Urban road congestion in Latin America and the Caribbean:

characteristics, costs, and mitigation

TRANSPORTATION DIVISION

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EXECUTIVE SUMMARY

Congestion is a phenomenon found in most medium and large cities and megacities around the world. Every year, it generates huge **economic, social and environmental losses worldwide. In the European Union, the cost of time spent in traffic congestion in 2016 was estimated at €200 billion, equivalent to 1.4% of the region's GDP** (European Commission, 2020). As for the United States, it has been estimated that, considering the time and overall fuel consumed in congested roads, traffic congestion cost US cities US$151 billion in 2020, which is approximately equivalent to 0.7% of the national GDP. By 2030, these costs are forecast to reach US$186 billion (Cebr, 2014). Congestion is also associated with higher levels of fatigue, anxiety and depression, with variations in road incident rates, and with barriers to the positive effects of urban agglomeration - i.e. in terms of productivity and labor market - ultimately hindering the sustainable development of societies.

Available data for Latin America and the Caribbean (hereinafter, LAC) indicate that cities such as Bogota, Lima, Mexico City and Rio de Janeiro are among the **most congested cities in the world**, with levels similar to those of Mumbai and Bangkok in Asia, and well ahead from some of the most congested cities in the United States (Los Angeles) and the European Union (Dublin) (Tom Tom, 2019). General mobility trends in LAC, which show an increase in motorization rates and a reduction in the use of public transport, combined with the overall growth of urban population, suggest that the levels of congestion currently present in our cities will not go down in the near future (Calatayud and Muñoz, 2020). Moreover, the distrust towards public transportation caused by the COVID-19 pandemic could **lead to an increase in the use of private vehicles**. Signs of this shift can already be seen in cities such as Shanghai and Madrid. In the latter case, public transportation went from being the most used mode of transportation before the pandemic to being the third (25% of trips), after private vehicles (44%) and active transportation (32%) (El País, 2020).

Despite the relevance of this issue in LAC, **studies on urban traffic congestion and its costs for cities are scarce.** The lack of recent evidence on the characteristics and the economic impact of congestion in the cities of the LAC region, including local and regional perspectives, limits the understanding of the scale of this phenomenon and its consequences, as well as the design of effective mitigation measures. While international indices such as TomTom and INRIX are a first positive step towards providing valuable guidance on how some LAC cities currently compare to the rest of the world, the results lack the temporal and geographic granularity necessary to analyze congestion management. Indeed, congestion is a dynamic phenomenon and policy makers need a **comprehensive understanding of its spatial and temporal characteristics** in order to design effective mitigation policies.

In this context, this report offers the first comprehensive analysis carried out in the **region regarding the characteristics and costs of urban congestion,** and provides results for the cities of Bogota (Colombia), Buenos Aires (Argentina), Mexico City (Mexico), Lima (Peru), Montevideo (Uruguay), Rio de Janeiro (Brazil), San Salvador (El Salvador), Santiago (Chile), Santo Domingo (Dominican Republic) and Sao Paulo (Brazil). **Big data and data science** are used to explain the dynamics of congestion in each city and **estimate direct and indirect costs to society.** The aim is to provide more and better information to design public policies. This analysis also lays the foundation for other research agendas to explore, for example, urban efficiency losses due to congestion and the consequences of congestion-related regulations.

In this study, we applied the **approach used in Transportation Engineering** to estimate the level of congestion on a set of urban roads and the related direct and indirect costs. Based on Goodwin's (2004) definition, we can estimate congestion by calculating the additional travel time incurred due to excess traffic on a road segment at a given time, either due to recurrent, non-recurrent or pre-congestion causes. This results in lower speeds than those under free-flow conditions. To calculate delay, we use the information provided by Waze for the 10 above-mentioned cities of the LAC region, including location and speed of traffic jams and free-flow speed for each congested segment for the year 2019. There are more than **10 billion records** in the database. To estimate the road network, we used a **neural network model trained with more than 7,000 road images**, which reports an accuracy of more than 80%. To calculate the monetary cost of congestion, we based our calculations on the literature that defines the **value of time as approximately equal to 50% of the market wage for car travel.** To estimate the cost of congestion on road traffic incidents, we used a **Poisson model in panel data with city fixed effects.**

The results show that, in absolute terms, the cities with the longest delays among the ten analyzed are those with the largest **number of inhabitants**, namely: Sao Paulo (21.8 million inhabitants and 700 million hours lost in 2019) and Mexico City (21.6 million inhabitants and 650 million hours lost). San Salvador, the city with the smallest number of inhabitants among those considered (1.1 million), recorded the lowest number of hours lost due to congestion, reaching 37 million hours in 2019. However, when estimating the **delay per inhabitant and car user**, the positioning of the cities changes significantly. Thus, in 2019, the inhabitants of Montevideo, for example, lost 51% more time in congestion than the inhabitants of Mexico City, even though the population of the Mexican capital is 12 times greater than that of Montevideo. The same is true for San Salvador, where its inhabitants lost 33 hours standing in traffic in 2019, above megacities such as Bogota (31 hours), Rio de Janeiro (25 hours) and Buenos Aires (20 hours). Similarly, if we take into account only private vehicle users rather than the number of inhabitants, Bogota was the city with the highest congestion losses, amounting to 186 hours per user. This figure is almost three times higher than the losses of private vehicle users in Sao Paulo and Mexico City.

The **value of time in each city has an important impact on congestion losses**. For example, while Mexico City lost more than twice as many hours in congestion in 2019 as Buenos Aires (650 million and 305 million hours, respectively), the value of each hour lost in the latter is higher. Consequently, while the cost of congestion equals 0.5% of the GDP in Mexico City, the cost for Buenos Aires amounted to 1.1% of its GDP. The same is true for Santiago (1% of its GDP) compared to Rio de Janeiro (0.9%) and Bogota (0.9%). To get a **proportion** of what these losses represent, by way of example, congestion costs Buenos Aires and Mexico City 1.9 and 2.3 times what local governments invest in education. The direct cost of congestion in Sao Paulo is equivalent to what the city spends on health care.

At the individual level, the cost of congestion per person in 2019 was highest in the cities of Montevideo (US$ 177), Santiago (US$ 156) and Buenos Aires (US$ 112). Considering the **cost per private vehicle user** -people who travel by car on a recurrent basis-, the greatest losses occurred in Montevideo (US$ 474), Santiago (US$ 409) and Bogota (US$ 341). Again, the difference in the value of time explains the lower costs for cities such as San Salvador and Lima, even though delays are longer in these cities. And if we look at how much congestion costs per day, Montevideo and Santiago are the cities with the most discouraging figures: in a working day, drivers lose US$ 1.2 and US$ 1.3 respectively in congestion. This figure is worrisome considering that the median daily wage[1] is US$31 and US$25, respectively, which represents 4% and 5% of the median labor income for each city. Finally, if we compare the time lost in congestion with the number of weekly hours worked per person, we can see that a driver in Bogota, for example, spends the **equivalent of 9%** of the hours worked in congestion. In Lima and Montevideo, these figures correspond to 8% and 6%, respectively.

With regard to the **indirect costs of congestion,** here we analyze their relationship with the **level of traffic incidents** in the selected cities. Our findings suggest that, if the aggregate delay on an average workday were reduced by 10%, then traffic incidents would decrease by 5% in Sao Paulo and Mexico City; 3% in Lima; 2% in Rio de Janeiro, Bogota, Buenos Aires and Santiago; 1% in Santo Domingo; 0.4% in Montevideo; and 0.3% in San Salvador. Particularly, this means that, if congestion in 2019 had been 10% lower, the number of reported traffic incidents would have been reduced by 3.5% on average for the region. This is equivalent to a reduction of more than 73 thousand incidents. The largest proportion of this reduction would have taken place in Mexico City and Sao Paulo, with 26,627 and 23,247 fewer incidents respectively; followed by Bogota (11,000); Lima (4,000); Rio de Janeiro (3,000); Santiago and Buenos Aires (2,000); San Salvador (194); Montevideo (143); Santo Domingo (117).

Once the direct and indirect costs of congestion were estimated, in the last chapter of this publication we include a range of **instruments used** at the international level to achieve better congestion management. These solutions can be grouped into **five categories:** (i) traffic management instruments; (ii) policies that restrict the use of private vehicles; (iii) policies that promote the use of public transportation, active transportation and shared transportation; (iv) integrated mobility and land use planning; and (v) policies for urban logistics management.

1. The median wage has been calculated as the median labor income of employed people-according to the ILO definition- with data from INE-Uruguay, INE-Chile and ILO.

It is important to emphasize that, for congestion reduction initiatives to be successful, they must be applied within a **comprehensive framework** that, on the one hand, promotes the improvement of alternative modes of transportation to the private vehicle and, on the other, discourages the use of cars. In particular, these measures must be contained in an integrated land use and transportation plan that promotes more sustainable and resilient cities, focused on moving people, not vehicles. To this end, it is important to plan cities using a systemic approach that generates greater accessibility to job, health and education opportunities, based on mixed land uses and an integrated and efficient transportation network.

Likewise, the level of acceptance and effectiveness of such measures will depend on their **proper sequencing**. International experience shows that improving the quality, accessibility and flexibility of the public and active transportation system is key to providing an efficient and reliable service that attracts trips once made by car. Thus, quality improvement should begin prior to the implementation of measures such as road pricing and continue in parallel to it, now leveraged on resources from road pricing and operational improvements in public transport, facilitated by the lower number of vehicles on the streets. In general, the paradigm that the use of road infrastructure —including parking spaces, loading and unloading bays, curbs and streets themselves— is free of charge must be changed. In contrast, infrastructure is a service that must be paid for through tariffs that cover the costs of providing such service and reflect its value to users (Calatayud and Muñoz, 2020). By allocating tariff revenues to the improvement of public transportation systems, equity in resource allocation would also be improved: eliminating subsidies for higher income private car users and directing those resources to improving the quality of the public transportation, most frequently used by the lower income population. Another aspect to consider is the pace of implementation of **piloting solutions** prior to full-scale adoption. This can help increase citizens' awareness of the benefits provided by the measures implemented and help public policy makers to take the necessary steps to adapt the approach to increase the effectiveness of such measures.

Finally, given that urban space, especially in the case of large cities and megacities, often includes more than one level of government, **coordination between** planning and mobility **agencies** at all levels is critical for developing and implementing comprehensive land use and transportation plans that are effective in increasing sustainability and reducing levels of road congestion. This objective also requires coordination with agencies outside the transportation sector. Fuel and car purchase subsidy policies are examples of some of the measures external to the sector that encourage motorization and generate unfair competition for public and active transportation, to the detriment of a more globally efficient and environmentally sustainable mobility.

INTRODUCTION

Congestion is a phenomenon found in most medium and large cities and megacities around the world. Every year, it generates huge economic, social, and environmental losses worldwide. In the European Union, the cost of the time spent in traffic in 2016 was estimated at €200 billion, equivalent to 1.4% of the region's GDP (European Commission, 2020). Likewise, estimates of the direct costs of traffic jams in the United States for 2020, taking into account total time and fuel lost, amount to US$151 billion, approximately 0.7% of US GDP. By 2030, these costs are forecast to reach US$186 billion (Cebr, 2014). Congestion is also associated with higher levels of fatigue, anxiety, and depression, with variations in road accident rates, and with barriers to the positive effects of urban agglomeration —i.e., in terms of productivity and labor market—, ultimately hindering the sustainable development of societies.

Available data for Latin America and the Caribbean (hereinafter, LAC) indicate that cities such as Bogota, Lima, Mexico City, and Rio de Janeiro are among the most congested cities in the world, with levels similar to those of Mumbai and Bangkok in Asia, and with much higher levels than the most congested cities in the United States (Los Angeles) and the European Union (Dublin) (TomTom, 2019). General mobility trends in LAC, with increasing motorization rates and a reduction in the use of public transport, together with the population growth in urban areas, do not suggest that the levels of congestion currently present in our cities will be reversed in the near future (Calatayud and Muñoz, 2020). Moreover, the distrust towards public transportation caused by the COVID-19 pandemic could lead to an increase in the use of private vehicles. Signs of this modal shift can already be seen in cities such as Shanghai and Madrid. In the latter case, this mode of transportation went from being the most used mode before the pandemic to being the third (25% of trips), after private vehicles (44%) and active transportation (32%) (El País, 2020).

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This document is organized into five chapters. Chapter 1 answers the following questions: What is congestion and what causes it? Why is it interesting from a public policy point of view? How widespread is the use of private cars in the region and what are the future trends? Chapter 2 details the methodology used to calculate road congestion in the cities examined and its direct and indirect costs. Chapter 3 shows the results on the spatial and temporal characteristics of traffic congestion in the ten cities examined, the monetary costs involved and the costs in terms of road incidents. Chapter 4 includes specific cases of urban congestion related to economic, social, cultural and essential activities. Finally, Chapter 5 provides international solutions and best practices, which comprise a range of policy instruments that LAC policy makers can use to improve congestion management and reduce congestion costs.

This study used data provided by Waze through its Waze for Cities program (https://www.waze.com/ccp). The authors would like to thank Waze for providing and allowing the analysis of said data. They are also particularly grateful for the inputs provided to the development of the methodology used by Ignacio Cerrato and Xioayu Wang of the Technology Department of the Inter-American Development Bank (IDB), the inputs provided to Chapter 5 by Amado Crotte of the Transport Division of the IDB, and the valuable feedback on previous versions of this document and derivative articles received from Tomás Serebrisky, Alex Riobo, Oscar Mitnik, Joao Carabetta, Cristian Navas, Manuel Rodríguez, Rodrigo Rendón and Rafael Capristán (IDB), Andrés Gómez-Lobo (Universidad de Chile), Alan Thomas (Universidad Católica de Chile), Florencia Visciglia and Andrés Meiss (Department of Transportation of the city of Buenos Aires) and anonymous reviewers and participants of the 100th Annual Meeting of the Transportation Research Board of the National Academy of Sciences of the United States. Graphical editing was carried out by Valmore Castillo.

Chapter 1.

THE RELEVANCE OF TRAFFIC CONGESTION

01

What is congestion, and what causes it? Why is it interesting from a public policy point of view? How widespread is the use of private vehicles in the region, and what are the future trends? This first chapter will provide answers to these questions, and it will serve as the starting point to undertake a detailed study of congestion in LAC cities.

1.1 What is congestion?

Even though the word **congestion** is frequently used in the field of transportation, both in general publications and in specialized literature, there is no single agreed definition of this term. The differences can be attributed to the fact that the term can be used in different contexts, such as port, urban and interurban congestion. In this report, we will refer only to road congestion in the urban environment, adopting the definition stipulated by Goodwin (2004):

> ***"Congestion is defined as the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity"***

The disciplines of Transportation Engineering and Economics have developed different approaches to assess the extent of urban road congestion. **Transportation Engineering** defines congestion as the situation where "traffic demand exceeds maximum sustainable throughput of the link" (DMRB, 1997). Consequently, traffic flow is disrupted, the average speed decreases, its variability increases, and, as the maximum sustainable flow rates are exceeded, queues start to form on the link. Depending on its predictability and duration, congestion can take three forms, which have been outlined by Brownfield et al. (2003) and Grant-Muller & Laird (2007) as follows:

- Recurrent congestion: It occurs at regular times at fixed locations, for example, during peak hours. It can be easily anticipated by road users that generally travel in the same route.
- Non-recurrent congestion: It occurs at non-regular times at a site and, therefore, it cannot be predicted by road users. A good example of this is traffic congestion caused by road incidents.
- Pre-congestion state: It occurs where free-flow conditions break down, but complete congestion has not yet occurred. This form may happen at the beginning or end of the time when congestion occurs. It can also occur between periods of congestion, due to fluctuations in vehicle movement and speed, depending on the type of traffic jam.

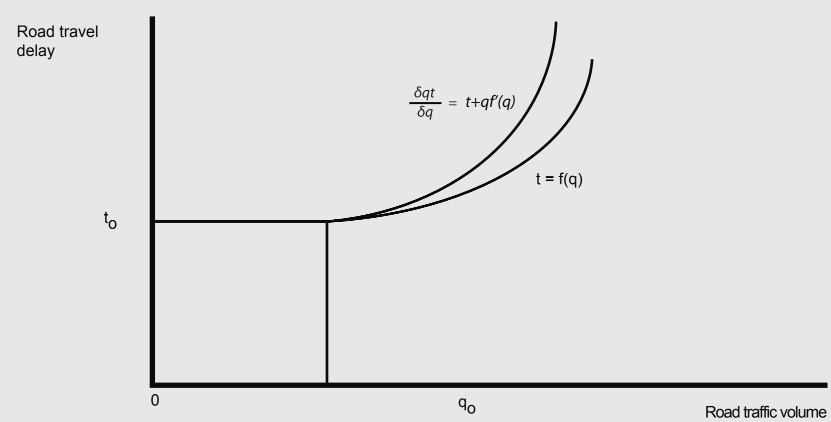
From the Transportation Engineering approach —which is far more widespread in the literature—, congestion can be measured according to **observable roadways performance features** such as speed, flow, density, queue length,

and duration. A technically "optimal" performance of a specific roadway can be determined based on these features (World Bank, 2013). Next, factual information collected is compared with said optimal roadway performance to establish and monitor the level of service provided to users. This method of estimating congestion levels is used by numerous transportation agencies, including the US Department of Transportation's Federal Highway Administration (FHWA), the European Commission, and the OECD, amongst others[2].

One of the aspects that has been mainly discussed in the literature is the definition of optimal flow. Although there has been a general tendency to use the maximum speed allowed in a roadway, this has recently begun to be questioned, particularly concerning urban areas. Indeed, in large cities and areas with a high concentration of economic activities, it is unreasonable to think that the maximum speed limit can be reached (see the discussion presented by Goodwin, 2004, and Wallis & Lupton, 2013). In this context, using the maximum speed as a benchmark speed may unintentionally bias congestion management policies, with targets that would be impossible to achieve in practice. Recent studies have sought to circumvent this problem by using speeds obtained during off-peak times as a reference. Another option indicated in the literature is to use speeds considered "normal" or "expected" depending on the particular road type, even when this may make it difficult to compare service levels between different cities or regions (Kriger et al., 2007).

The field of **Transportation Economics** understands congestion as an externality associated to traffic demand, arguing that its implications should be examined under the basic principle of marginal cost. Pigou (1920) was the first to theoretically estimate the cost of congestion from this point of view. To do this, he used as an example the case of two roads with different numbers of cars driving on each road. Every additional car entering would have a differentiated effect on the time it takes all incumbent drivers to complete a specific section of the road. Numerous academic papers have sought to estimate Pigou's early approaches quantitatively in order to demonstrate the need to use taxes to internalize congestion costs. Among them, the one published by Bull & Thomson (2002) should be highlighted. They used the following figure to graphically represent **congestion as an externality**.

Figure 1.1 Graphic representation of congestion as an externality



Source: Taken from Bull & Thomson (2002).

Where function $t=f(q)$ refers to the average time required to transit a road and depends on the number of vehicles (q). The second function, $\frac{\delta qt}{\delta q}=t+qf'(q)$ derives from the first function. In other words, the first function represents the average time cost and the second one, the marginal cost. The difference between these two functions -regardless of

2. Based on the seminal study carried out by Vickery, different ways of estimating congestion have emerged using static or dynamic models and considering different traffic scenarios (for more details, see Vickery, 2019).

the number of vehicles (q)- is equal to the increase in travel time for all vehicles when one additional vehicle is added to the flow. It must be observed that both curves coincide along segment Oq_0 which means that adding a new vehicle to the traffic flow does not slow down the rest of the vehicles already on the road. However, from there onwards, both curves diverge, with $\frac{\delta qt}{\delta q}$ running above t. It implies that an additional vehicle not only imposes an extra delay on itself but it also affects journey times for the rest of the vehicles. Thus, the new vehicle entering the traffic flow only assumes part of the traffic congestion it causes, while the rest is assumed by the rest of the vehicles already on the road. In this scenario, the economic literature suggests that a taxation scheme should be implemented to internalize the marginal cost to society generated by the new vehicle. In Chapter 5 of this report we will address this issue in greater detail.

Despite the substantial theoretical development of this matter, measuring congestion in practice from this point of view has proven challenging by requiring data that is not easy to obtain by public agencies. Indeed, to identify that efficiency level -that is, the level of congestion that is "optimal" from an economic point of view- we must obtain the travel demand function from information provided by vehicle users themselves, usually gathered through surveys. The cost and effort involved in collecting such data make this approach impractical —currently— for measuring and monitoring congestion regularly, particularly in urban areas where multiple roads under different conditions must be considered. Another objection to this approach is that econometric estimates may be easily affected by biased parameters due to the double causality between speed and traffic flow, leading to biased estimates for policymaking (Yang et al., 2020). Consequently, given the advantages offered by the approach used in Transportation Engineering, such as the availability of information, simplicity of estimation, and easy monitoring, it is not surprising that agencies in the field have chosen to use metrics derived from this approach.

Among them, the most common metric is the **aggregate delay index**, calculated by adding the total time lost on a road segment by all vehicles affected by the excess traffic. Apart from being easy to estimate and monitor, the added advantage is that this measure may show the effects of an intervention on a particular road segment, report the result of the cost-benefit analysis of an intervention, and allow the comparison between different road segments or links. In the following section, we will discuss the importance of using these types of indicators to monitor and evaluate congestion in urban areas, thus allowing appropriate actions to be designed to mitigate traffic congestion.

1.2 Why is traffic congestion important?

Urban congestion has **direct and indirect costs** for individuals and cities. For US cities, for example, the total direct cost has been estimated at US$151.2 billion in 2020, and it is expected to reach US$186.2 billion by 2030. As for the European Union, in Germany, costs are expected to reach US$37.3 billion in 2020, followed by France and the United Kingdom (US$25.4 billion each), and the forecast for 2030 stands at US$43.8 billion in Germany, US$33.4 billion in the United Kingdom and US$29.6 billion in France (Cebr, 2014). Some of the factors that explain congestion levels in these countries are the territorial concentration in urban centers of economic activity, the large number of trips by private vehicles, and the high population density (Cebr, 2014). Regarding the first factor: half of US GDP is created in a handful of cities representing only 1.5% of the national territory.

Similarly, the main urban areas in the United Kingdom, which barely cover 7% of the territory, produce 39% of this country's GDP (Kirk, 2014; UKNEA, 2011; USCM, 2014). Simultaneously, cars are involved in 73% of daily urban trips in France, 69% in the USA, 68% in the United Kingdom, and 67% in Germany. Finally, the population density in the main cities of these countries should be taken into account. Paris, for example, has 53,000 inhabitants per square mile, New York has 27,000, and London, 13,200.

The direct cost of congestion is **the time lost on a congested road**, which could be spent on other activities. From the perspective of cities, this time implies a loss of production and productivity. It is usually estimated by multiplying the total estimated time lost in traffic and the estimated subjective value of time (VoT) for individuals in a given city (Parry & Small, 2009; Small et al., 2007; Yang et al., 2020).

Urban congestion is also associated with a set of negative externalities or indirect costs that affect individuals and cities in different ways and ultimately impede societies' sustainable development. On the one hand, congestion is an **obstacle for the Wider Economic Impacts (WEI)** caused by mobility, arising from the so-called agglomeration economies. As shown by the studies carried out by Duranton & Puga (2004) and Venables (2007), the clustering of economic activities positively impacts productivity, increasing the size of labor markets, knowledge interactions, specialization, and the sharing of inputs and outputs. The model developed by Venables (2007), which focuses on inter-urban transportation, concluded that greater productivity, achieved thanks to a reduction in the costs of commuting to the city center, generates wage gains for all workers and other 'wider impacts' not captured in traditional CBA calculations. Congestion, on the contrary, increases the daily costs of traveling to the main manufacturing areas of the city and is therefore detrimental to these benefits. On the other hand, urban congestion causes **adverse health effects** on individuals (Crotte et al., 2018). According to a study carried out by Wang et al. (2019) in 11 Latin American cities in 2016, ten additional minutes of commuting time due to congestion is associated with a 0.8% higher chance of suffering from depression. This probability is higher than the one resulting from travel delays due to other causes (0.5%). Likewise, this study found that private vehicle users are 4.8% more likely of suffering from depression than public transportation users. Higher levels of fatigue, alterations to social behavior (more aggressiveness, for example), communication difficulties, and sleep disruption are also associated with long-term and short-term effects on health (World Health Organization, 2007).

Congestion is also associated with variations in the **incident rate** and the severity of registered cases. Previous studies have shown mixed results on these effects depending on the type of road analyzed. The results showed that the accident rate for highways in congested conditions was near twice the rate in uncongested conditions, while the accident rate for two-wheeled motor vehicles was more than seven times that rate. However, recent evidence suggests that the relationship between congestion and incidents is U-shaped. The lowest and highest speeds are more likely to be involved in incidents than those driving at medium speeds (Retallack & Ostendorf, 2019). Finally, congestion **affects pollution levels** due to the emissions arising from the increase in fossil fuel consumption. For instance, the study carried out by Barth & Boriboonsomsin (2008) in California suggests that by increasing the average speed in Southern California roads by 20 mph, CO_2 emissions could be reduced by approximately 21 metric tons (12%)[3].

Due to the negative impact of congestion on the quality of life in cities, its appropriate monitoring using performance metrics is critical, enabling more efficient policy decisions that improve the performance of the transportation system and, as a result, increase the wellbeing of its users. With particular reference to the transportation system, the United States Federal Highway Administration has identified the following **advantages of monitoring congestion** by government agencies (US Department of Transportation, 2012):

- It improves communication with users: Performance measurements, including travel time, delays, or other concepts that are easy to understand, may provide better ways of informing about the conditions of the system and facilitating the implementation of public policies to mitigate congestion.
- It improves the performance of the transportation system: Transportation operators may use congestion metrics to modify the time or the characteristics of their operations, thus enhancing the quality of the services offered.
- It provides information on public policy design: Performance measurement and a program for data collection before and after implementing actions aimed at reducing congestion may be very effective in monitoring implementation progress, correcting the course of action when facing potential policy deviations, and identifying the impact of such actions.

3. Other studies have also shown that very high speeds increase fuel consumption and emissions (see Asensio et al., 2014), which is why, there usually is a U-shaped relationship between speed and its effect on emissions: the slowest speeds and the highest speeds generate more emissions than medium speeds.

- It improves access to funding for the transportation system: Congestion monitoring may be used to show conditions that allow the implementation of policies such as congestion charges, with the double aim of reducing congestion levels in a particular urban area while also obtaining resources to improve the transportation system (See Chapter 5).

1.3 Determinants of traffic congestion

Urban congestion is caused by different factors, which, according to the literature, can be divided into two categories: **micro-level and macro-level factors** (OECD, 2007). The first group includes those factors strictly related to traffic flow in a road, such as traffic signals, traffic circles, intersections, incidents, and weather events, among others. On the other hand, macro-level factors relate to the reasons why some roads are more heavily used than others and depend on, for example, land use patterns, business locations, motorization rates, and regional dynamics in general. Indeed, as mentioned previously in the cases of the USA and Europe, the clustering of economic activities in some urban regions —intrinsic to city dynamics— leads to an influx of people and goods to cities and, therefore, to an overuse of the installed road infrastructure to a certain extent. In these areas, achieving speeds similar to those under free-flow conditions would be unrealistic. However, the literature agrees that, when the use of the transportation system reaches its maximum capacity and vehicles mutually obstruct traffic, the positive effects of the clustering of economic and social activities are generally canceled, and actions to manage traffic demand in the affected areas are required (OCDE/ITF, 2007; VTPI, 2020).

With special reference to LAC, the reasons behind an increase in urban congestion may be found in macro-level factors related to **structural aspects** —outside the transportation sector— in the cities of this region, as well as **operational, institutional and infrastructure-related aspects**, which adversely affect the provision of quality public transportation services and encourage the use of private vehicles.

First, it should be noted that the **rapid increase in urbanization rates,** which, together with the lack of efficient land-use planning, has created significant challenges for urban mobility. Between 1950 and 2015, the urban population in LAC went from 41.3% to 80% of the total population and is expected to reach 90% by 2050 (BID, 2020b). In parallel, the cities of the region have experienced **a process of territorial expansion** characterized by low population density, and which has been the result of the search for lower housing prices and the formation and/or expansion of informal settlements in peripheral urban areas[4]. In general, this process has not been accompanied by integrated land use planning and transportation services. As a result, the peripheral areas are inadequately connected by public transportation networks, while the low population density in these areas makes the operation of transportation services unprofitable. All this has resulted in greater use of private vehicles.

Second, the provision of **road infrastructure** in LAC cities and the setting of priorities regarding its use have favored individual modes of transportation over public and active transportation. According to the latest data available, the road network of the 29 largest metropolitan areas of LAC is made up of 277,000 km of roads, of which less than 1% is for the exclusive use of the public transportation system and 1.2% for cyclists (Estupiñan et al., 2018)[5]. The unbalanced road space allocation is even more apparent when considering that public and active transportation accounts for about 70% of daily trips (Vasconcellos & Mendonça, 2016).

Third, recent data show that the **quality of public transportation services** in the region is significantly lower than in other regions, which leads to a lower use of the system. Deficiencies have been found regarding transportation fleet, accessibility, interoperability, reliability, availability of services, and passenger safety (Rodríguez et al., 2020). The average age of the surface public transportation fleet is more than 15 years old, reaching in some countries more than 20 years old (compared to 11.4 years in Europe). An aging fleet affects users' perceived level of comfort and safety,

4. The annual rate of territorial expansion of cities (4%) is double the population growth (1.9%) (BID, 2016b). Nearly 25% of the population of LAC live in the suburbs, with limited access to basic services (AfDB et al., 2019).
5. New York, for example, has more than 600 kilometers of bicycle lanes, which makes it the first city in the world ranking in this regard (McKinsey, 2018).

while also reducing the operational efficiency of the units (e.g., due to increased fuel consumption, emissions, and maintenance) (BID, 2016a). The **accessibility to transportation modes**[6] provided by the system is also reduced due to the above-mentioned territorial expansion experienced, the low population density and the high presence of informal settlements. Besides, the **interoperability** of passenger transportation services is limited, which affects not only user convenience, but also the possibility of improving the overall efficiency of the urban transportation system. At the same time, the low availability and reliability of services result in longer travel times[7]. The region has an average waiting time of 18.7 minutes (higher than in Europe and the United States, with 14.3 and 13.3 minutes respectively), which is one reason for the low user-perceived system reliability (Deloitte, 2019). Likewise, travel time is affected by the increase in the number of transfers: on average, 52.9% of public transportation users in LAC make two transfers during a trip (higher than Europe and the United States, with 47.4% and 42.6%, respectively) (Moovit, 2019). In terms of safety, the high level of physical or verbal violence towards women in public transportation is worrying, reaching 59% of female users in Santiago, 65% in Mexico City, 67% in Quito, and 80% in Buenos Aires (BID, 2018).

Fourth, improving the quality of services would require significant investments, even more than the 1% of the GDP already invested by the largest countries (Mexico, Brazil, and Argentina) and above the 2%-3% of the GDP invested by smaller countries (e.g., Bolivia and Nicaragua) (BID, 2020b). However, investments are now constrained by **public transportation funding and financing challenges.** Some of the causes of these challenges are: (i) accelerated growth and urbanization dynamics, which demand more resources for infrastructure funding; (ii) deficiencies in the financial planning strategy and lack of vision for long-term sustainability; (iii) legal barriers and legal restrictions regarding the amount and type of involvement of public entities regarding funding and financing sources; (iv) lower income[8] and dependence on traditional funding sources which are insufficient to cover operational costs; and (v) inefficiencies in transportation mode pricing and internalization of the costs of transportation externalities, such as congestion, pollution or road incidents (Ariza et al., 2018a).

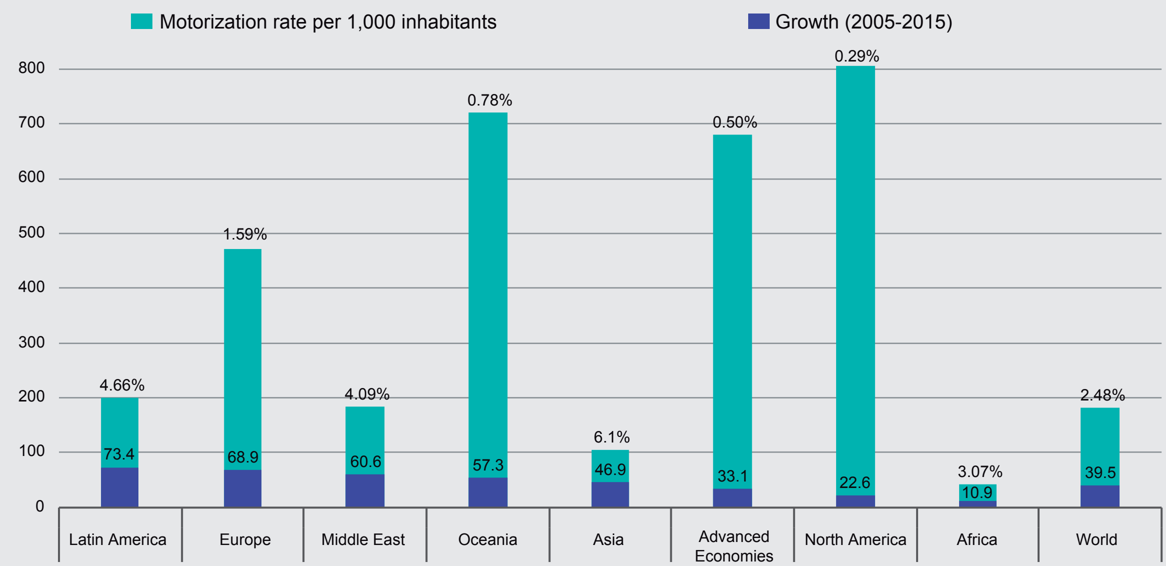
In this context, it is not surprising that motorization rates have increased, while the use of public transportation for urban mobility has dramatically decreased. These facts will be discussed in the next section, where we will analyze mobility patterns in LAC.

1.4 Mobility patterns in LAC

As a result of the trends indicated in the previous section, together with the increase in average income in LAC countries, the region has experienced an **increase in its motorization rate** (Figure 1.2). While the number of vehicles in the region (201 vehicles per 1,000 inhabitants) is below the figures reported by advanced economies such as Europe and the United States (471 and 805 vehicles per 1,000 inhabitants, respectively), the average annual growth rate in LAC over the past 10 years has been higher than in advanced economies (4.7% compared to 0.5%, respectively) (Rivas et al., 2019). Also, the share of private mobility in the total number of trips has increased from 20.6% in the 1990s to 29.1% in the 2010s[9]. The consequence is **lower public transportation use**, whose share has decreased from 50.5% in the 1990s to 35.5% in the 2010s[10] (Rivas et al., 2019) (Figure 1.3). **The increase in the fleet of motorcycles** should also be highlighted, as they offer a more affordable option for private mobility (with a growth of 153% between 2007 and 2014 in the main 29 cities of LAC, reaching 7.2 million units in circulation [Estupiñan et al., 2018]).

6. Accessibility refers to people's overall ability to reach desired services and activities (together called opportunities). In the context of increasing climate deterioration, the additional challenge will be to improve the accessibility provided by the transportation system, while also reducing the level of pollutant emissions. On another note, the term affordability refers to the financial costs of traveling in relation to user income (VTPI, 2020).
7. Although the average distance traveled per trip in LAC is less than the average in advanced economies, travel times are longer (Rivas et al., 2019). In five megacities of the region (Bogota, Buenos Aires, Mexico City, Lima and Sao Paulo), 28.1 million people spend more than 1.5 hours a day traveling, this is equivalent to ten working weeks a year (BID, 2014).
8. Lower levels of income in LAC limit the number of people using public transportation, and lead to greater fare evasion. This modal shift from public transportation to private vehicles and motorcycles leads to a reduction in the number of users, the level of fare income and the availability of resources to improve the quality of services. In addition, the progressive increase in costs and the reduction in the productivity of the transportation system also affect its profitability (Gómez-Lobo & Price, 2020).
9. The opposite happened in Europe: in the same period, the share of private transport went from 37.5% to 29.5%.
10. In contrast, over the same period, the share of public transport in Europe increased by 0.7%.

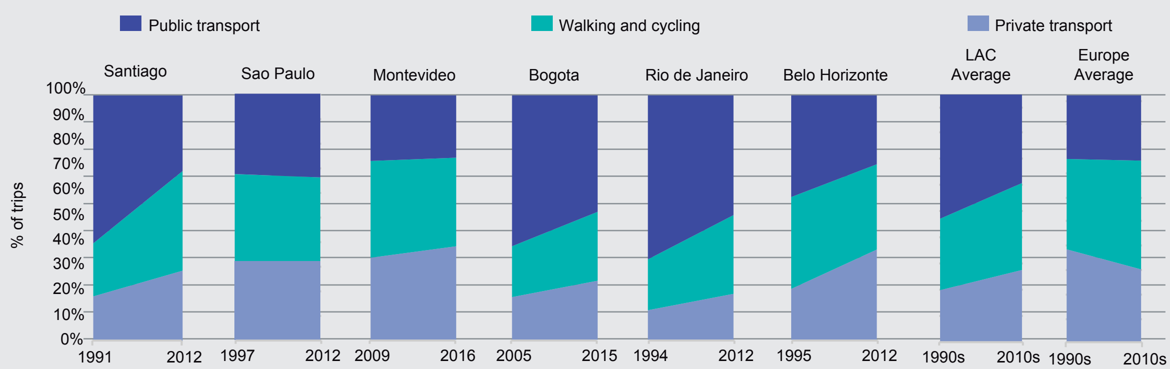
Figure 1.2 Motorization rate per 1,000 inhabitants and its growth (2005-2015)



Note: The dark blue bar represents the absolute growth of the motorization rate between 2000 and 2015. The percentage value above the light red bar, is the annual growth rate of the motorization rate (the average rate at which it has been growing in the last 10 years).

Source: Rivas et al. (2019).

Figure 1.3 Percentage of trips made by mode of transportation (selected cities)

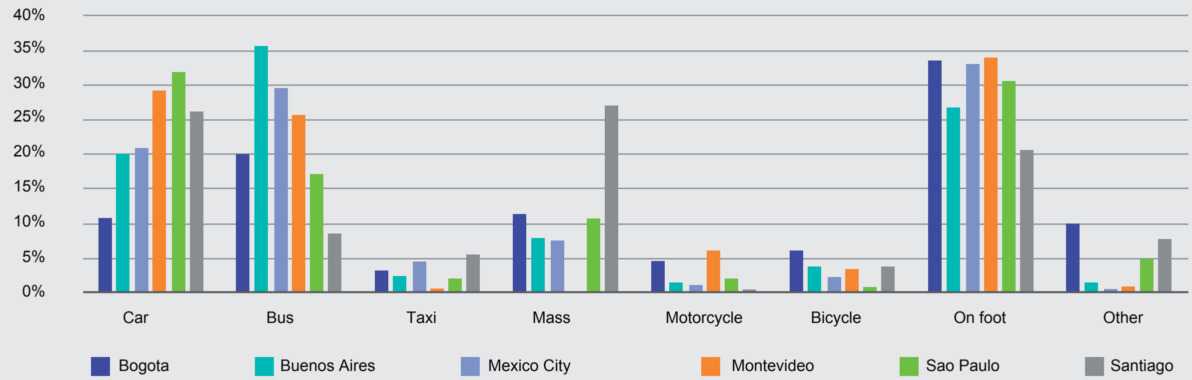


Note: Comparisons between cities are limited by differences in methodologies and timing of surveys. Private transportation includes cars and motorcycles. The cities included in the European average are Stockholm, Hamburg, London, Munich, Berlin, Vienna, Copenhagen, Zürich, Amsterdam, and Paris.

Source: Rivas et al. (2019).

In several cities in the region, including those with extensive public transportation systems, private vehicles represent a significant share of urban trips. Figure 1.4 shows mobility patterns for Bogota, Buenos Aires, Mexico City, Montevideo, Santiago, and Sao Paulo, according to the latest origin-destination surveys (ODS) available. Private vehicles are the second most used mode of transportation in Santiago (accounting for 26.2% of the total number of trips on a typical day) and Montevideo (29.2%), and the most used in Sao Paulo (31.8%) (Figure 1.4).

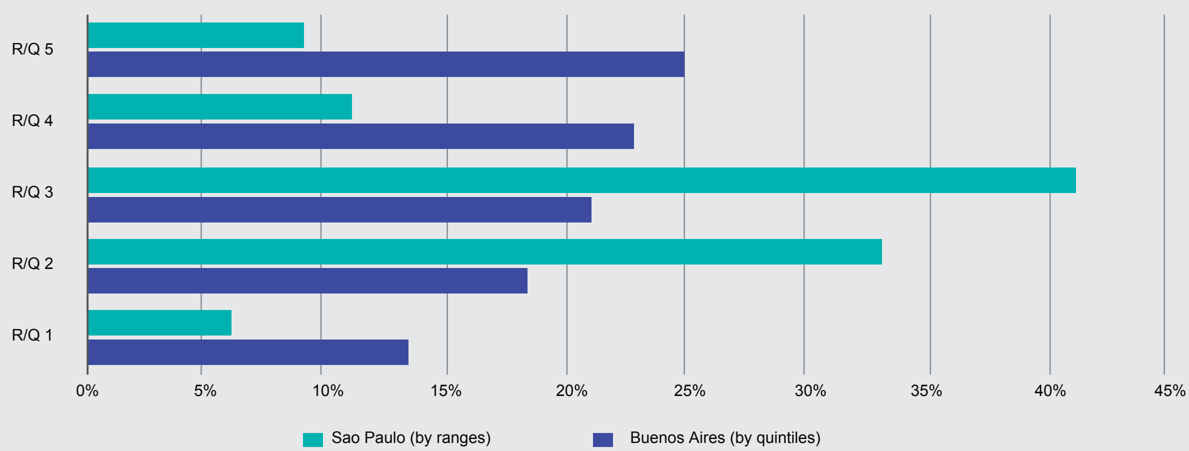
Figure 1.4 Modal distribution on a typical day in selected cities



Source: ODS of the corresponding cities.

The ODSs carried out by the cities of the region help identify **the characteristics of private vehicle users**. First, there is a direct and positive relationship with the socioeconomic status of users. In Sao Paulo, a large percentage of car-using households report monthly household incomes in the range of R$ 3,816 to R$ 7,632 (approximately US$ 681 to US$ 1,363, at an exchange rate of 5.6 R$/US$). When analyzing the distribution by quintiles, as in the case of Buenos Aires, it can be observed that the higher the quintile of income, the greater the use of private vehicles. In total, 25% of users in Buenos Aires are part of the last quintile (Figure 1.5).

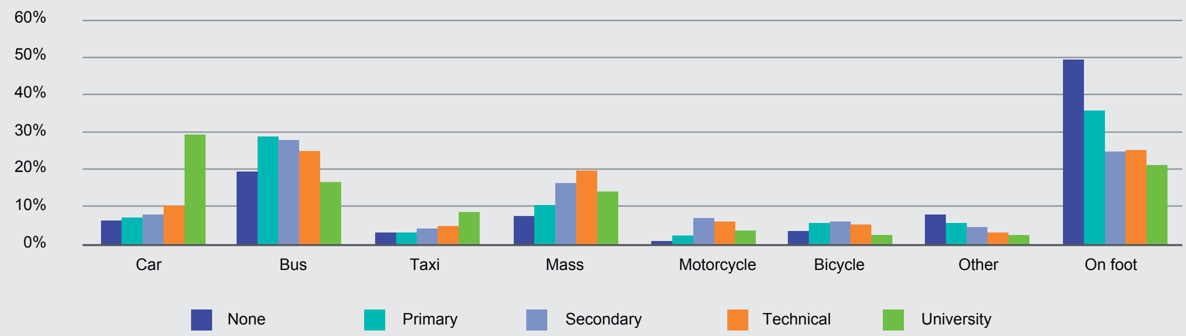
Figure 1.5 Percentage of private vehicle users by range or quintile of household income



Notes: Own preparation based on ODS. The first range and quintile correspond to the lowest level. Monthly household income ranges in Sao Paulo are: 1) up to R$1,908; 2) from R$1,908 to R$3,816; 3) from R$3,816 to R$7,632; 4) from R$7,632 to R$11,448; and 5) above R$11,448.)

