based approach for transit route system planning and design. *Journal of Advanced Transportation*, *25*(2), 187–209. https://doi.org/10.1002/atr.5670250205

Badia Rodríguez, H. (2016). *PhD THESIS Comparison of bus network structures versus urban dispersion : A monocentric analytical approach Evidences from Barcelona's bus network*. Technical University of Catalonia - Barcelona Tech.

Bagchi, M., & White, P. R. (2005). The potential of public transport smart card data. *Transport Policy*, *12*(5), 464–474. https://doi.org/10.1016/j.tranpol.2005.06.008

Benenson, I., Martens, K., & Rofé, Y. (2010). Measuring the Gap Between Car and Transit

Accessibility Estimating Access Using a High-Resolution Transit Network Geographic Information System. *Transportation Research Record: Journal of the Transportation Research Board*, *2144*, 28–35. https://doi.org/10.3141/2144-04

Benenson, I., Martens, K., Rofe, Y., & Kwartler, A. (2011). Public transport versus private car GIS-based estimation of accessibility applied to the Tel Aviv metropolitan area. *Annals of Regional Science*, *47*(3), 499–515. https://doi.org/10.1007/s00168-010-0392-6

Borndörfer, R., Grötschel, M., & Pfetsch, M. E. (2005). *A Path-Based Model for Line Planning in Public Transport*. *Informationstechnik* (Vol. 18).

Bruno, G., Ghiani, G., & Improta, G. (1998). A multi-modal approach to the location of a rapid transit line. *European Journal of Operational Research*, *104*(2), 321–332. https://doi.org/10.1016/S0377-2217(97)00187-2

Burke, M., & Brown, L. (2007a). Active transport in brisbane: How much is happening and what are its characteristics? *State of Australian Cities National Conference, 2007, Adelaide, South Australia*, 12P.

Burke, M., & Brown, L. (2007b). Distances people walk for transport. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice*, *16*(3), 16–29. Retrieved from https://search.informit.com.au/documentSummary;dn=880016006301032;res=IELENG

Burns, C. M., & Inglis, A. D. (2007). Measuring food access in Melbourne: Access to healthy and fast foods by car, bus and foot in an urban municipality in Melbourne. *Health and Place*, *13*(4), 877–885. https://doi.org/10.1016/j.healthplace.2007.02.005

Cancela, H., Mauttone, A., & Urquhart, M. E. (2015). Mathematical programming formulations for transit network design. *Transportation Research Part B: Methodological*, *77*, 17–37. https://doi.org/10.1016/j.trb.2015.03.006

Ceder, A. (2016). *Public Transit Planning and Operation: Modeling, Practice and Behavior*. CRC press.

Ceder, A., & Wilson, N. H. M. (1986). Bus network design. *Transportation Research Part B: Methodological*, *20*(4), 331–344. https://doi.org/10.1016/0191-2615(86)90047-0

Chakroborty, P. (2003). Genetic algorithms for optimal urban transit network design. *Computer-Aided Civil and Infrastructure Engineering*, *18*, 184–200.

https://doi.org/10.1111/1467-8667.00309

Chakroborty, P., & Wivedi, T. (2002). Optimal Route Network Design for Transit Systems Using Genetic Algorithms. *Engineering Optimization*, *34*(1), 83–100. https://doi.org/10.1080/03052150210909

Chapleau, R., Lavigueur, P., & Baass, K. G. (1987). A posteriori impact analysis of a subway extension in Montreal. In *Rapid Rail Transit and Planning Tools*.

Chapleau, R., & Morency, C. (2005). *Dynamic spatial analysis of urban travel survey data using GIS*. *25th Annual ESRI International User Conference*.

Chen, J., Liu, Z., Zhu, S., & Wang, W. (2015). Design of limited-stop bus service with capacity constraint and stochastic travel time. *Transportation Research Part E: Logistics and Transportation Review*, *83*, 1–15. https://doi.org/10.1016/j.tre.2015.08.007

Cheng, C., & Agrawal, A. W. (2010). TTSAT: A New Approach to Mapping Transit Accessibility. *Journal of Public Transportation*, *13*(1), 55–72. https://doi.org/10.5038/2375-0901.13.1.4

Chew, J. S. C., Lee, L. S., & Seow, H. V. (2013). Genetic algorithm for biobjective urban transit routing problem. *Journal of Applied Mathematics*, *2013*. https://doi.org/10.1155/2013/698645

Chica-Olmo, J., Gachs-Sanchez, H., & Lizarraga, C. (2017). Route effect on the perception of public transport services quality. *Transport Policy*, 0–1. https://doi.org/10.1016/j.tranpol.2017.03.024

Cipriani, E., Gori, S., & Petrelli, M. (2012). Transit network design: A procedure and an application to a large urban area. *Transportation Research Part C: Emerging Technologies*, *20*(1), 3–14. https://doi.org/10.1016/j.trc.2010.09.003

Currie, G. (2010). Quantifying spatial gaps in public transport supply based on social needs. *Journal of Transport Geography*, *18*(1), 31–41. https://doi.org/10.1016/j.jtrangeo.2008.12.002

Curtis, C., & Scheurer, J. (2010). Planning for sustainable accessibility: Developing tools to aid discussion and decision-making. *Progress in Planning*, *74*(2), 53–106. https://doi.org/10.1016/j.progress.2010.05.001

da Silva, C. do C. F. (2008). *Comparative Accessibility for Mobility Management: the*

Structural Accessibility Layer. University of Oporto.

de Oña, J., de Oña, R., Eboli, L., & Mazzulla, G. (2016). Index numbers for monitoring transit service quality. *Transportation Research Part A: Policy and Practice*, *84*, 18–30. https://doi.org/10.1016/j.tra.2015.05.018

De Oña, J., De Oña, R., Eboli, L., & Mazzulla, G. (2013). Perceived service quality in bus transit service: A structural equation approach. *Transport Policy*, *29*, 219–226. https://doi.org/10.1016/j.tranpol.2013.07.001

Doerner, K., Focke, A., & Gutjahr, W. J. (2007). Multicriteria tour planning for mobile healthcare facilities in a developing country. *European Journal of Operational Research*, *179*(3), 1078–1096. https://doi.org/10.1016/j.ejor.2005.10.067

Dong, X., Ben-Akiva, M. E., Bowman, J. L., & Walker, J. L. (2006). Moving from trip-based to activity-based measures of accessibility. *Transportation Research Part A: Policy and Practice*, *40*(2), 163–180. https://doi.org/10.1016/j.tra.2005.05.002

Dufourd, H., Gendreau, M., & Laporte, G. (1996). Locating a transit line using tabu search. *Location Science*, *4*(1–2).

Echaniz, E., Dell'Olio, L., & Ibeas, Á. (2017). Modelling perceived quality for urban public transport systems using weighted variables and random parameters. *Transport Policy*, (In press). https://doi.org/10.1016/j.tranpol.2017.05.006

El-Geneidy, A. M., Tétreault, P., & Surprenant-Legault, J. (2009). Pedestrian access to transit: Identifying redundancies and gaps using a variable service area analysis. *89th Transportation Research Board Annual Meeting*, (July), 1–19.

Fan, W., & Machemehl, R. B. (2004). *Optimal Transit Route Network Design Problem : Algorithms, Implementations and Numerical Results*. *Center for Transportation Research* (Vol. 7).