The direct and positive relationship can also be observed concerning the **level of schooling**. In Bogota, for example, about 30% of individuals with a university degree use a private vehicle, while only 15% use bus services and 13% use mass public transportation (Figure 1.6).

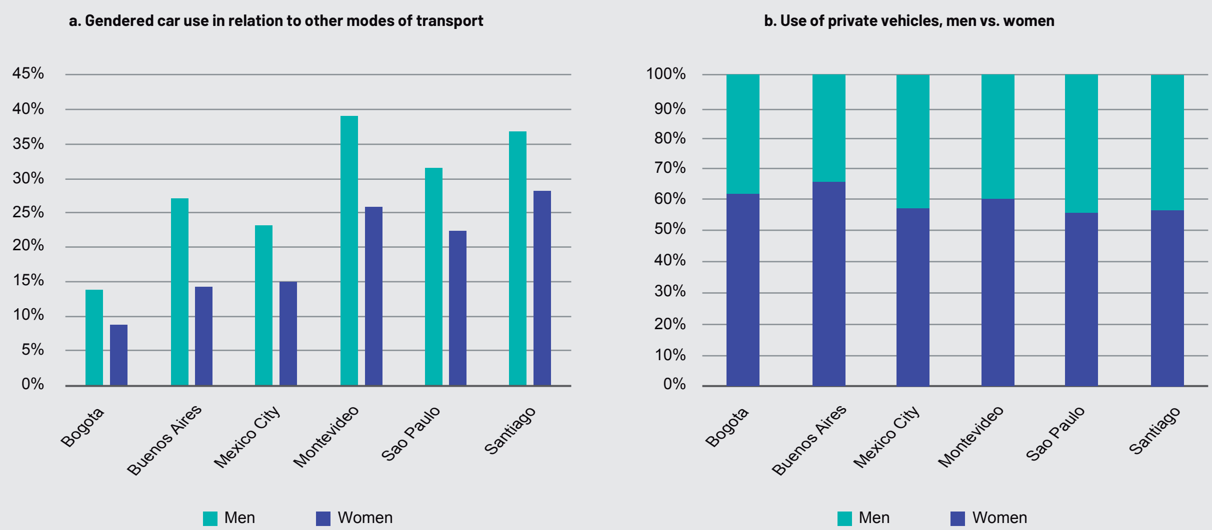
Figure 1.6 Mode distribution in Bogota according to the level of schooling



Source: 2016 Origin-Destination Survey.

Gender distribution is also an essential aspect of private vehicle usage patterns. To a greater extent, men are more likely to use this mode of transportation (Figure 1.7-a). Among the cities considered, the most significant disparities are observed in Buenos Aires and Bogota. In the first case, 66% of private vehicle users are men, and 34% are women. In the second, the percentages are 61% and 39% respectively. It should be noted, however, that in Santiago and Sao Paulo gender distribution among users is more equitable (Figure 1.7).

Figure 1.7 Use of private vehicles according to gender



In terms of age, men often stop driving later than women. Among men, the highest median ages are found in Montevideo and Sao Paulo (43 years old) and the lowest in Buenos Aires and Mexico (41 years old). Buenos Aires has the most significant age dispersion concerning car users, while in Mexico and Bogota, the distribution is more consistent (Table 1.1). For women, the median age is about two years lower than for men in all cities, although variability follows a very similar pattern.

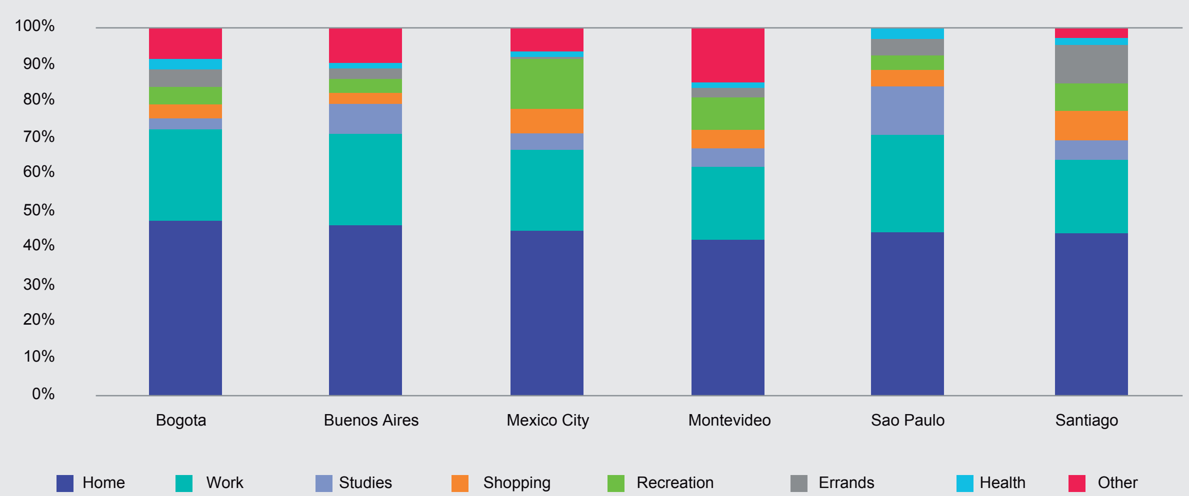
Table 1.1 Age of private vehicle users

City	Men	Women
Bogota	43	40
	(16.1)	(17.4)
Buenos Aires	41	37
	(33.3)	(27.4)
Mexico City	41	39
	(17.0)	(17.7)
Montevideo	43	40
	(17.9)	(18.2)
Sao Paulo	43	42
	(18.5)	(18.9)
Santiago	42	39
	(18.7)	(18.9)

Note: Median age outside parentheses and standard deviation in parentheses.

In all the cities analyzed, returning home and traveling to work were the main **motives for using private vehicles**. There is considerable variability in the rest of the activities that follow in order of importance. For example, for Sao Paulo and Buenos Aires, the following principal reason is education (13% and 8%, respectively); while in Mexico City, recreation and shopping follow next (9%); and in Santiago, running errands is also one of the main reasons (11%) (Figure 1.8).

Figure 1.8 Reasons for traveling by car



Source: ODS of the corresponding cities.

Finally, Table 1.2 provides an overview of the characteristics of private vehicle trips in selected cities in the region. Sao Paulo is the city where the most kilometers are covered on a typical day and where the highest number of trips are made by private vehicle, which is linked to the size of the city and its number of inhabitants. However, if the distance traveled by private vehicle is considered as the proportion to the distance traveled in all modes of transportation, Sao Paulo (28.86% of the total) is surpassed by Montevideo (39.04%) and Santiago (34.4%). Likewise, if we look at the average daily kilometers traveled per vehicle, Sao Paulo (5.67 VKT per day) falls behind Mexico City (9.94) and Santiago (6.46).

Table 1.2 Characteristics of daily travel in private vehicle (selected cities)

City	Bogota	Mexico City	Montevideo	Sao Paulo	Santiago
Total VKT	6,749,278	43,727,144	6,790,502	64,310,624	28,836,933
VKT/Total Distance	12.83%	23.65%	39.04%	28.86%	34.44%
Number of car trips	1,420,231	4,399,571	1,243,052	11,341,237	4,462,071
Average VKT per vehicle	4.75	9.94	5.46	5.67	6.46
Maximum travel distance (km)	48.39	76.52	50.13	76.86	74.34

Note: Only trips that start and end within the metropolitan area have been taken into consideration. VKT refers to kilometers traveled by car. Total distance refers to the distance traveled in all modes on a typical day.

Source: ODS of the corresponding cities.

What is the outlook for the region in light of the COVID-19 pandemic? The use of private vehicles will continue to increase in LAC. Studies carried out before the pandemic already predicted that motorization rates would increase by almost 40% by 2030, reaching 276 vehicles per 1,000 inhabitants (BID, 2020b). This trend could be exacerbated when considering the impact of the pandemic on urban mobility preferences. Data from China show that, after the lockdown, a significant group of people who previously used public transportation shifted to other modes of transportation (ITDP, 2020). The share of the metro in the total number of journeys dropped by 12 percentage points while the bus share dropped by more than seven percentage points. For the most part, passengers chose to travel in private vehicles, crystallizing the loss of confidence in public transportation due to the fear of contracting the virus. In this scenario, together with the population growth (a 9% increase by 2030) and the territorial expansion of cities, congestion in the region is expected to increase rapidly.

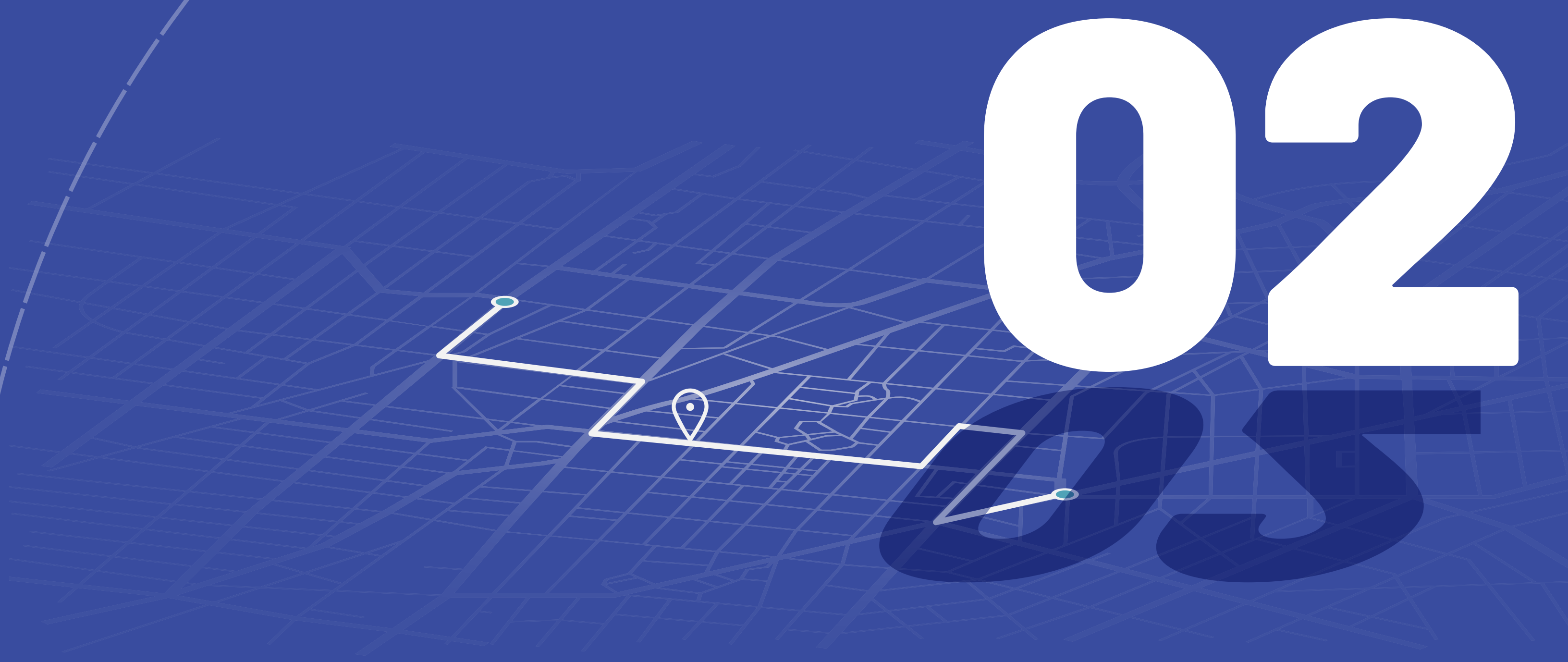
Despite the relevance of this issue in LAC, studies on urban traffic congestion and its costs for cities are scarce. From the literature review carried out, it is worth noting the study carried out by Bull & Thomson (2002), who analyzed the time spent in traffic for cities with more than 100,000 inhabitants and pointed out that the social value of that time for the analyzed year amounted to 3% of the cities GDP. More recently, the study carried out by Lopez-Ghio et al. (2018) used survey data to define areas in Bogota, Mexico City, and Santiago to implement a congestion pricing scheme, estimating the daily cost of congestion for those areas in US$70,571 for Bogota, US$401,064 for Mexico City, and US$137,878 for Santiago. In the case of Mexico, in 2019, the Mexican Institute for Competitiveness calculated congestion costs for 32 cities, considering private vehicles and public transportation, and pointed out that each person on average loses 100 hours a year, equivalent to US$ 4.9 billion.

The lack of recent evidence on the characteristics and economic impact of congestion in LAC cities, including local and regional perspectives, limits the understanding of the scale of this phenomenon and its consequences and the design of effective mitigation measures. While international indices such as TomTom (2020) and INRIX (2018) are the first attempts to provide helpful guidance on the current situation of some LAC cities compared to the rest of the world, the results lack the temporal and geographic granularity necessary to analyze congestion management and make decisions in this regard. Indeed, congestion is a dynamic phenomenon, and policymakers need a comprehensive understanding of its spatial and temporal characteristics in order to design effective mitigation policies.

In this context, this report offers the first comprehensive analysis carried out in the region regarding the characteristics and costs of urban congestion. It provides results for the cities of Bogota, Buenos Aires, Mexico City, Lima, Montevideo, Rio de Janeiro, San Salvador, Santiago, Santo Domingo, and Sao Paulo. Big data and data science have been used to explain the dynamics of congestion in each city and estimate direct and indirect costs to society. The aim is to provide more and better information to design public policies.

Chapter 2.

HOW TO MEASURE CONGESTION AND ITS COSTS IN LAC CITIES?



As mentioned in the previous chapter, in this document we will apply **the approach used in Transportation Engineering** to estimate the level of congestion on a set of urban roads and its related direct and indirect costs. We will then detail the proposed methodology for calculating the aggregate delay, as well as the costs of such delay in terms of money and incidents. In our analysis, **we will use big data** from one of the most widely adopted navigation applications in the region. While data collected by mobile phone applications only allow the analysis to be focused on private vehicle users, unlike traditional data sources such as surveys or fixed roadside devices, this information allows capturing the temporal and spatial variability of congestion on a large scale, with greater data granularity, accuracy, and reliability (Rendón et al., 2020). This is done at a lower cost, with a higher update frequency and for larger areas than those covered with traditional sources (Goodall & Lee, 2019). The possibility of obtaining information in almost real time is particularly interesting, given that congestion is indeed a dynamic process, related to the constantly changing relationship between infrastructure demand and capacity (Q. Shi & Abdel-Aty, 2015).

The data used came from the Waze application, which has more than 130 million active users in 185 countries (Waze, 2020). The application collects data in two ways. On the one hand, it allows users to directly report events such as collisions, traffic congestion, hazards, and weather events. On the other hand, after a route has been set by a user, the app collects speed data via the GPS signal of the mobile device on which the application is installed. If a significant set of users traveling on the same road and at the same time slow down in an unusual manner, the API will generate/update traffic information, and a traffic jam will be reported. For the purpose of our analysis, we used more than 10 billion observations collected through the *Waze for Cities* initiative. The data corresponds to the year 2019, for the urban areas of the following **ten metropolitan areas of LAC:** Bogota, Buenos Aires, Mexico City, Lima, Montevideo, Rio de Janeiro, San Salvador, Santiago, Santo Domingo and Sao Paulo.

2.1 Model for the estimation of aggregate delay

Based on the definition of congestion developed by Goodwin (2004) (see Chapter 1), we will estimate the **level of congestion according to the extra travel time** due to excess traffic on a section of the road at a given time, either due to recurrent, non-recurrent or pre-congestion causes. This results in lower speeds than those under free-flow conditions. Given the source of information used in this study, which is frequently used by car drivers, the estimates made here do not include public transportation directly. However, given that in several road sections buses and vehicles share the same space, it can be concluded that the results obtained provide a conservative estimate of the level of congestion experienced by buses in those sections.

2.1.1 Data and variables

Figure 2.1 -urban areas selected for analysis- shows the urban areas that have been analyzed in this study, defined according to the metropolitan areas of each city:

Figure 2.1 Urban areas selected for analysis

Source: Google Maps. Demarcation by the authors.

The data obtained for these areas exceeds **10 billion observations for the year 2019** (Table 2.1). Mexico City and Sao Paulo account for 45% of the data, which was to be expected given the higher population in both cities. Montevideo is the city where fewer records were registered, with an average of 360 thousand daily records of data, while Sao Paulo recorded up to 6.7 million data per day. The traffic jams registered in 2019 for the areas analyzed exceeded 175 million. Once again, Mexico City (37.1 million) and Sao Paulo (43.4 million) are the cities with the highest number of traffic jams. On the other hand, traffic jams last longer in Montevideo and Bogota, averaging 74.7 and 20.9 minutes, respectively. At the other end we find Sao Paulo, with an average duration of just over 10 minutes. Finally, it should be noted that, on average, two thirds of the traffic jams recorded in the cities examined are of short duration, lasting less than ten minutes.

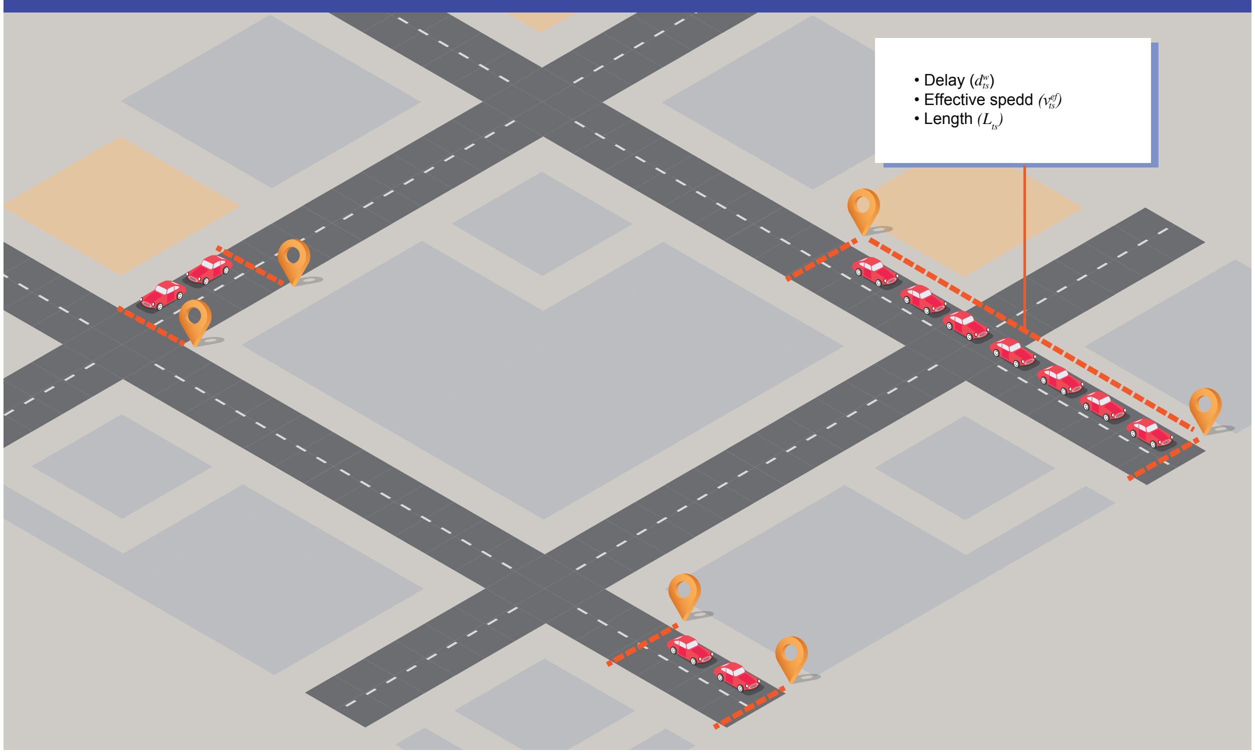
Table 2.1 General statistics based on data collected by Waze

City	Observations (in millions)	Traffic jams (in minutes)	Average duration (in minutes)	Traffic jams lasting less than 10 min (in millions)	Coefficient of variation of duration
Bogota	1,101	17.8	20.9	12.9	5.2
Buenos Aires	634	21.5	15.4	16.9	6.3
Mexico City	2,162	37.1	14.7	23.1	3.7
Lima	1,456	15.5	15.8	11.0	4.9
Montevideo	132	2.1	74.7	1.6	3.6
Rio de Janeiro	1,148	18.2	13.6	12.0	4.0
San Salvador	169	2.1	15.6	1.3	1.9
Santiago	576	11.8	12.9	8.7	4.1
Santo Domingo	371	5.9	13.2	4.0	3.0
Sao Paulo	2,432	43.4	15.5	29.0	3.8

Source: Own calculations based on the data collected by Waze.

The following **information** obtained through the Waze application will be used to calculate the aggregate delay: (i) coordinates where a traffic jam has been detected by the application, referred to as "segment"; (ii) effective speed at which traffic flows; and (iii) free-flow speed for the segment where the traffic jam has been detected or the delay it would take to cross the segment at the moving speed of the traffic jam (Figure 2.1). Data is recorded by Waze every 120 seconds.

Figure 2.2 Illustration of the information recorded by Waze



The **variables derived** from the information directly provided by Waze are:

d_{ts}^{w} : Delay, defined as the additional time it would take for a vehicle to cross a segments s of the road compared to a free-flow scenario [in seconds].

v_{ts}^{ef} : Effective speed, which refers to the average traffic speed in the traffic jam [meters per second].

L_{ts} : Length of the traffic jam in segment s [in meters].

From these, the **following variables** are constructed to estimate the aggregate delay:

t : Time interval between times of data capture (120 seconds).

$t_{ts}^{ef} = \frac{L_{ts}}{v_{ts}^{ef}}$: Effective time, or the total time it would take a vehicle to pass through the traffic jam [s].

$t_{ts}^{ff} = t_{ts}^{ef} - d_{ts}^{w}$: Free flow time, which represents the time it would take a vehicle to pass through segment *s* if there were no traffic jam [s].

$v_{ts}^{ff} = \frac{L_{ts}}{t^{ff}}$: Free-flow speed, which is the maximum flow speed [m/s].

$k_{ts} = f(v_{ts}^{ff},\ v_{ts}^{ef},\ k^{c},\ k^{j})$: Density of vehicles in the traffic jam [veh/m].

$q_{ts} = f(v_{ts}^{ff},\ v_{ts}^{ef},\ k\ ,\ k^{j})$: Vehicle flow per second [veh/s].

$\Gamma_{ts} = k_{ts} \cdot L_{ts}$: Stock, which represents the number of vehicles trapped in the traffic jam at the beginning of data capture [veh].

$\Omega_{ts} = q_{ts} \cdot t$: Flow, which indicates the number of vehicles entering the traffic jam over the time interval [veh].

$d_{ts}^{max} = \frac{d_{ts}^{w}}{t_{ts}^{ef}} \cdot min(t,\ t_{ts}^{ef})$: Maximum delay, referring to the maximum amount of time a vehicle can lose during the data capture interval [s].

La_{s} : Number of lanes.

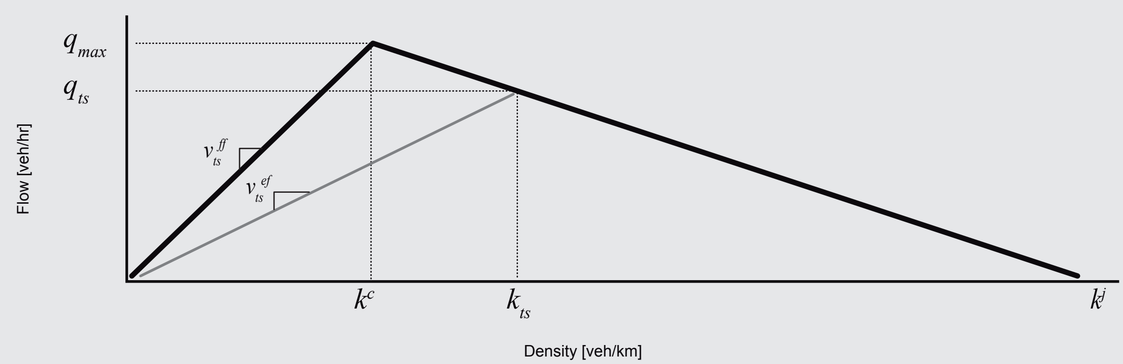
OR : Is the average vehicle occupancy rate. According to Tirachini & Gomez-Lobo (2020), an OR of 1.4 persons per vehicle is assumed.

Delay is defined as the additional time a vehicle remains on the road due to traffic congestion. In this case, to calculate the delay at a given arc and instant the free-flow speed was used, — i.e., the speed of vehicles circulating through a specific segment when there is no traffic congestion—. As demonstrated in Chapter 1, there are several ways to determine the reference speed which will serve to calculate the extra travel time due to congestion. The maximum permitted speed on roads is an issue that has been widely discussed (see the discussion presented by Goodwin, 2004, and Wallis & Lupton, 2013). In this context, using the maximum speed as a benchmark speed may unintentionally bias congestion management policies, setting targets that would be impossible to achieve in practice. Another option indicated in the literature is using speeds that are socially considered as "normal" or "expected" depending on the

particular road type, or the optimal speeds that emerge from technical design. However, given the need for specific speed limits depending on the type of road, these options make it difficult to compare the level of service between different cities or regions (Kriger et al., 2007). To overcome this limitation, recent studies have sought to circumvent this problem by using **speeds obtained during off-peak hours**, such as the ones considered herein, as a reference.

To estimate the number of vehicles that make up the *stock* (Γ) and the *flow* (Ω) —information not provided by Waze—, we have followed the method designed by Yperman et al. (2005) and Xu & González (2017) and assumed a **functional relationship between traffic flow q and density k**. According to Newell (1993), we can approximate this flow-density relationship using a triangular-shaped fundamental relationship, as illustrated in Figure 2.3. The black function in this figure shows the relationship between the flow of vehicles and their number. As can be seen in the following figure, as the number of vehicles on the road increases, the flow is higher. However, as soon as the road reaches its maximum capacity, and vehicles start to get in each other's way, the flow starts to slow down and a traffic jam is formed. Given the fact that this study applies to an urban context, the maximum density (k^j) has been estimated assuming a space occupancy of 6 meters per vehicle at peak congestion levels. Following Daganzo (1997), critical density (k^c) is calibrated equal to $1/6\ k^j$. From this information, the density and flow of each of the congested segments is calculated as a function of free-flow speed, effective speed, and the common parameters of maximum road density and critical density (see Appendices 1 and 2 for more details).

Figure 2.3 Fundamental triangular relationship



From this relationship and according to the values obtained from q_{ts} and k_{ts}, the values of Ω_{ts} and Γ_{ts} are then estimated for each congested segment.

2.1.2 Estimation of the road network

Waze does not report information about the number of lanes on each road. Nor is this information generally available for the different cities included in this study. In this context and in order to develop a methodology that can be replicated in any city in the region, we have generated a **deep neural network model to estimate the number of lanes** in a given road, for each segment s of the traffic jam (La_s). This model uses the characteristics of traffic jams to classify the different roads according to the number of lanes in each direction ranging from 1 to 5. This does not imply that traffic jams in segments with the same number of lanes will have the exact same behavior, but it is expected that they share some common characteristics. The model also includes input variables related to the characteristics of the city, which are detailed in the following Table 2.2.

Table 2.2 Description of model input variables

Variable name	Variable description	Unit
Avenue	Boolean variable. Its value is 1 when the segment is part of an avenue.	-
Queue	Sum of the number of vehicles in the initial queue, taking into account each traffic jam observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	Veh
Average queue length	Average number of vehicles in the initial queue, taking into account each traffic jam observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	Veh
Flow	Sum of the number of vehicles that were part of all traffic jams observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	Veh
Average flow	Average number of vehicles that were part of all traffic jams observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	Veh
Average traffic jam density	Average density in the initial queue, taking into account each traffic jam observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	Veh/m
Free-flow speed	Average free flow speed observed in the segment.	m/s
Average queue speed	Average speed in the initial queue, taking into account each traffic jam observed in the segment over the course of a month. The traffic model used is the single-lane scenario.	m/s
Total delay	Cumulative delay observed in the segment over the course of a month.	s
Average delay	Average delay per vehicle observed, taking into account each traffic jam observed in the segment over the course of a month.	s
Average duration	Average time duration of all traffic jams observed in the segment.	s
Duration - Delay (R_{DD})	Mean of the variable that relates the duration to the delay of a traffic jam $R_{DD} = \sqrt{\text{Delay*Duration}}$	s
Congestion level	Numerical scale representing the average congestion level (1 to 5).	-
Number of traffic jams	Total number of traffic jams observed in the segment.	-
Population of the city	Total inhabitants of the metropolitan area where the city is located.	-
Average hours worked per week	Average working hours per person in the selected city.	h
Value of time	The value of time for a citizen. It is calculated following the method presented in section 2.2.3.	US$
GDP	Gross Domestic Product (GDP) of the city, estimated as the result of multiplying the GDP per capita and the number of inhabitants of the city.	US$

The neural network used is a 6-hidden layer perceptron, with 40, 35, 30, 20, 18, 15 neurons respectively with a *He Normal* initialization. The activation function is *relu*, which speeds up the convergence of model training. These hyperparameters were chosen through trial and error, moving from a simple model to a more complex one. The output of the neural network model is the probability that the observed segment belongs to a given category (from 1 to 5 lanes). The number of lanes in the segment is assigned according to the category to which the segment is most likely to belong. Since there may be many segments that belong to the same road, the number of lanes for the specific road shall be defined according to the number of lanes in statistical mode for all segments.

A total of 7,684 observations, which were manually added using Google Street View, was used to train the network, the number of which have been broken down by city in Table 2.3.

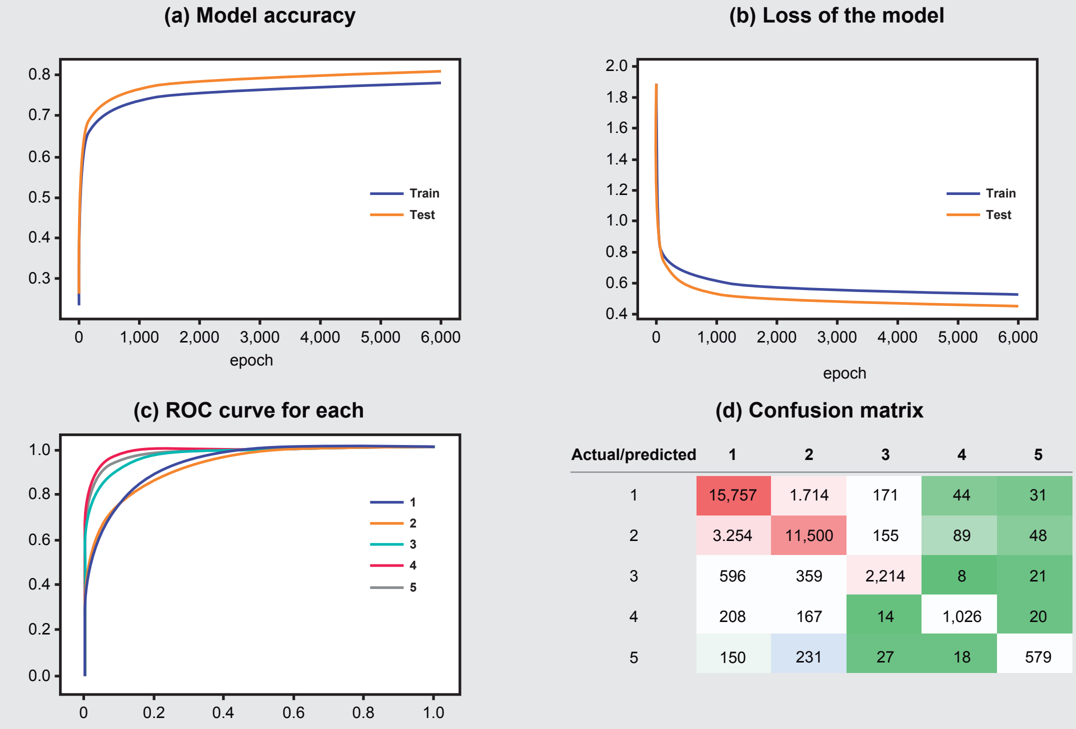
Table 2.3 Number of streets labeled by city

City	Number of segments for the training dataset	Number of segments for the test dataset
Buenos Aires	71,820	7,980
Montevideo	44,537	4,949
Santiago	57,519	6,391
Bogota	68,301	7,589
Sao Paulo	78,930	8,770
San Salvador	24,611	2,735
Total	345,718	38,414

The training data were divided into two parts. The first part contains 90% of the data and was used for the algorithm learning process, while the remaining 10% of data was used to evaluate the model. As shown in Figure 2.4 (a) and 2.4 (b) the algorithm shows good prediction performance on both the evaluation and training data, with an accuracy of 82% and 86%, respectively.

Figure 2.4 (c) shows the ROC curves for each category (from 1 to 5 lanes), indicating that the model performs better for streets with 3, 4 and 5 lanes. The average area under the curve (AUC) is 0.82, which means that there is an 82% probability that the model forecast is more accurate than random selection. Figure 2.4 (d) is the confusion matrix, where the columns are the model predictions, and the rows correspond with an actual class of the segments. The diagonal concentrates the largest number of segments, suggesting that the model is classifying the classes correctly. False positives and negatives outside the diagonal have a low representation. Low performance corresponds to segments with 1 and 2 lanes. However, this is offset by a high F1 score for all segments (0.81) (Figure 2.4)

Figure 2.4 Model fit indicators



Actual/predicted	1	2	3	4	5
1	15,757	1.714	171	44	31
2	3.254	11,500	155	89	48
3	596	359	2,214	8	21
4	208	167	14	1,026	20
5	150	231	27	18	579

Accuracy represents the number of correct cases versus the total number of cases classified in a class. *Recall* corresponds to the percentage of correct cases with respect to the total number of cases that originally belonged to that class. This reflects the power of the model to identify a specific class. The AUC corresponds to the area under the ROC curve (operating characteristic curve), which is created by plotting the true positive rate against the false positive rate with respect to the selected threshold settings (between 0 and 1). The closer the value of AUC is to 1, the better the performance of the model. These values are shown at Table 2.4.

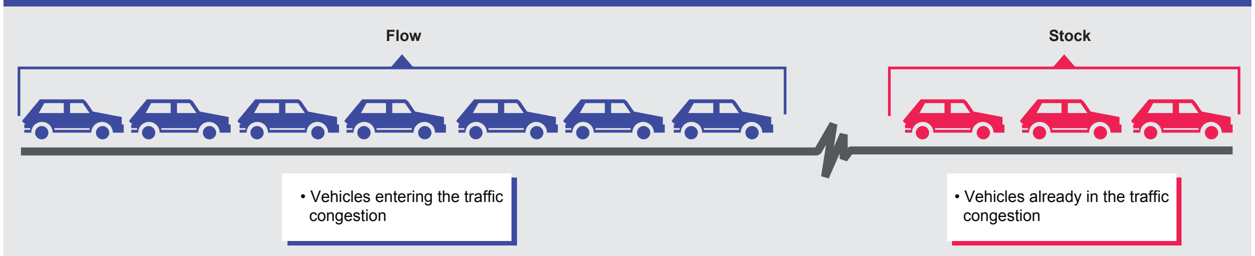
Table 2.4 Results of the neural network model

	Precision	Recall	F1 Score	Support
1	0.79	0.89	0.84	17,717
2	0.82	0.76	0.79	15,046
3	0.86	0.69	0.77	3,198
4	0.87	0.71	0.78	1,435
5	0.83	0.58	0.68	1,005
Precision			0.81	38,401
Macro average	0.83	0.73	0.77	38,401
Weighted average	0.81	0.81	0.81	38,401

2.1.3 Estimating aggregate delay

As mentioned above, the data collected from the application is obtained in 120-second intervals. However, traffic jams continue to evolve in the meantime. For example, as illustrated in Figure 2.5, there are the vehicles make up in the traffic jam at the time of data capture (what we call *stock* or Γ) while other vehicles will enter the traffic jam during the time interval —120 seconds— that happens between captures (what we call *flow* or Ω).

Figure 2.5 Traffic jam



Based on this information, it is reasonable assuiming:

i) *Traffic jam behavior:* The traffic jam maintains constant characteristics during the 120-second interval between two data captures. That is, the transit speed (v^{ef}_{ts}), the delay when crossing the segment (d^{w}_{ts}), the density (k_{ts}), the length (L_{ts}) and the rest of variables are invariant across the time interval (t).

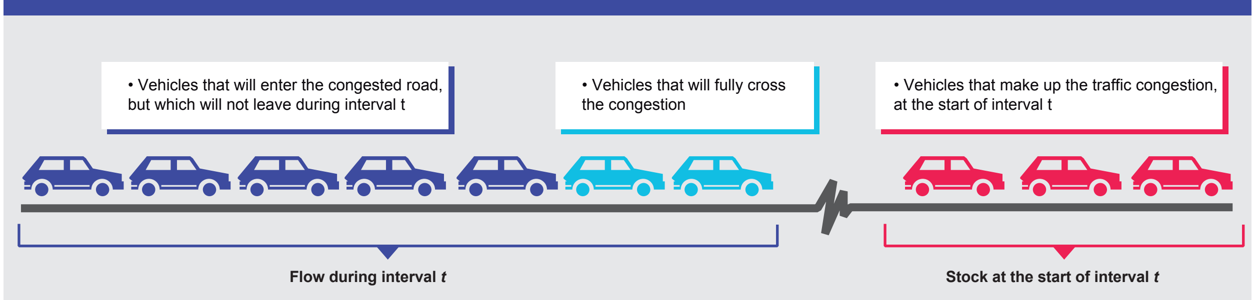
ii) *Infinite flow:* As a consequence of the previous assumption (i), to ensure that the stock (Γ) is equal at the end of the interval (t), each vehicle leaving the traffic jam is immediately replaced by another vehicle entering the flow (q).

In other words, it is assumed that the characteristics of the traffic jam —congestion length and effective speed— remain unchanged between data captures. Given that the time interval between data captures is quite short —two minutes—, it is reasonable to think that this assumption will not affect the results of the model. Consequently, given that congestion is presumed to be invariant between data captures, it is assumed that for every vehicle leaving the congested road, a new one enters, replacing it. This implies that the *stock* remains invariant between data capture and, under this framework, the flow is symmetric between vehicles entering and leaving the congestion.

The **aggregate delay estimate is based on two scenarios** that may occur in a congestion:

Scenario 1 ($t^{ef}_{ts} < t$): In this scenario, all vehicles in stock make it through the congestion during interval t, which means that the effective time is less than two minutes (interval t):

Figure 2.6 Scenario 1



In this scenario, the delay is estimated as follows:

$$D_{ts}^{stock} = OR * La_s * \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\gamma=1}^{\Gamma_{ts}} \gamma \quad (1)$$

$$D_{ts}^{flow} = OR * La_s * (\Omega_{ts} - \Gamma_{ts}) * d_{ts}^{max} + OR * La_s * \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\gamma=1}^{\Gamma_{ts}-1} \gamma \quad (2)$$

where D^{stock} refers to the additional aggregate travel time for all car users in the stock; and D^{flow} represents the extra time lost by car users entering the traffic jam during the interval .

Equation 2 can be divided into two parts: the first part $[OR * La_s * (\Omega_{ts} - \Gamma_{ts}) * d_{ts}^{max}]$ represents the aggregate delay of all car users who enter the congested road and manage to completely pass through segment s during interval t (illustrated by the black vehicles in Figure 2.6). The second part of the equation corresponds to the delay of the vehicles that will enter the traffic jam, but, because of their location in the congested queue, will not have enough time to exit the congested segment during interval t and, consequently, will be included in the stock of the next data capture (illustrated by the blue vehicles in Figure 2.5). It should be noted that the delay of the second part of the equation is equal to that of the stock, but in this case the sum reaches Γ-1 because the moment when the vehicle enters the traffic jam is not considered as a delay, so as not to alter the conditions of the traffic jam. Therefore, the aggregate delay of segment s at time t is the sum of:

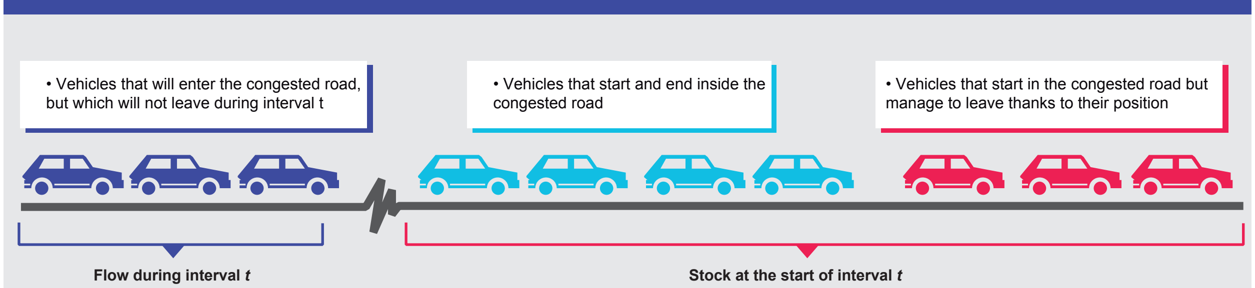
$$D_{ts} = D_{ts}^{stock} + D_{ts}^{flow}$$

$$D_{ts} = OR \cdot La_s \cdot d_{ts}^{w} \cdot \Omega_{ts} \quad (3)$$

Using equation (3) the total delay for segment s at the end of interval t can be estimated. The intuition of this equation indicates that, because vehicles that started as stock add to the complementary delay of incoming vehicles that will not make it through the congested road (blue cars in Figure 2.6), the aggregate delay can be calculated as the sum of the delay reported by Waze for each vehicle entering the traffic jam. The aggregate delay for a given area will be the sum of the delays reported by all segments included in the area, during a given period of time.

Scenario 2 ($t_{ts}^{ef} \geq t$): In this scenario, not all vehicles that started as stock in a traffic jam at the beginning of t will manage to completely cross through it at the end of that interval. In other words, the effective time is greater than the time between data captures (Figure 2.7)

Figure 2.7 Scenario 2



In this scenario, the delay is estimated as follows:

$$D_{ts}^{flow} = OR \cdot La_s \cdot \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\omega=1}^{\Omega_{ts}-1} \omega \tag{4}$$

$$D_{ts}^{stock} = OR \cdot La_s \cdot (\Gamma_{ts} - \Omega_{ts}) \cdot d_{ts}^{max} + OR \cdot La_s \cdot \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\omega=1}^{\Omega_{ts}} \omega \tag{5}$$

Equation (4) reports the aggregate delay for vehicles in *flow* under scenario 2. Since vehicles entering the traffic jam will not be able to cross the entire segment during they will add a delay proportional to their position in the queue ($\frac{\omega}{\Gamma_{ts}}$). Equation (5) refers to the aggregate delay for the stock. This equation also has two parts: the first part [$OR \cdot La_s \cdot (\Gamma_{ts} - \Omega_{ts}) \cdot d_{ts}^{max}$] refers to the vehicles that, due to their position in the traffic jam, will not manage to cross it completely during interval t and, consequently, will add to the maximum possible delay; the second part refers to the vehicles that, given their position in the traffic jam, will manage to cross it during interval t and, therefore, will only add to the aggregate delay an amount proportional to their position in the queue at the beginning of t. The aggregate delay for this second scenario will be the sum of these equations:

$$D_{ts} = D_{ts}^{stock} + D_{ts}^{flow}$$

$$D_{ts} = OR \cdot La_s \cdot d_{ts}^{max} \cdot \Gamma_{ts} \tag{6}$$

Equation (6) indicates the aggregate delay estimate for the second scenario. The intuition behind this equation is that, because no vehicle could cross the traffic jam during interval t, and since the vehicles entering the traffic jam as part of the flow are symmetric in terms of aggregate delay to those in the stock exiting the traffic jam, the aggregate delay can be calculated as the sum of the maximum delay for each vehicle in stock. It should be noted that equations (3) and (6) are algebraically identical (see Appendix 1 for the algebraic derivation).

2.2 Value of time (VoT) and monetary cost of congestion

Once the total delay due to congestion in a city has been calculated, we can then estimate the monetary cost of congestion. To do this, it is necessary to estimate the value that individuals attach to the time they lose in traffic in quantitative terms.

There are a number of studies in the literature which focus on studying how people value time (VoT) when traveling. Barrett (2010), Beesley (1965) and Shiaw (2004) estimated VoT by using a method that compared different travel modes, —car, plane, and train—, relative to the travel cost and time requirements. The main criticism of this approach is the heterogeneous attributes of each travel mode. A typical example is that reading a book on a train is easy, but it is not so easy in a car, so the subjective value of time differs (Wolff, 2014).

To address these concerns, other methods have focused on a single mode of travel, using location variability to identify VoT. Along that same line, Deacon & Sonstelie (1985) estimated the willingness of drivers to pay to avoid waiting at differentially priced gas stations, resulting in a VoT that exceeded 70% of the gross wage rate. Later, Small et al. (2005) used an econometric approach to compare motorists who were willing to pay more to avoid congestion in Los Angeles, finding a VoT above 90% of the wage rate.

Subsequent studies have pointed out variables that have likely been omitted in these approaches, related to the physical or psychological concerns of drivers which may lead them to choose to pay more or less. These variables depend on the specificities of each road and the expected time of arrival. In fact, the unpredictability of arrival times when traveling opened a subfield of study, referred to as the Value of Reliability (VoR). With this in mind, Fezzi et al. (2014),

after gathering data from revealed preference surveys, conducted Monte Carlo simulations to estimate the value of travel time to recreation sites, finding in this case a VoT of 70% of the wage rate. Stated preference studies have also been used to orthogonalize omitted variables in revealed preference surveys, thus providing a cleaner causal inference. This type of studies report results that hover around a VoT estimate of 50% or less. The meta-analysis presented by Wardman (2001) identified that, in general, time is valued 48% higher under congested conditions than in a free-flow scenario. The study conducted in Sweden by Eliasson (2004) found that VoT is 50% higher in congested areas and the value attached to time is between 20% to 100% higher depending on the degree of traffic congestion.

Finally, Wolff (2014) presented an entirely different method to estimate the VoT parameter by analyzing the relationship between drivers' speeding behavior and gasoline prices in free-flow conditions. Consistent with trends reported in the literature, Wolff estimates a VoT of approximately 50% of the wage rate after considering a list of potential bias such as incidents and speeding tickets.

From this group of studies, academics and policy makers generally adopt the following rule to estimate VoT when measuring and analyzing traffic congestion costs: **The VoT for car travel is approximately equal to 50% of the market wage** (véase Parry & Small, 2009; Small et al., 2007; Yang et al., 2020)[11]. Consistent with this rule, in this study we estimate the VoT for vehicle occupants as follows:

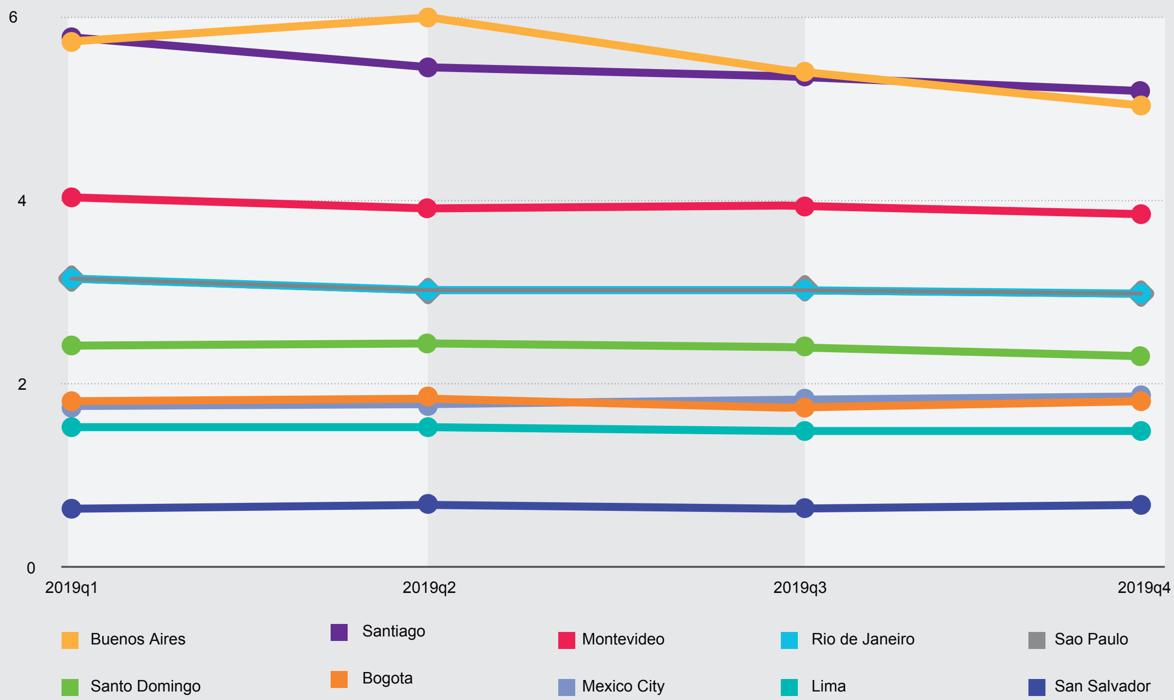
$$VoT_{cq} = 0.5 * \frac{Y_{cq} * WS_c}{L_{cq} * h_{cq} * 13} \quad (7)$$

Where subscripts *c* and *q* indicate city and quarter; Y represents the city's output; WS refers to the wage share of the city's output; L is the number of people employed; and h refers to the average number of hours worked by employees during a week.

WS and h were obtained from International Labor Organization (ILO) country statistics, the former for the year 2017 and the latter for 2019. Given that this information is not available at city level, data available at country level were used. For Lima, Montevideo and San Salvador, the average hours worked per week with annual granularity are available. L was calculated from the number of urban employees at country level and re-scaled using the share of the population of the city with respect to the total urban population of the country. Employment data were obtained from ILO (2015) and the urban population rate was obtained from the World Development Indicators (WDI) (World Bank, 2019) —except for Rio de Janeiro, which comes from SimpleMaps. In the case of San Salvador, this indicator is only available on an annualized basis. Y was obtained from the International Financial Statistics database (IFS, 2019) and re-scaled using the share of the population of the city with respect to the total population of the country, according to WDI.

11. This calculation of the Value of Time implicitly includes the Value of Reliability (VoR), which relates to travel time uncertainty (Grant-Muller & Laird, 2007).

Figure 2.8 Value of time in selected cities



Source: Own calculations using ILO and IFS data.

2.3 Model to estimate the indirect costs of traffic congestion

As mentioned in Chapter 1, congestion is associated with a series of indirect costs, among which we find variations in the **level of road incidents and in the severity of the cases recorded.** Previous studies have reported mixed results on these effects depending on the type of road being analyzed. One of the most prominent studies is that of Brownfield et al. (2003) which analyzes the case of the United Kingdom, reporting that the accident rate on highways is almost twice as high in congested conditions as in free-flow conditions, while the rate for motorcycle users is seven times higher. It also shows that the proportion of fatal or serious incidents is lower in congested conditions. In the case of urban roads, the authors report that the accident rate is 50% lower in congested conditions, both for vehicles and motorcycles. The proportion of fatal and serious pedestrian and cyclist incidents in this case showed no variation[12]. The State Highway Administration (SHA) obtained similar results for the United States (Chang & Xiang, 2003) rate, and severity. Recent evidence highlights that the most statistically powerful studies report a U-shaped relationship between congestion and accident rates, and emphasizes the need to obtain better spatially and temporally disaggregated data to deepen understanding of this relationship (Retallack & Ostendorf, 2019). In this regard, and in order to analyze the impact of congestion on urban accident rates in LAC, this section illustrates the methodology developed using the wealth of data collected[13].

12. It should be noted that the frequency and severity of incidents may be different in conditions of hypercongestion. See Small & Chu(2003)known as hypercongestion, in which speed increases with flow. We argue that this relationship is unsuitable as a supply curve for equilibrium analysis because observed hypercongestion occurs as a response to transient demand fluctuations. We then present tractable models for handling such fluctuations, both for a straight uniform highway and for a dense street network such as in a central business district (CBD for a complete description of this phenomenon.
13. Due to the number of Waze users, a representative sample of road alerts can be collected. Previous studies have validated the quality of the data by comparing it with traffic management system (ATMS) reports, taking into account reporting time and geographic coverage (Amin-Naseri et al., 2018; Goodall & Lee, 2019). In the United States, the Department of Transportation has integrated this information to support public policy decision-making regarding the frequency of road traffic crashes (Flynn et al., 2018).

We have defined accident rate as the number of alerts registered in the course of one hour in the whole city, obtaining the data through the Waze platform. Users of this mobile application can report about different incidents on the road while, simultaneously, other users make a record of the validity of said incident report. Based on other users' reactions, each incident is given a 1 to 10 reliability score, 10 being the most reliable. Based on this criterion, we selected those incidents whose reliability level was 5 or higher. In addition, considering that several alerts may correspond to the same incident, we filtered alerts according to the following spatial & temporal criteria: alerts of the same type reported within a radius of less than 20 meters and within the next 20 minutes of the first report are considered to be the same alert. Finally, we considered a time interval from 7 a.m. to 8 p.m., in order to exclude any anomalous observations in the estimates, due to the lack of urban mobility. After this processing, we obtained a base of approximately 100 million alert records for the ten cities analyzed.

The model used to estimate the impact of congestion on accident rates is a **Poisson model for panel data with fixed-effects per city**

$$\lambda_{it} = E(Y_{it}|X_{it}) = e^{X_{it}\theta+\delta_i} \tag{8}$$

where the subscripts i and t represent city and date with hourly disaggregation; λ refers to the mean accident rate per city; δ represent the fixed effects of each metropolitan area; and X is a matrix containing the explanatory variables of the model among which we find: *ln(hazard)*, which represents the natural logarithm of the number of hazard alerts caused by the effects of nature, such as floods, rains or objects on the road, registered in each city by Waze users; *Monday, Tuesday, Wednesday, Thursday, Friday* and *Saturday* which are dummies that take a value of 1 if it is the day of the week to which they refer, and 0 otherwise; and delay, which refers to the total delay experienced by vehicles when traveling on the road. Thus, the Poisson distribution function proposed for the execution of the model is as follows:

$$pr(Y_{it} = y_{it}|X_{it}) = \frac{\lambda_{it}^{y_{it}} * e^{-\lambda_{it}}}{y_{it}!} = \frac{e^{(X_{it}\theta+\delta_i)y_{it}} * e^{-e^{X_{it}\theta+\delta_i}}}{y_{it}!} = \frac{e^{X_{it}\theta y_{it}} * e^{\delta_i y_{it}-e^{X_{it}\theta} * e^{\delta_i}}}{y_{it}!} \tag{9}$$

From this function, the joint distribution function can be formulated as follows:

$$pr\left(Y_{i1} = y_{i1}, \dots, Y_{iT_i} = y_{iT_i}\middle|X_{it}\right) = \prod_{t=1}^{T_i} \frac{e^{X_{it}\theta y_{it}} * e^{\delta_i y_{it}-e^{X_{it}\theta} * e^{\delta_i}}}{y_{it}!} \tag{10}$$

$$pr\left(Y_{i1} = y_{i1}, \dots, Y_{iT_i} = y_{iT_i}\middle|X_{it}\right) = \left(\prod_{t=1}^{T_i} \frac{e^{X_{it}\theta y_{it}}}{y_{it}!}\right) e^{\left[-e^{\delta_i}\sum_t e^{X_{it}\theta}+\delta_i \sum_t y_{it}\right]}$$

where, based on the methodology proposed by Wooldridge (2016), we obtain the maximum likelihood function that needs to be optimized:

$$L = ln \prod_{i=1}^{T_i} \left[\frac{(\sum_t y_{it})!}{\prod_t y_{it}!} \prod_{t=1}^{T_i} p_{it}^{y_{it}}\right] \tag{11}$$

where $p_{it} = \frac{e^{X_{it}\theta}}{\sum_t e^{X_{it}\theta}}$

In order to guarantee the exogeneity of the control variables, congestion was instrumented due to the simultaneity between congestion and accident rates. The instrumentation was designed based on the two-stage estimation of the following system of simultaneous equations:

$$delay_{it} = \beta_o + \alpha_i + \omega_t + h_t + \beta_1 \ln(accident_{it}) + \beta_2 delay_{it-164} + \beta_3 \ln(RoadClosed_{it-1}) + \beta_4 \ln\,(\text{hazard}_{it-1}) + \mu_{1it} \quad (12)$$

$$\ln(accident_{it}) = \gamma_o + \delta_i + \gamma_1 delay_{it} + \gamma_3 \ln(\text{hazard}_{it-1}) + \sum_{dow=1}^{7} \gamma_{dow+3} dow_t + \mu_{2it} \quad (13)$$

where *ln(accident)* refers to the logarithm of the aggregate number of incidents in city i during hour t; α and η are the city fixed effects estimated for each of the equations; ω are fixed effects per week of the year and h are fixed effects per hour of the day to control for the high volatility of congestion over time. The variables used as an instrument of the aggregate delay, in addition to the previously mentioned time fixed effects, are: the aggregate delay (*delay*) at the same time lagged behind the immediately preceding week; and *ln(RoadClosed)* which represents the logarithm of the aggregation of the number of road closures. On the other hand, it is proposed to run the model controlling for the effect of: *ln(hazard)* which symbolizes the logarithm of the aggregation of the number of reported road hazard alerts (these hazards may vary from stranded vehicles on the side of the road or objects obstructing traffic, to natural effects such as heavy rains or floods); and *dow* which is a fixed effect per day of the week to control for this dimension. Finally, to carry out the econometric model, and due to the configuration of the aggregate data, lagged variables regarding road closure and hazards were used as hourly time-series and on a geographical-area basis.

In the following chapter, we present the results of the application of the methodology, including delay, direct costs and the impact of congestion on road incidents, for the ten cities included in this study.

Chapter 3.

MAGNITUDE AND COST OF CONGESTION IN LAC

In this chapter, we present the results of the traffic congestion analysis carried out for the ten selected urban areas of LAC, according to the methodology detailed in Chapter 2. The cities under study are: Bogota (Colombia), Buenos Aires (Argentina), Mexico City (Mexico), Lima (Peru), Montevideo (Uruguay), Rio de Janeiro (Brazil), San Salvador (El Salvador), Santiago (Chile), Santo Domingo (Dominican Republic) and Sao Paulo (Brazil). Table 3.1 summarizes the main characteristics of these cities. All of them have more than one million inhabitants, four are home to more than 10 million people (Bogota, Buenos Aires, Lima and Rio de Janeiro) and two have more than 21 million inhabitants (Mexico City and Sao Paulo). Five cities (Buenos Aires, Lima, Montevideo, Santiago and Santo Domingo) are home to between one-third and one-half of the population of their respective countries. They bring together the main economic and social activities, and are crucial for the development of the selected countries.

Table 3.1 Overview (2019)

City	Population (millions)[14]	% of the country population	GDP per capita (US$)[15]
Bogota	10.78	21.4	6,432
Buenos Aires	15.06	33.4	10,006
Lima	10.55	32.5	6,978
Mexico	21.67	17.0	9,863
Montevideo	1.74	50.4	16,190
Rio de Janeiro	11.75	5.6	8,717
San Salvador	1.10	17.1	4,187
Santiago	6.72	35.5	14,896
Santo Domingo	3.24	30.2	8,282
Sao Paulo	21.85	10.4	8,717

Source: Own calculations using data from IFS, WDI, and Simplemaps.

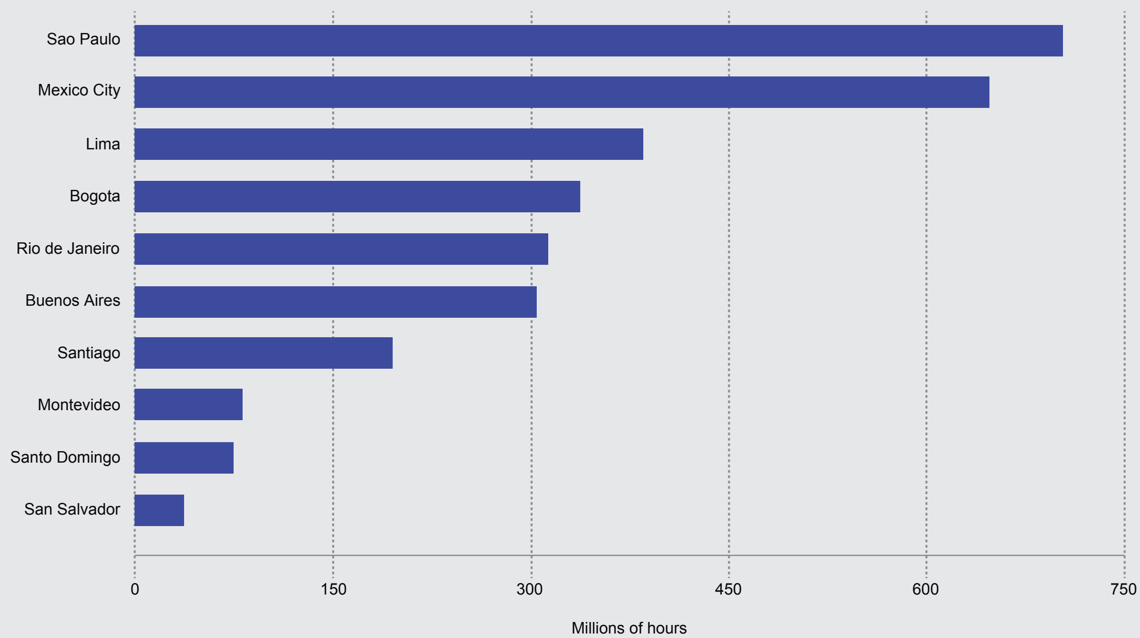
The chapter is organized as follows: in the first section, we estimate the magnitude of congestion in the selected cities; in the second, we analyze the monetary cost of congestion from different perspectives; in the third, we zoom in on each city and describe the temporal and spatial dynamics of congestion and its monetary costs; and finally, in the fourth section, we analyze the impact of congestion on road incidents as an indirect cost of congestion.

3.1 Magnitude of traffic congestion in LAC

Figure 3.1 shows the result of calculating the **total delay for private transportation in 2019**, for each of the ten cities. As discussed in Chapter 1, the determinants of congestion include the level of concentration of economic activities, as well as supply and demand factors, some of which are: the capacity and extension of the road network, the coverage by substitute goods to the private car, the share of private vehicle trips typically made by the population, and population density. Initial results for LAC cities show a correlation between total delay and population size, as the highest delays in 2019 were found in the megacities of Sao Paulo (21.8 million inhabitants and 702 million hours lost) and Mexico City (21.6 million inhabitants and 647 million hours lost). Conversely, San Salvador, the city with the smallest number of inhabitants among the ten cities analyzed (1.1 million), was the city with the lowest number of hours lost to congestion, reaching 37 million hours in 2019.

14. Due to data availability, the population of the entire metropolitan region is used for each city.
15. National GDP per capita multiplied by population is used as a proxy for city output. This is to ensure homogeneity of the source in the first instance, as well as to ensure a uniform GDP allocation methodology. In this regard, the statistical institutes carry out national accounting and subsequently allocate by region, using non-standardized statistical techniques, the production to the different States/Provinces/Departments.

Figure 3.1 Total delay in selected cities (millions of hours, 2019)

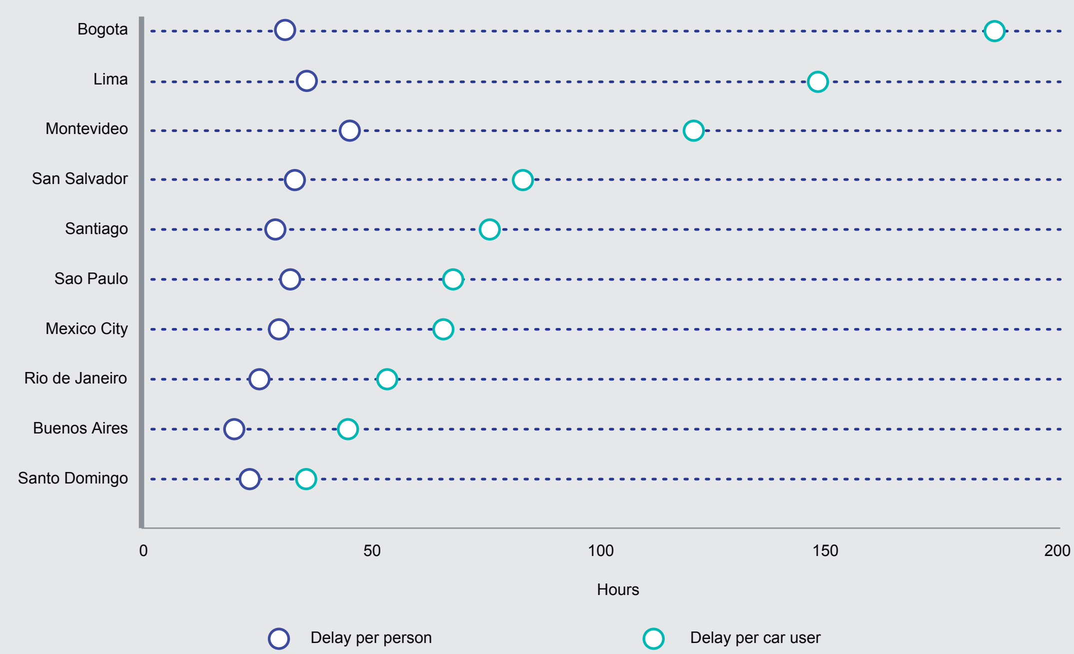


Source: Own calculations using data from Waze.

However, if we analyze the **delay per inhabitant and per car user** to control for the size of the city, the positioning of the cities changes significantly (Figure 3.2). Hereinafter, every resident of the city is understood to be an inhabitant and every frequent user of the private vehicle is considered a car user. The latter is calculated as the population multiplied by the motorization rate and the average vehicle occupancy. Thus, in 2019, the inhabitants of Montevideo, for example, lost 51% more time in congestion than those of Mexico City, even though the population of the Mexican capital city is 11 times greater than that of Montevideo. The same goes for San Salvador —let us recall that it was the city with the lowest total delay—, where its inhabitants lost 33 hours stopped in traffic in 2019, above megacities such as Bogota (31 hours), Rio de Janeiro (25 hours) and Buenos Aires (20 hours).

Similarly, if we take into account only private vehicle users, Bogota lost the most time stuck in traffic in 2019, with a total of 186 hours per car user. This figure is 2.7 and 2.8 times higher than the time lost by private vehicle users in Sao Paulo and Mexico City, respectively. It is worth mentioning that, in part, these differences are due to the intensity of private vehicle use in the ten cities. According to the most recent OD surveys (available for Bogota, Buenos Aires, Mexico City, Montevideo, Santiago and Sao Paulo), Montevideo is one of the cities with the highest percentage of car travel which start and end within the metropolitan area (32.2%), only behind Santiago (32.5%) and well above Bogota (11.3%), Buenos Aires (20.4%) and Mexico City (18.8%). In addition, Montevideo has a higher proportion of kilometers traveled by private vehicle, equivalent to 32% of all modes of transportation. In the case of San Salvador, it is interesting to note that about 43% of the country's vehicles are found in its metropolitan area, against only 17% of the national population, while it is also the destination of numerous trips from outside the metropolitan area, for educational, health, commercial and work-related purposes (COAMSS-OPAMSS, 2010, 2020).

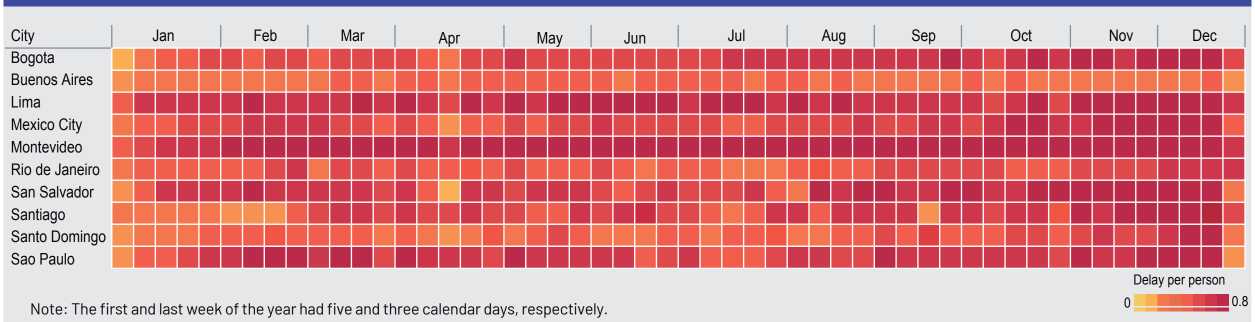
Figure 3.2 Delay per person and per car user in selected cities (hours, 2019)



Source: Own calculations using data from Waze and ILO.

Figure 3.3 shows the **weekly delay per person** for the ten cities throughout the year. This graph allows us to identify in which months road congestion intensifies. Overall, congestion in 2019 was relatively less intense in January and reached its trend level in February. Sao Paulo was the city that experienced the highest relative weight during the first quarter of the year, when a quarter of the total annual delays occurred, compared to 22% of the overall average. In Santiago and Bogota, the delays experienced per person increased significantly from the second quarter onwards, reaching a critical point in December, a month that accounted for 11% of the total annual congestion for both cities.

Figure 3.3 Weekly delay per person in 2019



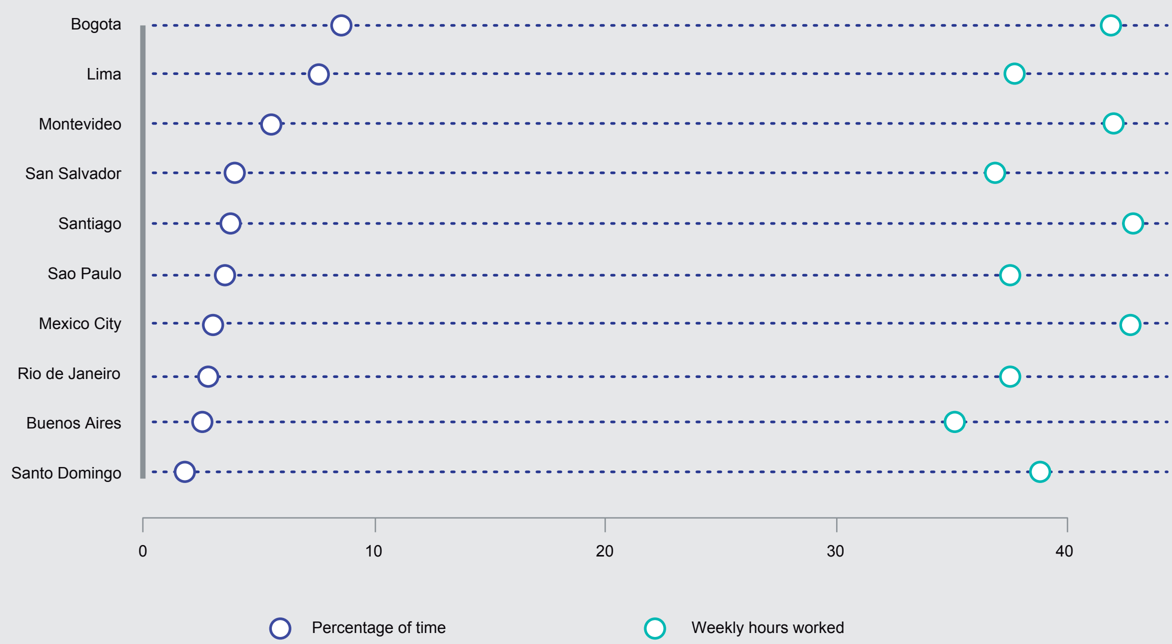
Note: The first and last week of the year had five and three calendar days, respectively.

Source: Own calculations using data from Waze.

By comparing the time lost in congestion to the number of hours worked per person per week, we can obtain an interesting perception of the scale of the burden of congestion on daily life. This figure can be considered as a proxy for labor productivity losses generated by congestion. Figure 3.4 shows this relationship for private vehicle users. In

2019, each car user in Bogota wasted in traffic the equivalent of 10% of the time they spent working. In second place we find Lima, where this figure accounts for 8%. San Salvador, the city with the highest average number of hours worked, ranked fifth, with almost 4% of hours lost in traffic. Interestingly, despite the large differences in average hours worked and congestion dynamics per car user shown between the four largest cities in the ranking —Sao Paulo, Mexico City, Buenos Aires and Rio de Janeiro —all of these cities are among those that lost the least amount of time in relation to the average hours they worked, ranging from 2.5% to 3.5%. The city with the lowest proportion was Santo Domingo, where the loss was equivalent to 2% of the weekly hours worked.

Figure 3.4 Weekly hours worked per person vs. delay per car user in selected cities (2019)

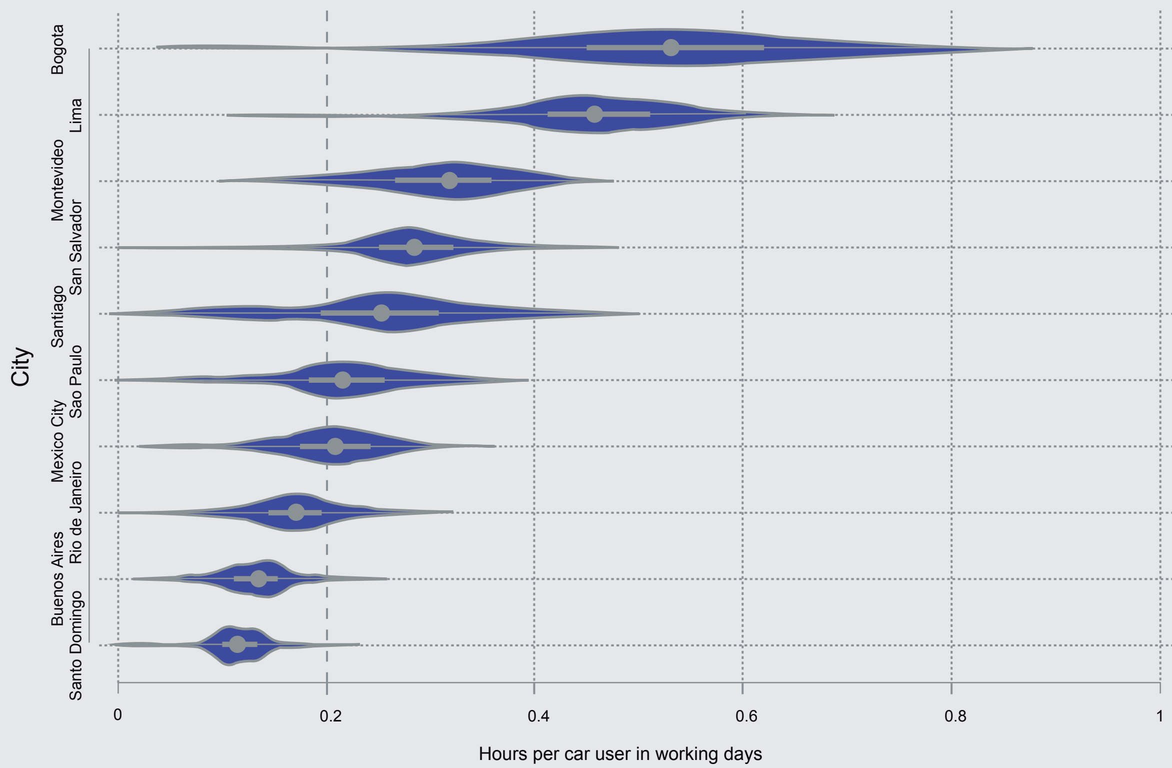


Source: Own calculations using data from Waze, ILO and WDI.

How variable is congestion in the cities analyzed? In Figure 3.5 we have included the distribution of hours lost in congestion per private vehicle user, on working days (Monday to Friday). The cities are ordered from highest to lowest according to the number of hours lost. The dotted line represents the overall median for the ten cities and the blue dots in each distribution represent the median of each city. On this basis, it can be observed that the **distribution of congestion** is quite volatile. Although some of the cities show a relatively normal distribution, especially Bogota, Rio de Janeiro and Buenos Aires[16], none of the cities met the threshold for a normal distribution as per the Shapiro-Wilk test. On the other hand, cities such as Santiago and Santo Domingo show a more irregular behavior with two marked peaks in the distribution. Two groups of cities are derived from Figure 3.5: San Salvador, Santiago, Santo Domingo, Sao Paulo and Rio de Janeiro, a group with high relative volatility, with a coefficient of variation greater than 0.4; while the other group: Mexico, Lima, Buenos Aires, Bogota, and Montevideo are the cities with the lowest coefficient of variation. The highest aggregate delay was recorded in Bogota with a peak of 58 minutes lost on average per car user on December 6.

16. Buenos Aires is the city with the highest tendency towards a normal distribution. The null hypothesis of normality at 5% cannot be rejected according to the Shapiro-Wilk test

Figure 3.5 Delay distribution for car users on working days, in selected cities (hours, 2019)

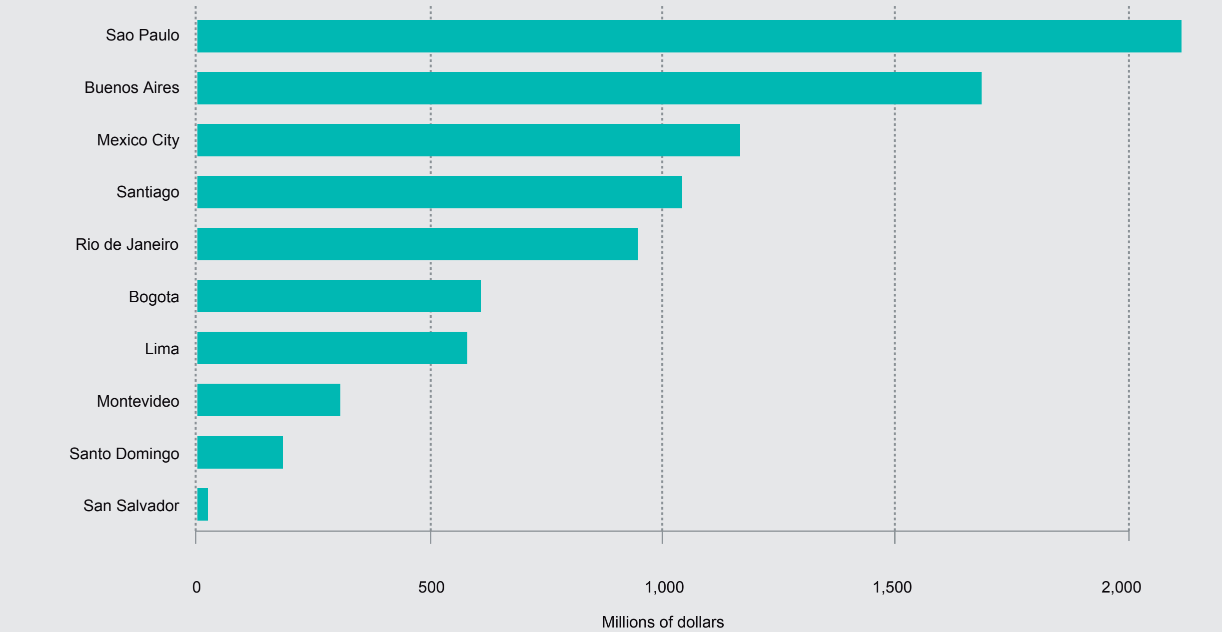


Source: Own calculations using data from Waze.

3.2 The cost of congestion in LAC cities

Having estimated the delay generated by congestion, the next step was to calculate the cost of congestion. To do so, we used the methodology described in Chapter 2, obtaining results for the ten cities under study. Figure 3.6 shows the **total congestion costs** for these cities. The difference in the positioning of the cities with respect to Figure 3.1 is mostly due to the value given to time in each of them. Thus, although 647 million hours were lost in Mexico City in 2019, compared to the 305 million hours in Buenos Aires, the value of each hour lost in Buenos Aires is higher. Consequently, while delays cost Mexico City US$ 1,168 million, the cost to Buenos Aires was 45% higher, amounting to US$ 1,691 million. The same can be said for Santiago with respect to Bogota and Rio de Janeiro.

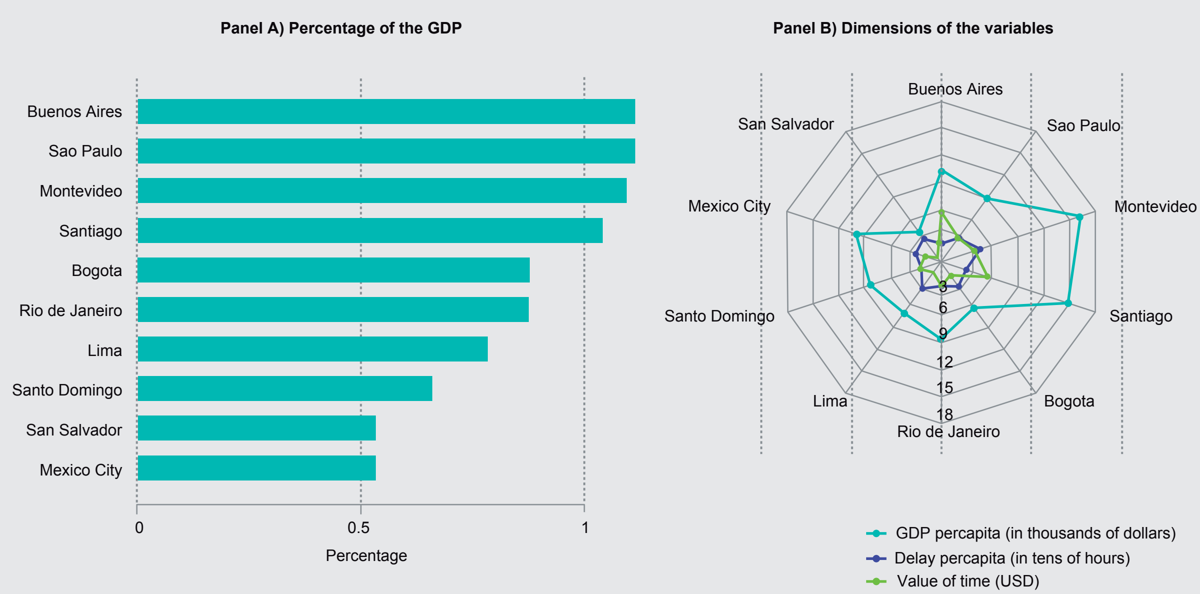
Figure 3.6 Total cost of congestion in selected cities (US$ million, 2019)



Source: Own calculations using data from Waze, ILO, and IFS.

In economic terms, these losses represent: 1.1% of the GDP in Buenos Aires, Montevideo and Sao Paulo; 1% in Santiago; 0.9% in Bogota and Rio de Janeiro; 0.8% in Lima; 0.7% in Santo Domingo; and 0.5% in San Salvador and Mexico City. To put into perspective what these losses imply, by way of example, congestion costs Buenos Aires and Mexico City 2 and 2.3 times what the local government invests in education. Sao Paulo's investment in health is equivalent to the cost of congestion. Similarly, Bogota's investment in providing care services for the vulnerable population is equivalent to two-thirds of what the city loses because of congestion.

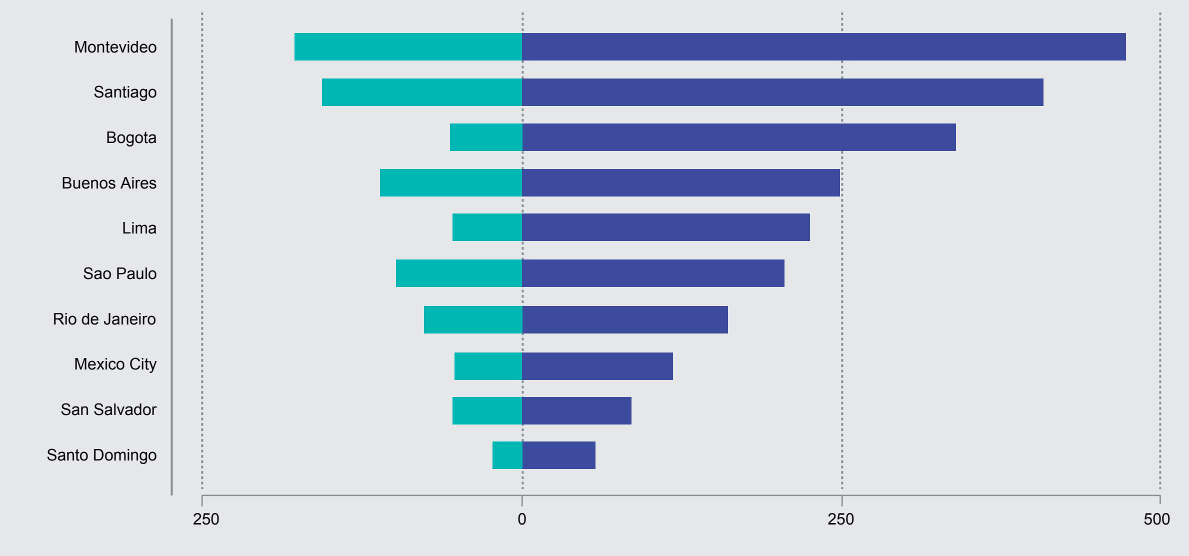
Figure 3.7 Total cost of congestion in selected cities



Source: Own calculations using data from Waze, ILO and IFS.

At the individual level, the annual cost of **congestion per person** in 2019 was highest in the cities of Montevideo (US$ 177), Santiago (US$ 156) and Buenos Aires (US$ 112) (Figure 3.8). Considering the cost per private vehicle user, the greatest losses occurred in Montevideo (US$ 474), Santiago (US$ 409) and Bogota (US$ 341). Again, the difference in the value of time explains the lower costs for cities such as San Salvador and Mexico City, and the rise to the top of the ranking for Montevideo and Santiago, with respect to the data presented on Figure 3.2.