Fan, W., & Machemehl, R. B. (2008). Tabu search strategies for the public transportation network optimizations with variable transit demand. *Computer-Aided Civil and Infrastructure Engineering*, *23*(7), 502–520. https://doi.org/10.1111/j.1467-8667.2008.00556.x

Fayyaz, S. K., Liu, X. C., & Porter, R. J. (2017). Dynamic transit accessibility and transit gap causality analysis. *Journal of Transport Geography*, *59*, 27–39.

https://doi.org/10.1016/j.jtrangeo.2017.01.006

Fernández L., J. E., de Cea Ch., J., & Malbran, R. H. (2008). Demand responsive urban public transport system design: Methodology and application. *Transportation Research Part A: Policy and Practice*, *42*(7), 951–972. https://doi.org/10.1016/j.tra.2007.12.008

Foth, N., Manaugh, K., & El-Geneidy, A. M. (2013). Towards equitable transit: Examining transit accessibility and social need in Toronto, Canada, 1996-2006. *Journal of Transport Geography*, *29*, 1–10. https://doi.org/10.1016/j.jtrangeo.2012.12.008

Fransen, K., Neutens, T., Farber, S., De Maeyer, P., Deruyter, G., & Witlox, F. (2015). Identifying public transport gaps using time-dependent accessibility levels. *Journal of Transport Geography*, *48*, 176–187. https://doi.org/10.1016/j.jtrangeo.2015.09.008

Garrido, C., De Oña, R., & De Oña, J. (2014). Neural networks for analyzing service quality in public transportation. *Expert Systems with Applications*, *41*(15), 6830–6838. https://doi.org/10.1016/j.eswa.2014.04.045

Georgiadis, G., Politis, I., & Papaioannou, P. (2014). Measuring and improving the efficiency and effectiveness of bus public transport systems. *Research in Transportation Economics*, *48*, 84–91. https://doi.org/10.1016/j.retrec.2014.09.035

Golub, A., & Martens, K. (2014). Using principles of justice to assess the modal equity of regional transportation plans. *Journal of Transport Geography*, *41*, 10–20. https://doi.org/10.1016/j.jtrangeo.2014.07.014

Guihaire, V., & Hao, J.-K. (2008). Transit network design and scheduling: A global review. *Transportation Research Part A: Policy and Practice*, *42*(10), 1251–1273. https://doi.org/10.1016/j.tra.2008.03.011

Guirao, B., García-Pastor, A., & López-Lambas, M. E. (2016). The importance of service quality attributes in public transportation: Narrowing the gap between scientific research and practitioners' needs. *Transport Policy*, *49*, 68–77. https://doi.org/10.1016/j.tranpol.2016.04.003

Guo, Z., & Wilson, N. H. M. (2011). Assessing the cost of transfer inconvenience in public transport systems: A case study of the London Underground. *Transportation Research Part A: Policy and Practice*, *45*(2), 91–104. https://doi.org/10.1016/j.tra.2010.11.002

Han, A. F.-W. (1987). Assessment of Transfer Penalty to Bus Riders in Taipei: A

Disaggregate Demand Modeling Approach. *Transportation Research Record*, *1139*(Table 1), 8–14.

Hassan, M. N., Hawas, Y. E., & Ahmed, K. (2013). A multi-dimensional framework for evaluating the transit service performance. *Transportation Research Part A: Policy and Practice*, *50*, 47–61. https://doi.org/10.1016/j.tra.2013.01.041

Hawas, Y. E., Hassan, M. N., & Abulibdeh, A. (2016). A multi-criteria approach of assessing public transport accessibility at a strategic level. *Journal of Transport Geography*, *57*, 19–34. https://doi.org/10.1016/j.jtrangeo.2016.09.011

Hensher, D. A. (1992). Total factor productivity growth and endogenous demand: Establishing a benchmark index for the selection of operational performance measures in public bus firms. *Transportation Research Part B*, *26*(6), 435–448. https://doi.org/10.1016/0191-2615(92)90009-L

Hess, D. B. (2009). Access to public transit and its influence on ridership for older adults in two U.S. Cities. *Journal of Transport and Land Use*, *2*(1), 3–27. https://doi.org/10.5198/jtlu.v2i1.11

Horner, M. W., & Murray, A. T. (2004). Spatial Representation and Scale Impacts in Transit Service Assessment. *Environment and Planning B: Planning and Design*, *31*(5), 785–797. https://doi.org/10.1068/b3046

Hsiao, S., Lu, J., Sterling, J., & Weatherford, M. (1997). Use of Geographic Information System for Analysis of Transit Pedestrian Access. *Transportation Research Record: Journal of the Transportation Research Board*, *1604*, 50–59. https://doi.org/10.3141/1604-07

Huang, R., & Wei, Y. D. (2002). Analyzing Neighborhood Accessibility via Transit in a GIS Environment. *Annals of GIS*, *8*(1), 39–47. https://doi.org/10.1080/10824000209480572

Ibarra-Rojas, O. J., López-Irarragorri, F., & Rios-Solis, Y. A. (2015). Multiperiod Bus Timetabling. *Transportation Science*, *50*(3), 805–822. https://doi.org/10.1287/trsc.2014.0578

Ibeas, Á., Dell 'olio, L., Alonso, B., & Sainz, O. (2010). Optimizing bus stop spacing in urban areas. *Transportation Research Part E: Logistics and Transportation Review*, *46*(3), 446–458. https://doi.org/10.1016/j.tre.2009.11.001

Jang, W. (2010). Travel Time and Transfer Analysis Using Transit Smart Card Data. *Transportation Research Record: Journal of the Transportation Research Board*, *2144*, 142–149. https://doi.org/10.3141/2144-16

John, M. P. (2016). *Metaheuristics for Designing Efficient Routes & Schedules For Urban Transportation Networks*. Cardiff University.

Jones, A. P., Haynes, R., Sauerzapf, V., Crawford, S. M., Zhao, H., & Forman, D. (2008). Travel times to health care and survival from cancers in Northern England. *European Journal of Cancer*, *44*(2), 269–274. https://doi.org/10.1016/j.ejca.2007.07.028

Kaza, N. (2015). Time dependent accessibility. *Journal of Urban Management*, *4*(1), 24–39. https://doi.org/10.1016/j.jum.2015.06.001

Kim, H. M., & Kwan, M. P. (2003). Space-time accessibility measures: A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration. *Journal of Geographical Systems*, *5*(1), 71–91. https://doi.org/10.1007/s101090300104

Kimpel, T. J., Dueker, K. J., & El-Geneidy, A. M. (2007). Using GIS to Measure the Effect of Overlapping Service Areas on Passenger Boardings at Bus Stops. *Urban and Regional Information Systems Association Journal*, *19*(1), 5–11.

Kittelson and Associates, I., Parsons Brinckerhoff, I., KFH Group, I., Texas A&M Transportation Institute, H., & Arup. (2013). *Transit Capacity and Quality of Service Manual. Third Edition*. *TCRP Report*. https://doi.org/10.17226/24766

Kwan, M.-P. (1999). Gender and Individual Access to Urban Opportunities: A Study Using Space–Time Measures. *The Professional Geographer*, *51*(2), 211–227. https://doi.org/10.1111/0033-0124.00158

Lao, Y., & Liu, L. (2009). Performance evaluation of bus lines with data envelopment analysis and geographic information systems. *Computers, Environment and Urban Systems*, *33*(4), 247–255. https://doi.org/10.1016/j.compenvurbsys.2009.01.005

Laporte, G., Ortega, F. A., Pozo, M. A., & Puerto, J. (2017). Multi-objective integration of timetables, vehicle schedules and user routings in a transit network. *Transportation Research Part B: Methodological*, *98*, 94–112. https://doi.org/10.1016/j.trb.2016.12.018

Lattman, K., Olsson, L. E., & Friman, M. (2016). Development and test of the Perceived Accessibility Scale (PAC) in public transport. *Journal of Transport Geography*, *54*, 257–