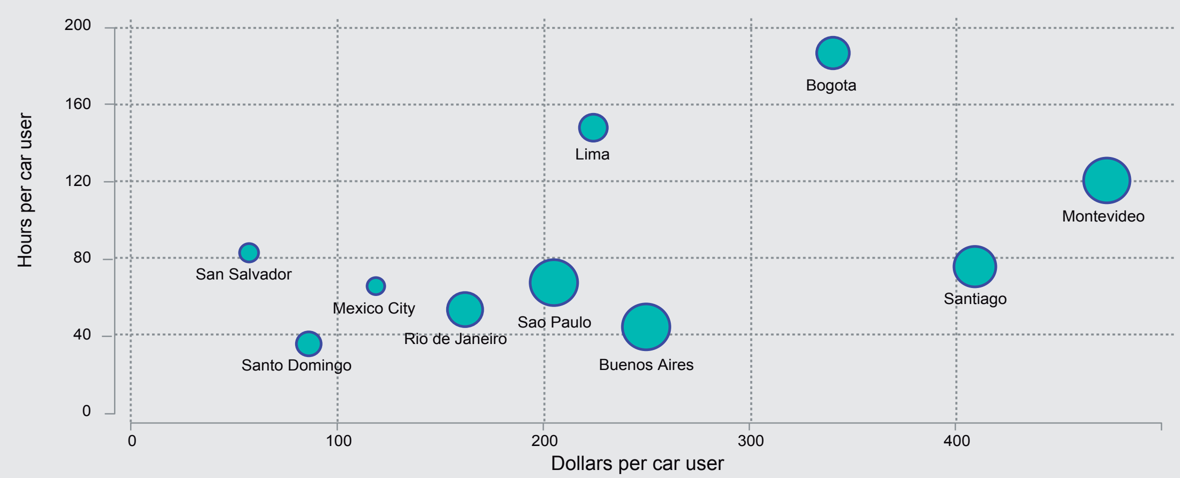
Figure 3.8 Cost per person vs. cost per car user, selected cities (US$, 2019)



Source: Own calculations using data from Waze, ILO, IFS and WDI

Figure 3.9 compares the cost of **congestion per car user and per capita**. The size of the circumference indicates the weight of the aggregate cost of congestion on the city's GDP. The graph shows that while Bogota and Lima registered higher delays per car user than Santiago and Montevideo, congestion costs in the latter two cities are higher. In addition, even though Sao Paulo and Mexico show very similar aggregate delay dynamics, they differ significantly in terms of the cost per car user and the weight of congestion in their economies.

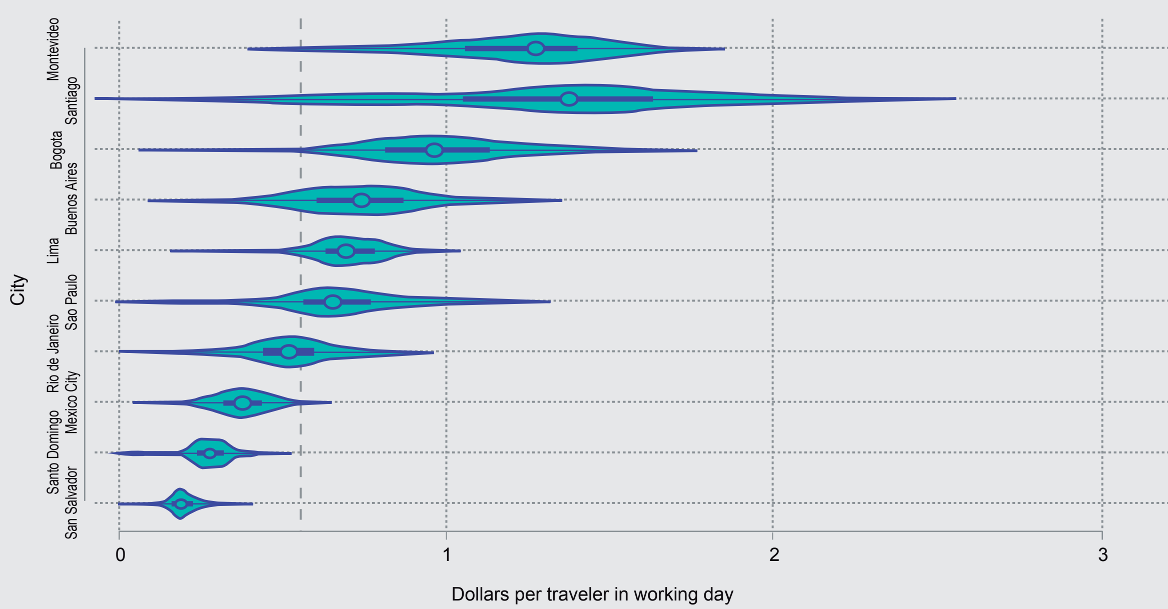
Figure 3.9 General comparison of the results, selected cities (2019)



Source: Own calculations using data from Waze, ILO, IFS and WDI.

How much does congestion cost per day? Montevideo and Santiago are the cities with the most discouraging figures: on a **working day**, drivers lose US$ 1.2 and US$ 1.3 in congestion, respectively. This figure is worrisome considering that the median daily wage[17] is US$31 and US$25, respectively, which represents 4% and 5% of the median labor income for each city. Among all the cities analyzed, Santiago registered the maximum congestion costs in 2019 in one day, reaching a loss of more than 3 dollars per driver. This figure was recorded on October 18, when several road and public transportation closures occurred due to demonstrations in the city. Among the cities analyzed, Santiago and San Salvador are the cities with the highest relative volatility, while Montevideo and Lima are the cities with the lowest relative variance.

Figure 3.10 Congestion cost per traveler on weekdays, selected cities (US$, 2019)

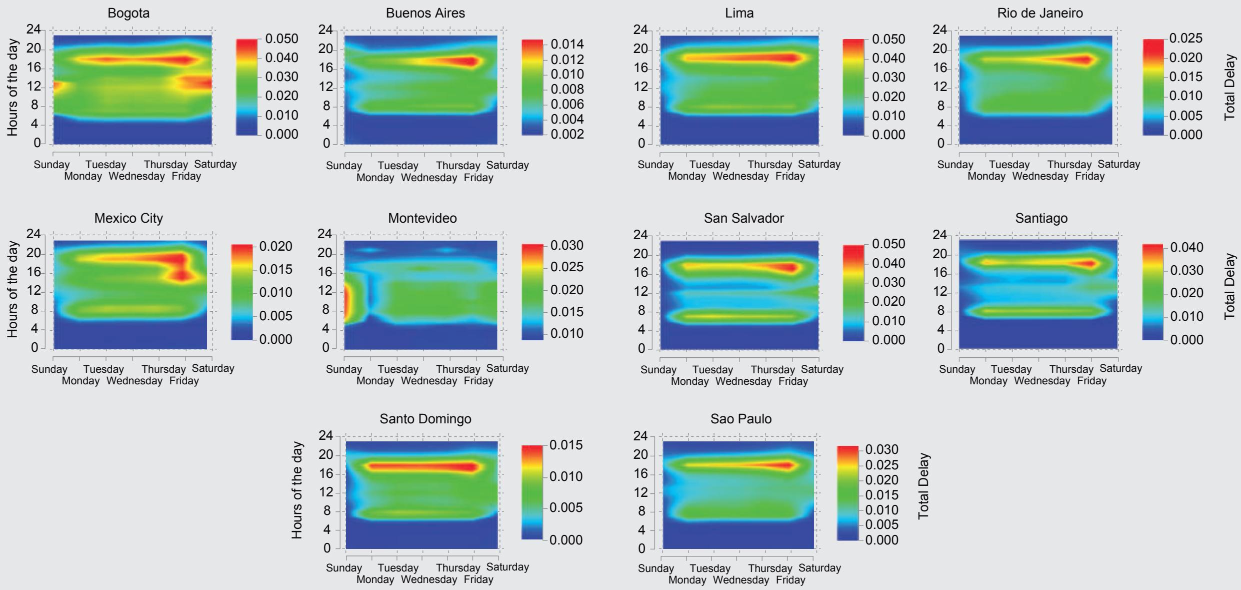


Source: Own calculations using data from Waze, IFS and WDI.

Finally, the **temporal distribution of congestion** can shed more light on when the greatest delays —and, therefore, the greatest economic losses— occur. This can be very useful for the development of public policies to reduce congestion. In Figure 3.11, it becomes apparent that, in most cities, congestion tends to worsen in the evening peak, especially towards the end of the work week (Thursday and Friday). Some cities have other peaks around midday (Bogota, Mexico and Montevideo). Morning peak congestion is usually less severe than evening peak congestion.

17. The median wage has been calculated as the median labor income of employed people —according to the ILO definition— with data from INE-Uruguay and INE-Chile.

Figure 3.11 Hourly distribution of congestion in selected cities (hours, 2019)



Source: Own calculations using data from Waze.

3.3 Analysis by city

A detailed analysis of congestion and its costs for each of the ten selected cities is presented below. In this analysis, we identify **spatial and temporal congestion patterns** as an input for public policy decisions. In fact, knowing these patterns will allows, among others: (i) to establish critical areas/moments that require public sector action to improve urban mobility; (ii) to make geographic and temporal comparisons within the urban area and with other cities; and (iii) to monitor trends and evaluate the effects of the measures taken to mitigate congestion.

Bogota

In 2019, Bogota recorded an aggregate delay of 335 million hours, ranking as the fourth city with the longest delays among the ten LAC cities analyzed. Each inhabitant of the Colombian capital lost 31 hours in traffic (position 5/10), however, if we consider the delay per private vehicle user, the delay amounted to 186 hours (position 1/10).

In the same year, the total cost of congestion in Bogota exceeded US$ 600 million, which translates into almost US$ 2 million per day. This figure is highly relevant, since it represents close to 1% of the city's GDP and is similar to what the local government invests in health. With regard to the number of car users, each Bogota driver loses more than US$340 per year due to congestion (9% of median annual labor income), which makes it the third city with the highest costs of congestion.

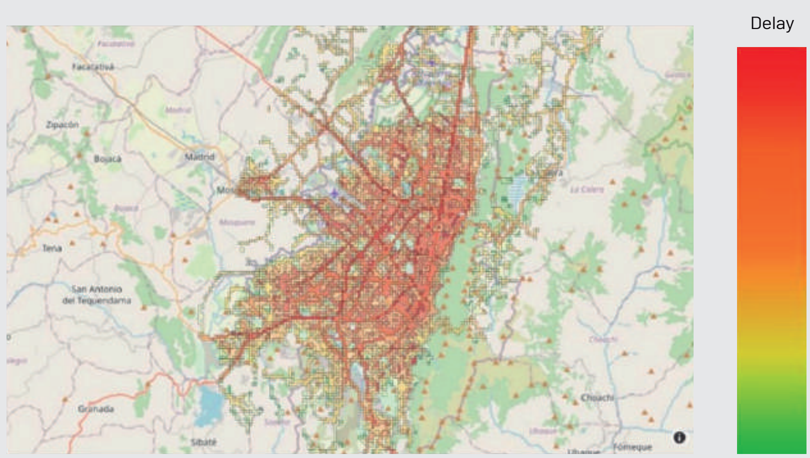
Table 3.2 Overall results for Bogota

Indicator	Value (2019)	
Total congestion	335	Millions of hours
Congestion per person	31	Hours
Congestion per car user	186	Hours
Daily congestion	0.9	Millions of hours
Total congestion cost	612	US$ Millions
Congestion cost per person	57	US$
Congestion cost per car user	340	US$
Total daily congestion cost	1.7	US$ Millions
Congestion cost in relation to the GDP	0.88%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

With regard to the spatial patterns of congestion in Bogota, a greater number of congested areas can be observed in the central-eastern and northern sectors of the city. However, when compared to other LAC cities, congestion is much less geographically concentrated than in cities such as Buenos Aires and Lima, for example. This may have relevant implications for the implementation of public policies such as cordon congestion tolls, which are usually applied in cities where congestion is concentrated in a certain geographic area. The most congested roads in Bogota are Autopista Norte, Calle 80, Autopista Sur - NQS and Avenida El Dorado.

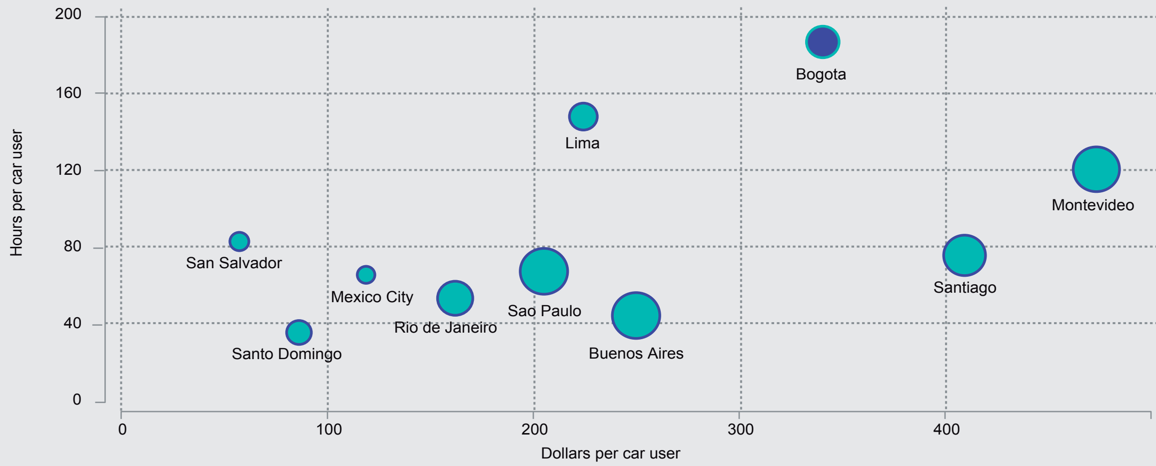
Figure 3.12 Spatial distribution of congestion (Bogota, 2019)



Source: Own calculations using data from Waze.

Figure 3.13 shows a comparison in three dimensions: the delay per car user on the abscissa axis, the cost per car user on the ordinate axis and the cost relative to the size of the economy on the relative size of the circumference. This graph shows that Bogota registers average values with respect to the other cities considered. It is the third city in terms of monetary cost per car user and the city that accumulates the longest delay. Bogota has the fifth highest cost of congestion relative to its economy.

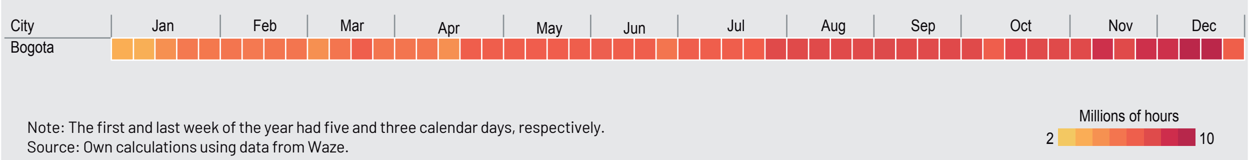
Figure 3.13 Comparison of results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

As for the temporal distribution of congestion, Figure 3.14 shows a clear upward trend throughout the year, with a peak of 9.7 million hours lost in the second week of December, representing almost 3% of the total delay. These figures were determined, in part, by the public demonstrations encountered during the last two months of 2019, which were more intense that week. On the other hand, traffic congestion levels in January and February were particularly light. These two months added about 40 million hours, representing 12% of the total 2019 congestion.

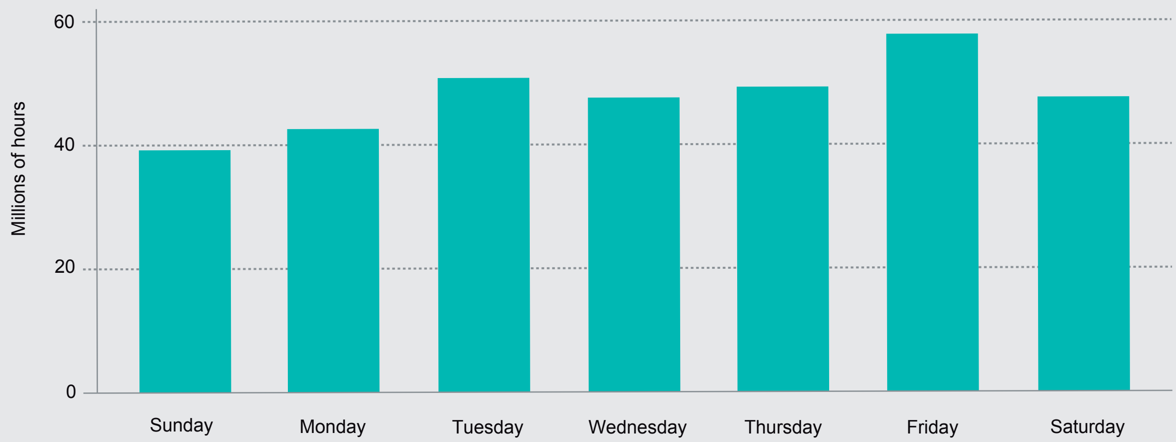
Figure 3.14 Annual congestion distribution by month (Bogota, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

As for the distribution by day of the week, the longest delays were recorded on Tuesdays and Fridays (Figure 3.15). It is worth noting the high level of congestion on Saturdays, with higher levels than on Wednesdays. Likewise, on Sunday, levels were 82% higher than the levels for the same day in the rest of the cities.

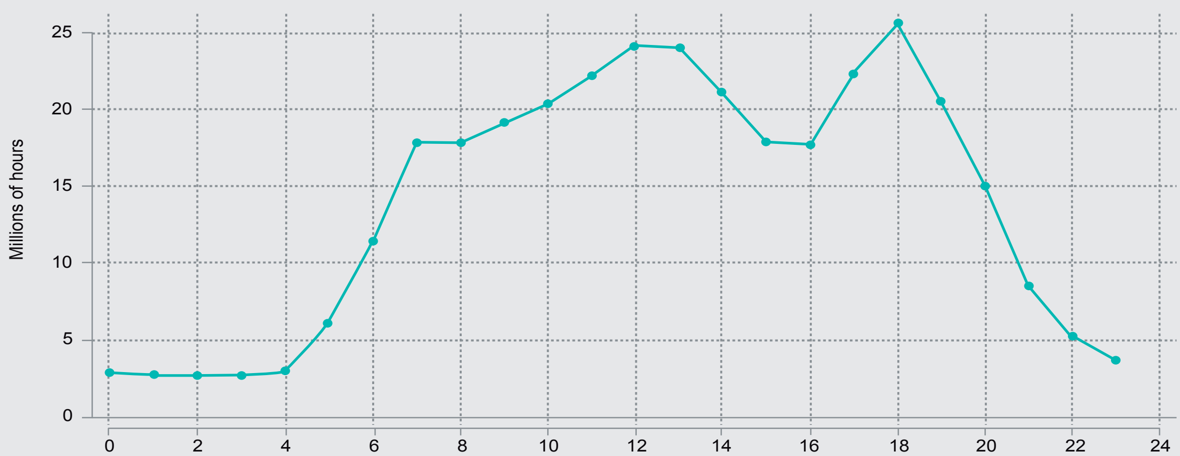
Figure 3.15 Congestion distribution by day of the week (Bogota, 2019)



Source: Own calculations using data from Waze.

Finally, Figure 3.16 shows the distribution of congestion throughout the day. There are two peaks of delays: between 10 am and 2 pm, and between 5 pm and 7 pm. As in the other cities analyzed, the longest delays occur in the evening peak. Unlike other cities, the morning peak takes place later in the day, which could be attributed to the city's *Pico y Placa* driving restriction policy.

Figure 3.16 Congestion distribution by time of day (Bogota, 2019)



Source: Own calculations using data from Waze.

Buenos Aires

Argentina's capital ranked as the sixth city with the highest aggregate congestion level, exceeding the 300-million-hour mark in 2019. In relative terms to its population, this translated into a loss of 20 hours per person (position 10/10) and 45 hours per car user (position 9/10), obtaining a better relative performance in comparison to the rest of the cities analyzed.

Despite this, congestion costs are considerably high for the city. In total, these exceeded US$ 1.69 billion -US$ 4.6 million on average per day-, which means that the capital city of Argentina is the second city with the highest costs, surpassing Mexico City and only behind Sao Paulo -despite being significantly smaller in terms of population. This figure translates into 1.1% of the city's GDP, or almost twice what the local government invests in education. At the individual level, each private vehicle user lost US$ 250 per year to congestion (3% of per capita income).

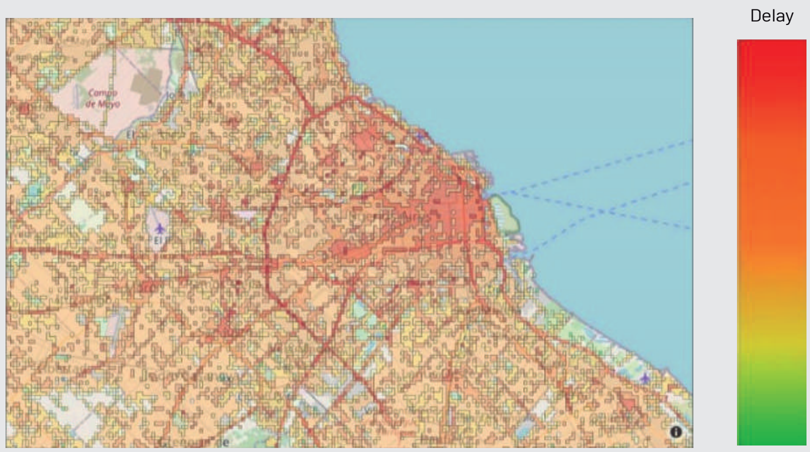
Table 3.3 Overall results for Buenos Aires

Indicator	Value (2019)	
Total congestion	305	Millions of hours
Congestion per person	20	Hours
Congestion per car user	45	Hours
Daily congestion	0.8	Millions of hours
Total congestion cost	1,691	US$ Millions
Congestion cost per person	112	US$
Congestion cost per car user	249	US$
Total daily congestion cost	4.6	US$ Millions
Congestion cost in relation to the GDP	1.12%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.17 shows the spatial distribution of congestion in Buenos Aires. This shows the high concentration of congestion in the downtown area and the area surrounding the port. Avenida General Paz, the boundary between the Autonomous City of Buenos Aires and the rest of the Metropolitan Area, is the most congested avenue, followed by the freeways connecting the downtown area with the rest of the province of Buenos Aires (Autopista Panamericana, Autopista General Pablo Riccheri and Autopista Dr. Ricardo Balbín).

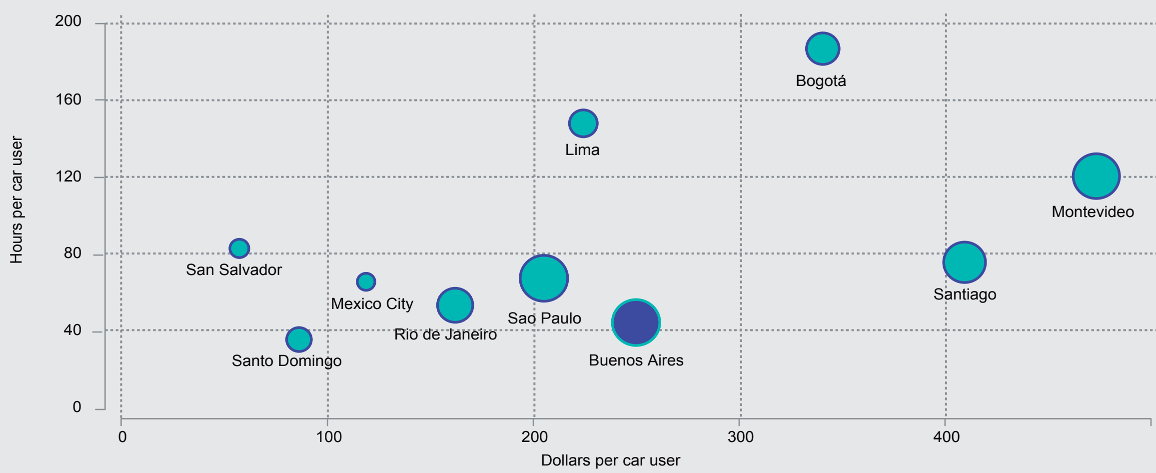
Figure 3.17 Spatial distribution of congestion (Buenos Aires, 2019)



Source: Own calculations using data from Waze.

According to Figure 3.18, Buenos Aires was the city with the highest congestion costs in relation to its GDP -although quite close to Sao Paulo and Montevideo- and the fourth city with the highest cost per car user. However, it should be noted that this is so because of the high value of time in this city, since, in terms of delay per car user, it only ranked ninth (out of 10), with a delay of 45 hours.

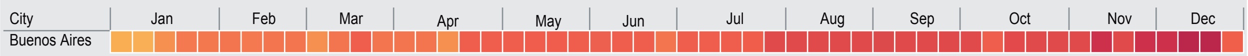
Figure 3.18 Comparison of results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

As regards the temporal behavior of congestion, Figure 3.19 shows that congestion was relatively low in the first months of the year, and then numbers increased until they reached their maximum levels halfway through the year. From that moment on, figures decreased slightly, returning to the levels seen at the beginning of the year. Thus, both the second and third quarters registered 27% of the congestion in the capital city of Argentina, in contrast to the 23% and 24% estimated for the first and fourth quarters, respectively.

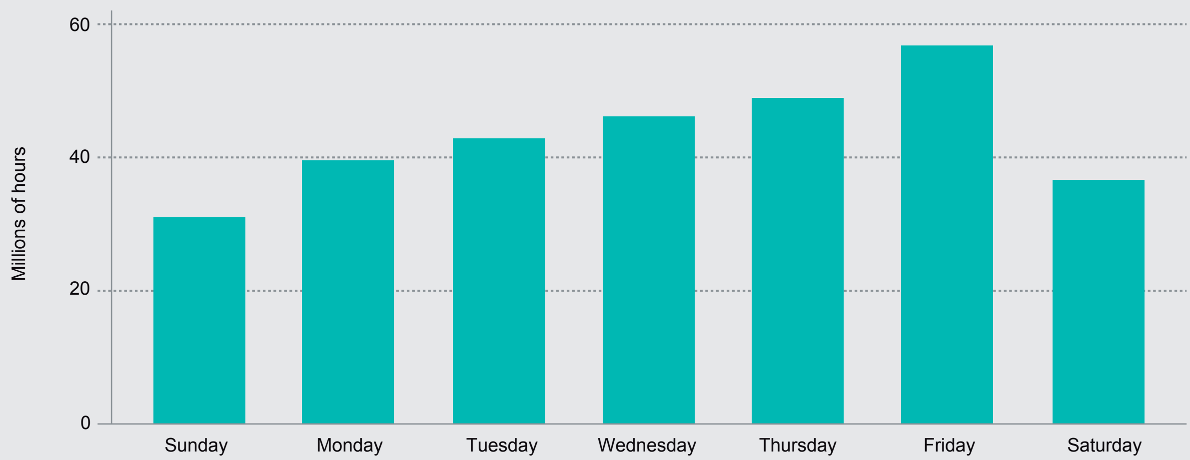
Figure 3.19 Annual congestion distribution by month (Buenos Aires, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

With regard to the weekly distribution of congestion, it increases between Monday and Friday, reaching the highest delays on the latter day. On average, the level of congestion on weekdays was 39% higher than on weekends. On the other hand, Sundays were the days with the lowest aggregate delay.

Figure 3.20 Spatial distribution of congestion (Buenos Aires, 2019)



Source: Own calculations using data from Waze.

On a daily basis, congestion in Buenos Aires tends to increase between 4 pm and 7 pm. In fact, 28% of the city's total congestion occurred between those hours, with more than 86 million hours lost to delays throughout 2019. This figure is higher than the total delay calculated for all of Montevideo. Two other peaks occur at 8 am and 12 pm, although their levels are significantly lower than those of the evening peak.

Figure 3.21 Congestion distribution by time of day (Buenos Aires, 2019)

Source: Own calculations using data from Waze.

Lima

The Peruvian capital ranked as the third city with the highest aggregate congestion level, with a total loss of 384 million hours for 2019. Lima recorded the second longest delay per person (36 hours) and the second longest delay per private vehicle user (148 hours), surpassed only by Montevideo in the first indicator and Bogota in the second. In 2019, the cost of congestion reached US$ 582 million, amounting to almost US$ 1.6 million per day. The loss per car user in the Peruvian capital city was US$224 (position 5/10), which represents 5% of the median labor income of the city's inhabitants.

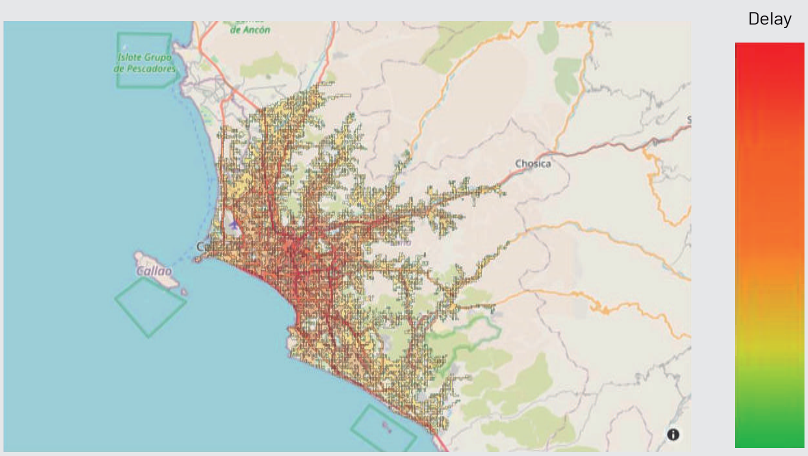
Table 3.4 Overall results for Lima

Indicator	Value (2019)	
Total congestion	384	Millions of hours
Congestion per person	36	Hours
Congestion per car user	148	Hours
Daily congestion	1.1	Millions of hours
Total congestion cost	582	US$ Millions
Congestion cost per person	55	US$
Congestion cost per car user	224	US$
Total daily congestion cost	1.6	US$ Millions
Congestion cost in relation to the GDP	0.79%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

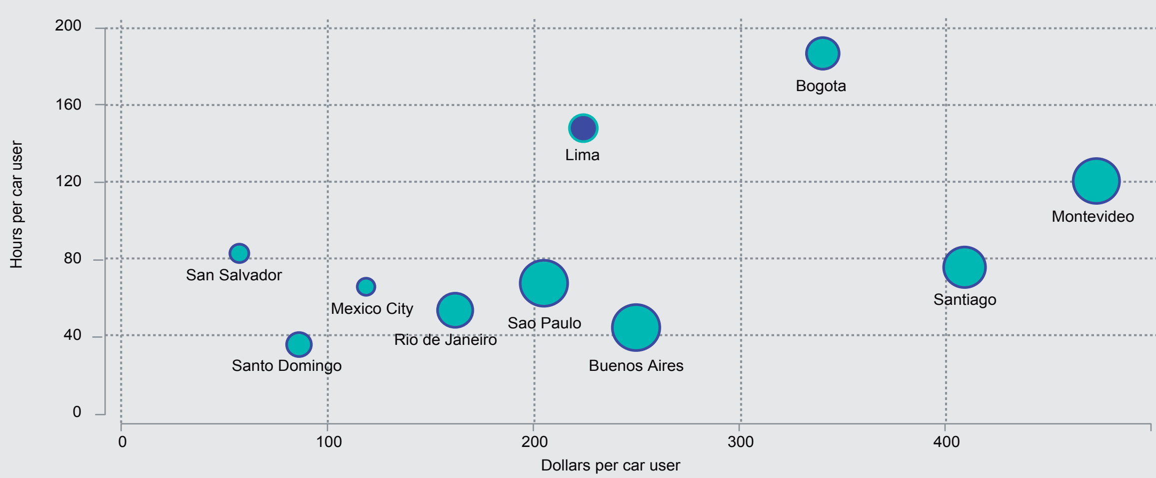
Congestion in Lima is quite spatially dispersed. Figure 3.22 allows us to identify at least 3 main areas with the highest congestion levels: (1) the *Cercado de Lima*, the city center, the hub of economic activities and where the Plaza de Armas is located; (2) the *Malecón* in the central-west area of the city; and (3) *Miraflores and La Victoria*, two districts that are inhabited by the city's higher-income population and where is usually a higher motorization rate. Paseo de la República is the avenue with the highest aggregate congestion levels.

Figure 3.22 Spatial distribution of congestion (Lima, 2019)



According to Figure 3.23, Lima ranked second among the cities with the longest delays per car user. However, the cost per car user in this city was only US$224 per year, thus occupying fifth place in the ranking. Due to its low value of time, together with its relatively low motorization rate, the Peruvian capital city ranked 7/10 in terms of congestion costs in relation to its GDP (0.8%). This is despite having the third highest level of total congestion, surpassing cities with larger populations such as Rio de Janeiro and Buenos Aires.

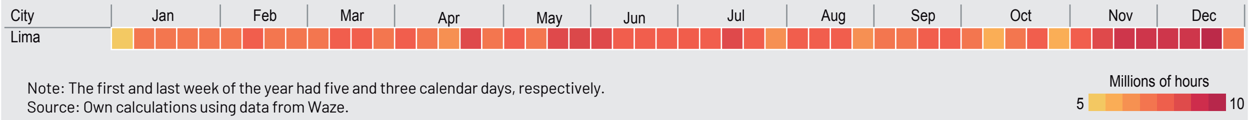
Figure 3.23 Comparison of results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Regarding the annual dynamics of congestion, the lowest levels occurred at the beginning of the year and in October (Figure 3.24). November and December recorded the highest aggregate delay volumes, with more than 70 million hours lost in these two months (almost 20% of the total hours). The penultimate week of the year alone accumulated more than 10 million hours of delay.

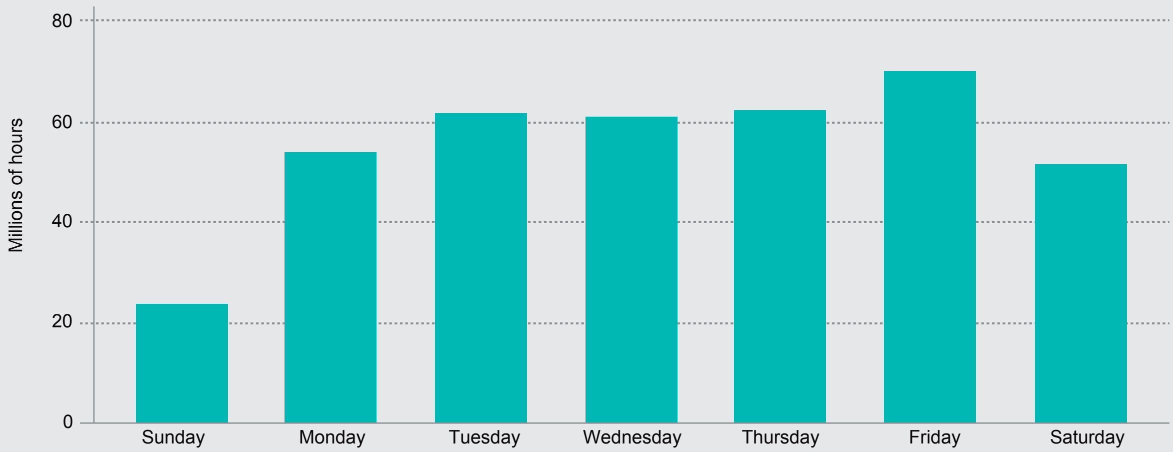
Figure 3.24 Annual congestion distribution by month (Lima, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

The weekly distribution of congestion is within the expected parameters: the highest peak was registered on Friday, an increasing trend between Monday and Friday and a marked decrease on weekends. On average, there is 65% more congestion on a weekday than on a weekend day.

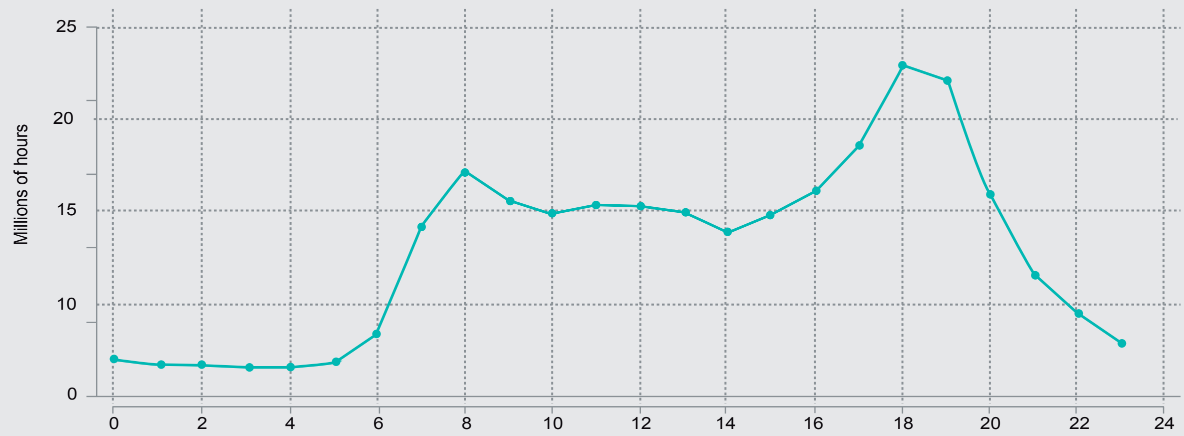
Figure 3.25 Congestion distribution by day of the week (Lima, 2019)



Source: Own calculations using data from Waze.

Figure 3.26 shows the distribution of congestion throughout the day. Lima has three distinct congestion peaks in the morning, midday and evening, the latter - between 4 p.m. and 7 p.m. - being the most acute peak, registering almost a third of the total congestion. Congestion is so intense during the evening peak that, even though 14 out of the 24 hours of a day have more congestion than the hourly average, between 6 p.m. and 7 p.m. congestion levels more than double that average.

Figure 3.26 Congestion distribution by time of day (Lima, 2019)



Source: Own calculations using data from Waze.

Mexico City

In 2019, Mexico City ranked second for the highest level of congestion. Together with Sao Paulo, they are the only two cities that surpassed the 500-million-hour mark of hours lost to congestion. Aggregate congestion in Mexico City was 70% higher than in Lima, which holds the third position in the ranking; this means there is a wide gap between the two cities with the highest levels and the rest of cities. However, when analyzing delays per person (30 hours) and per car user (66 hours), Mexico City ranks relatively better: sixth and seventh place, respectively.

Mexico recorded the third highest congestion cost, being one of the four cities that exceeded US$1 billion. This means that every day, on average, the city lost more than US$3.2 million to congestion. This figure is more than double what the local government invests in education. The cost per car user amounted to nearly 3% of the city's median labor income, totaling US$119 over 2019.

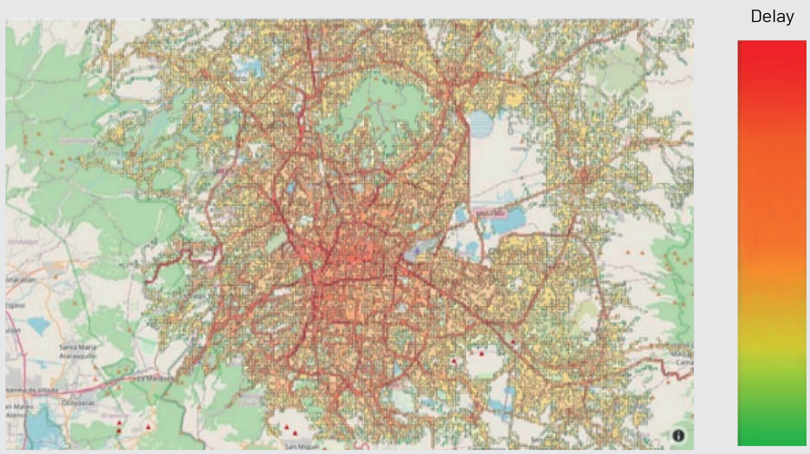
Table 3.5 Results of the analysis for Mexico City

Indicator	Value (2019)	
Total congestion	647	Millions of hours
Congestion per person	30	Hours
Congestion per car user	66	Hours
Daily congestion	1.8	Millions of hours
Total congestion cost	1,168	US$ Millions
Congestion cost per person	54	US$
Congestion cost per car user	119	US$
Total daily congestion cost	3.2	US$ Millions
Congestion cost in relation to the GDP	0.55%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

In Figure 3.27 it can be observed that the central axis of congestion dynamics in Mexico City is made up of the areas of La Condesa, Zócalo, Chapultepec and the financial center. It is also worth noting the importance of the Circuito Interior, Vialidad Río de la Piedad and Avenida Río Churubusco. However, the longest delays occur on the main avenues and peripheral highways that move traffic to and from downtown Mexico City.

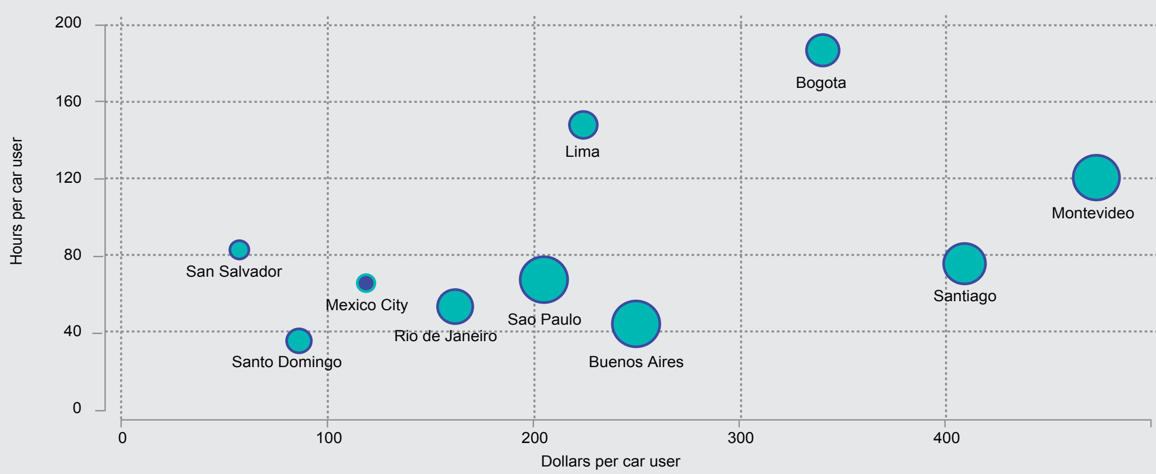
Figure 3.27 Spatial distribution of congestion (Mexico City, 2019)



Source: Own calculations using data from Waze.

Despite being the city with the second highest aggregate delay, and the sixth city controlling for population, the Mexican capital stands out for having relatively low congestion costs with respect to its economy. This amounted to 0.6% of its GDP in 2019, being the ninth in the ranking and very close to San Salvador, the city with the lowest value in this indicator (see Figure 3.28). Also, influenced by the low value of time, the annual cost per car user represented about US$ 119 (position 8/10).

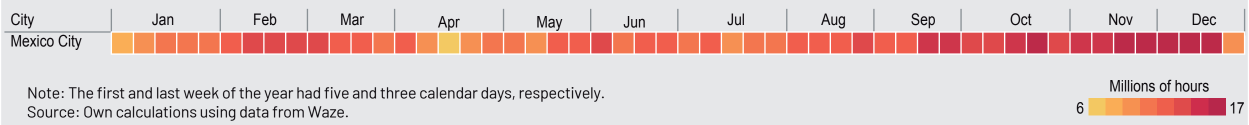
Figure 3.28 Comparison of results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.29 shows the distribution of congestion throughout the year in Mexico City. There is an upward trend, interrupted only on three occasions: April, July and the last week of the year. October stands out as the month with the highest congestion levels, accounting for almost 70 million hours lost, which is equivalent to almost the total aggregate delay of Montevideo in 2019. Congestion in Mexico City is particularly concentrated in the last quarter of the year: 190 million hours, equivalent to 30% of the annual value.