263. https://doi.org/10.1016/j.jtrangeo.2016.06.015

Lei, T. L., & Church, R. L. (2010). Mapping transit-based access: integrating GIS, routes and schedules. *International Journal of Geographical Information Science, 24*, 283–304. https://doi.org/10.1080/13658810902835404

Leiva, C., Muñoz, J. C., Giesen, R., & Larrain, H. (2010). Design of limited-stop services for an urban bus corridor with capacity constraints. *Transportation Research Part B: Methodological*, *44*(10), 1186–1201. https://doi.org/10.1016/j.trb.2010.01.003

Li, J., Chen, X., Li, X., & Guo, X. (2013). Evaluation of Public Transportation Operation based on Data Envelopment Analysis. *Procedia - Social and Behavioral Sciences*, *96*(Cictp), 148–155. https://doi.org/10.1016/j.sbspro.2013.08.020

Liu, T., & Ceder, A. (2017). Integrated Public Transport Timetable Synchronization and Vehicle Scheduling with Demand Assignment: A Bi-objective Bi-level Model Using Deficit Function Approach. *Transportation Research Procedia*, *23*, 341–361. https://doi.org/10.1016/j.trpro.2017.05.020

Lovett, A., Haynes, R., Sunnerberg, G., & Gate, S. (2002). Car travel time and accessibility by bus to GP services: a study using patient registers and GIS. *Social Science and Medicine*, *55*, 97–111.

Mamun, S. A., Lownes, N. E., Osleeb, J. P., & Bertolaccini, K. (2013). A method to define public transit opportunity space. *Journal of Transport Geography*, *28*, 144–154. https://doi.org/10.1016/j.jtrangeo.2012.12.007

Mandl, C. E. (1979). *Applied network optimization*. Academic Press.

Mavoa, S., Witten, K., McCreanor, T., & O'Sullivan, D. (2012). GIS based destination accessibility via public transit and walking in Auckland, New Zealand. *Journal of Transport Geography*, *20*(1), 15–22. https://doi.org/10.1016/j.jtrangeo.2011.10.001

Miller, H. J. (1991). Modelling accessibility using space-time prism concepts within geographical information systems. *International Journal of Geographical Information Systems*, *5*(3), 287–301. https://doi.org/10.1080/02693799108927856

Miller, H. J. (2006). Modelling accessibility using space-time prism concepts within geographical information systems: fourteen years on. *Classics from IJGIS: Twenty Years of the International Journal of Geographical Information Science and Systems*, *5*(3), 175–179.

Mondou, V. (2001). Daily mobility and adequacy of the urban transportation network a gis application. *CyberGeo*.

Morency, C., Trépanier, M., & Agard, B. (2007). Measuring transit use variability with smart-card data. *Transport Policy*, *14*(3), 193–203. https://doi.org/10.1016/j.tranpol.2007.01.001

Morton, C., Caulfield, B., & Anable, J. (2016). Customer perceptions of quality of service in public transport: Evidence for bus transit in Scotland. *Case Studies on Transport Policy*, *4*(3), 199–207. https://doi.org/10.1016/j.cstp.2016.03.002

Mumford, C. L. (2013). New heuristic and evolutionary operators for the multi-objective urban transit routing problem. *2013 IEEE Congress on Evolutionary Computation, CEC 2013*, 939–946. https://doi.org/10.1109/CEC.2013.6557668

Munizaga, M. A., & Palma, C. (2012). Estimation of a disaggregate multimodal public transport Origin-Destination matrix from passive smartcard data from Santiago, Chile. *Transportation Research Part C: Emerging Technologies*, *24*, 9–18. https://doi.org/10.1016/j.trc.2012.01.007

Murray, A. T. (2003). A Coverage Model for Improving Public Transit System. *Annals of Operations Research*, *123*(1–4), 143–156. https://doi.org/10.1023/A:1026123329433

Murray, A. T., Davis, R., Stimson, R. J., & Ferreira, L. (1998). Public transportation access. *Transportation Research Part D: Transport and Environment*, *3*(5), 319–328. https://doi.org/10.1016/S1361-9209(98)00010-8

Nayeem, M. A., Rahman, M. K., & Rahman, M. S. (2014). Transit network design by genetic algorithm with elitism. *Transportation Research Part C: Emerging Technologies*, *46*, 30–45. https://doi.org/10.1016/j.trc.2014.05.002

Nesheli, M. M., Ceder, A., & Liu, T. (2015). A robust, tactic-based, real-time framework for public- transport transfer synchronization. *Transportation Research Procedia*, *9*, 246–268. https://doi.org/10.1016/j.trpro.2015.07.014

Nikolić, M., & Teodorović, D. (2013). Transit network design by Bee Colony Optimization. *Expert Systems with Applications*, *40*(15), 5945–5955. https://doi.org/10.1016/j.eswa.2013.05.002

Nikolić, M., & Teodorović, D. (2014). A simultaneous transit network design and frequency setting: Computing with bees. *Expert Systems with Applications*, *41*(16), 7200–7209. https://doi.org/10.1016/j.eswa.2014.05.034

O'Sullivan, D., Morrison, A., & Shearer, J. (2000). Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. *International Journal of Geographical Information Science*, *14*(1), 85–104. https://doi.org/10.1080/136588100240976

Polzin, S., Pendyala, R., & Navari, S. (2002). Development of Time-of-Day-Based Transit Accessibility Analysis Tool. *Transportation Research Record: Journal of the Transportation Research Board*, *1799*, 35–41. https://doi.org/10.3141/1799-05

Pternea, M., Kepaptsoglou, K., & Karlaftis, M. G. (2015). Sustainable urban transit network design. *Transportation Research Part A: Policy and Practice*, *77*, 276–291. https://doi.org/10.1016/j.tra.2015.04.024

Reades, J., Calabrese, F., Sevtsuk, A., & Ratti, C. (2007). Cellular Census: Explorations in Urban Data Collection. *Pervasive Computing*, *6*(3), 30–38. https://doi.org/10.1109/MPRV.2007.53

Saghapour, T., Moridpour, S., & Thompson, R. G. (2016). Public transport accessibility in metropolitan areas: A new approach incorporating population density. *Journal of Transport Geography*, *54*, 273–285. https://doi.org/10.1016/j.jtrangeo.2016.06.019

Saini, T., Sinha, A., & Srikanth, S. V. (2015). Urban Travel Demand Estimation using Genetic Algorithm. In *2015 International Conference on Cognitive Computing and Information Processing(CCIP)*. https://doi.org/10.1109/CCIP.2015.7100705

Shih, M.-C., Mahmassani, H., & Baaj, M. (1998). Planning and Design Model for Transit Route Networks with Coordinated Operations. *Transportation Research Record: Journal of the Transportation Research Board*, *1623*, 16–23. https://doi.org/10.3141/1623-03

Shimamoto, H., Murayama, N., Fujiwara, A., & Zhang, J. (2010). Evaluation of an existing bus network using a transit network optimisation model: A case study of the Hiroshima City Bus network. *Transportation*, *37*(5), 801–823. https://doi.org/10.1007/s11116-010-9297-6

Silva, C., & Pinho, P. (2010). The Structural Accessibility Layer (SAL): Revealing how

Urban Structure Constrains Travel Choice. *Environment and Planning A*, *42*(11), 2735–2752. https://doi.org/10.1068/a42477

Stelzer, A., Englert, F., Horold, S., & Mayas, C. (2016). Improving service quality in public transportation systems using automated customer feedback. *Transportation Research Part E: Logistics and Transportation Review*, *89*, 259–271. https://doi.org/10.1016/j.tre.2015.05.010