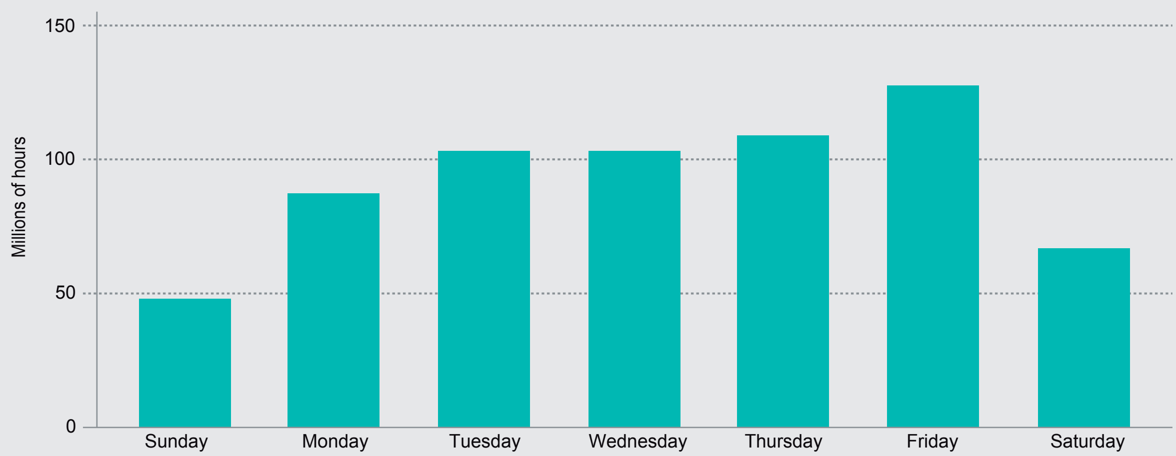
Figura 3.29 Annual congestion distribution by month (Mexico City, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

Mexico City presents a weekly distribution of congestion quite similar to that of the preceding cities, with an upward trend from Monday to Friday, reaching the highest aggregate delay on Friday (almost 130 million hours) and decreasing on weekends (see Figure 3.30). With regard to the latter, on average, congestion on a working day is 85% higher than on a typical weekend day.

Figure 3.30 Congestion distribution by day of the week (Mexico City, 2019)



Source: Own calculations using data from Waze.

The city registered three well-marked peaks (see Figure 3.31), although a little later than in other cities. The most significant peak happens in the evening, between 5 p.m. and 8 p.m., when 29% of the city's aggregate delay accumulates. It is worth noting that, in this time interval, Mexico City loses to congestion an amount close to the total of what Santiago loses in the whole year.

Figure 3.31 Congestion distribution by time of day (Mexico City, 2019)

Figure 3.31 Source: Own calculations using data from Waze.

Montevideo

The capital city of Uruguay was the third city with the lowest aggregate delay among those analyzed, registering a total of 79 million hours lost in 2019. However, it recorded the longest delay per inhabitant (45 hours; 24% longer than Lima, the second city in the ranking). This, coupled with the higher value of time, resulted in Montevideo having the highest congestion cost per person and per car user: US$ 177 and US$ 474, respectively. The value of the delay per car user is equivalent to 4% of the median labor income. Montevideo is the city with the third highest congestion cost relative to its economy, exceeding 1% of its local GDP.

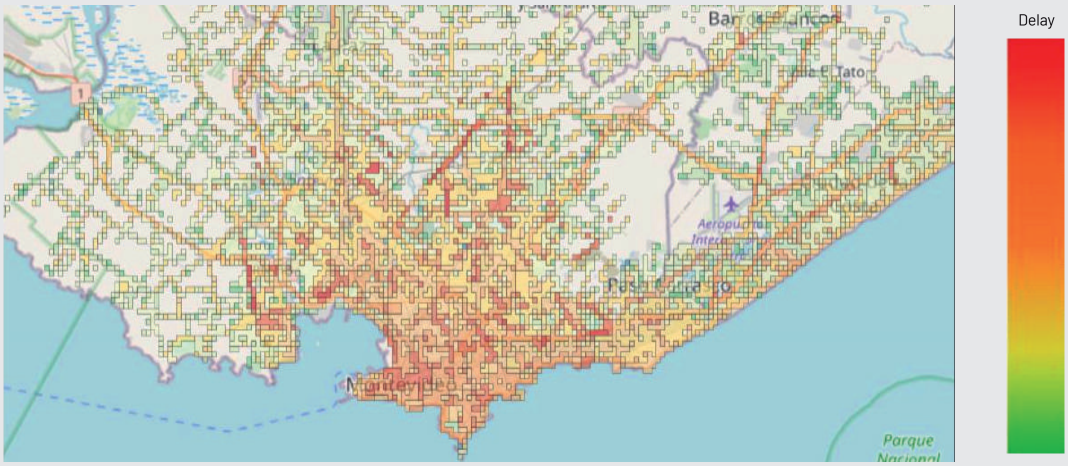
Table 3.6 Results of the analysis for Montevideo

Indicator	Value (2019)	
Total congestion	79	Millions of hours
Congestion per person	45	Hours
Congestion per car user	121	Hours
Daily congestion	0.2	Millions of hours
Total congestion cost	310	US$ Millions
Congestion cost per person	177	US$
Congestion cost per car user	474	US$
Total daily congestion cost	0.8	US$ Millions
Congestion cost in relation to the GDP	1.10%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.32 shows the spatial distribution of congestion in Montevideo. Although it is spread throughout the city, the highest levels are found in the downtown area and the area around the port. The main roads where congestion is concentrated are General Manuel Oribe, entering from the west to downtown, and Avenida General Flores.

Figure 3.32 Spatial distribution of congestion (Montevideo, 2019)

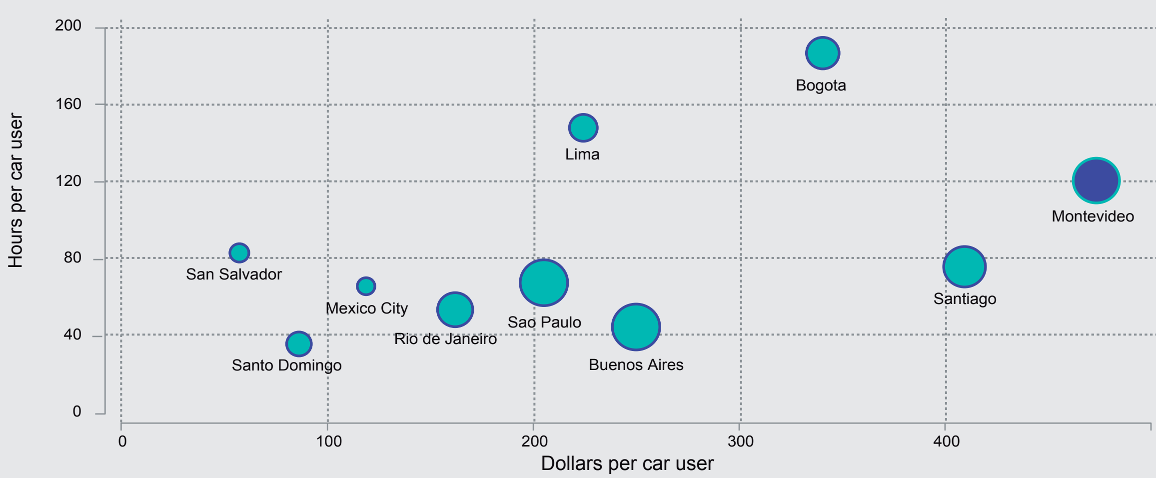


Source: Own calculations using data from Waze.

Figure 3.33 compares Montevideo's results with those of the other cities analyzed. Montevideo registered the third highest delay per private vehicle user and cost relative to its GDP, apart from being the city with the highest cost per car user.

These figures are mainly driven by an atypical year in the capital of Uruguay due to an excessive number of reparations on the road network in 2019. In fact, the city had a total of 22 road closures per resident compared to the regional average of 1 road closure per habitant. These closures have caused a significant increase of congestion in Montevideo relative to a regular year and, more importantly, they have caused an irregular distribution of congestion during the year, hour of the day, and day of the week as will be shown in the following figures of this section.

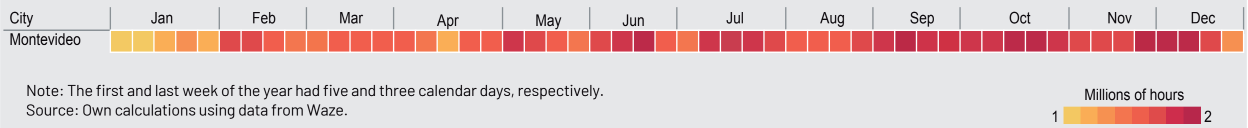
Figure 3.33 Comparison of the results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.34 shows the temporal distribution of congestion in Montevideo for the year 2019. Delays increased over the course of the year, reaching a peak in October (80% increase over January levels, going from 4.3 million hours of delay to 7.9 million). The weeks with the highest congestion were the second week of December and the third week of June, accumulating 2.4 and 2.3 percent of the year's total, respectively.

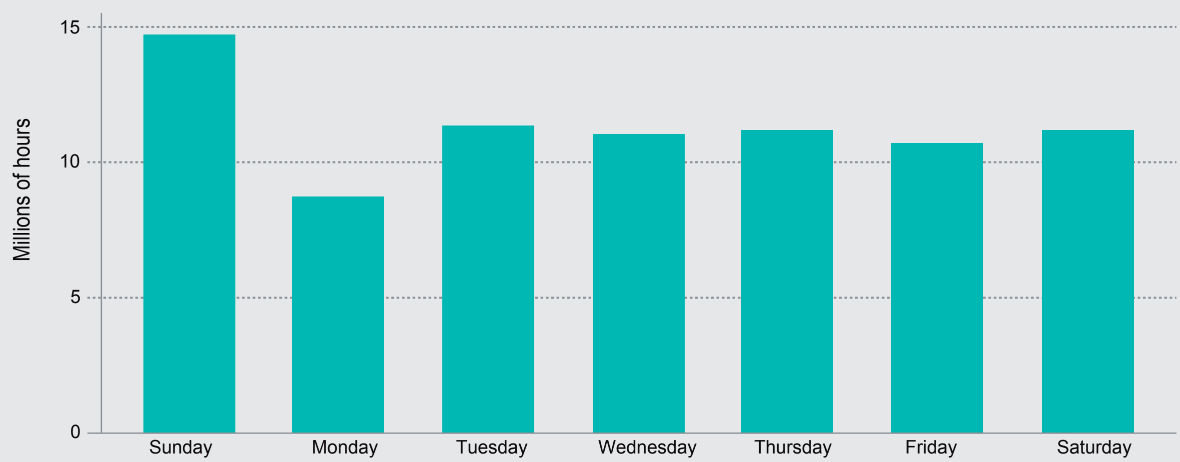
Figure 3.34 Annual congestion distribution by month (Montevideo, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

Figure 3.35 shows the distribution of congestion during the week. The Uruguayan capital city shows an atypical behavior of the aggregate delay, since, unlike the trend in most cities, Sunday is the day with the longest aggregate delay. On this day, 14.6 million hours were lost in congestion, representing more than 19% of the total. It is worth mentioning that, given that the urban area considered in this analysis includes the coastal areas surrounding the city limits, which receive a large number of trips during the weekend, it is to be expected that high levels of congestion will occur on Sundays, mainly due to the return to the Uruguayan capital city before the start of the work week.

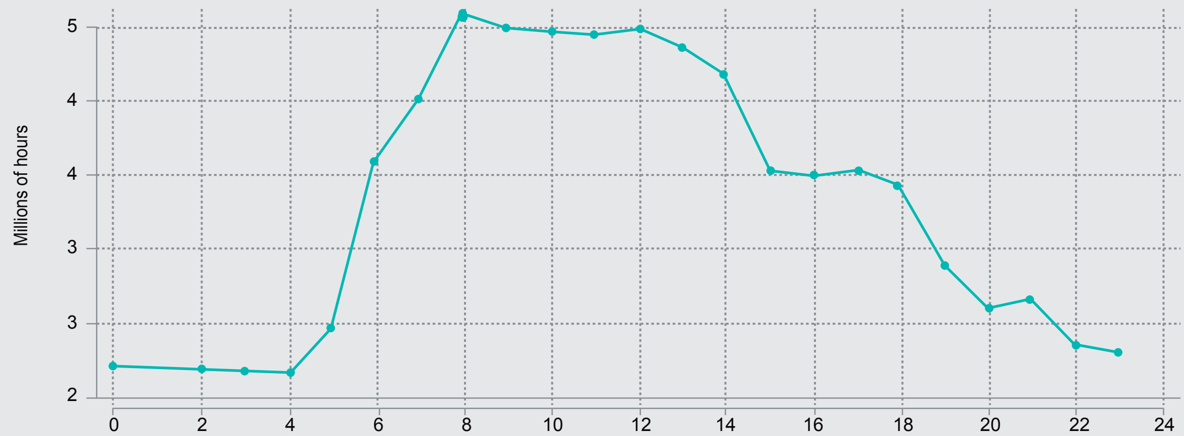
Figure 3.35 Congestion distribution by day of the week (Montevideo, 2019)



Source: Own calculations using data from Waze.

Similarly, congestion behaved differently during the day in comparison to the previous cities (see Figure 3.36). The busiest hours are registered during the morning, especially at 8:00 am. From then on, constant trend is maintained until 2:00 p.m., when it begins to decrease.

Figure 3.36 Congestion distribution by time of day (Montevideo, 2019)



Source: Own calculations using data from Waze.

Rio de Janeiro

Rio de Janeiro had an aggregate delay of more than 312 million hours in 2019 (position 5/10). Due to the size of the city, each person lost, on average, 25 hours, which is why it ranked eighth for this indicator, a position it maintained if the number of car users is considered (54 hours).

In 2019, congestion cost the city more than US$ 943 million (5/10 position), representing 0.9% of its aggregate output. In context, congestion cost Rio de Janeiro more than half of what the city invested in education. Costs per person amounted to US$ 77 (5/10 position), and each car user recorded losses of almost US$ 162, representing 3% of the median labor income.

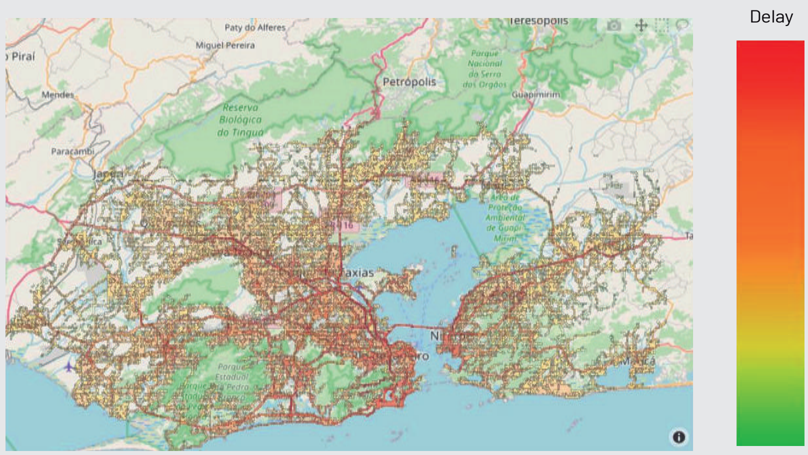
Table 3.7 Results of the analysis for Rio de Janeiro

Indicator	Value (2019)	
Total congestion	312	Millions of hours
Congestion per person	25	Hours
Congestion per car user	54	Hours
Daily congestion	0.9	Millions of hours
Total congestion cost	943	US$ Millions
Congestion cost per person	77	US$
Congestion cost per car user	162	US$
Total daily congestion cost	2.6	US$ Millions
Congestion cost in relation to the GDP	0.88%	

Source: Own calculations using data from Waze, ILO, IFS and .

The spatial distribution of congestion in Rio de Janeiro is highly polycentric. The most relevant focal points are located in the northwest, downtown (near the port area), the east and the areas of greatest tourist activity in the south of the city. Joao Goulart Avenue, which crosses the city from north to south, registers the highest levels of aggregate congestion, followed by Brasil and Trajano Silva Avenues, which connect the northwest with the city center.

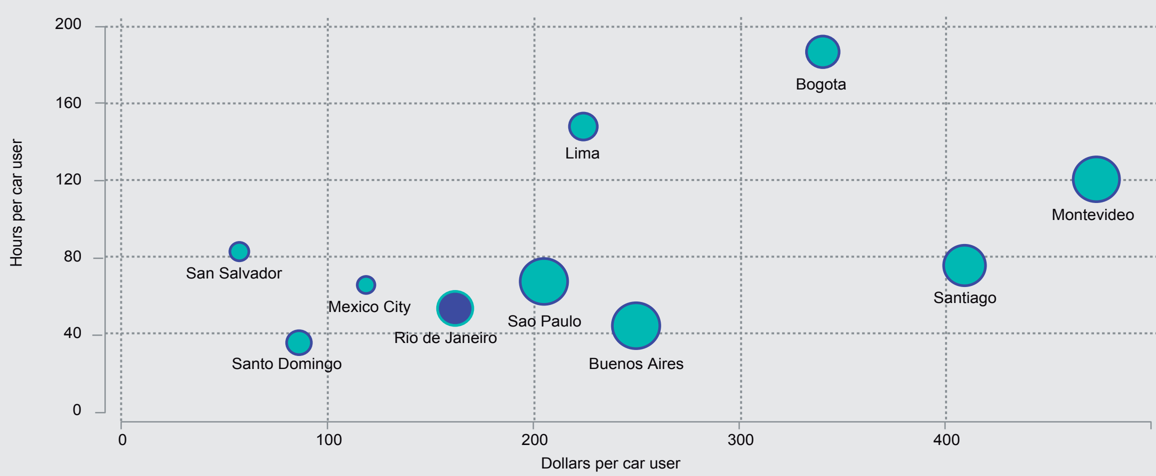
Figure 3.37 Spatial distribution of congestion (Río de Janeiro, 2019)



Source: Own calculations using data from Waze.

Compared to the other cities analyzed, Rio de Janeiro performed relatively well in terms of congestion in LAC (see Figure 3.38). It was the eighth city with the longest delay and the seventh with the highest cost per car user. In relation to its GDP, the cost of congestion was 0.9%, which makes it the sixth city with the highest value for this indicator.

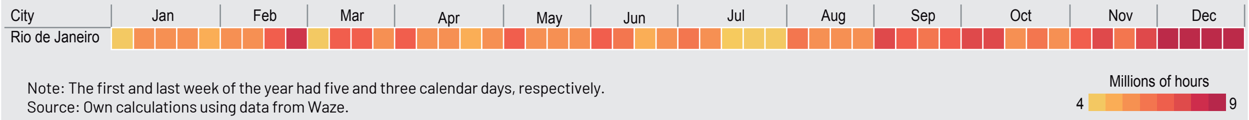
Figure 3.38 Comparison of the results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Congestion in Rio de Janeiro has a particular temporal dynamic: it maintains a relatively constant trend throughout the year, with marked exceptions such as the end of February, when the carnival takes place, or the first weeks of September. Thus, each of the first three quarters of the year accounts for 23% of congestion. In the last quarter, congestion intensified, accumulating more than 90 million hours of delay, equivalent to 30% of the total. December alone recorded more than 11% of the aggregate congestion, reaching a peak in the third week of this month, with almost 9 million hours lost (see Figure 3.39).

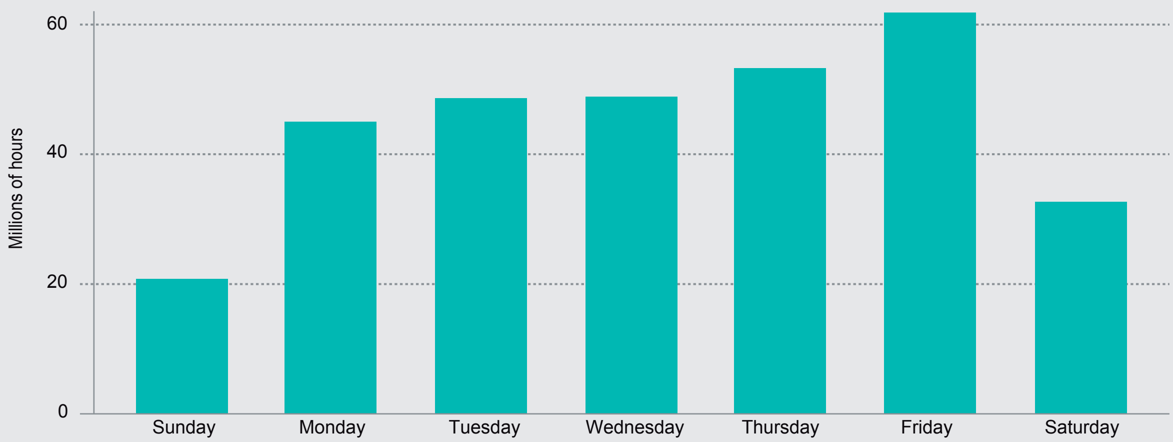
Figure 3.39 Annual congestion distribution by month (Rio de Janeiro, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

Figure 3.40 shows the distribution of congestion on weekdays, which exhibits a fairly typical behavior. The most congested day is Friday, with about 62 million cumulative hours, representing 20% of the total congestion. There is also a marked difference between weekdays and weekends, as, on average, a weekday accumulates twice as much congestion delay as a weekend day.

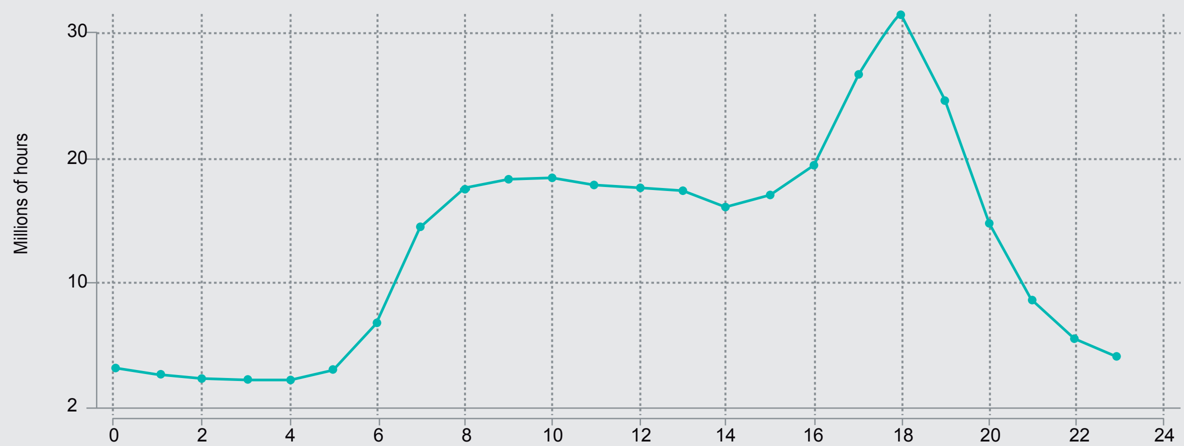
Figure 3.40 Congestion distribution by day of the week (Rio de Janeiro, 2019)



Source: Own calculations using data from Waze.

Figure 3.41 shows the behavior of congestion in Rio de Janeiro during daylight hours. Again, this shows a fairly typical trend, with a marked growth in the morning hours which is sustained until the evening. The highest congestion peak is recorded between 4 pm and 8 pm, representing 38% of the congestion of the whole day, with a total of 118 million hours lost.

Figure 3.41 Congestion distribution by time of day (Rio de Janeiro, 2019)



Source: Own calculations using data from Waze.

San Salvador

In 2019, San Salvador obtained the lowest aggregate delay among the cities analyzed, with less than 37 million hours in total. However, if we consider the size of the urban population, congestion amounted to 33 hours per person (position 3/10). Likewise, each car user lost 83 hours (position 4/10). This city had the lowest congestion costs, totaling US$ 25 million (US$ 70,000 per day on average). This represents 0.6% of its economy. Partly because San Salvador has the lowest value of time among the cities analyzed, the cost of congestion per capita was only US$23 per person (10/10 position) and the cost per car user was US$57 (10/10 position).

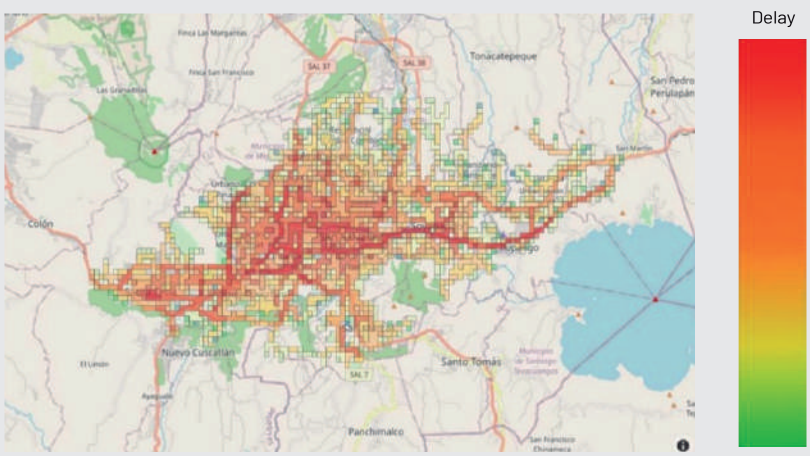
Table 3.8 Results of the analysis for San Salvador

Indicator	Value (2019)	
Total congestion	37	Millions of hours
Congestion per person	33	Hours
Congestion per car user	83	Hours
Daily congestion	0.1	Millions of hours
Total congestion cost	25	US$ Millions
Congestion cost per person	23	US$
Congestion cost per car user	57	US$
Total daily congestion cost	0.1	US$ Millions
Costo de la congestión relativo al PIB	0.55%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

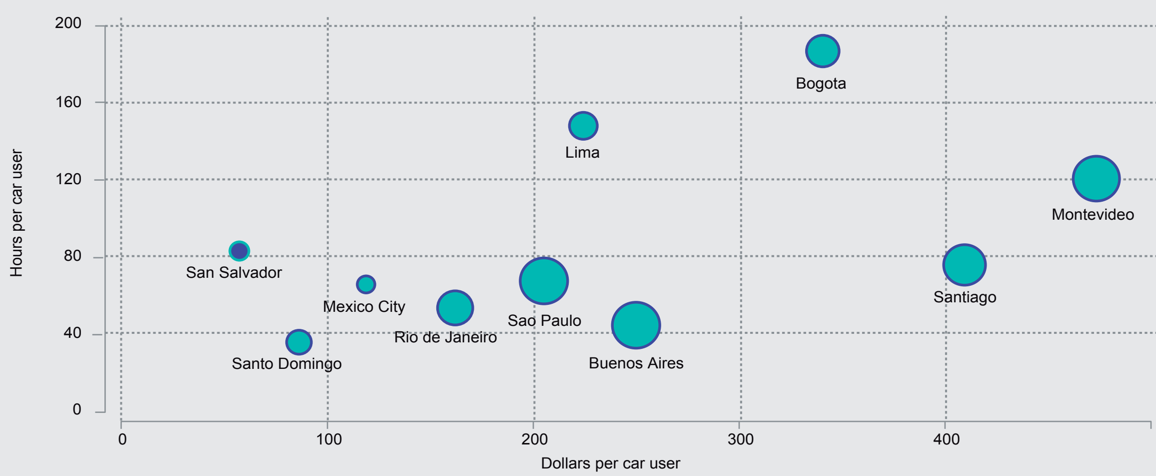
From a spatial point of view, although congestion is quite widespread in the city, the highest are concentrated in the central-eastern sector (Figure 3.42). Alameda Roosevelt, an avenue that crosses the city from east to west, and *Avenida Alameda Manuel Enrique Araujo*, in a parallel direction, are the most congested roads.

Figure 3.42 Comparison of the results between LAC cities (San Salvador, 2019)



In line with the above, due to its low value of time in comparison to the other cities, San Salvador had the lowest total cost of congestion and the lowest cost in relation to its economy. However, it was the fourth city with the most time lost per car user (see Figure 3.43), in addition to being the fifth city with the most time lost in traffic with relation to the average hours worked.

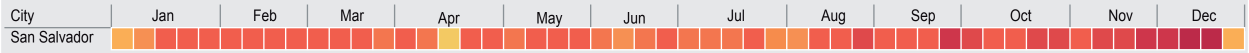
Figure 3.43 Comparison of the results obtained for the analyzed cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.44 shows the annual dynamics of congestion in San Salvador. The largest proportion was concentrated in the last quarter and intensified in the last month. Thus, the third week of December alone accounted for 3.2% of total congestion.

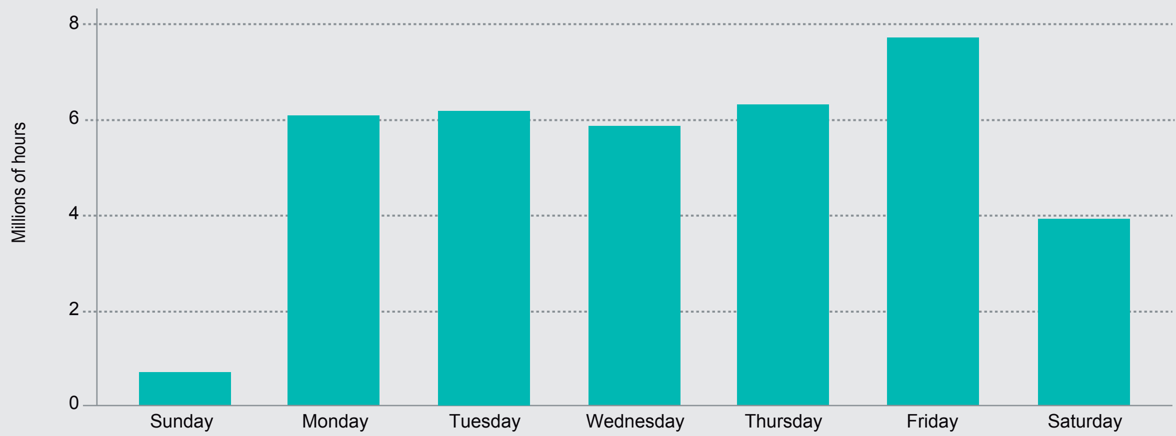
Figure 3.44 Annual congestion distribution by month (San Salvador, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

The distribution of congestion throughout the week is marked by a large difference between weekdays and weekends (Figure 3.45). This gap averages 176% (the highest among the LAC cities analyzed). The most congested day is Friday, accumulating 21% of the total delay (more than 7.7 million hours).

Figure 3.45 Congestion distribution by day of the week (San Salvador, 2019)



Source: Own calculations using data from Waze.

Figure 3.46 shows the dynamics of congestion throughout the day. There are three moments with the highest levels of congestion, the highest being during the evening. This third peak accounts for a total of 15 million hours lost, equivalent to 42% of the total.

Figure 3.45 ongestion distribution by day of the week (San Salvador, 2019)

Source: Own calculations using data from Waze.

Santiago

The Chilean capital presented an aggregate delay of 194 million hours in 2019, ranking as the seventh most congested city. This means that each inhabitant lost, on average, 29 hours (position 7/10). Considering only car users, this figure amounted to almost 76 hours/car user (position 5/10). From a monetary point of view, in 2019 congestion cost over US$ 1 billion (about US$ 3 million per day on average) in Santiago, equivalent to 1% of the city's GDP. Santiago ranked as the city with the second highest congestion costs per person and per car user, amounting to US$156 and US$409, respectively. The latter is equivalent to 5% of the median annual labor income of Santiago residents.

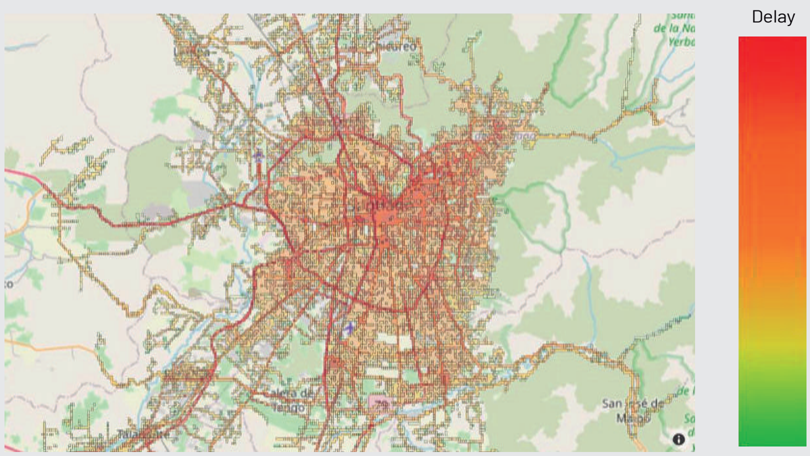
Table 3.9 Results of the analysis for Santiago

Indicator	Value (2019)	
Total congestion	194	Millions of hours
Congestion per person	29	Hours
Congestion per car user	76	Hours
Daily congestion	0.5	Millions of hours
Total congestion cost	1,046	US$ Millions
Congestion cost per person	156	US$
Congestion cost per car user	409	US$
Total daily congestion cost	2.9	US$ Millions
Congestion cost in relation to the GDP	1.04%	

Source: Own calculations using data from Waze, ILO and WDI.

Congestion in the city of Santiago is concentrated in the central and central-eastern sectors, as can be seen in Figure 3.47. Most of the congestion is concentrated on the *Vespucio highway*, which forms the city's ring road. Other roads with heavy congestion are *Avenida Panamericana-Norte, Avenida Libertador O'Higgins* and *Autopista Central.*

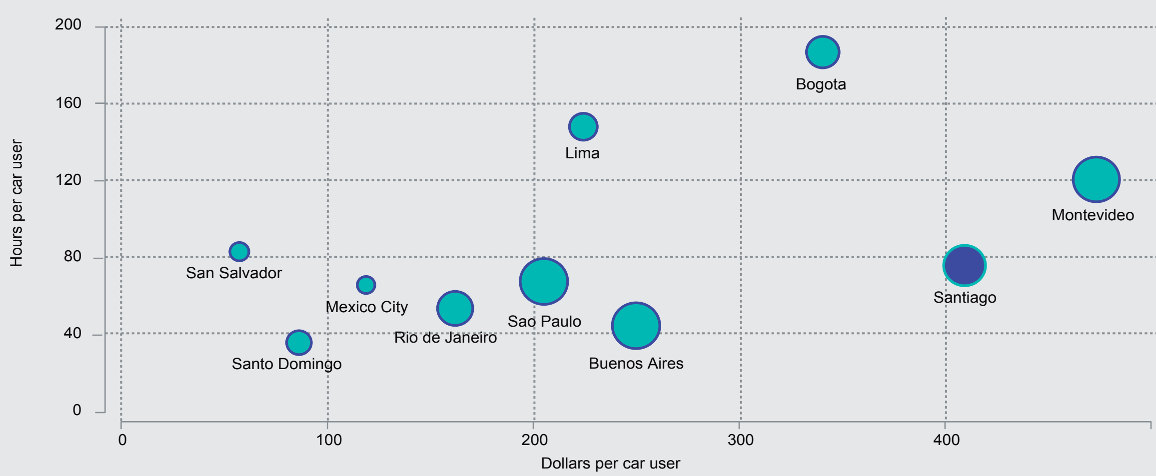
Figure 3.47 Spatial distribution of congestion (Santiago, 2019)



Source: Own calculations using data from Waze.

Figure 3.48 shows a comparison of delays and their costs between Santiago and the other cities analyzed. Santiago is the city with the second highest cost per car user, despite ranking fifth in terms of hours lost in traffic. This is explained by the higher value of time in that city.

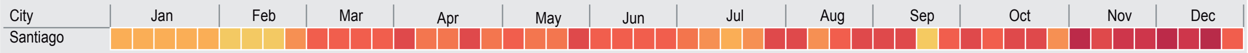
Figure 3.48 Comparison of the results obtained for the analyzed cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Congestion in Santiago has shown a clear upward trend throughout the year, partly due to the February holiday period and the resumption of activities in March, see Figure 3.49. The Chilean capital city recorded the lowest relative accumulated congestion during the first quarter, with only 18% of total congestion. The months with the highest total congestion were October and December, the former probably affected by public demonstrations and the temporary closure of public transportation. The last month of the year accumulated more than 20 million hours lost in congestion, which represented 11% of the total hours, reaching a peak in the third week of December, with almost 6 million hours of delay.

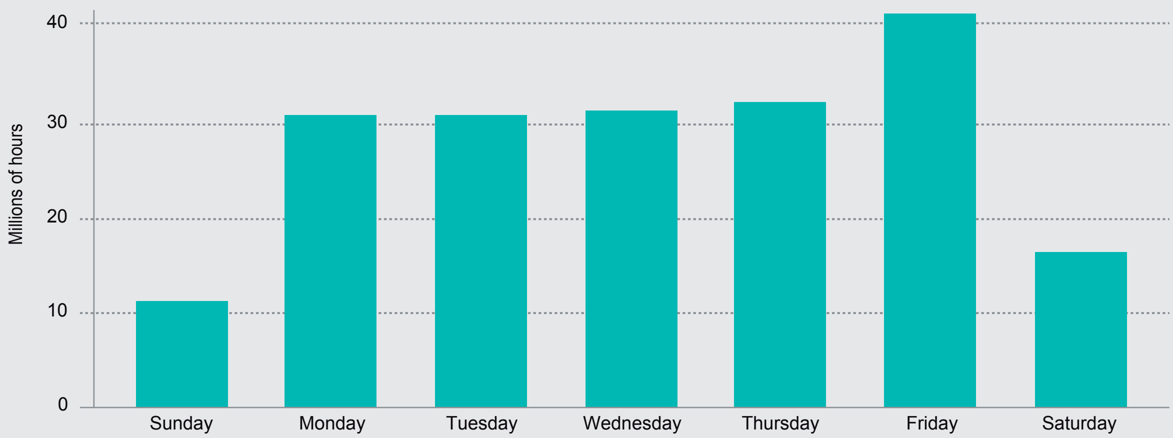
Figure 3.49 Annual congestion distribution by month (Santiago, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

If weekly patterns are analyzed, a gap between workdays and weekends is evident. From Monday to Thursday, congestion registered very close values. On Friday, however, it grows sharply, with 32% more time lost than on all other working days (Figure 3.50), thus accumulating more than one fifth of the total congestion. On Fridays alone, the Chilean capital city lost 41 million hours in 2019, higher than the total delay recorded in San Salvador.

Figure 3.50 Congestion distribution by day of the week (Santiago, 2019)



Source: Own calculations using data from Waze.

Finally, in terms of its distribution by time of day, congestion in Santiago shows a fairly regular behavior, with two major peaks in the morning and evening (Figure 3.51). Regarding hourly distribution, 6 pm is the time that accumulates the highest congestion level in the city, with almost 25 million hours lost. The peak around this time - from 4 p.m. to 7 p.m. - accumulates 41% of the total congestion, reaching 80 million hours lost.

Figure 3.51 Congestion distribution by time of day (Santiago, 2019)

Source: Own calculations using data from Waze.

Santo Domingo

In 2019, the aggregate delay in Santo Domingo amounted to 75 million hours (position 9/10). This figure corresponds to 23 hours/inhabitant (position 9/10) and 36 hours/car user. With respect to the latter, it was the best placed city among those analyzed. Congestion costs represented US$ 180 million, equivalent to almost half a million dollars per day (position 9/10). The cost per person was US$ 56 (position 7/10) and the cost per car user was US$ 86 (position 9/10). In addition, the Dominican capital city had one of the lowest costs in relation to its economy, with a total weight of 0.7% of the city's GDP.

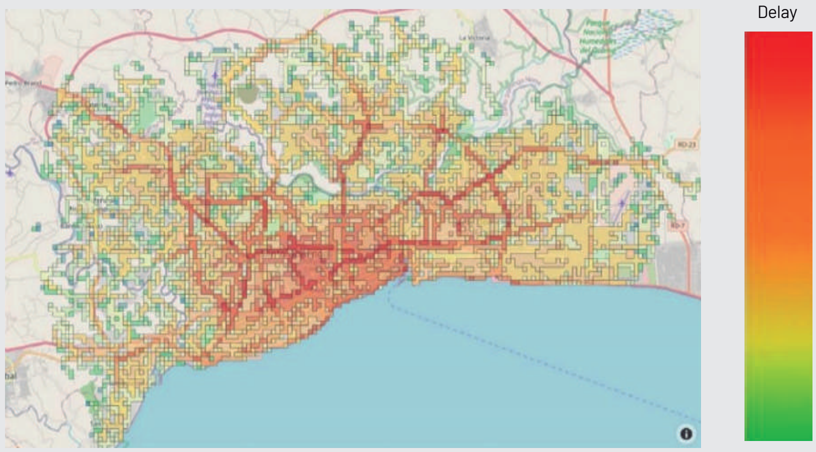
Table 3.10 Results of the analysis for Santo Domingo

Indicator	Value (2019)	
Total congestion	75	Millions of hours
Congestion per person	23	Hours
Congestion per car user	36	Hours
Daily congestion	0.2	Millions of hours
Total congestion cost	180	US$ Millions
Congestion cost per person	56	US$
Congestion cost per car user	86	US$
Total daily congestion cost	0.5	US$ Millions
Congestion cost in relation to the GDP	0.67%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

Geographically, the highest levels of congestion are recorded in the central area of the city. The roads with the longest delays are Expreso 27 de febrero, Avenida Máximo Gómez and Autopista Juan Pablo Duarte.

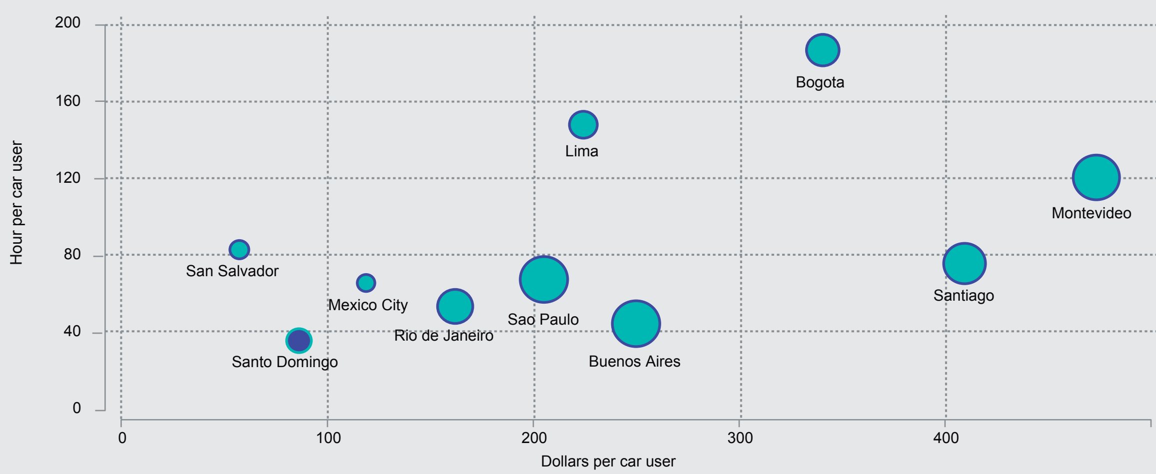
Figure 3.52 Spatial distribution of congestion (Santo Domingo, 2019)



Source: Own calculations using data from Waze.