Tsami, M., & Nathanail, E. (2017). Guidance Provision for Increasing Quality of Service of Public Transport. *Procedia Engineering*, *178*, 551–557. https://doi.org/http://dx.doi.org/10.1016/j.proeng.2017.01.108

van Lierop, D., & El-Geneidy, A. (2016). Enjoying loyalty: The relationship between service quality, customer satisfaction, and behavioral intentions in public transit. *Research in Transportation Economics*, *59*, 50–59. https://doi.org/10.1016/j.retrec.2016.04.001

Venkatesh, A., & Kushwaha, S. (2016). Short and long-run cost efficiency in Indian public bus companies using Data Envelopment Analysis. *Socio-Economic Planning Sciences*. https://doi.org/10.1016/j.seps.2017.04.001

Verbas, I. Ö., Frei, C., Mahmassani, H. S., & Chan, R. (2014). Stretching resources: sensitivity of optimal bus frequency allocation to stop-level demand elasticities. *Public Transport*, *7*(1), 1–20. https://doi.org/10.1007/s12469-013-0084-6

Verbas, İ. Ö., & Mahmassani, H. S. (2015). Integrated Frequency Allocation and User Assignment in Multimodal Transit Networks. *Transportation Research Record: Journal of the Transportation Research Board*, *2498*, 37–45. https://doi.org/10.3141/2498-05

Wang, R.-T., Feng, C.-M., & Wang, R.-T. (2000). Performance evaluation for airlines including the consideration of financial ratios . J Air Transp Performance evaluation for airlines including the consideration of " nancial ratios. *Journal of Air Transport Management*, *6*(JULY), 133–142. https://doi.org/10.1016/S0969-6997(00)00003-X

Wirasinghe, S. C., & Vandebona, U. (1987). *Some aspects of the location of subway stations and routes.* Namur, Belgium.

Yan-yan, C., Pan-yi, W., Jian-hui, L., Guo-chen, F., Xin, L., & Yi, G. (2016). An Evaluating Method of Public Transit Accessibility for Urban Areas Based on GIS. *Procedia Engineering*, *137*, 132–140. https://doi.org/10.1016/j.proeng.2016.01.243

Yang, W., Chen, B. Y., Cao, X., Li, T., & Li, P. (2017). The spatial characteristics and influencing factors of modal accessibility gaps: A case study for Guangzhou, China. *Journal of Transport Geography*, *60*, 21–32. https://doi.org/10.1016/j.jtrangeo.2017.02.005

Yeh, C.-H., Deng, H., & Chang, Y.-H. (2000). Fuzzy multicriteria analysis for performance evaluation of bus companies. *European Journal of Operational Research*, *126*, 459–473. https://doi.org/10.1016/S0377-2217(99)00315-X

Yigitcanlar, T., Sipe, N., Evans, R., & Pitot, M. (2007). A GIS-based land use and public transport accessibility indexing model. *Australian Planner*, *44*(3), 30–37. https://doi.org/10.1080/07293682.2007.9982586

Yu, B., Cheng, C., Yang, Z., & Liu, C. (2005). Optimizing Bus Transit Network With Parallel Ant Colony Algorithm. *Proceedings of the Eastern Asia Society for Transportation Studies*, *5*, 374–389.

Zaourar-Michel, S. (2016). Efficient decomposition method for the stochastic optimization of public transport schedules. In *30th Conference on Neural Information Processing Systems (NIPS 2016)*. Barcelona, Spain.

Zhang, C., Juan, Z., Luo, Q., & Xiao, G. (2016). Performance evaluation of public transit systems using a combined evaluation method. *Transport Policy*, *45*, 156–167. https://doi.org/10.1016/j.tranpol.2015.10.001

Zhao, F., Chow, L.-F., Li, M.-T., Ubaka, I., & Gan, A. (2003). Forecasting Transit Walk Accessibility: Regression Model Alternative to Buffer Method. *Transportation Research Record: Journal of the Transportation Research Board*, *1835*, 34–41. https://doi.org/10.3141/1835-05

Zhao, F., & Gan, A. (2003). *Optimization of Transit Network To Minimize Transfers*.

APPENDIX I – LOADS BY THE MUNICIPALITY

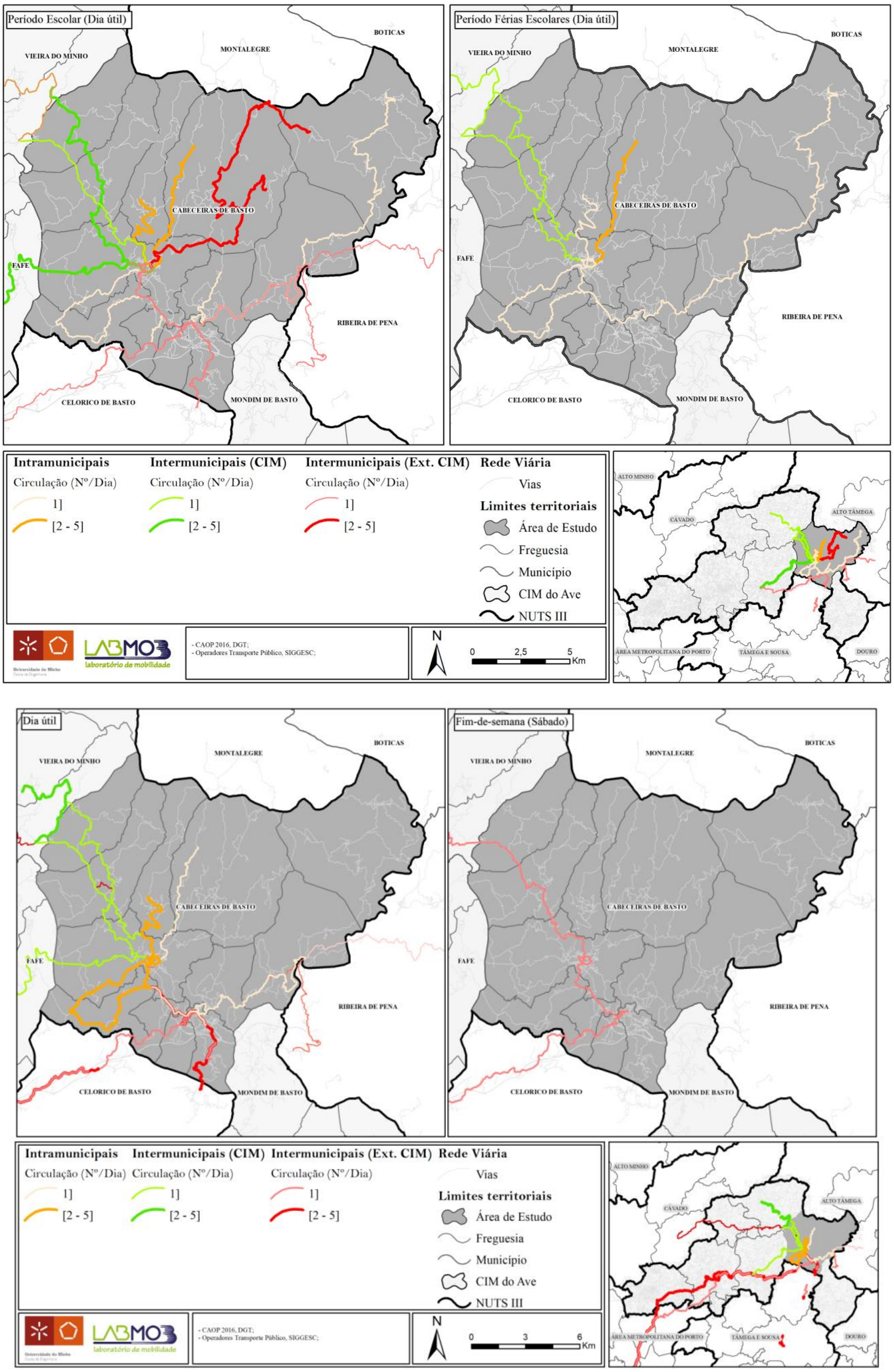


Figure 21 - Frequency of circulations (all operators): Cabeceiras de Basto

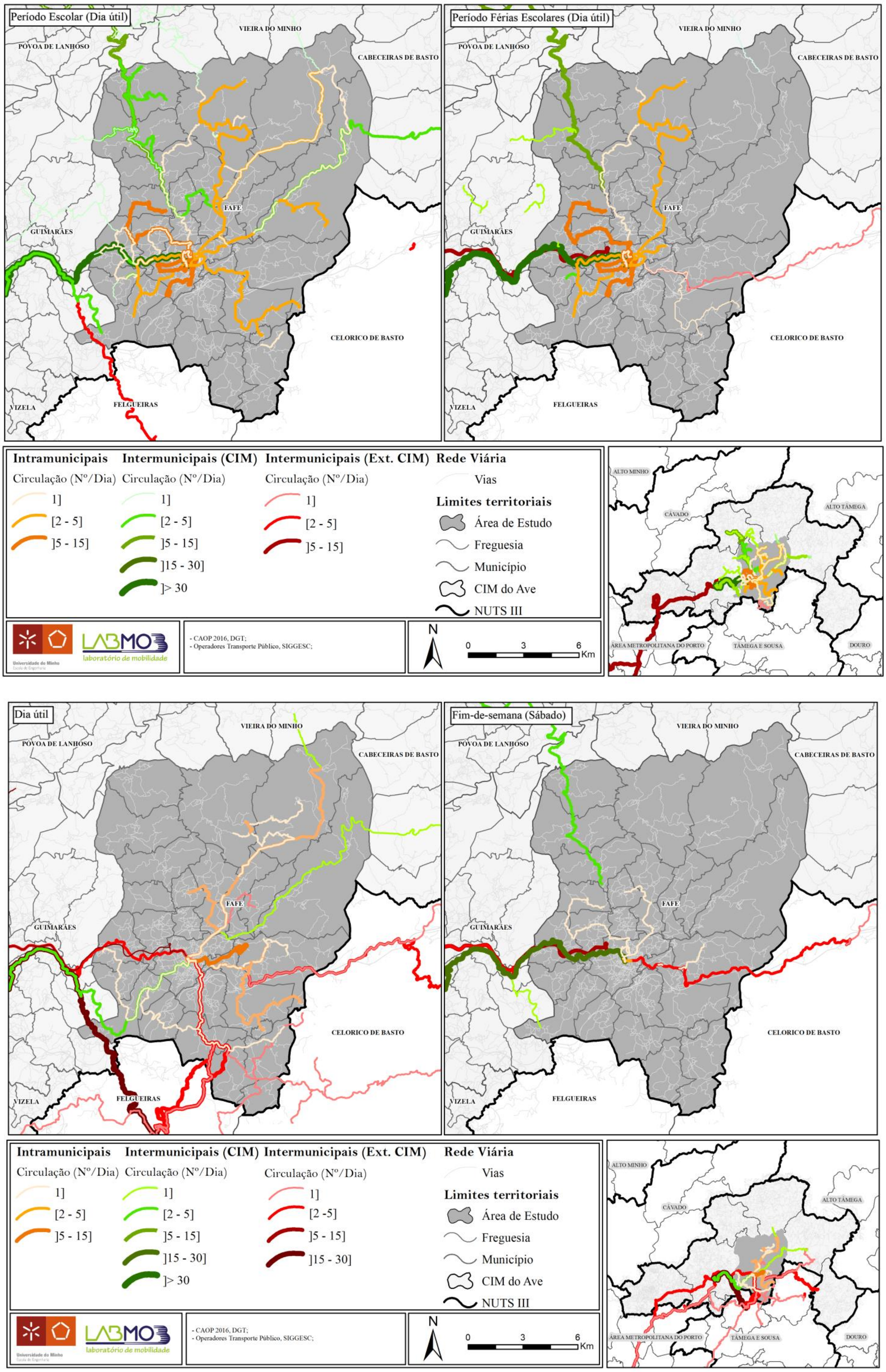