In general terms, Santo Domingo is the city that, comparatively speaking, presented the best results in the region (Figure 3. 53). It ranked seventh in terms of costs in relation to its economy, second to last in terms of costs per car user and last in terms of congestion per driver.

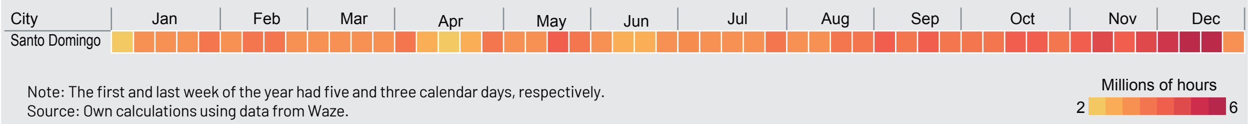
Figure 3.53 Comparison of the results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Very similar to the situation in Santiago, the annual dynamics of congestion in Santo Domingo showed an upward trend throughout the year (Figure 3.54). The first half of the year accumulated 44% of total congestion (with more than 33 million hours lost). In the second half of the year, the months of November and December accounted for 21% of total congestion. The highest congestion level in this city occurred in the second week of December, reaching 3.21% of total congestion.

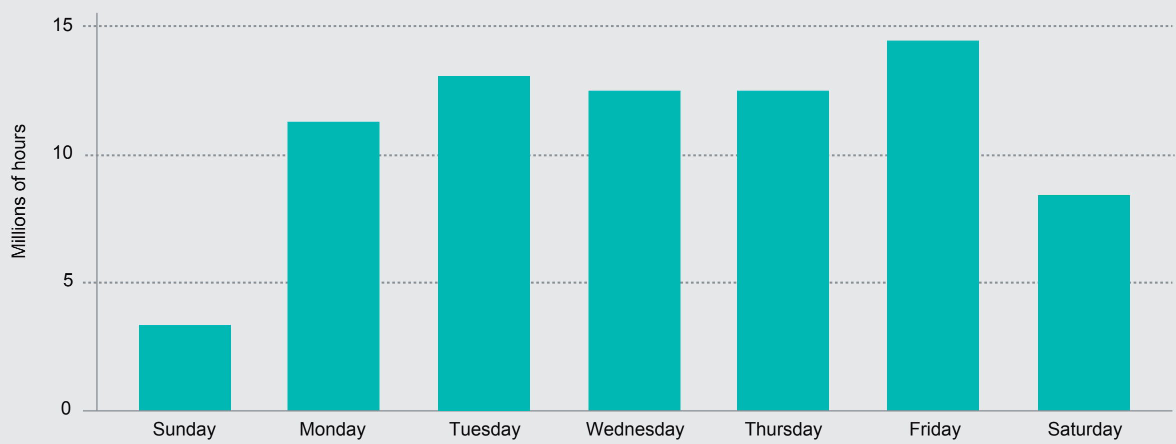
Figure 3.54 Annual congestion distribution by month (Santo Domingo, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

Figure 3.55 shows the distribution of congestion in Santo Domingo throughout the week. Similar to other cities analyzed, Friday is the day with the longest delays. Congestion levels for the remaining workdays are quite similar. It is worth noting that, on an average working day, more than twice as much time is lost as on a weekend day.

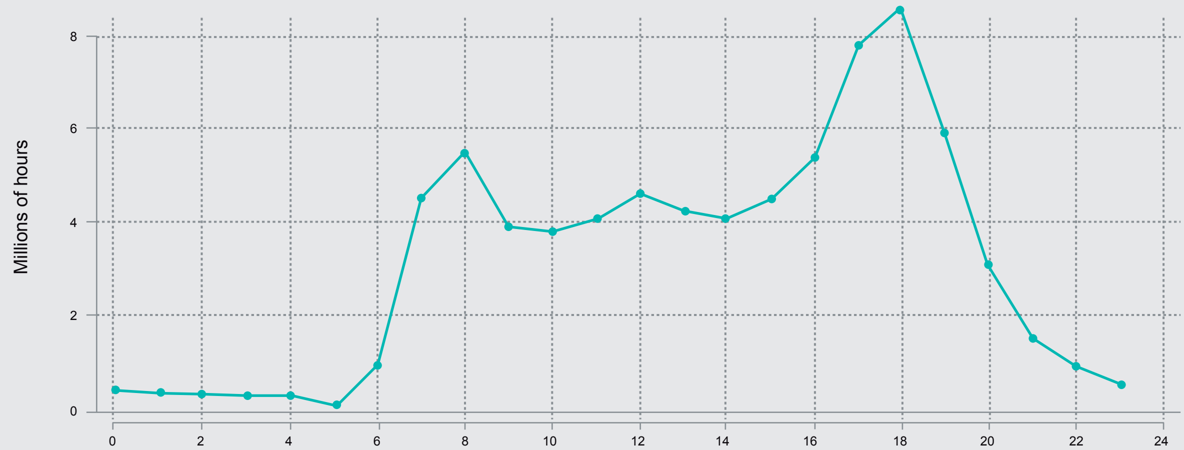
Figure 3.55 Congestion distribution by day of the week (Santo Domingo, 2019)



Source: Own calculations using data from Waze.

Figure 3.56 shows the distribution of congestion in Santo Domingo throughout the day. The behavior is fairly typical, with three daily peaks. Similar to other LAC cities, the highest peak is recorded in the evening, accumulating more than 31 million hours lost in congestion (41% of the city's total delay).

Figure 3.56 Congestion distribution by time of day (Santo Domingo, 2019)



Source: Own calculations using data from Waze.

Sao Paulo

Among the cities analyzed, Sao Paulo registered the highest levels of congestion. This city is the only one that surpassed the 700-million-hour mark for delays in 2019. However, if per capita congestion is considered, Sao Paulo ranks fourth, with a loss of more than 32 hours per inhabitant. On the other hand, if vehicle users are considered, the city drops to the sixth position, registering a loss of 68 hours/car user.

Congestion costs in 2019 amounted to more than US$ 2 billion, about US$ 5 million per day. This is equivalent to 1.1% of Sao Paulo's GDP. To put these figures in perspective, the losses represent two-thirds of what the city spends on education or 90% of what it spends on health. In 2019, each Sao Paulo inhabitant lost, on average, around US$ 100 (position 4/10). Considering only car users, they lost more than US$ 200 (6/10 position), which represents 4% of the median wage.

Table 3.11 Results of the analysis for Sao Paulo

Indicator	Value (2019)	
Total congestion	702	Millions of hours
Congestion per person	32	Hours
Congestion per car user	68	Hours
Daily congestion	1.9	Millions of hours
Total congestion cost	2,124	US$ Millions
Congestion cost per person	97	US$
Congestion cost per car user	205	US$
Total daily congestion cost	5.8	US$ Millions
Congestion cost in relation to the GDP	1.12%	

Source: Own calculations using data from Waze, ILO, IFS and WDI.

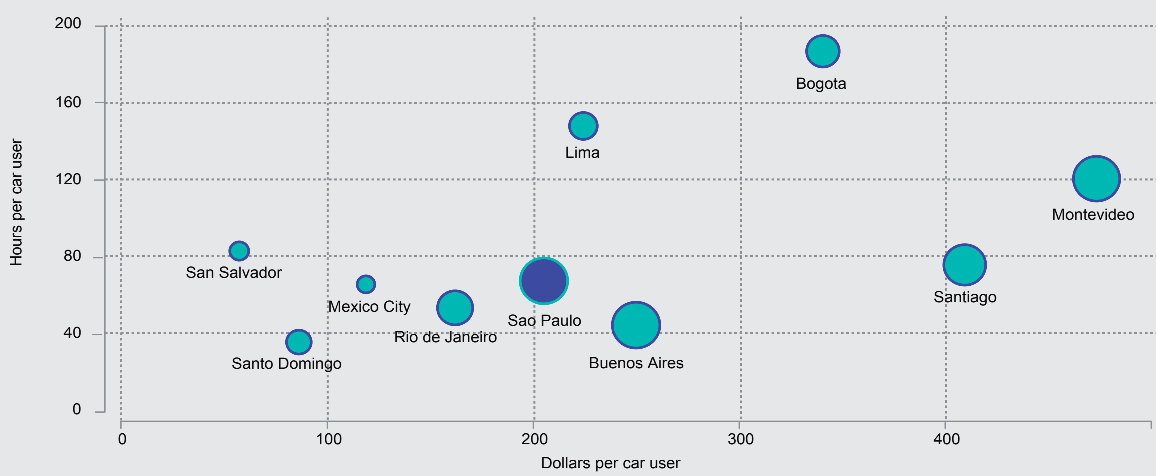
Congestion in Sao Paulo is widespread throughout the area (Figure 3.57), particularly in the city center. The roads with the longest delays are: *Avenida Marginal Tiete*, which crosses the city from west to east in the north; *Autopista Presidente Dutra*, as an access channel from the northeast to downtown; and Avenida Washington Luís, as an access channel from the south to downtown and located near the local airport.

Figure 3.57 Spatial distribution of congestion (Sao Paulo, 2019)

Source: Own calculations using data from Waze.

Figure 3.58 compares the results of Sao Paulo and other LAC cities. In terms of delay per car user, the Brazilian city is similar to Mexico City and Santiago. Costs per car user are comparable to those of cities such as Lima. The cost of congestion in relation to the city's GDP is the second highest in the region, surpassed only by Buenos Aires.

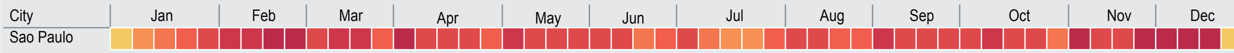
Figure 3.58 Comparison of the results between LAC cities



Source: Own calculations using data from Waze, ILO, IFS and WDI.

Figure 3.59 shows the behavior of congestion throughout the year. The last quarter was the period that accumulated the greatest delay (26% of total congestion), with approximately 190 million hours equally distributed among the 3 months.

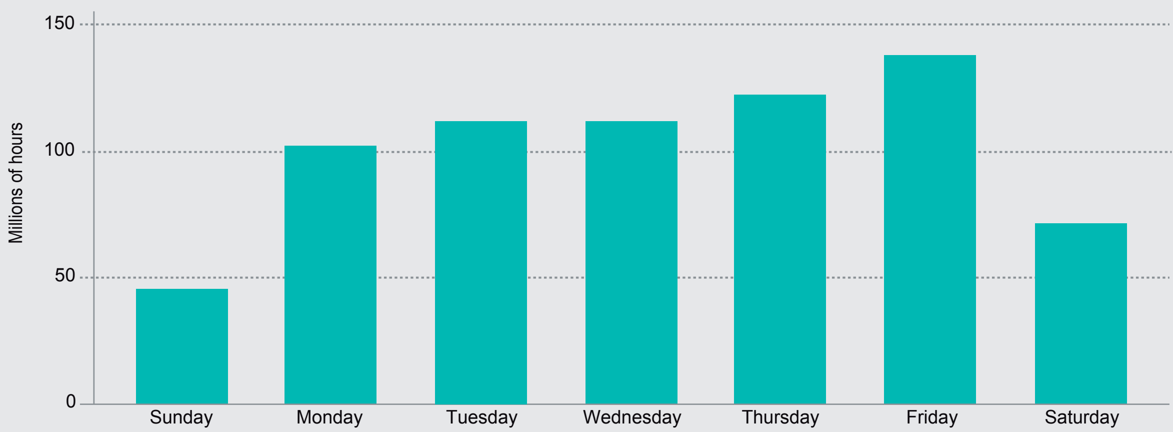
Figura 3.59 Annual congestion distribution by month (Sao Paulo, 2019)



Note: The first and last week of the year had five and three calendar days, respectively.
Source: Own calculations using data from Waze.

The behavior of congestion in Sao Paulo throughout the week is similar to that of other cities (Figure 3.60). Friday is the day with the highest congestion level, accumulating about 140 million hours, representing 20% of the total hours. It is worth noting the marked difference between weekdays and weekends, since on weekdays 99% more time on average is lost due to congestion.

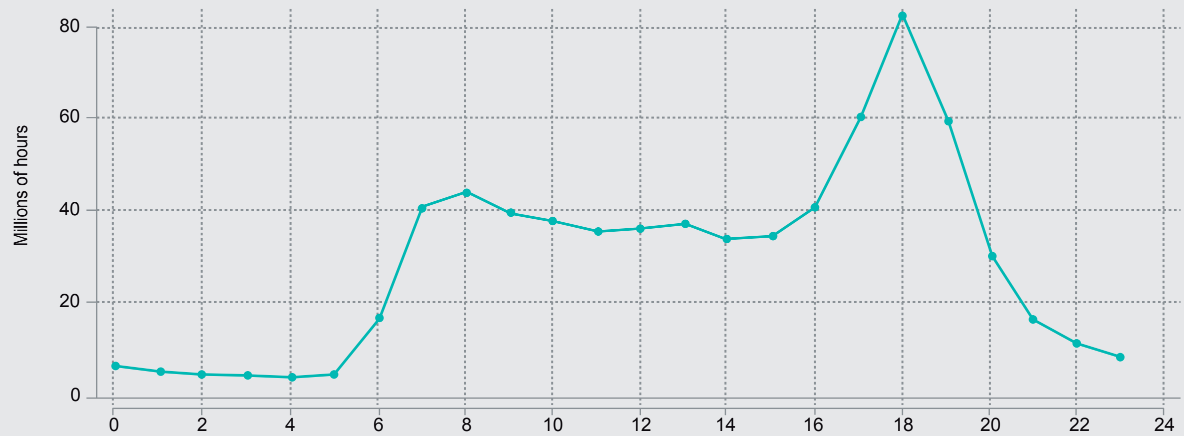
Figure 3.60 Congestion distribution by day of the week (Sao Paulo, 2019)



Source: Own calculations using data from Waze.

Figure 3.61 shows the behavior of congestion in Sao Paulo throughout the day. Congestion starts at 6 am and continues until the evening. The highest peak is recorded at 6 pm which amounts to a total of 12% of the congestion time, that is, more than 80 million hours. The evening peak period -between 4 pm and 7 pm - accumulates 39% of the total congestion, registering 275 million hours. This is higher than the aggregate delay of cities such as Santiago.

Figure 3.61 Congestion distribution by time of day (Sao Paulo, 2019)



Source: Own calculations using data from Waze.

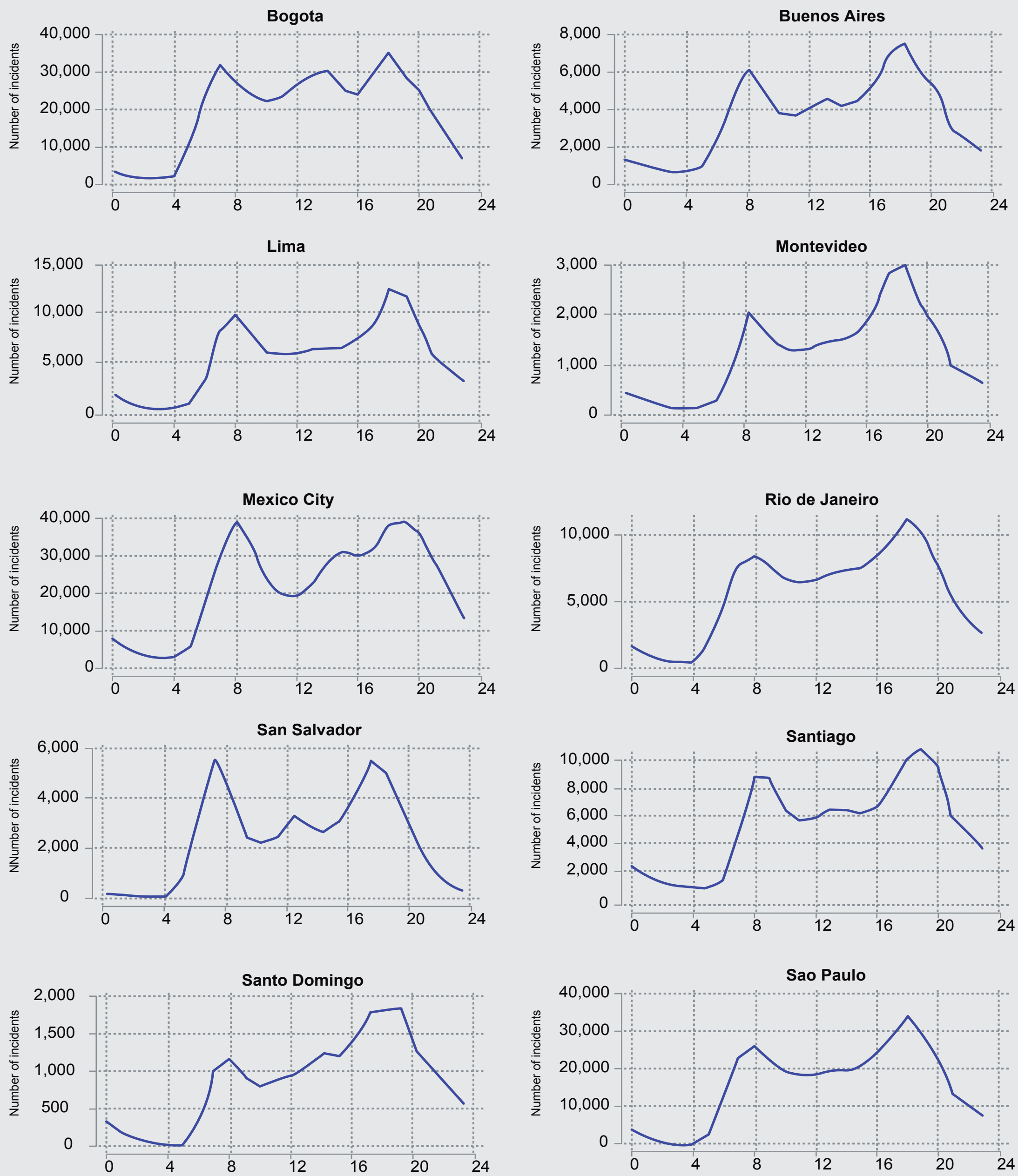
3.4 Indirect congestion costs

According to the literature, the indirect costs of congestion include road incidents (see Chapter 1)[18]. In this section, we will apply the methodology presented in Chapter 2 to estimate the **relationship between congestion and the incident rate** in the 10 LAC cities analyzed. The database we use shows that, in 2019, there were about **2 million traffic incidents** on the roads of these 10 cities. In absolute terms, Mexico City is the city with the highest number of traffic incidents, accounting for 27% of the total, followed by Bogota and Sao Paulo with 23% and 20%, respectively. Santo Domingo and Montevideo had the lowest incident rates, with 1.1% and 1.5% of the total, respectively. In relative terms, San Salvador was the city with the highest number of traffic incidents per inhabitant (0.05/inhabitant), while the Argentine capital city had the lowest incident rate (0.01/inhabitant).

Figure 3.62 shows the **distribution of the number of traffic incidents throughout the hours of the day.** Most cities have at least two peaks, coinciding with peak congestion times: morning and evening. Some cities such as Bogota, Buenos Aires and San Salvador show three high indicent peaks, including one around midday.

18. For a detailed analysis of road safety in LAC, see Zamora et al. (2021).

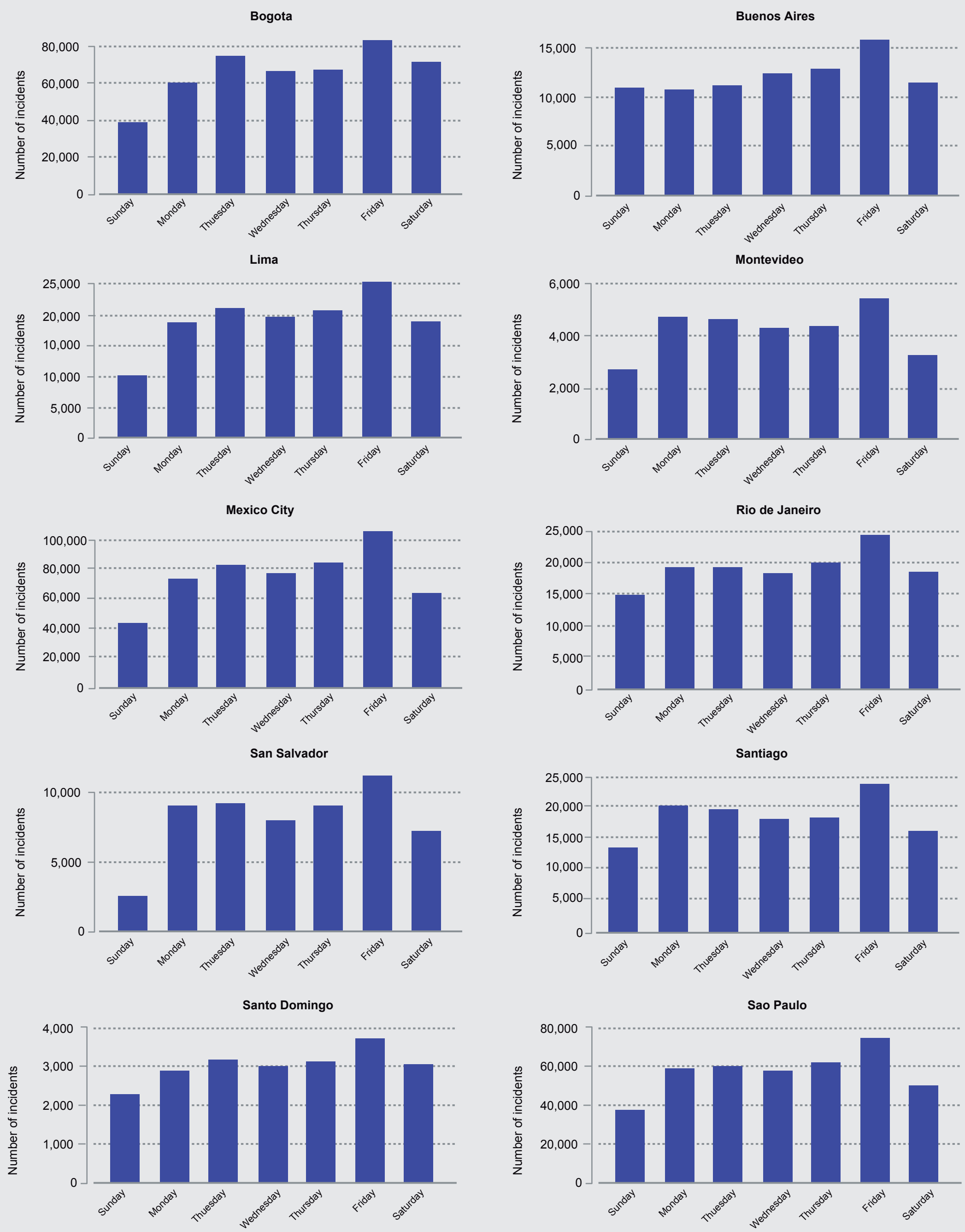
Figure 3.62 Distribution of traffic incidents by time of day (2019)



Source: Own calculations using data from Waze.

Similar to the distribution of congestion by day of the week, the number of traffic incidents tends to increase during **weekdays** (see Figure 3.63). Fridays account for 19% of the total number of traffic incidents recorded in 2019.

Figure 3.63 Distribution of traffic incidents by day of the week (2019)

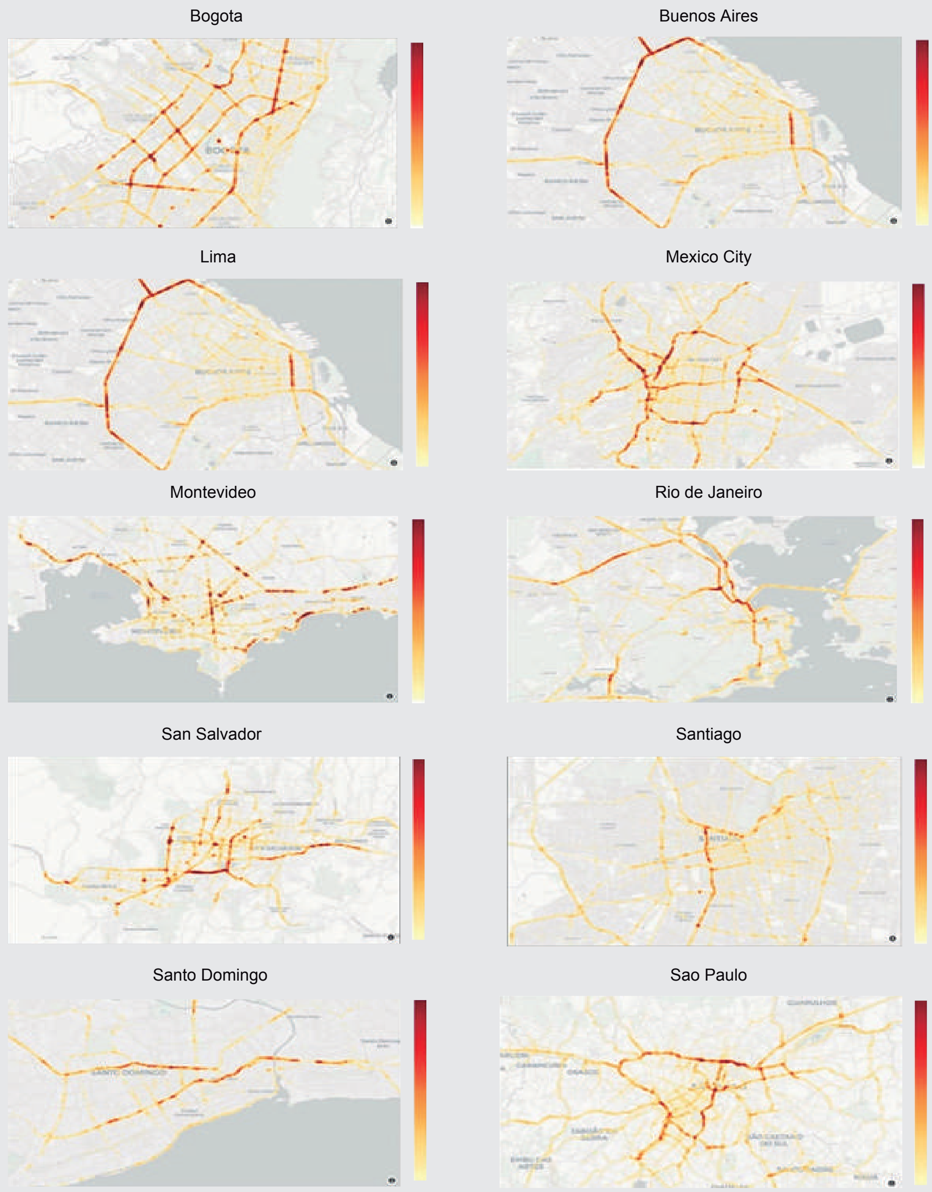


Source: Own calculations using data from Waze.

Mexico City is the city with the highest number of **traffic incidents per hour**, with an average of 63 traffic collisions in 2019. The maximum number of traffic incidents occurred on Thursday, October 17 at 8:00 am, with more than 300 traffic incidents. At the other extreme is Santo Domingo, with 2.6 traffic incidents per hour on average. It is worth highlighting the case of Buenos Aires, which, despite being the third largest city among those analyzed, had an average of 10 traffic incidents per hour, a figure five times lower than that of Bogota and 1.6 times lower than that of Santiago.

Figure 3.64 shows the spatial distribution of traffic incidents that occurred in 2019. For cities with high incident rates, traffic incidents usually occur on the most congested roads. Bogota and San Salvador are the cities with the highest density of traffic incidents. These are located on the city's main roads, i.e., Avenida NQS, Avenida El Dorado and Avenida Boyacá on the first, and Paseo General Escalón and Avenida Alameda on the second. It is worth noting that in Buenos Aires, Mexico City, Rio de Janeiro and Sao Paulo incident rates overlap almost perfectly with aggregate delay, as illustrated in section 3.2 regarding the spatial distribution of congestion.

Figure 3.64 Spatial distribution of traffic incidents (2019)



Source: Own calculations using data from Waze.

Figure 3.65 shows the number of traffic incidents in comparison to total congestion —in thousands of hours— over the 52 weeks of 2019. As for the time series aggregation, there is a **highly positive and statistically significant correlation** for all cities. The lowest correlation is seen in Rio de Janeiro, with a coefficient of 0.68. The highest correlation

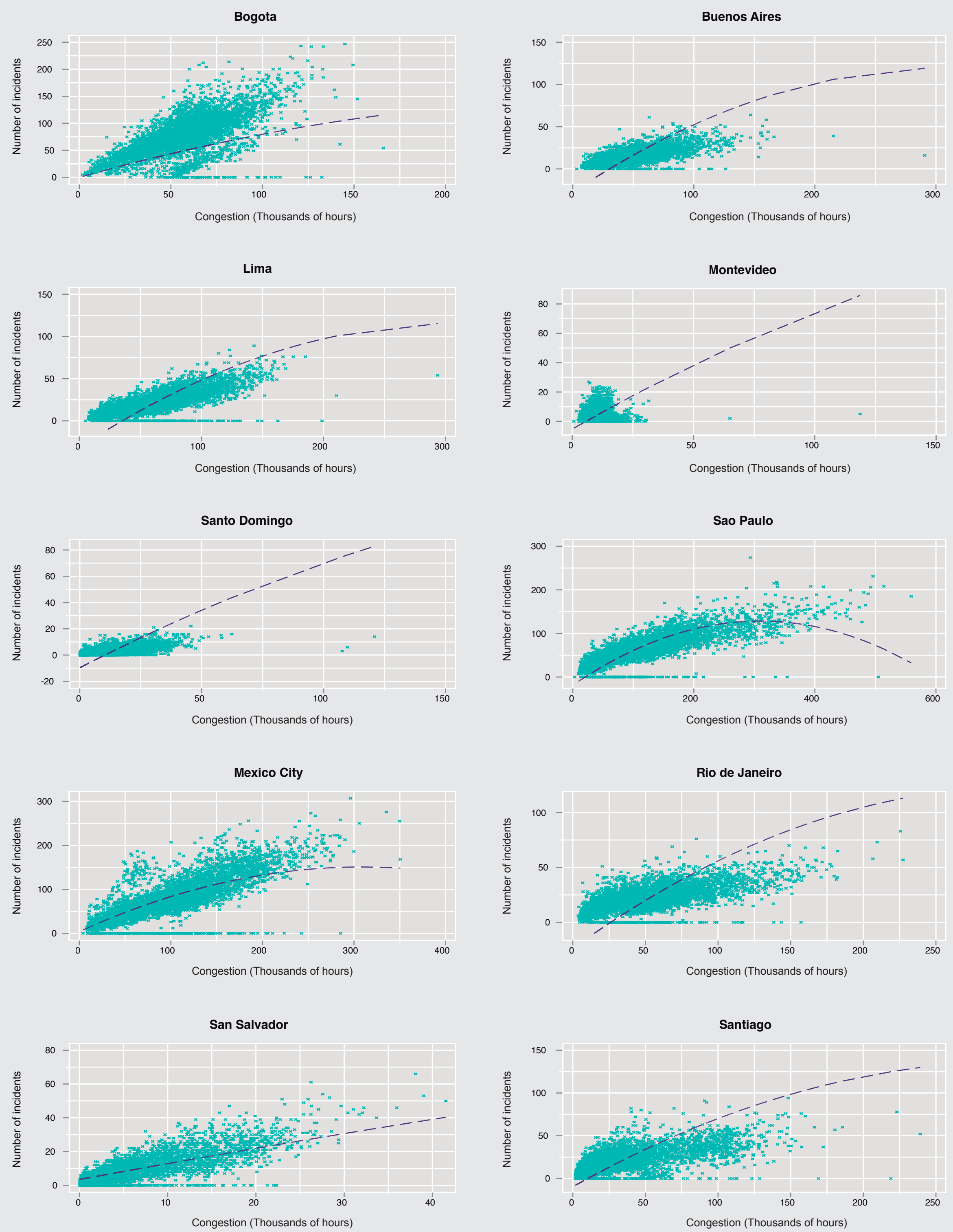
was found in Bogota, Santo Domingo and San Salvador, with coefficients of 0.92, 0.91 and 0.90, respectively. It is important to note that, without exception, all the series show statistical significance in the correlations for the different statistics used, namely: Bonferroni and Sidak.

Figure 3.65 Number of traffic incidents vs. hours lost due to congestion per week

Source: Own calculations using data from Waze.

Figure 3.66 illustrates the relationship between traffic incidents and congestion in the different cities, at one-hour intervals. The dotted line represents the quadratic relationship between these two variables. All cities show a positive trend between congestion and number of traffic incidents. The overall correlation is 0.76 and statistically significant. The strongest correlations are found in Sao Paulo and Lima, with 0.84 and 0.82, respectively. Montevideo is the only city with an atypically less pronounced relationship (coefficient of 0.09), although positive and statistically significant.

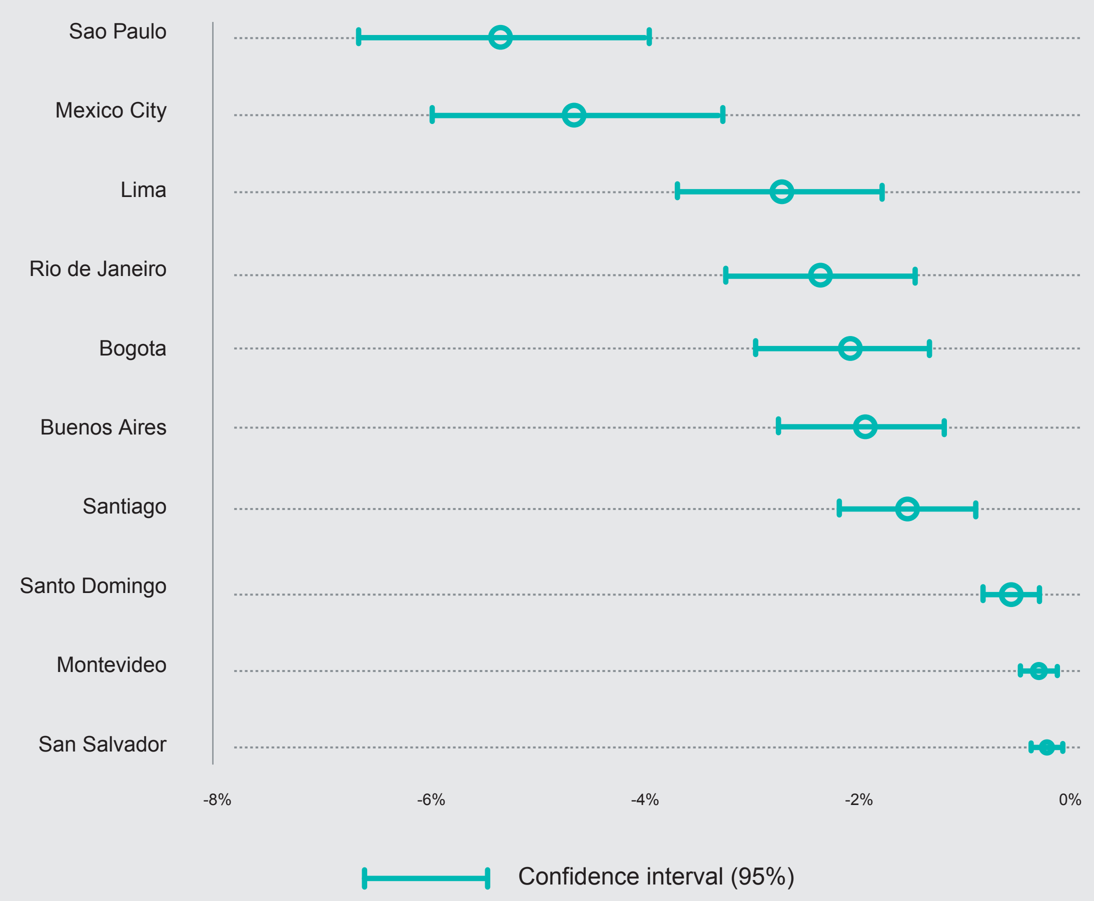
Figure 3.66 Relationship between traffic incidents and congestion (2019)



Source: Own calculations using Waze data

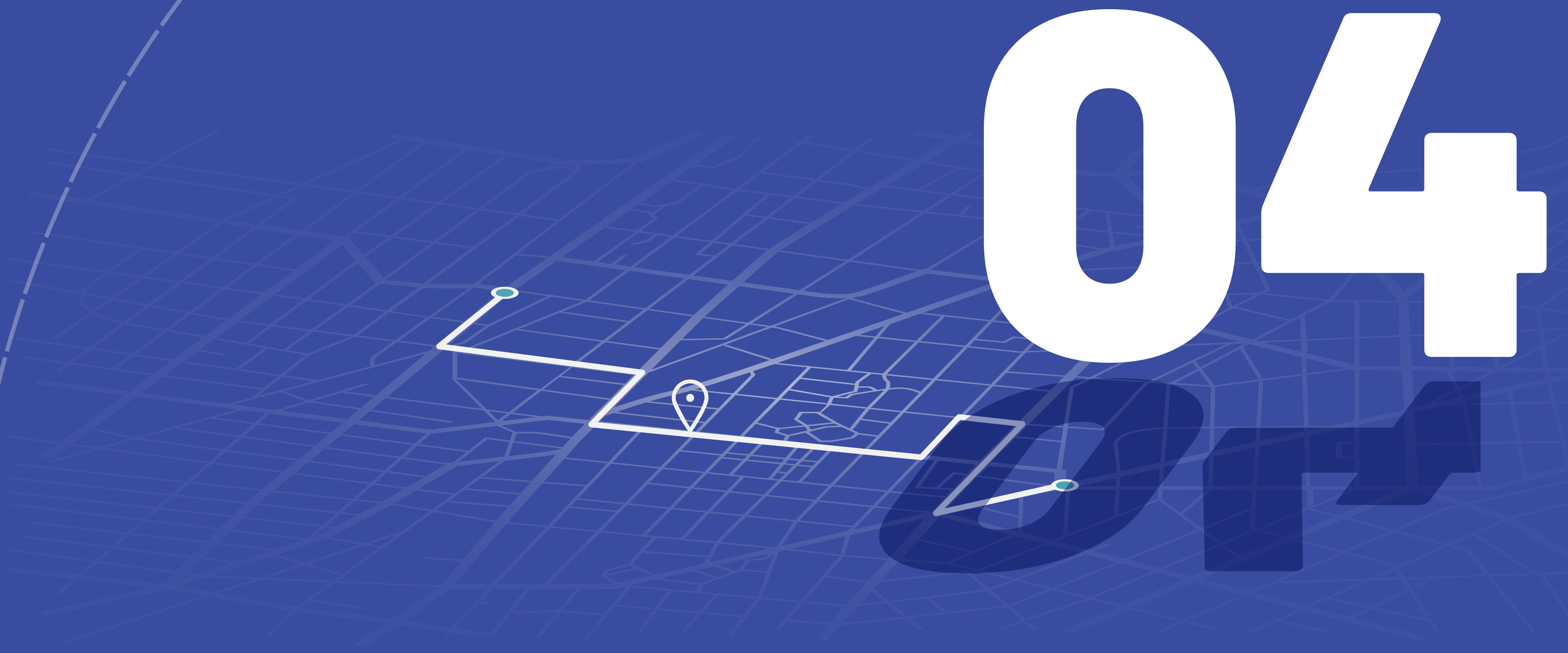
The application of the model described in Chapter 2 yields results that are consistent with the academic literature, which points to a **positive causal relationship between congestion and incident rate** (Dias et al., 2009; Wang et al., 2009; Green et al., 2016). Our findings suggest that, if the aggregate delay on an average workday were reduced by 10%, then traffic incidents would decrease by 5% in Sao Paulo and Mexico City; 3% in Lima; 2% in Rio de Janeiro, Bogota, Buenos Aires and Santiago; 1% in Santo Domingo; 0.4% in Montevideo; and 0.3% in San Salvador (Figure 3.67). In particular, this means that, if congestion in 2019 had been 10% lower, the number of reported traffic incidents would have been reduced by 3.5% on average for the region. This is equivalent to a reduction of 73 thousand traffic incidents. The largest proportion of this reduction would have taken place in Mexico City and Sao Paulo, with 26,627 and 23,247 fewer traffic incidents respectively; followed by Bogota (11,000); Lima (4,000); Rio de Janeiro (3,000); Santiago and Buenos Aires (2,000); San Salvador (194); Montevideo (143); Santo Domingo (117).

Figure 3.67 Percentage reduction in the number of traffic incidents in the event of a 10% decrease in congestion



Chapter 4.

CHARACTERISTICS AND DYNAMICS OF CONGESTION: SELECTED CASES



The geographic and temporal concentration of economic, social, and cultural activities is one factor that gives rise to urban congestion. Consequently, a significant part of traffic management in cities focuses on designing and implementing mechanisms to reduce congestion derived from such activities and improve mobility. In recent years, digital navigation services and big data analytics have improved the understanding of the impact that factors such as tourism activities, mega-events, logistics operations, and weather conditions have on traffic. This chapter will analyze a series of case studies from Latin America to illustrate this impact. The selected cases can be classified into three groups:

1. Economic activities: (i) cruise tourism; (ii) food market and logistics areas.

2. Cultural and social activities: (iii) mega-sports event; (iv) music festival.

3. Areas of primary importance: (v) presence of schools; and (vi) presence of health centers.

For each case, we will analyze congestion behavior, including its temporal and geographic dimensions. This chapter aims to illustrate the potential use of these techniques **to understand better the characteristics and dynamics of congestion** in our cities whenever it is **related to specific activities**. This will allow the implementation of more appropriate traffic management measures adapted to the changing conditions of congestion when such events occur.

4.1 Urban congestion related to economic activities

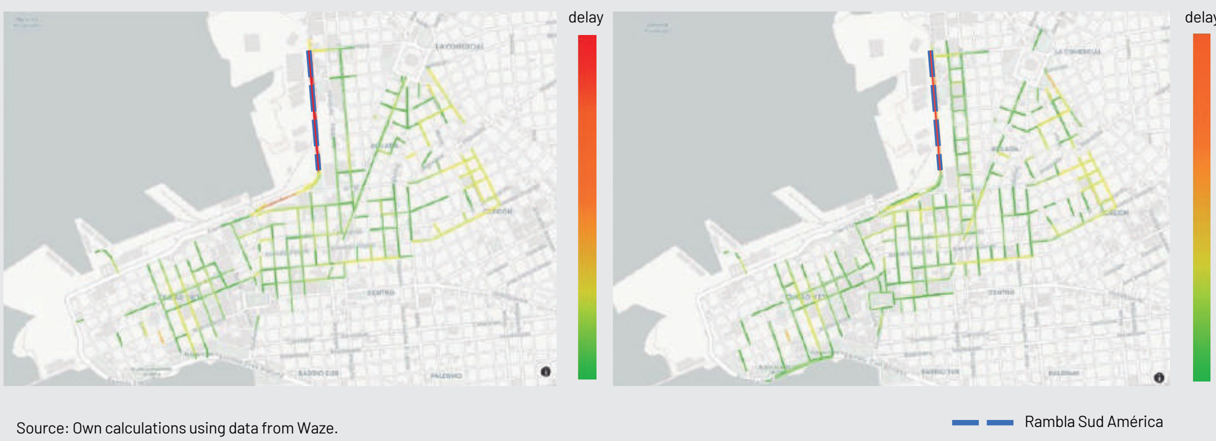
The increase in data availability and granularity related to mobility in cities allow for a more detailed analysis of the **relationship between congestion and economic activities**. Below, we will explore two types of widely present activities in LAC megacities: **tourism and logistics**. Regarding tourism, we will focus our analysis on the cruise industry in two cities: Buenos Aires and Montevideo. Before the COVID-19 pandemic, this industry was one of the fastest-growing tourism sectors in the region, and everything seems to indicate that it will resume its growth trend once the pandemic is over. On the other hand, we will also analyze the case of Corabastos in Bogota and will explore the relationship between the location of central markets, logistic activities, and urban congestion.