Figure 22 - Frequency of circulations (all operators): Fafe

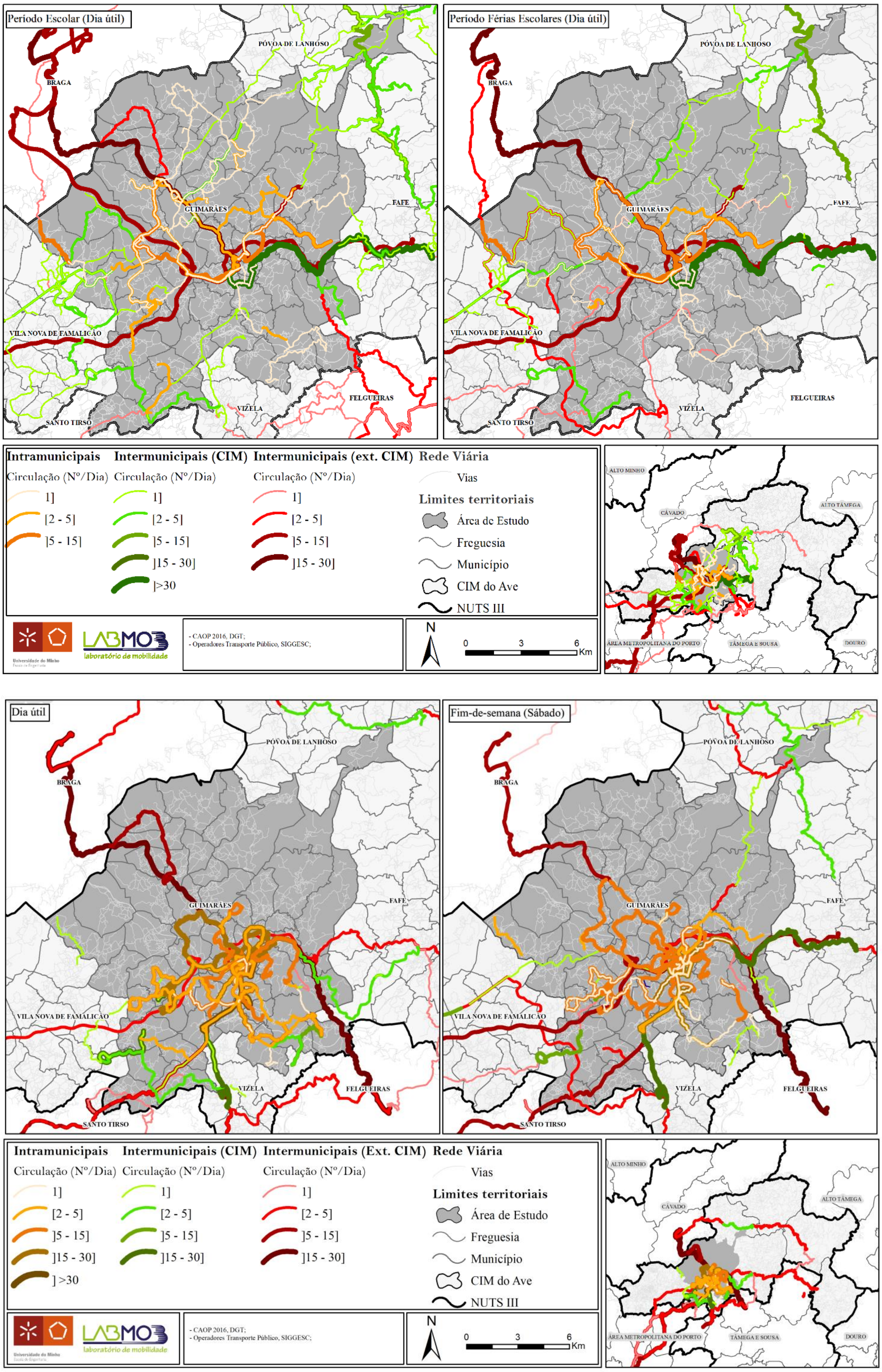


Figure 23 - Frequency of circulations (all operators): Guimarães

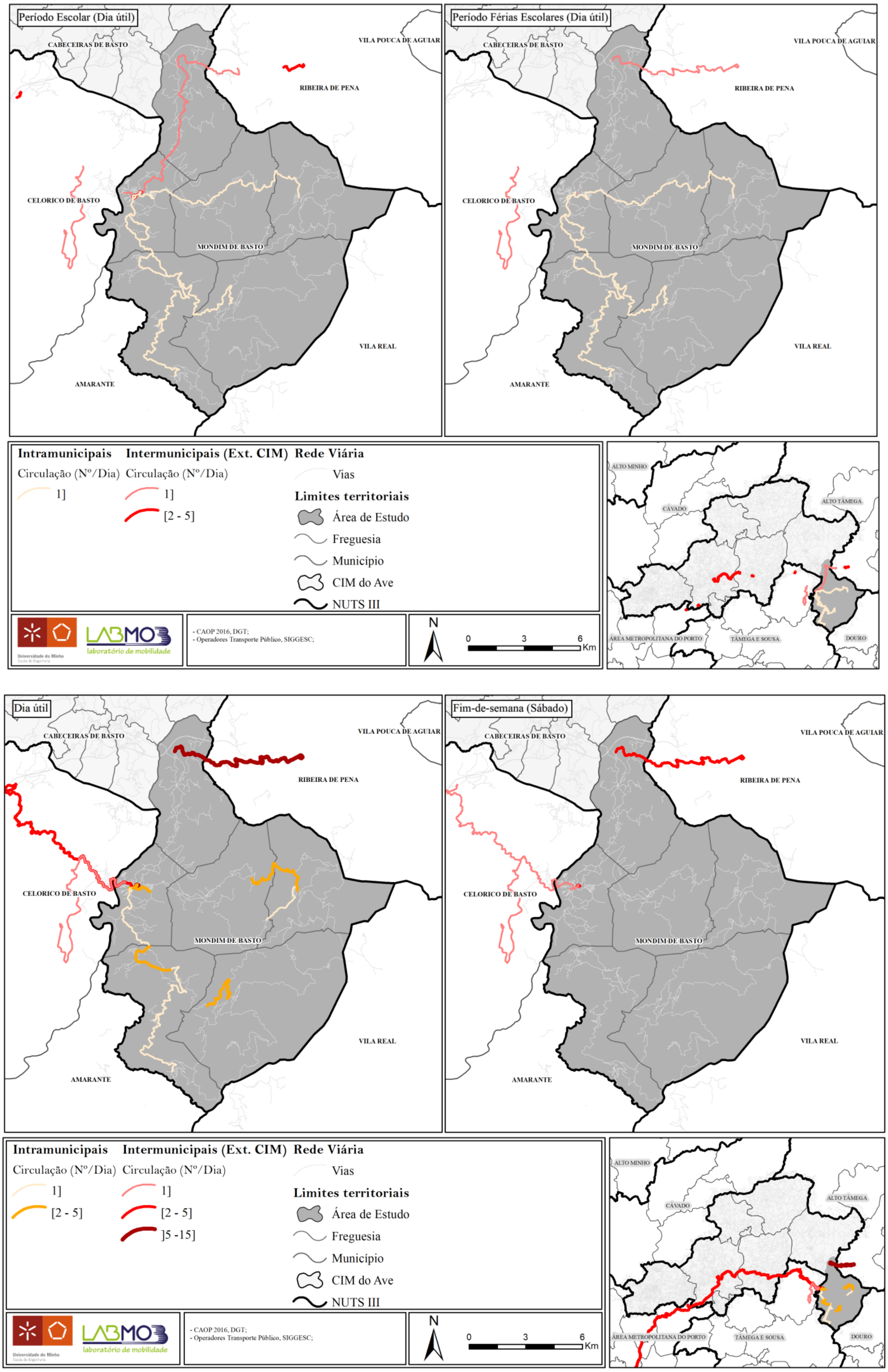


Figure 24 - Frequency of circulations (all operators): Mondim de Basto

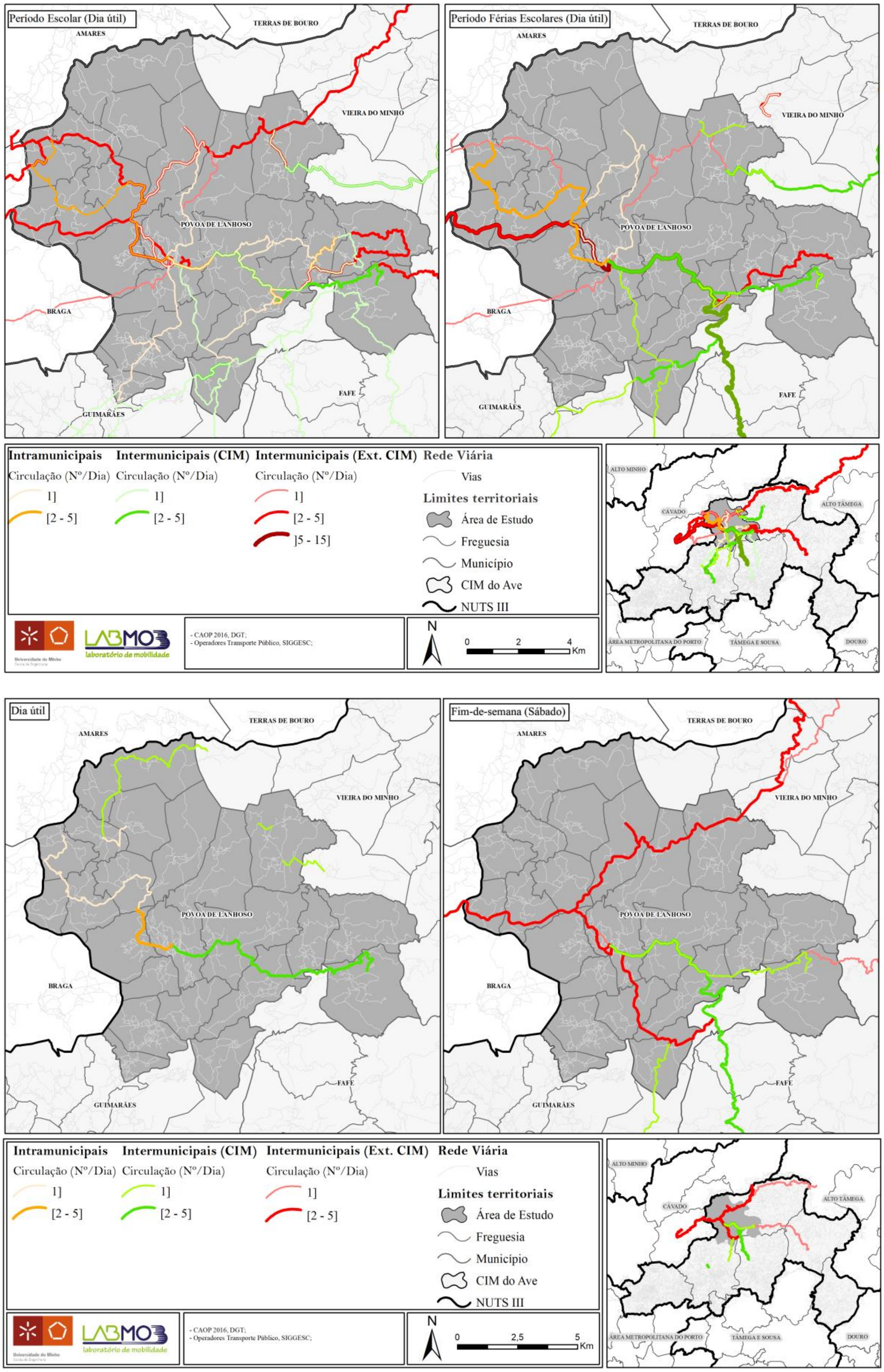
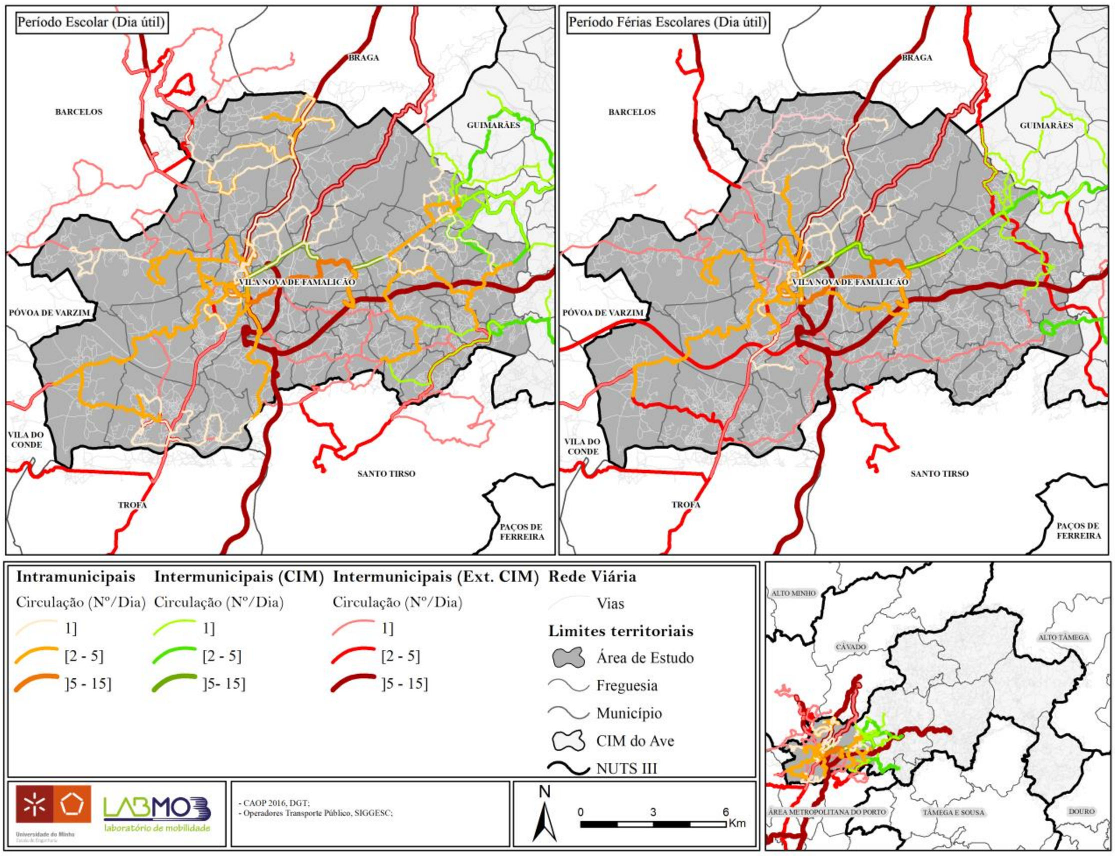