In recent years, there has been an increasing debate about the impact —both positive and negative— that **cruise activities have on cities and countries** where cruises dock (Brida et al., 2011). Among the negative effects, one of the main issues that cause social discontent is the consequences of cruises on urban mobility, especially when the terminals are located in central areas of the host cities. To examine its effects in LAC cities, we will use data on congestion from the areas surrounding the cruise terminals of Montevideo and Buenos Aires, located within the urban area, as well as data on cruise ship arrivals and departures for both ports for the year 2019.

With the aim of estimating the impact of cruise activity on the increase in total delay in the port area, we implemented a panel data regression that allows us to control for several factors. This is detailed in Appendix 3. Based on these estimates, our findings show that **each cruise ship increases congestion in the port area by about 15%**. Figure 4.1 illustrates the results for Montevideo, between 8:00 am and 12:00 pm in 2019. Panel (a) shows the average congestion on the days when there was at least one cruise ship entering or leaving the port in 2019. Panel (b) shows the average congestion in the same area on days when there was no cruise activity. On average, congestion around the port of Montevideo increased by 21% on days when there was cruise activity, which is statistically significant. A large part of this increase was verified on the *Rambla Sud América*, which indicates the need to pay greater attention to mobility planning in this area on days and at times when passengers embark or disembark.

Figure 4.1 Port of Montevideo with and without cruise activity (average in 2019)

a) With cruise activity **b) Without cruise activity**

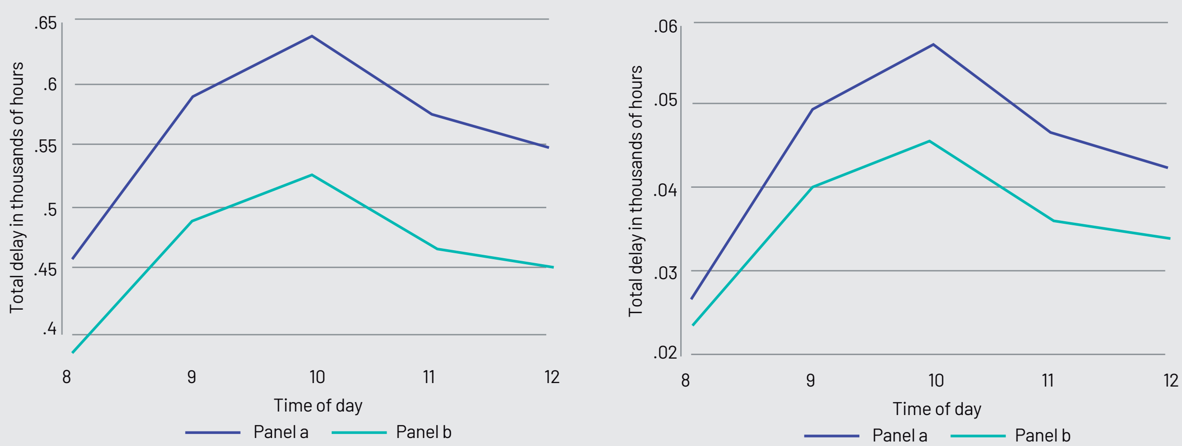


Source: Own calculations using data from Waze.

Taking advantage of the opportunities provided by big data analysis in terms of disaggregation, we explored the dynamics of congestion under the presence of cruise ships. Figure 4.2 shows that congestion is systematically higher when there are cruise ships between 8:00 am and 12:00 pm. The most extended delay occurs between 9:00 am and 10:00 am, with a maximum delay of 640 hours, while on days when there are no cruise ships, the delay is of 520 hours. The increased delay is associated with the duration of traffic jams around the port area (Figure 4.2.b).

Figure 4.2 Dynamics of congestion around the Port of Montevideo (2019)

a) Hourly distribution of congestion **b) Hourly distribution of total duration**

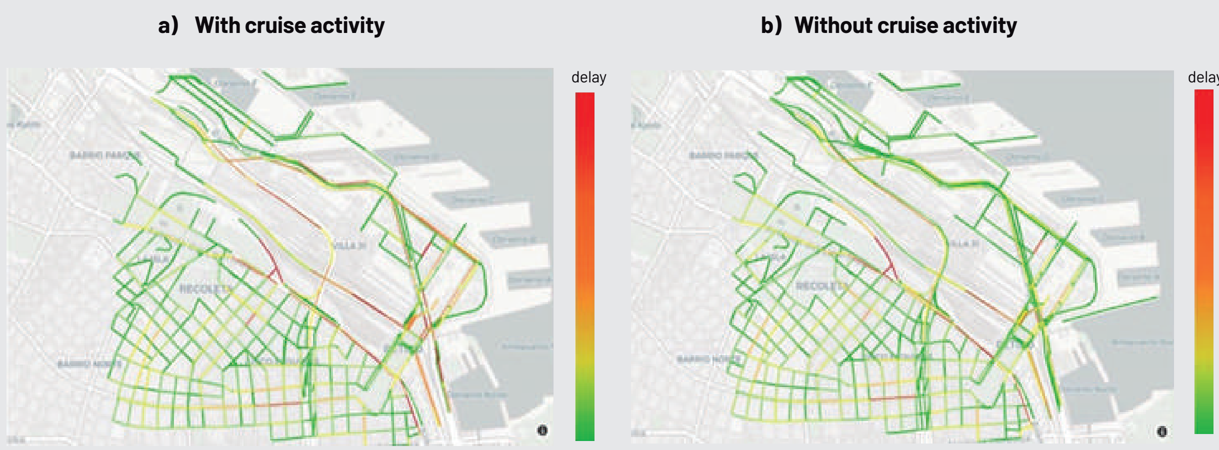


Source: Own calculations using data from Waze.

Figure 4.3 illustrates the dynamics of congestion in the area surrounding the port of Buenos Aires. On average, the difference in aggregate delay between days with and without cruise ship activity amounts to 47%, being statistically significant. Unlike Montevideo, the impact of congestion is not geographically isolated to a single road, but it extends

over the entire area surrounding the port. Thus, in order to improve mobility, a comprehensive approach should be applied to the area when cruise ships are docked. Notice that this area holds numerous commercial and social activities, and it is one of the most important transportation hubs in the city (Retiro Bus and Train Terminal).

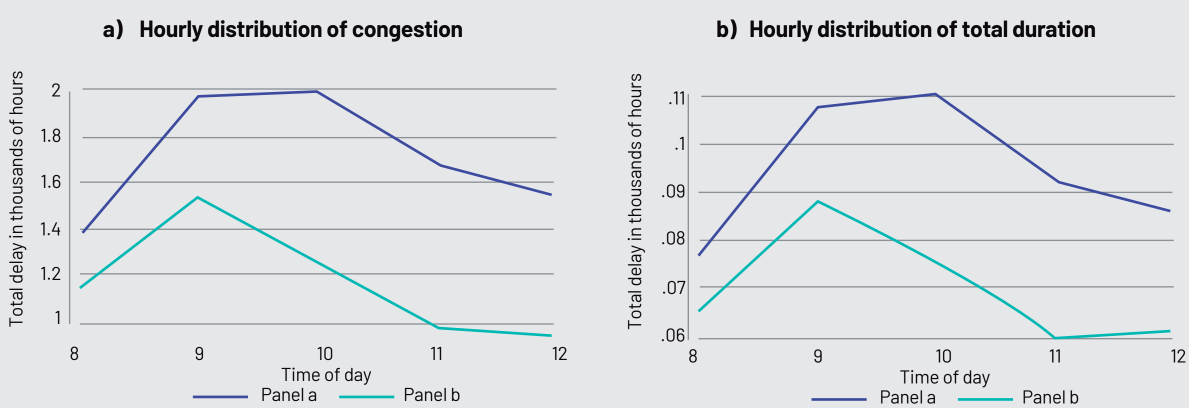
Figure 4.3 Port of Buenos Aires with and without cruise activity (average in 2019)



Source: Own calculations using data from Waze.

The temporal dynamics of congestion around the port of Buenos Aires show an initial peak at 9:00 am in both scenarios. In the event of cruise ship activity, this peak extends until 10:00 am, reaching an aggregate delay of over 2,000 hours in 2019 (1,550 hours when there is no cruise ship activity) (Figure 4.4a). The duration of traffic jams is longer on days with cruise activity, and it takes place from 10:00 am to 12:00 pm (Figure 4.4b). However, between 11:00 am and 12:00 pm a decrease in aggregate delay can be observed in panel b as well as an increase in the total duration. A possible explanation for this is the rise in minor traffic jams, which increases the duration, but has a low impact on the aggregate delay in the area.

Figure 4.4 Dynamics of congestion around the Port of Buenos Aires (2019)

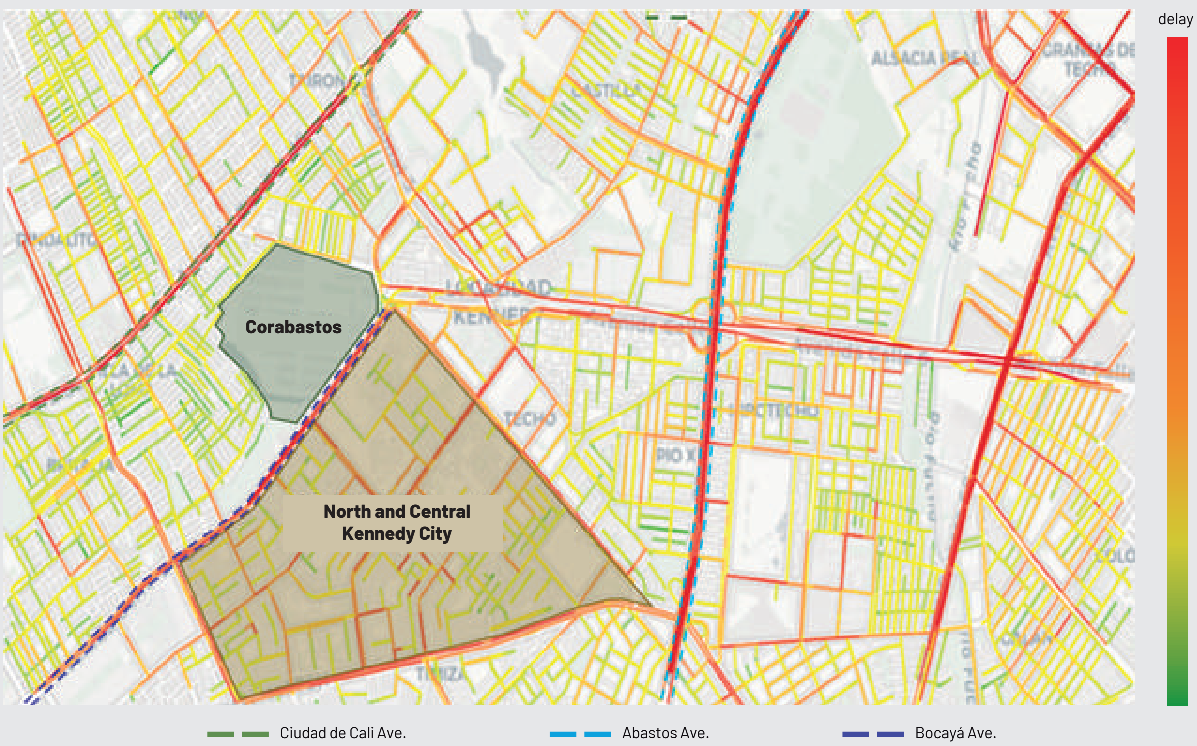


Source: Own calculations using data from Waze.

After analyzing the relationship between congestion and cruise ships, we will now focus on the second example of economic activity that we mentioned before. As stated in the first chapter, one of the most common and relevant congestion types is recurrent congestion (Brownfield et al., 2003). One of the causes for this type of congestion is the concentration of economic activities at a given area, where the influx of trips exceeds the capacity of the existing infrastructure. In Latin American cities, **central markets** are often congestion hotspots since numerous formal and informal businesses are brought together, and there is a myriad of commercial and logistical operations taking place around them. In these areas, freight vehicles concur with a high flow of collective transportation (formal and informal) and private vehicles of all types, used by consumers to travel to and from the market. Once the saturation point has been reached in that road network, congestion begins to spread, recurrently affecting the entire transportation network near such activity centers.

An interesting related case of study is **Colombia's most important wholesale center, Corabastos**. This wholesale center is in the western region of Bogota, in the most populated area of the capital city (Kennedy, with 1,200,000 inhabitants), and has 57 warehouses for food storage and distribution. Figure 4.5 shows how congestion concentrates in the transportation network near Corabastos. Congestion in Carrera 80 Avenue (also called Abastos Avenue), leading to the wholesale center, stands out. However, the two most affected roads are Ciudad de Cali Avenue and Boyacá Avenue, two arterial roads that run through the entire city of Bogota from north to south in the western region. Finally, we can also find high congestion levels on the main roads serving the residential neighborhoods of North Kennedy and Central Kennedy (lower part of the figure).

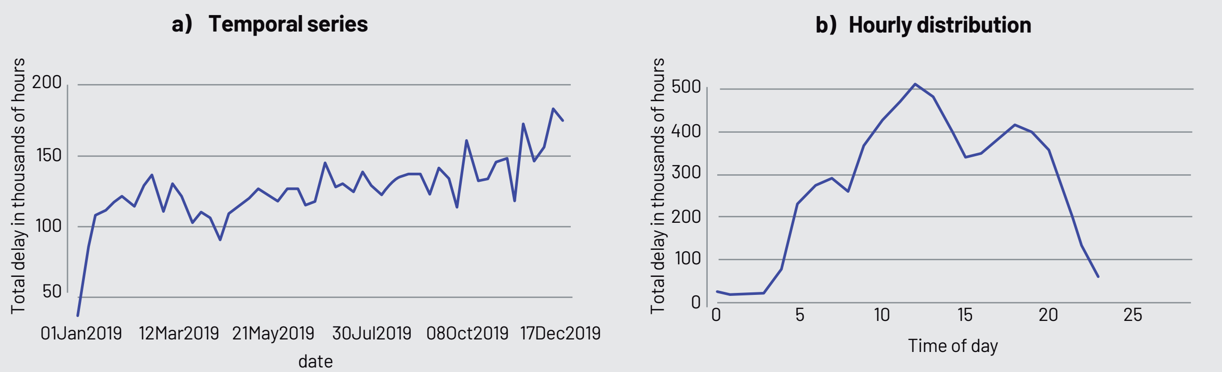
Figure 4.5 Urban congestion in Corabastos, Bogota



Source: Own calculations using data from Waze.

Figure 4.6a shows the temporal description of congestion around Corabastos during 2019. It shows an upward trend, being higher in the last quarter of the year. During the first quarter of 2019, the maximum total delay recorded was close to 131 thousand hours. However, just in the month of December, the average was 141 thousand hours, reaching a weekly maximum of 183 thousand hours. Congestion concentrates between 8 am and 8 pm, with two prominent peaks: the highest was recorded at 12 pm, with an accumulated delay exceeding 510 thousand hours for the year 2019, and the lowest was recorded at 6 pm, exceeding 400 thousand hours. These trends are correlated with the duration of traffic jams. While in the first quarter of the year the weekly average cumulative duration of traffic jams was close to 13.5 thousand hours, in December this duration rose to 18 thousand hours. Regarding the hourly distribution, the most prolonged traffic jams were recorded at 11 am and 6 pm, exceeding 57 thousand hours.

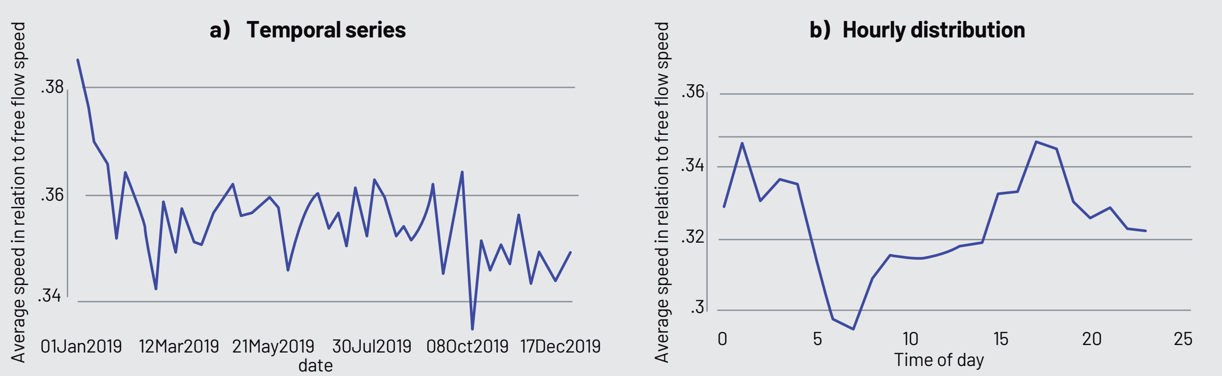
Figure 4.6 Temporal description of urban congestion in Corabastos, Bogota



Source: Own calculations using data from Waze.

The average speed during traffic jams was around 35% of the free-flow speed throughout 2019, with a drop in the October-December period, consistent with the overall congestion increase (Figure 4.7). It should be noted that the most significant reduction in average speed occurs from 4 am to 7 am, exceeding 30% of the average free-flow speed, and between 6 pm and 8 pm, approaching 32% of the average free-flow speed. Together with the geographic indications specified above, these temporal indications of congestion provide critical information for traffic management actions in the surrounding areas of the market to improve mobility in the region.

Figure 4.7 Average speed during traffic jams in Corabastos, Bogota (2019)



Source: Own calculations using data from Waze.

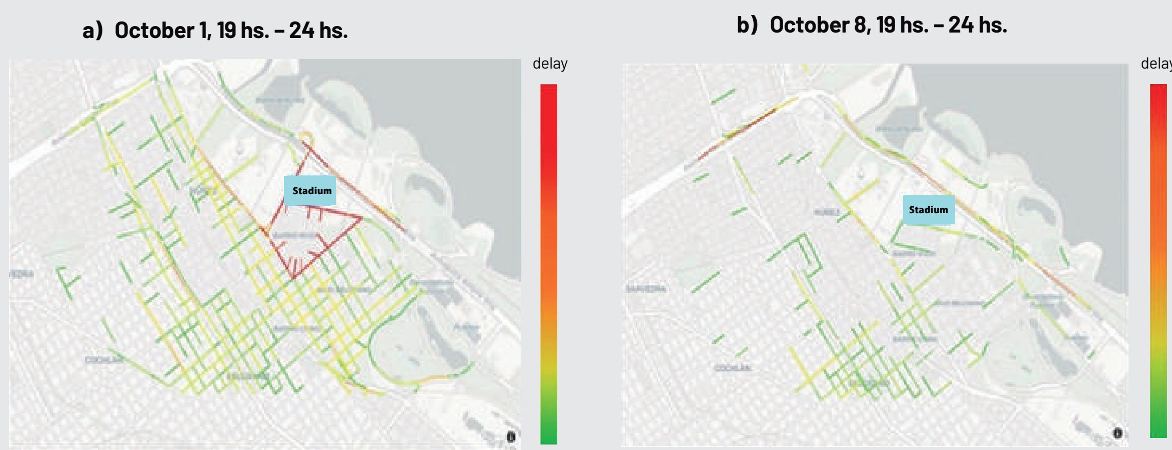
The examples used here help us demonstrate that economic activities can be associated with infrastructure saturation levels and, therefore, congestion. At the same time, congestion has specific characteristics and dynamics in each case. Given the direct and indirect economic costs derived from congestion for cities and their inhabitants, it is essential to know these characteristics to design effective traffic management measures, balancing the adverse effects of economic agglomeration on the territory. Regarding this issue, Chapter 5 mention the actions that have proven to be most effective for urban logistic management.

4.2 Urban congestion related to cultural and social activities

Cities are the nucleus of numerous **cultural and social activities**, including sporting and musical events. They are the focal point for multiple trips, and the capacity of the available transportation infrastructure is often exceeded. Although cultural events, as well as artistic and sporting events, are a functional element in the life of cities and act as generators of economic opportunities, from the point of view of transportation, it is vital to study the impacts that these activities have on traffic. It is also important to implement actions that mitigate the risk of traffic incidents and facilitate mobility in the areas involved. Below, we examine two examples of mega cultural events —a soccer match in Buenos Aires and a music festival in Santiago— to demonstrate their impact on urban congestion.

On Tuesday, October 1, 2019, the two most important soccer teams in Argentina, River Plate and Boca Juniors, faced each other on the pitch in Buenos Aires. It was the **semifinal match of the Copa Libertadores**, the soccer tournament that brings together the top clubs in South America. Approximately 70,000 spectators gathered at River Plate's "Monumental" stadium. The game started at 9:30 pm, ending shortly before 11:30 pm. Figure 4.8 shows the traffic conditions around the stadium for the period between 7 pm and midnight on October 1, compared to the similar period on the following Tuesday, October 8, when there was no soccer match at the Monumental. There is an apparent increase in congestion in the area surrounding the stadium, measured in more than 23,000 hours (an increase of 811%) for the specified period. Likewise, the geographic extension of the delays caused by this mega event reaches the neighborhoods adjacent to the River Plate district, such as Núñez, Bajo Belgrano, and Barrio Chino (Chinatown).

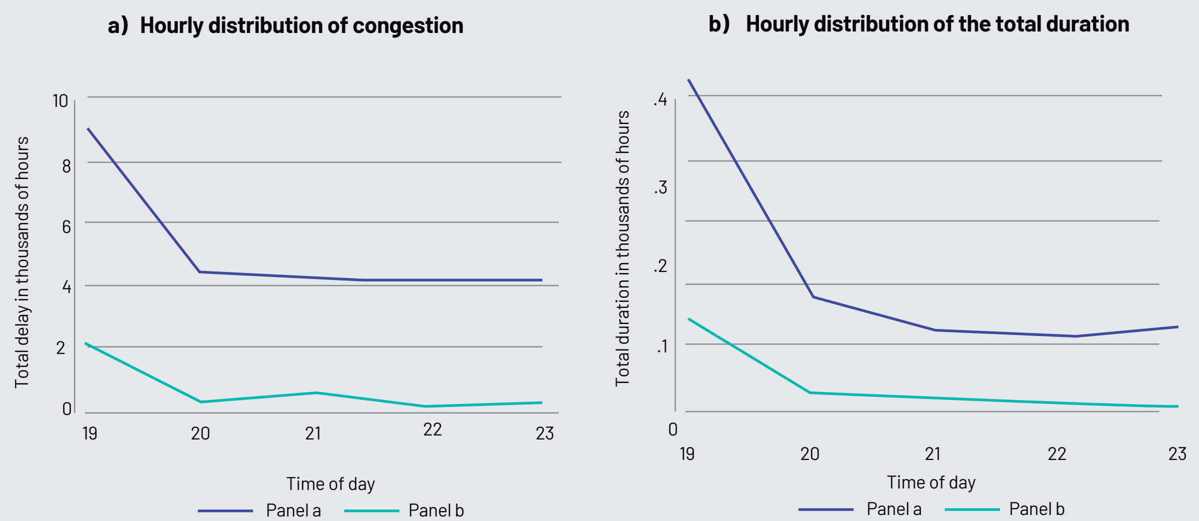
Figure 4.8 Semifinal of the Copa Libertadores and urban congestion (Buenos Aires, 2019)



Source: Own calculations using data from Waze.

Figure 4.9.a shows the total delay for October 1 and 8, between 7 pm and 11 pm. In panel b —the congestion scenario without the Copa Libertadores Semifinal— the total delay is reported to be less than 3,000 hours, partially disappearing after 11 pm. On the day of the match, the total delay was approximately 9,000 hours at 7 pm and remained above 4,000 hours thereafter, resulting in an overnight loss of almost 26,000 hours. Figure 4.9b shows the total duration of traffic jams. On the day of the match, we can observe a total traffic jam duration of nearly 1,000 hours. This is much higher than the reported congestion on days when there was no match, where only 200 hours were lost due to congestion.

Figure 4.9 Congestion dynamic during the Copa Libertadores Semifinal (Buenos Aires, 2019)

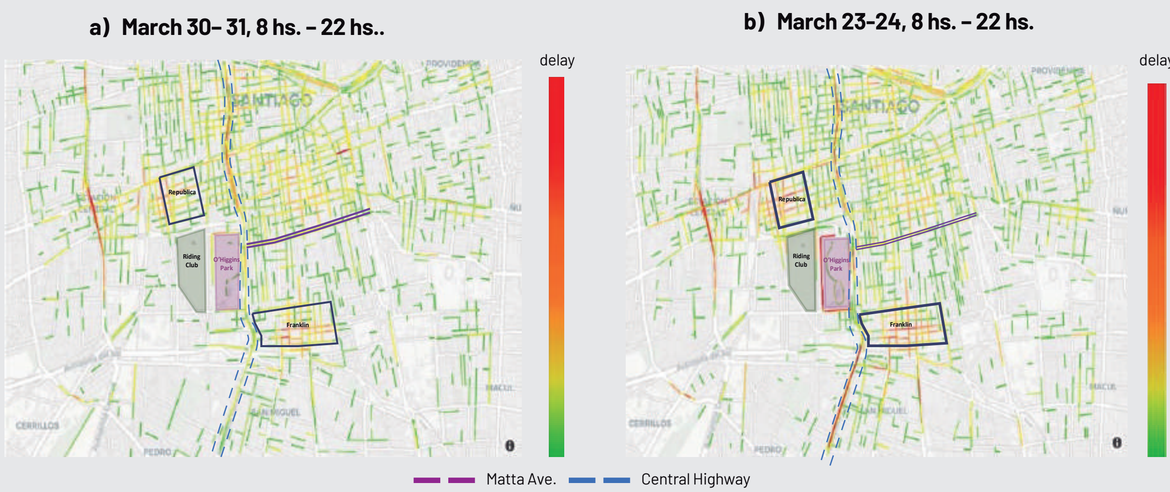


Source: Own calculations using data from Waze.

In addition to sporting events, concerts are also events that usually gather a large number of people in a reduced area and a specific period. In order to analyze the behavior of congestion in these cases, we chose the **music festival "Lollapalooza Chile"**, which took place in Parque O'Higgins during the last weekend of March 2019, gathering more than 240,000 people. The event had three access points, which opened at noon on Friday, March 29th, and closed on Sunday, March 31st, at 11:30 pm. O'Higgins Park is located in the municipality of Santiago Centro, close to three stations on Line 2 of the Santiago Metro: Toesca, Rondizonni, and Parque O'Higgins. Due to the magnitude of the event, the authorities decided to extend the operating hours of Metro Lines 1 and 2. On the other hand, people who wanted to attend the event in a private vehicle could pay for a parking space in advance at the Club Hípico de Santiago (Santiago Riding Club).

Figure 4.10 illustrates the state of congestion in the area surrounding Parque O'Higgins, for the period between 8 am and 10 pm on the weekend of March 30-31, compared to the same period in the previous weekend. This image shows the great contrast in congestion on the roads surrounding the park, such as Matta Avenue and the Central Highway (Autopista Central). Additionally, the impact that this massive event had on the traffic congestion of the neighborhoods located moderately close to the park, such as Franklin or República, can be observed.

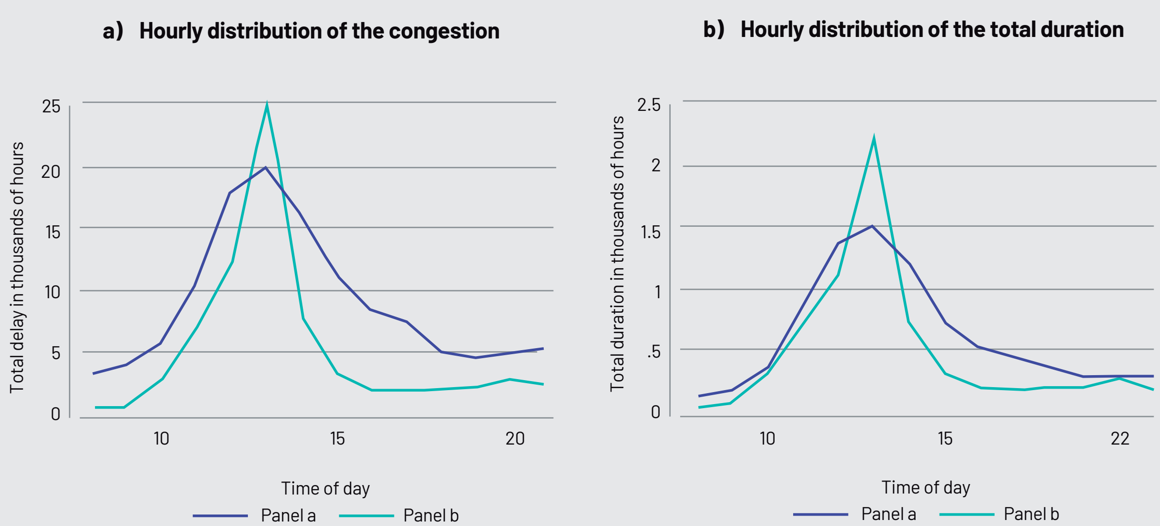
Figure 4.10 Urban congestion in Parque O'Higgins, Santiago (2019)



Source: Own calculations using data from Waze.

The accumulated delay on the days where the Lollapalooza occurs is consistently higher than the cumulative delay between March 23 and 24 (Figure 4.11). At 10 am, the total delay was almost 6,000 hours on the festival days, while the previous weekend, the delay barely reached 3,000 hours. The day ended with a similar margin of difference. In both cases (days with and without festival), an increase in congestion can be observed between 10 am and 1 pm, which exceeded 20 thousand hours of delay. It should be noted that the peak with the most extended delay was registered on the days when there was no festival, and it took place at 1 pm with a total delay of more than 25 thousand hours. However, in the entire period analyzed, congestion is 50 thousand hours higher on the days of the Lollapalooza festival, which represents almost 70% more congestion due to the event.

Figure 4.11 Congestion in Parque O'Higgins



Source: Own calculations using data from Waze.

In short, as evidenced in the cases mentioned above of the Copa Libertadores Semifinal and the Lollapalooza festival, mega-events generate great stress on urban roads, expanding beyond the areas merely adjacent to the places where such events are held. Having granular information about the impact on the mobility of this massive influx of people is key to designing effective traffic management plans that mitigate adverse effects on road safety and the welfare of the areas involved in such events.

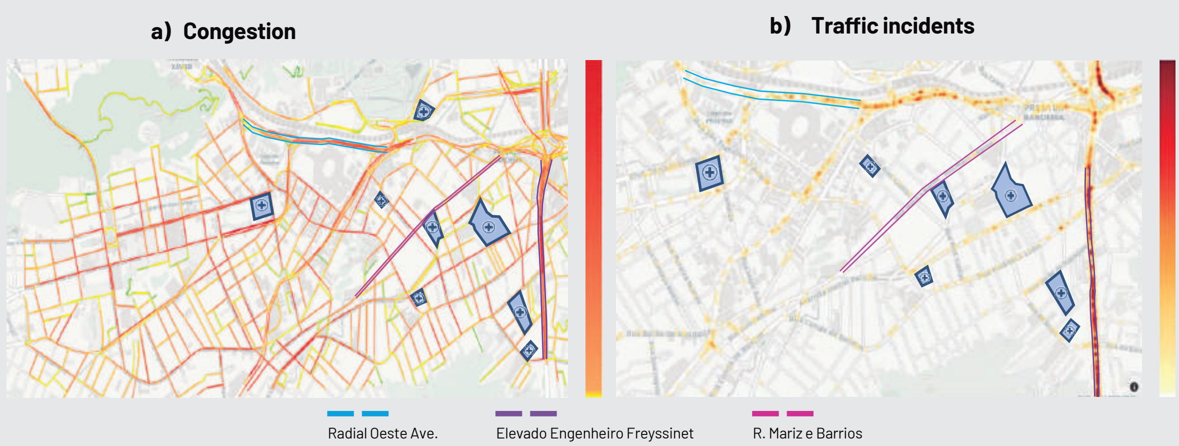
4.3 Urban congestion related to essential areas

Cities bring **together centers of primary importance** to society, such as health and educational centers. These places are frequented day after day by thousands of people, generating a high volume of traffic in their vicinity and, at certain times, recurrent congestion. In these cases, in addition to the economic costs of congestion, it is essential to consider its indirect impacts, such as a greater propensity to traffic incidents in areas where large numbers of children gather, and longer delays in areas where timely access to health care can be decisive. Thus, proper traffic management in areas surrounding primary care centers is essential to mitigate risks to road safety and health care. The granularity of traffic data available through big data makes it possible to understand congestion patterns in these areas in unprecedented detail. For this purpose, and as an example, in this section we will analyze the dynamics of congestion and incident levels around three essential areas in LAC cities: a hospital area in Rio de Janeiro, a university area in Sao Paulo, and a school area in Mexico City.

The area around the Maracaná stadium in **Rio de Janeiro** is home to a **hospital network with numerous centers and specialties**: between Maracaná Avenue, and the Dr. Satamini Street are the Clínica Médica, the Hospital Universitário Gaffrée y Guinle and the Hospital São Vicente de Paulo; to the southeast of Dr. Satamini Street are the Hospital Central da Aeronáutica and the Rede Hospital Casa de Portugal; to the southwest of the latter is the Hospital Casa Prontocor; in the northwest sector is the Hospital Universitário Pedro Ernesto; and to the northeast is the largest hospital in the State, the Hospital Quinta D'Or. Given the presence of a great number of health care centers in this area, we wonder what congestion and incident dynamics are like here.

Figure 4.12 shows that the most congested roads during 2019 were mainly the Radial Oeste Avenue and Engenheiro, crucial for traffic flow from north to south and to gain access to hospitals from the west. For its part, Mariz e Barrios street, which is key to ensure connectivity within the area, reports a high level of congestion in a stretch located to the south of the Maracaná stadium. As expected, the main roads show a high level of traffic incidents, which can be crucial if it is necessary to access the health services urgently.

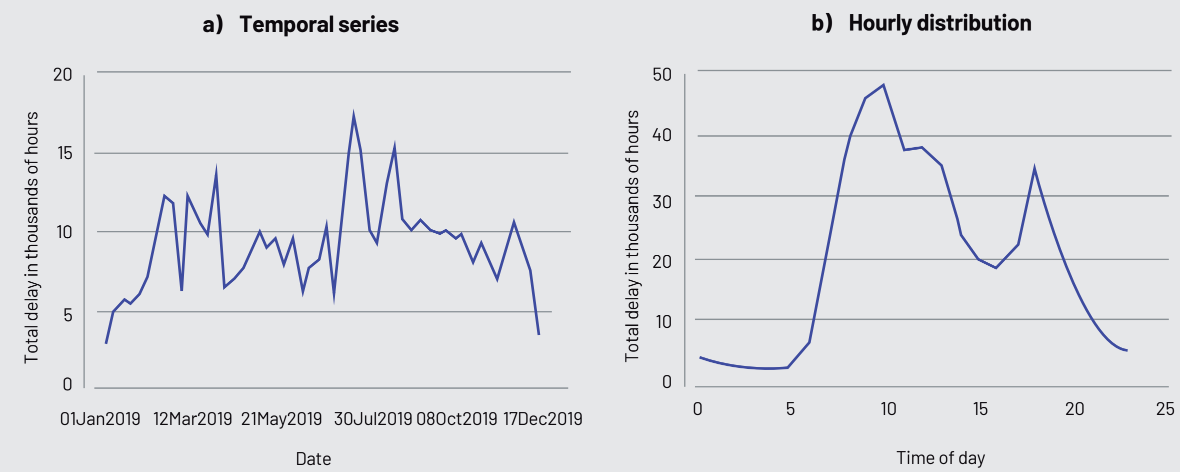
Figure 4.12 Urban congestion and traffic incidents in the hospital area, Rio de Janeiro (2019)



Source: Own calculations using data from Waze.

The average weekly delay due to congestion in the area surrounding the hospital was around 8 thousand hours during 2019, with a maximum of 17 thousand hours recorded at the end of July (Figure 4.13). In particular, it should be noted the high level of congestion in the periods between February and May, and from July to September. The bulk of congestion in this area occurs between 9:00 am and 9:00 pm, with particular emphasis on the period between 9:00 am, and 11:00 am (when a maximum of 48,000 hours of congestion is reached) and 6-7 pm (34 thousand hours). The total duration of traffic jams reaches 63 thousand hours.

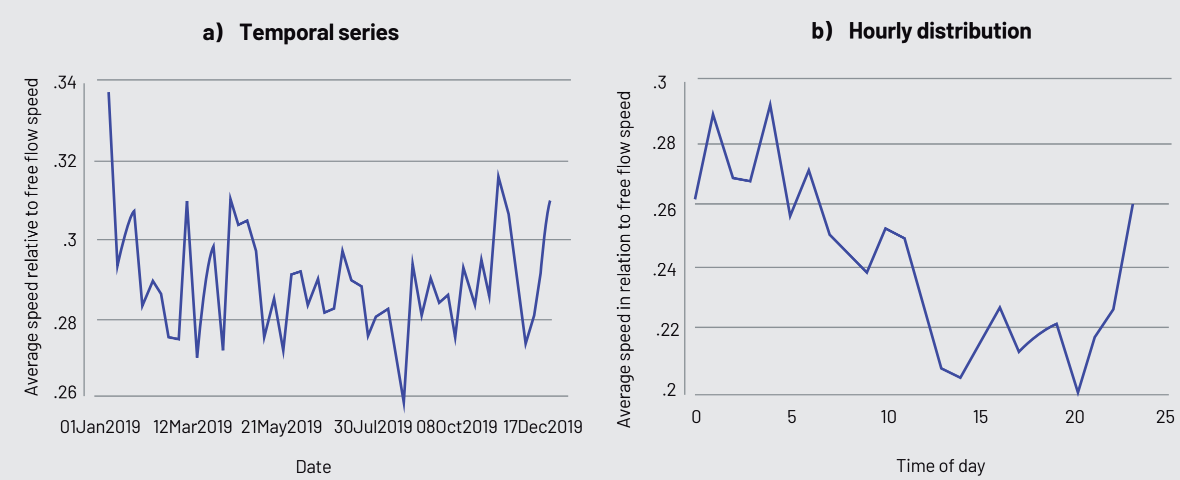
Figure 4.13 Temporal description of congestion in the hospital area, Rio de Janeiro (2019)



Source: Own calculations using data from Waze.

The average speed during traffic jams was below 29% of the free-flow speed during 2019, with a minimum reached in August below 26%. The trend by time of day shows that the average speed falls steadily from 4 am to 3 pm, particularly from 6 am to 9 am (a 3-percentage point drop), and from 11 am to 1 pm (a 5-percentage point drop). The minimum speed was recorded at 8 pm, with a 20% average speed in relation to the free-flow speed.

Figure 4. 14 Average speed during traffic jams in the hospital area, Rio de Janeiro (2019)

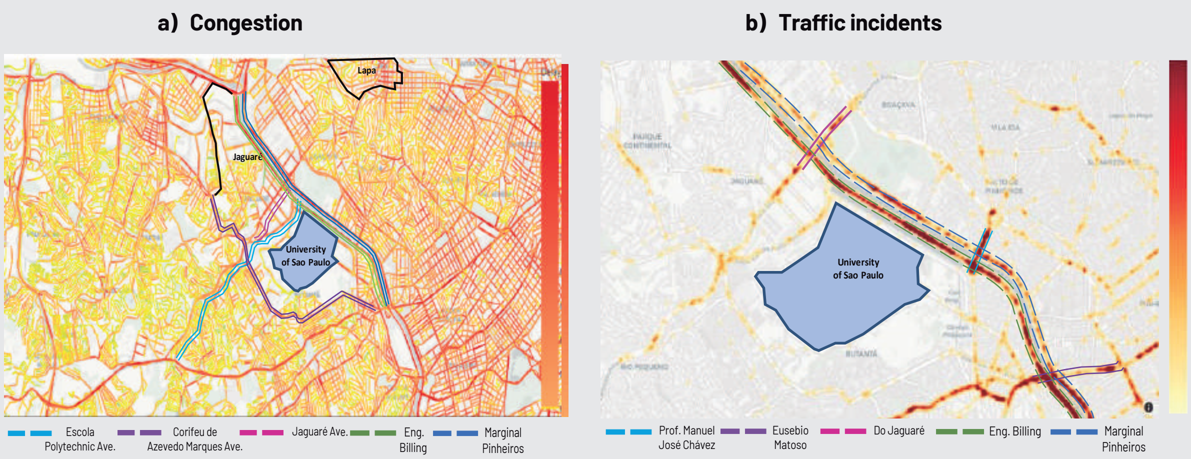


Source: Own calculations using data from Waze.

Next, we will consider the case of an **educational center**. The University of Sao Paulo is one of the largest and most influential higher education centers in Brazil and LAC, with about 75,000 students enrolled. The university has four campuses, the main one being the **Cidade Universitária Armando de Salles Oliveira**, located in the West Zone of Sao Paulo. The main teaching units, research units, and extension areas of the university are located there, and, consequently, that area is frequented daily by thousands of students and employees.

Figure 4.15 highlights high levels of congestion in the area surrounding the campus, comprising Jaguaré Ave. and Escola Politécnica Ave. (to the west), Corifeu de Azevedo Marques Ave. (to the southwest), and Eng. Billing Ave. and Marginal Pinheiros (to the east). The highest concentration of congestion occurs on Eng. Billing Ave. and Marginal Pinheiros, two essential roads that connect the University with the rest of the city, and on Jaguaré Ave., where the only bridge in the area is located over the Pinheiros River, connecting the neighborhoods of Jaguaré (to the south) and Lapa (to the north). The number of traffic incidents is higher in the area closest to the University, especially on the three bridges that connect this area to downtown Sao Paulo, crossing the Pinheiros River (Eusebio Matoso to the south, Cidade Universitária in the center and Jaguaré, north of the University).

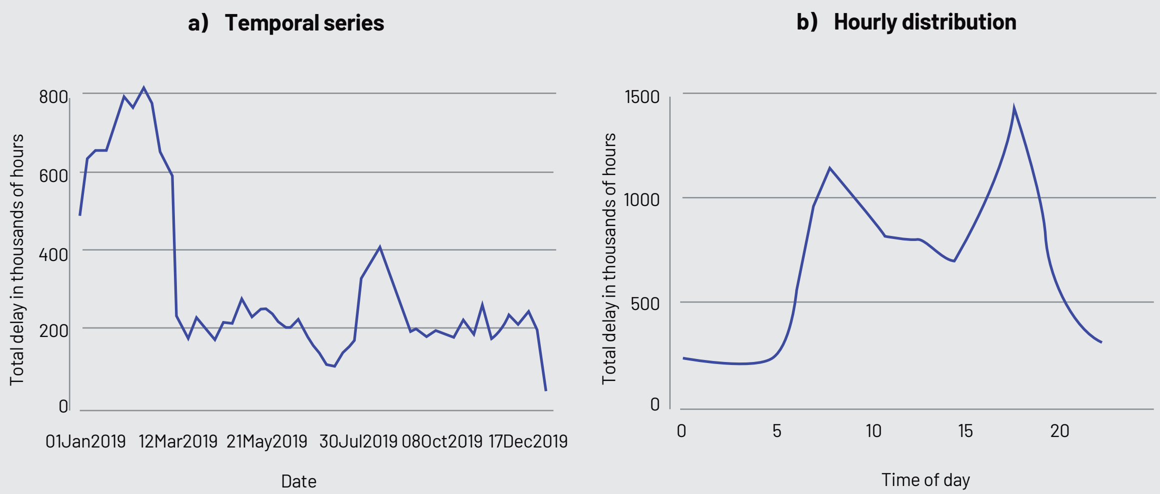
Figure 4.15 Urban congestion in the area surrounding the University of Sao Paulo, Sao Paulo (2019)



Source: Own calculations using data from Waze.