Figure 25 - Frequency of circulations (all operators): Póvoa de Lanhoso



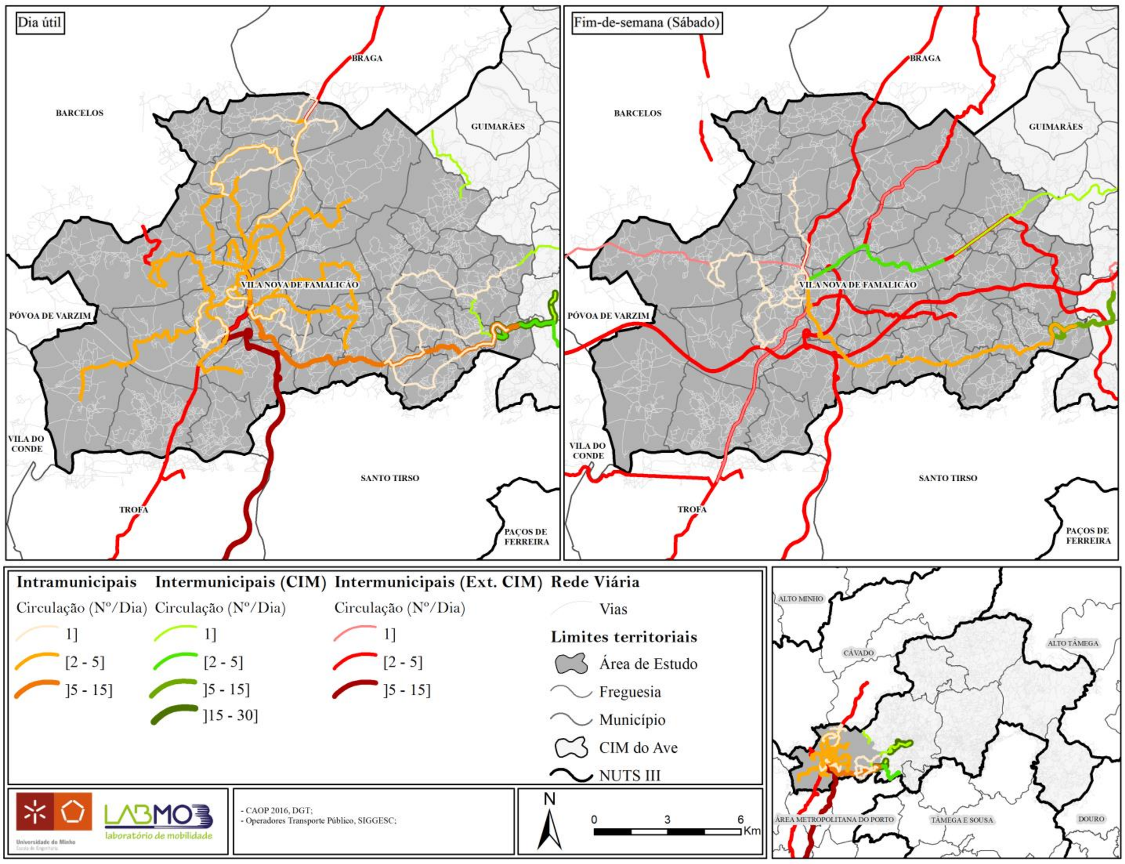


Figure 26 - Frequency of circulations (all operators): Vila Nova de Famalicão

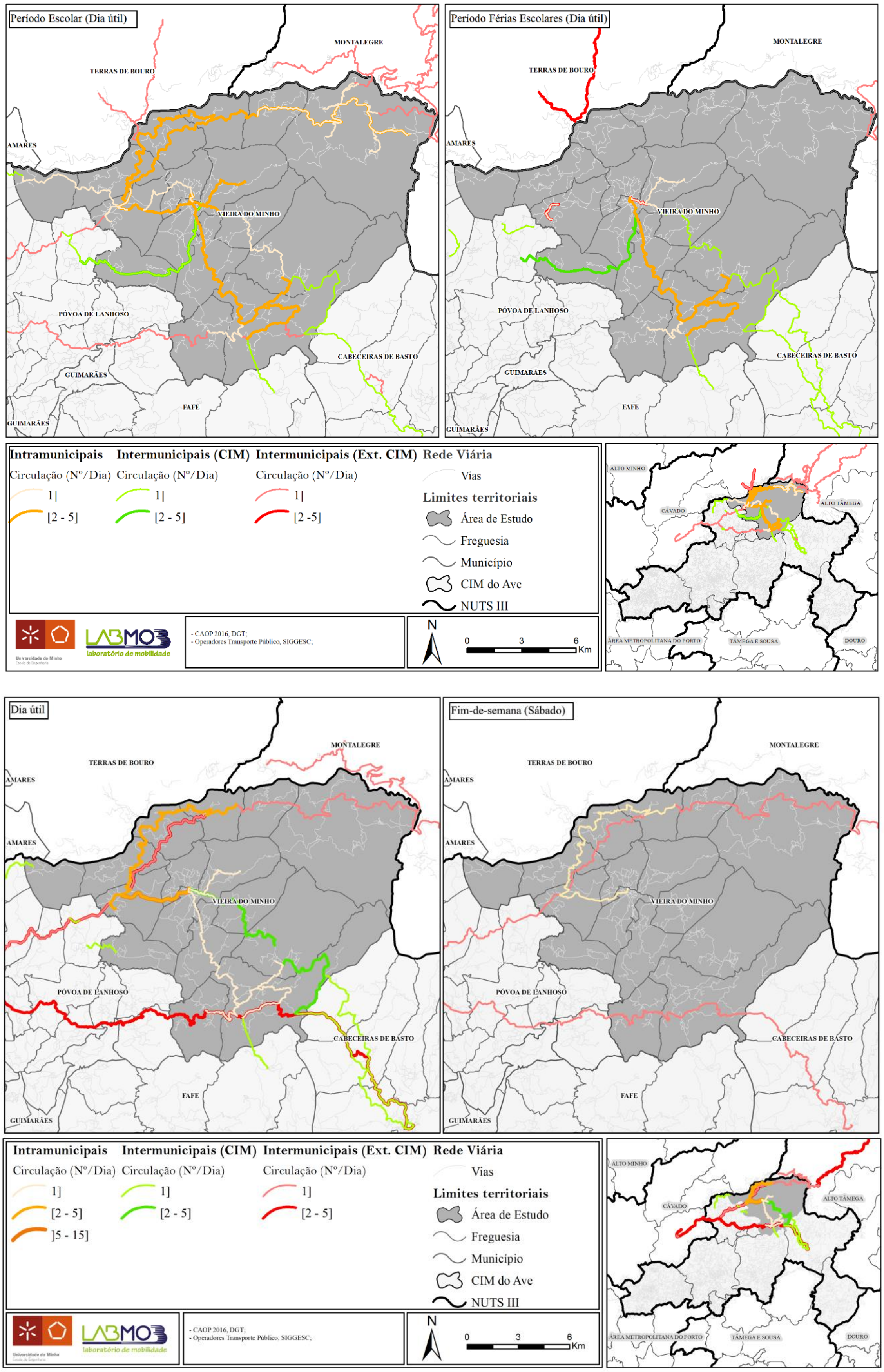


Figure 27 - Frequency of circulations (all operators): Vieira do Minho

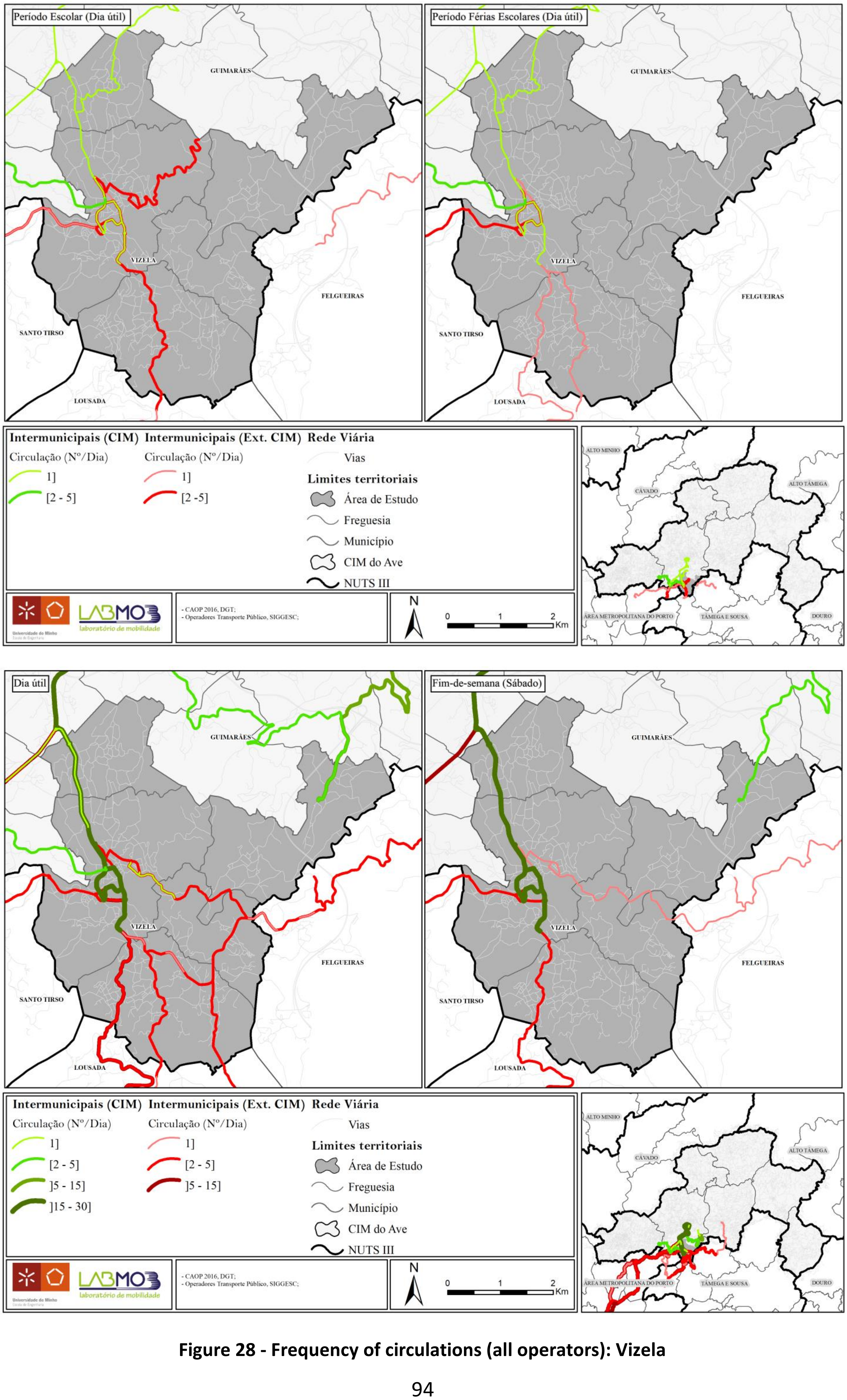


Figure 28 - Frequency of circulations (all operators): Vizela