Figure 4.16 shows that the highest congestion occurs during the first quarter of the year, exceeding 800 thousand hours of aggregate delay in February. From March onwards, congestion decreases considerably, remaining stable for the rest of the year, at around 200 thousand total hours. Two significant peaks can be observed regarding hourly distribution, one at 9 a.m. with more than 1,100 hours of total accumulated delay, and the most critical at 7 p.m., with almost 1,500 hours lost.

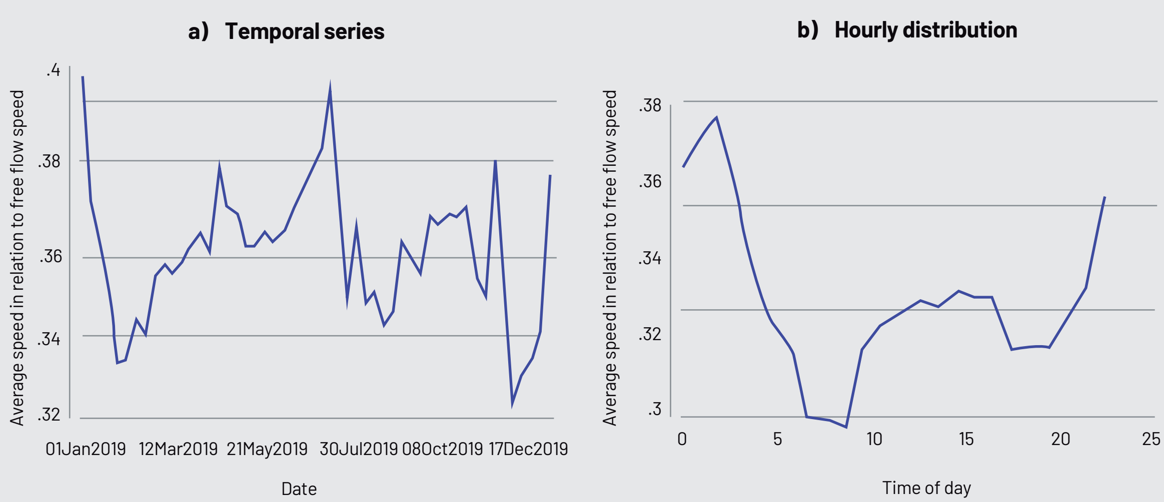
Figure 4.16 Temporal description of the congestion in the area surrounding the University of Sao Paulo, Sao Paulo (2019)



Source: Own calculations using data from Waze.

The average speed during traffic jams around the University of Sao Paulo was approximately 35% of the free-flow speed throughout 2019. The greatest reduction in speed occurred between 4 am, and 9 am, reaching a minimum of less than 30% (Figure 4. 17).

Figure 4.17 Average traffic jam speed around the University of Sao Paulo, Sao Paulo (2019)



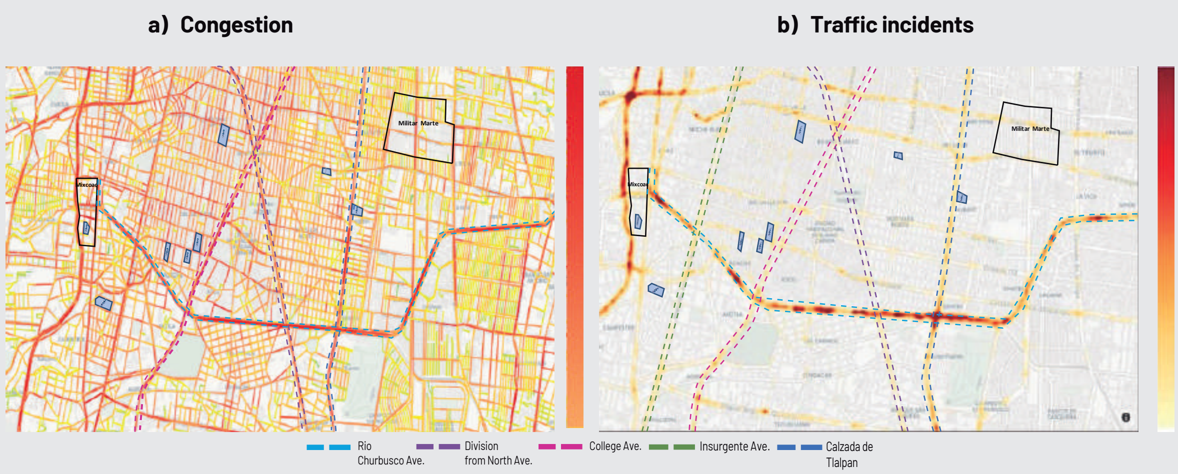
Source: Own calculations using data from Waze.

In **Mexico City,** there is also an area with a significant number of educational centers, mainly **primary schools**. This area is located between the Mixcoac neighborhood and the Militar Marte neighborhood, south of the city. The following schools are located in this area: to the east, the Guadalupe Victoria Elementary School, the Canadiense Del Valle

Elementary School, and the Republic of Paraguay Elementary School; in the center, the Mexican American School, the Mexicana Del Valle School, and the New Continent School, among others; to the north, the New Mexico School and a group of university centers; and to the west, the Cyprus Elementary School and the General Anaya Elementary School. Given the relationship between congestion levels and incident rates, as evidenced in the literature and our results, timely congestion management is key in the areas surrounding educational centers to reduce the risk of injury to children and adolescents.

Figure 4.18 shows a significant concentration of congestion on División del Norte Avenue, which crosses the metro station of the same name, and Universidad Avenue, both converging at the Glorieta de Rivera. In addition, high congestion levels are reported on Río Churbusco Avenue, one of the city's main thoroughfares running from the north to the west, and Calzada de Tlalpan Avenue, which connects the historic center with the southern zone. As expected, traffic incidents reflect a dynamic that closely follows congestion (panel b of Figure 4.18). Thus, congestion and incidents are significantly lower on the roads where educational centers are located, highlighting the need to manage congestion and traffic incidents together.

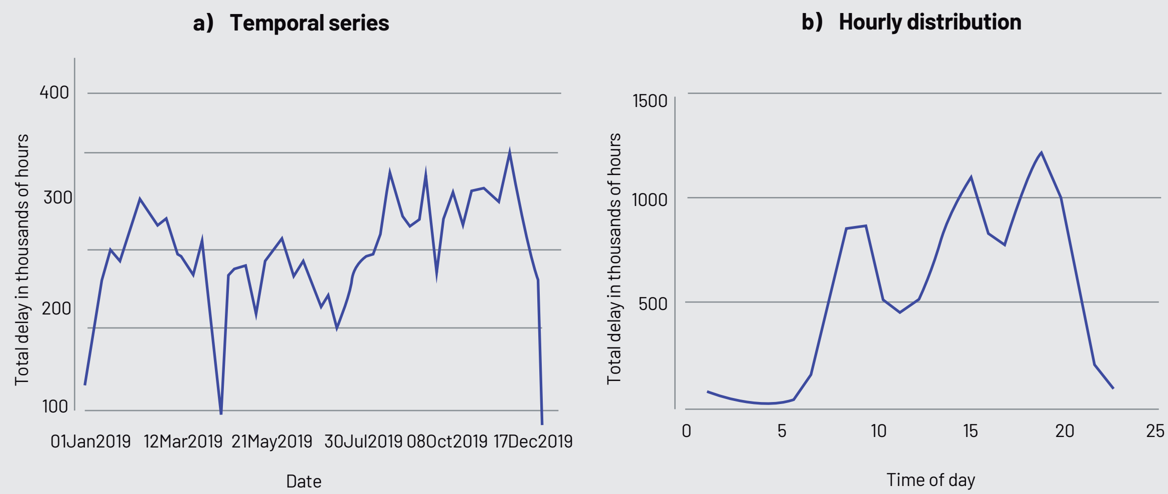
Figure 4.18 Urban congestion in the school areas, Mexico City (2019)



Source: Own calculations using data from Waze.

The average congestion level reported in this area was close to 210 thousand hours per week during 2019, with a negative trend during the first part of the year and a positive one during the second part. Peak congestion was recorded during the last weeks of the year, approaching 320 thousand total hours of delay. At this point, the average weekly duration of traffic jams reached 17,000 hours. Three peaks were identified for its hourly distribution: between 6 am and 9 am, then at noon, and finally between 6 pm and 8 pm. In this last peak, the maximum accumulation was close to 1,250 hours of the total delay (Figure 4.19).

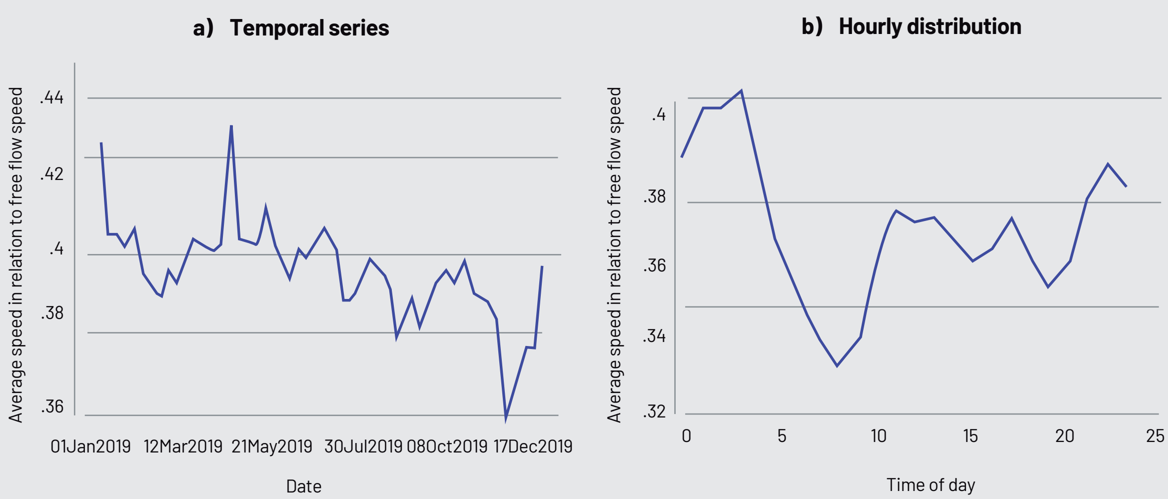
Figure 4.19 Temporal description of urban congestion in school areas, Mexico City (2019)



Source: Own calculations using data from Waze.

Figure 4.20 shows the downward trend of the average speed during traffic jams over time, with values around 40% of the free-flow speed, and dropping below 36% at the end of the year. The most considerable reduction in average speed occurs during the first peak of congestion, i.e., from 6 am to 9 am, falling below 34%; after that, speed remains relatively stable throughout the day, at around 37% of the free-flow speed.

Figure 4.20 Average traffic jam speed in school areas, Mexico City (2019)



Source: Own calculations using data from Waze.

In conclusion, the cases analyzed here show that, as in economic and social activities, the granularity of the traffic data available through big data allows for a better understanding of congestion patterns in priority areas. This is a

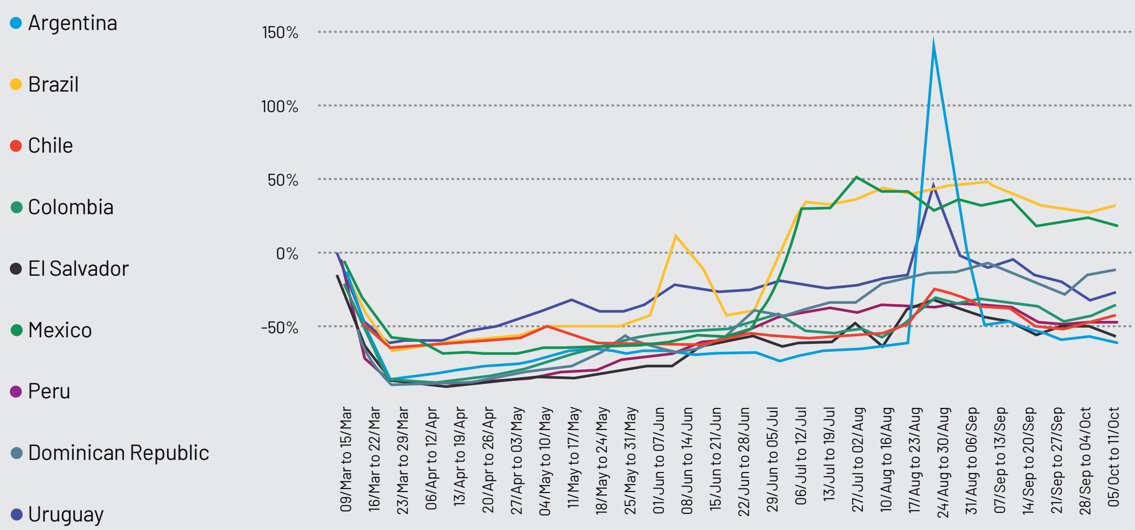
crucial input to design mobility improvement plans in such places, reduce access time to health services —especially in fast lanes used by ambulances— and mitigate the risk of traffic incidents that may result from congestion, particularly in areas where there are children.

Box 4.1 Impact of COVID-19 on congestion

Based on detailed information about the state of congestion in LAC cities, the IDB developed a traffic intensity index by country to analyze **the change and evolution of congestion during the COVID-19 pandemic**. Indeed, during the year 2020, the world population was greatly affected by this pandemic, which produced important changes in mobility patterns in cities. The prevention measures implemented by governments to contain the virus, such as encouraging teleworking, promoting active transportation modes (cycling and walking), and closing non-essential activities, led to a decrease in public and private transportation. As a result, congestion decreased significantly, with a 30% reduction in intensity compared to pre-pandemic levels by October 2020 (Figure 4.21). At that date, the countries with the highest congestion levels were Brazil and Mexico, where mobility restrictions were minimal. It is interesting to note that, in both countries, congestion was 50% higher than pre-pandemic levels. One hypothesis to explain this increase is the greater distrust of public transportation by citizens, perceived as a source of contagion of COVID-19. This could be in line with what has been evidenced in cities such as Madrid, where public transportation went from being the most used mode of transportation during the pre-pandemic period to being the third (25% of trips), after private vehicles (44%) and active transportation (32%) (El País, 2020). As progress is made in containing the spread of the virus and restoring activities in LAC cities, it will be essential to monitor the evolution of this index developed by the IDB in order to assess the impact of the pandemic on the modal choice and mobility patterns of the inhabitants of LAC cities and to design actions that encourage sustainable mobility in these cities.

Figure 4.21 Change in congestion intensity by country during 2020

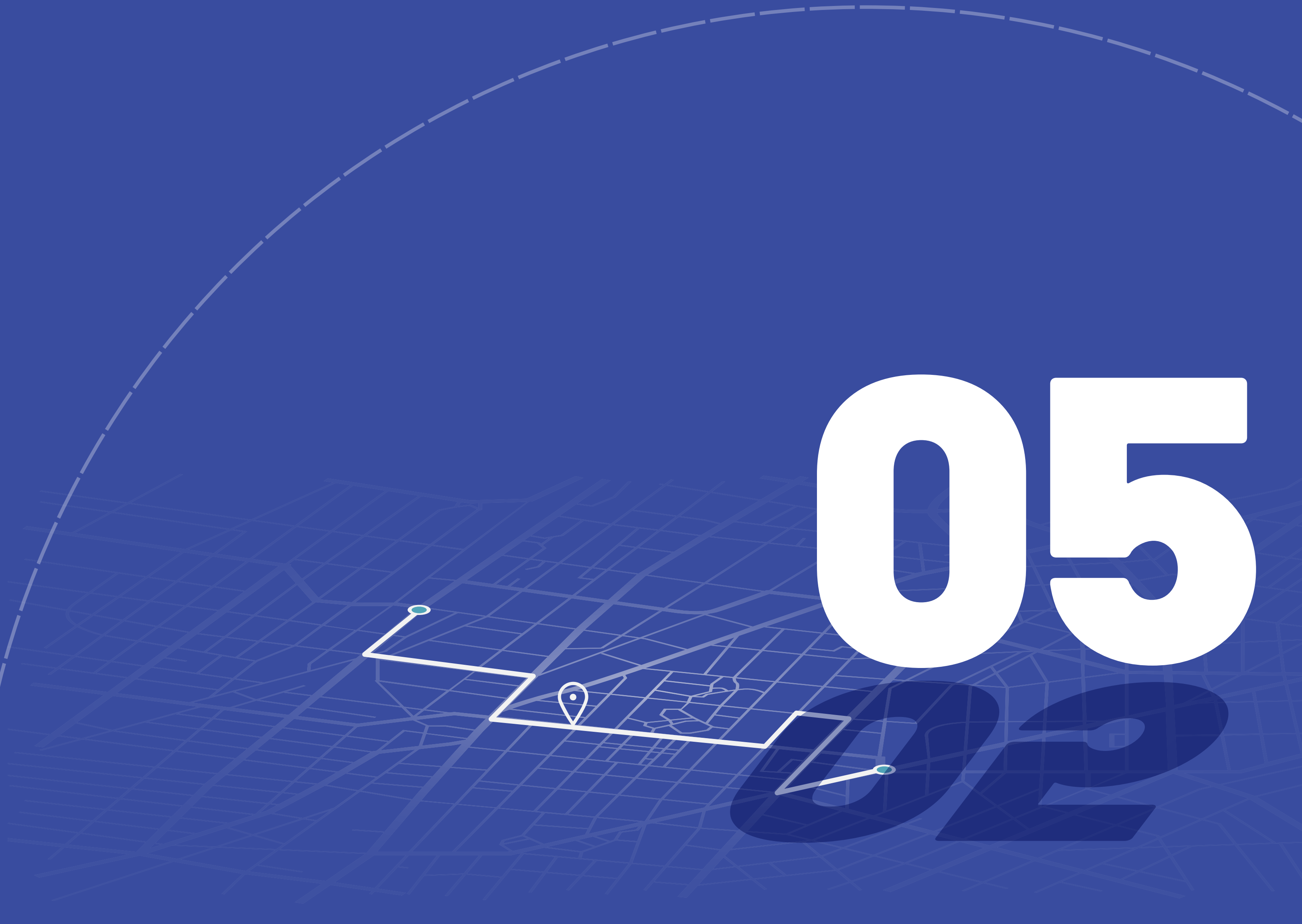
(percentage change with regard to the week from 2 to 8 March 2020)



Source: https://www.iadb.org/es/topics-effectiveness-improving-lives/coronavirus-impact-dashboard

Chapter 5.

PUBLIC POLICIES TO REDUCE ROAD CONGESTION



In the previous chapters, we showed the state of congestion in ten major LAC cities and estimated its direct and indirect costs. We also provided examples of how the agglomeration of economic, social, and basic activities inherently entail high congestion levels. The general trends of mobility in the region, with an increase in motorization rates and a reduction in the use of public transportation, together with an increase in urban population, do not suggest that the levels of congestion currently present will be reversed in the near future (Calatayud & Muñoz, 2020). Moreover, the distrust towards public transportation caused by the COVID-19 pandemic could increase the use of private vehicles. There are already some signs of this shift in cities such as Shanghai and Madrid. In the latter case, public transportation went from being the most used mode in the pre-pandemic period to being the third (25% of trips), after private vehicles (44%) and active transportation (32%) (El País, 2020).

In this context, the **design of effective public policies** will be the key to moving towards more efficient and sustainable mobility in our cities. Thus, this chapter aims to share solutions and best practices at the international level to provide policymakers with a set of instruments that will lead to better road congestion management. These solutions will be presented in **four groups** (Table 5.1), following the categories established by Buehler et al., namely: (i) **traffic management instruments**; (ii) policies that restrict the use of private vehicles; (iii) policies that promote the use of public and active transportation and ridesharing; and (iv) integrated mobility and land use planning. We also include a section on **urban logistics management**, a field that is beginning to gain attention among policymakers as the circulation of freight vehicles in cities increases, in part due to the boom in e-commerce. Many of the recommendations in this chapter have been developed, replicated, and reprinted in various Inter-American Development Bank publications, which will be included as a reference for the reader to consult for further details.

It is important to emphasize that for congestion reduction initiatives to be successful they must be contained within a **comprehensive** framework that, on the one hand, promotes the improvement of alternative modes of transportation to the private vehicle and, on the other, discourages the use of cars. Furthermore, not all measures address the same causes of congestion, nor do they have the same time horizon for implementation. Therefore, it is crucial to identify the most effective measures in reducing congestion according to the particular situation of the city to be addressed and assess the **timing required** for policy implementation. Above all, the measures should be contained in integrated land use and transportation plan that promotes more sustainable and resilient cities focused on moving people and not vehicles. To this end, it is crucial to plan the city from a systemic approach that generates greater accessibility to job, health, and education opportunities based on mixed land uses and an integrated and efficient transportation network. Based on the measures analyzed, in the last part of this chapter, we will reflect on the most necessary congestion control measures in LAC megacities and their implementation sequence. Clearly, these measures must be **adapted to the reality of each city**.

Table 5.1 Public policies to reduce congestion

Traffic management	Restriction of private vehicle use	Promotion of public and active transportation and ridesharing	Integration of mobility and land use	Urban logistics management
• Infraestructure supply • Traffic calming and road access control • High-occupancy vehicle lanes • Optimized and adaptive traffic signal cycles • Real-time traffic monitoring • Enforcement of traffic laws and regulations • Travel demand reduction	• Traffic restriction • On-street parking limitations • Fuel taxes • Car taxes • On-street parking charges • Road pricing	• Quality and availability of public transportation • *Park-and-ride* facilities • Bicycle and pedestrian infrastructure • School transportation • Institutional transportation • Carpooling systems • Transportation supply for people with disabilities	• Transit-Oriented Development (TOD) • Urban mobility master plan	• Off-peak delivery of goods • Allocation of special areas for loading and unloading • Congestion and/or parking charges

Source: Own elaboration.

5.1 Traffic management tools

These instruments aim to **optimize the flow of vehicles within the conditions established by the existing infrastructure**. In other words, they seek to generate the best possible performance from the infrastructure. Among the instruments most commonly used by sector specialists are: (i) provision of infrastructure; (ii) high-occupancy vehicle lanes; (iii) traffic calming and road access control; (iv) optimized and adaptive traffic signal cycles; (v) use of technologies for real-time traffic monitoring; (vi) use of navigation applications; (vii) traffic enforcement; (viii) travel demand reduction.

5.1.1 Provision of Infrastructure

For years it was thought that the solution to road congestion was the construction of new roads or the expansion of existing ones. However, this only partially solves the problem in the short term. The construction of more private vehicle infrastructure causes a greater demand for roads in the medium and long terms, a phenomenon known as induced demand. In other words, road congestion is back and often worse than before. In this regard, Noland (2001) analyzed roads in the USA and found that 25% of the overall growth in vehicle miles traveled (VMT) was attributable to the historical increase in road capacity, reporting higher elasticities in urban roads. Bagloee et al. (2019) conducted a review on real cases of the Braess paradox (1968), which suggests that closing a road/thoroughfare can improve road congestion. They found that, for example, the destruction of a six-lane highway in Seoul improved travel time to and from the city, even when the level of traffic remained constant (Easley & Kleinberg, 2010). Similarly, in Stuttgart, increasing the capacity of the road infrastructure worsened congestion, which was only reduced once part of the built infrastructure was closed to traffic (Knödel, 2013).

Indeed, when urban infrastructure is designed and built with the use of private vehicles in mind, the result will be more vehicles, more congestion, and greater negative environmental impacts. If, in contrast, infrastructure is designed and built *thinking on Complete Streets (see* *Manual de calles: diseño vial para ciudades mexicanas*, *Street Man-*

ual: Road Design for Mexican Cities) and to increase the efficiency of roads to move people and goods instead of vehicles, inhabitants are encouraged to diversify their modes of transportation, specifically recurring to active mobility and public transportation, and road congestion is therefore alleviated. This entails a change in the paradigm adopted by engineering for the design of the urban road network, now focused on improving vehicular flow and traffic speed, incorporating the concept of mobility, both active (pedestrian and bicycle) and public transportation of people and freight, which takes place on the streets. Thus, complete streets include wider sidewalks, bicycle lanes, and exclusive lanes for public transportation, based on prioritizing urban space users, where pedestrians and public transportation users are prioritized over those traveling in private vehicles. The literature shows the positive impacts of this type of design on modal choice. In this regard, after analyzing travel patterns in the 100 largest cities in Mexico, Guerra et al. (2018) confirmed that people tend to use the car less in areas endowed with better public transportation and less access to vehicular infrastructure use. An impact evaluation developed for this report found that the comprehensive infrastructure project in Buenos Aires called Paseo del Bajo significantly reduced road congestion in downtown Buenos Aires during 2019 (see Box 5.1).

Figure 5.1: Area directly influenced Paseo del Bajo

According to the Government of Buenos Aires, before the second trimester of 2019, around 91 thousand private vehicles, 28 thousand bus passengers, and 15 thousand heavy-duty vehicles used to cross the Buenos Aires downtown every day; forced to share the same road lanes, even though this area was not their destination (Government of Buenos Aires, 2019). In particular, the large influx of freight in the area is generated by the importance of connections to the city's seaport and the Retiro bus terminal. Faced with growing traffic demand, the lack of appropriate infrastructure made mobility in the micro center (Madero-Huergo axis) unsustainable, with effects on the connectivity of the different zones of Buenos Aires and its Metropolitan Area (MA). In fact, this area was among the most congested in the MA, mainly on Alicia Moreau de Justo and Huergo avenues, causing high levels of environmental and noise pollution (Government of Buenos Aires, 2019).

On May 27, 2019, the integral infrastructure work called Paseo del Bajo, whose construction process began approximately 50 years ago, was inaugurated in response to the problem. It consists of an exclusive highway for heavy traffic and long-distance buses, with an open (semi-underground) trench design from the Buenos Aires-La Plata highway to its junction in the north with the Illia highway (Figure 5.1). The project runs along Alicia Moreau de Justo and Huergo-Madero Avenues, Ramos Mejía, Antártida Argentina and Castillo Avenues. The extension of this project is 7.1 kilometers, with 12 new lanes (four for trucks and long-distance buses and eight for light vehicles), 15 crossways (five

Figure 5.1: Area directly influenced by Paseo del Bajo

Note: The entire layout corresponds to the structure of Paseo del Bajo. The colors of the layout represent the open semi-underground trench structure of the work.

Source: Own elaboration with information from the Government of Buenos Aires.

are pedestrian), and includes a total of 13.6 hectares of public and green spaces (Government of Buenos Aires, 2019b).

Based on the methodology proposed in Chapter 2, the total traffic congestion is calculated within the area directly influenced by the project, as shown Figure 5.1. The congestion trend reports a jump from the opening day of Paseo del Bajo (May 27, denoted as the cut-off point), and it is maintained until December 31, 2019 (Figure 5.2).

Before the work started, the level of congestion in the immediate area of influence amounted to 3,019.2 hours lost due to traffic delay, with a standard deviation of 2,012.3 hours, while the rest of the year this average fell by 46%, and its standard deviation by 35%, although the coefficient of variation increased by 22%. This reduction in congestion level is observed at all times of the day, but particularly in the afternoon and evening.

What was the impact of the work on road congestion? To answer this, we have developed an impact evaluation using this jump in the congestion trend. A Regression Discontinuity in Time (RDiT) design is implemented with the date as the running variable and May 27 as the discontinuity boundary, controlling for variables correlated with the presence of the work and the dynamics of congestion, including the number of lanes closed, road hazards, incidents duration, fixed effects, and the autoregressive process[19].

The results indicate that the average reduction in congestion caused by the inauguration of the project itself was 18%, compared to the period prior to the event (Table 5.2, PB is the treatment variable that takes the value of one from the date of the inauguration of the Paseo del Bajo and $date$ is the distance in days to May 27). The results are consistent regardless of the chosen bandwidth. The estimation by subsamples considering the peak-hour periods allows us to confirm that this reduction occurred mainly in the afternoon and evening hours, with a 26% reduction in the 7-11 am period and 30% in the 3-8 pm period[20].

Figure 5.2: Congestion in the area directly influenced by Paseo del Bajo during 2019

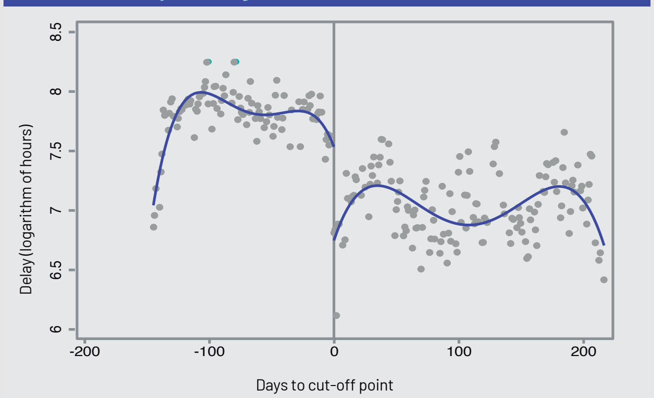


Table 5.2: Impact of Paseo del Bajo in the directly influenced area

	ln (delay)			
	Without bandwidth	With bandwidth	7-11 am	3-8 pm
PB	-0.18**	-0.18**	-0.26**	-0.30**
	(0.07)	(0.08)	(0.12)	(0.10)
PB*date	0.01	-0.001	-0.001	-0.004
	(0.01)	(0.001)	(0.001)	(0.01)
PB*date²	-0.0002	-	-	-
	(0.0003)			
PB*date³	-0.0001	-	-	-
	(0.000)			
Obs.	5,576	1,438	300	360
R^2	0.93	0.96	0.90	0.92

Notes: The first column includes all hours of the day. All controls are included, these are, logarithm of the number -plus one- of road hazards, closed roads and incidents (measured in minutes of duration), each one weighted by the accuracy factor, and a second order autoregressive polynomial. All estimates include fixed effects by month, week, days of the week, and hour of the day. Clustered standard errors by the day of the week and hour of the day are reported in parentheses, **p<0.05, *** p<0.01.

The total investment in Paseo del Bajo was US$702 million, 57% of which was financed by the Development Bank of Latin America (as per its Spanish acronym: CAF), and currently includes a toll charge for heavy-duty vehicles[21]. Considering the first 30 working days after the inauguration of the project and an average of 72,461 total hours that citizens lost per day in this area due to traffic congestion, an 18% reduction represents a monthly savings of 391,228 hours. As described in Chapter 2, we approximate the value individuals place on time in Buenos Aires when traveling by car (VoT). On this basis, we estimate that in the directly influenced area by Paseo del Bajo, the inhabitants of Buenos Aires avoided a loss of around US$1.9 million in the month following the inauguration of the project due to road congestion alone.

19. The detailed methodological development and robustness checks are available in Bedoya-Maya & Calatayud (2021).
20. In fact, the result is higher when ranges later in the night are considered.
21. Charging is performed by a laser system that detects the vehicle and determines its dimensions and category.

5.1.2 Traffic calming and road access control

Traffic jams on urban highways are triggered by a decrease in roadway unloading capacity, which results in less than demand, leading to a reduction in vehicle travel speeds and an increase in lane-changing maneuvers, which increases the likelihood of traffic incidents (J. Shi & Liu, 2019). These capacity losses can be caused by the infrastructure or by users.

The loss of infrastructure capacity is due to the singularities presented by the roads, such as the reduction in the number of lanes, which decreases the total capacity of the road and increases the traffic between lanes; the existence of entrance and exit ramps, which cause disruptions in the flow of the highway, produce queues and increase the number of lane changes; the presence of slopes or curves that vary the speed of vehicle traffic; the poor condition of the road surface, which leads to lower vehicle speeds and a higher probability of traffic incidents; and the heterogeneity in capacity between highways and intermediate streets, so that flows coming from highways end up being inserted into already congested roads (Gomes & Horowitz, 2006).

User-caused traffic jams are caused by obstruction of existing infrastructure in a fixed manner, such as an accident blocking one of the lanes for a while; or in a moving manner, when a vehicle travels at a low speed imposing a traffic speed for vehicles traveling upstream. Unbalanced use of lanes also results in a loss of capacity (Yan & Sun, 2012). For example, when the left lane has a notoriously higher speed than the right lane, there is an incentive to change lanes, which decreases its average circulating speed and generates an underutilization of the right lane, culminating in a lower operating capacity of the highway.

There are several management measures to increase the capacity of urban highways. Ramp metering consists of limiting the flow of vehicles from an entrance ramp to a highway. This allows for increased capacity of the main roadway and the ramp by maintaining the queue of incoming flow on the entrance ramp and allowing vehicles from the ramp to enter the highway, in most cases, at a minimum rate of 1 vehicle every 15 seconds (Gomes & Horowitz, 2006). This type of implementation also discourages the use of highways for short trips (OECD, 2007). A summary of the North American experience shows a reduction in travel times by 20-48%, an increase in travel speed by 16-62% and in road capacity by 17-25%, a decrease in accident rates by 15-50%, and a reduction in fuel consumption by 41% (Arnold, 1998).

Another management measure is limiting the number of lane changes, which is possible by improving lane separation through demarcation or infrastructure or changing the limit on maximum allowable speeds. One way to change speeds is to harmonize the lanes' maximum speeds so that they have a similar level of service and, consequently, drivers are not encouraged to change lanes. This allows for a more even distribution of intervals between vehicles, decreasing variability in travel times and the likelihood of traffic incidents. In Germany, the rate of severe injury incidents decreased by 23% with the implementation of this measure (Waller et al., 2009). Differentiated maximum speeds per lane can also be defined. In this regard, evidence suggests that this measure decreases the frequency and duration of lane changes, drivers avoid dangerous behaviors such as driving on the edge of lanes, and road safety is improved (J. Shi & Liu, 2019).

Additional action is to allow the use of temporary or permanent shoulders to increase roadway capacity at certain times of the day. Waller et al. (2009) show that permanently enabled shoulders in Germany decreased congestion by 68-82% and increased average speed by 9%, while shoulders temporarily enabled at preset times or at times of heavy congestion decreased the number of congestion-induced crashes.

5.1.3 High-occupancy vehicle lanes

One of the main problems concerning the use of cars is their low occupancy rate. Most cars have the capacity to transport five people, yet only one person usually uses them. In this sense, exclusive lanes for high-occupancy vehicles, which carry three or more people, are intended to promote carpooling among people with similar destinations. The literature has pointed out that, for those who use these lanes, miles traveled, travel time, and fuel consumption can be significantly reduced (Daganzo & Cassidy, 2008; Small et al., 2007). Cassidy et al. (2010) suggest a 30% de-

crease in person-hours traveled and a 15% decrease in vehicle-hours traveled. This also brings other benefits, such as a shared economy. Each passenger contributes to the cost of the trip and gasoline consumption is reduced due to the individual trips avoided (Shewmake, 2012). However, the literature also points out that this measure's effectiveness will depend on the utilization rate of these lanes, their location, and the ability to enforce their proper use (Shewmake, 2012). Also, their effects could be diluted over time: as speed increases in these lanes, more traffic could be induced, including trips that were not made before or that were made by public transportation or using other routes (Hughes & Kaffine, 2019).

5.1.4 Optimized and adaptive traffic signal cycles

Traffic volumes vary by roadway and by time of day throughout the day. In this sense, traffic signal cycles must be adapted to these changes to promote more efficient flows and fight congestion. Optimizing and adapting traffic signal cycles can be done through traditional traffic counts or real-time monitoring that responds to each moment's needs. In the latter case, recent simulations suggest that traffic signal synchronization with real-time data decreases delay by 23% over fixed scheduling (Jeon et al., 2018). For the case of LAC, the assessment carried out by Martinez et al. (2021) for Medellín shows that, with the implementation of adaptive traffic lights, traffic speed improves, and delay by congestion decreases.

5.1.5 Use of technologies for real-time traffic monitoring

Obtaining real-time information on traffic conditions in cities has become an essential input for decision making. Most cities already have public safety monitoring systems that can be used to reduce traffic congestion. Another data source is navigation applications, which can provide fundamental input to know the mobility patterns of a city by road and time. The information collected by these means ranges from the immediate identification of an accident on the road, which allows the rapid reaction of emergency services to address the problem and ensure the safety of those involved to a real-time gauging of road flows. This last information allows adapting, in real-time, traffic light cycles to make vehicle flows more efficient or to carry out road closures or other actions to reduce congestion. In addition to the information collected in real-time, historical databases can be generated to analyze better and understand the city's mobility, predict future traffic conditions, and thus propose changes in infrastructure design and public policies to reduce road congestion. Indeed, Singapore has improved its congestion charging system's efficiency by dynamically adjusting fares according to real-time traffic data (Lehe, 2019) (see 5.2.7).

A detailed analysis of the characteristics, methodologies and applications of this information can be found in the IDB publications: *Cómo aplicar Big Data en la planificación del transporte urbano: El uso de datos de telefonía móvil en el análisis de la movilidad* *(How to Apply Big Data in Urban Transportation Planning: The Use of Mobile Phone Data in Mobility Analysiss)* and *Cómo aplicar Big Data en la planificación del transporte: El uso de datos de GPS en el análisis de la movilidad urbana* *(How to Apply Big Data in Transportation Planning: The Use of GPS Data in Urban Mobility Analysis)* (Gutiérrez Puebla et al., 2020), and in *Nueva generación de modelos de transporte a través del uso de big data: Caso San Salvador* *(New Generation of Transportation Models through the Use of Big Data: The Case of San Salvador)* (Rendón et al., 2020).

5.1.6 Enforcement of traffic laws and regulations

Some drivers of private vehicles and public transportation operators do not comply with local traffic regulations, and their bad driving behavior results in traffic congestion. Some examples are parking in prohibited places, obstructing roads with objects to set aside parking spaces, making unauthorized turns, driving, or stopping in exclusive public transportation lanes or bicycle lanes, among others. All these actions have a negative impact on the flow of vehicles and people; they generate traffic congestion and increase the risk of traffic incidents. In this sense, ensuring compliance with traffic regulations by enforcing the law against violators is considered a good practice to improve road safety and reduce congestion.

5.1.7 Travel demand reduction

Work is the main generator of trips in a city. Thus, policies that promote remote working and staggered arrival and departure times can significantly reduce transportation demand and, consequently, road congestion levels. They can also generate significant environmental benefits, in line with the avoid-shift-improve approach, which aims to avoid unnecessary travel, particularly by private car, to reduce the environmental impact of transportation[22].

Remote working has become a necessity due to the COVID-19 pandemic; however, from a transportation point of view, it has previously demonstrated benefits over face-to-face schemes by reducing commuting time to the office, thereby improving people's quality of life. The impetus given by the COVID-19 pandemic to remote work generates reasonable expectations from this point of view: allowing people to work remotely, at least one day per week, would significantly impact travel reduction and city road congestion. Giovanis (2018) studied the relationship between remote work, congestion, and pollution for the case of Switzerland over a span of 12 years, finding that the implementation of remote work had reduced congestion by 2.7% and pollution by between 2.6% and 4.1%. Also, some studies point to a higher quality of life when practicing remote work due, among other things, to being able to avoid the time spent in traffic jams (Golden & Veiga, 2005; Vittersø et al., 2003).

In turn, commuting to work tends to be concentrated at specific times (peak hours) and specific areas. With respect to the latter, the spatial agglomeration of economic activities means that most people go to the same place, where job opportunities are concentrated. The combination of these two factors generates intense road congestion in most cities. Banister & Marshall (2000) found that in the Netherlands remote working reduced peak hour congestion by 26%. Staggered entry and exit times are considered good practices at the international level to combat this problem: they promote demand distribution over time and reduce road congestion (see Takayama, 2015). In this regard, Chile implemented a staggered entry schedule for public service employees, who have the flexibility to start work between 8:00 and 9:30 a.m., as long as they comply with the determined working hours (Library of National Congress of Chile, 2000). The impacts of this measure on congestion remain to be evaluated.

5.2 Policies that restrict the use of private vehicles

These policies include regulations and economic instruments to **discourage car use**. In particular, they include: (i) restrictions on vehicle circulation; (ii) limitation of on-street parking; (iii) fuel taxes; (iv) car taxes; (v) on-street parking charges; (vi) special taxes on public parking lots; and (vii) road pricing. Below, we describe each of them and present the available evidence on their effectiveness in reducing car use.

5.2.1 Traffic restrictions

Traffic restriction policies consist of reducing the days or hours on which a vehicle can be used. Usually, this is done based on some alphanumeric character in the license plate: for example, all cars with license plates ending in 1 or 2 do not circulate on Mondays. These policies have been implemented in different cities in the region, such as the "*hoy no circula*" (literally in Spanish: "today [your car] does not circulate", known as No-drive days) in Mexico City and the *"pico y placa"* (literally "Peak and Plate" (Spanish for peak [hour] and [license] plate") in Bogota. In the short term, these measures can help reduce road congestion by limiting the number of vehicles that can circulate. However, when there are no quality alternative means of transportation, citizens may choose to purchase an additional vehicle to use on the day or time of the restriction. That vehicle may be used by other family members the rest of the time (Ríos-Florez et al., 2013), which could generate more congestion.

In the case of Mexico City, Eskeland & Feyzioglu (1995) found evidence of increases in the purchase of cheaper and lower-quality vehicles due to the measures. Crotte et al. (2011) estimated that 38% of households affected by the

22. For more information on this approach, its application in LAC and its impact on the environmental impact of transportation, see Taddia et al. (2021).

policy in Mexico City opted to purchase the additional vehicle. In Bogota, Bonilla (2019) pointed out that *"pico y placa"* did not report air quality and car use improvements. *In fact, increases in vehicle stock, gasoline consumption, and* CO_2 concentration were found in the morning hours. The literature also questions the regressive nature of these measures, given that lower-income households tend to have older and more polluting vehicles and are unable to purchase another car (Gallego et al., 2013). Gallego et al. (2013) analyzed several Latin American cities and different types of restrictions, concluding that, although in the short term -two months- these policies seem to be effective, it is in the long term where their counterproductive effects become evident. These findings are consistent with experiences in other regions. For example, Cai & Xie (2011) evaluated the policy of restriction by registration plate digit implemented in Beijing during the 2008 Olympic Games, finding significant improvements in traffic speed and air quality during the sporting event. However, in the medium term, the increase in the vehicle fleet canceled these benefits. It led to the implementation of more restrictive measures to acquire vehicles, including a lottery system for purchase permits (Ma & He, 2016).

There are, however, specific measures that have reported positive results. For example, De Grange & Troncoso (2011) evaluated the pollution reduction policies implemented in Santiago between April and August 2008, consisting of limiting the circulation of: (i) vehicles without catalytic converter during the whole period, and (ii) vehicles with catalytic converter during the hours between 7:30 and 9:00 am on days declared as "pre-emergency". Their estimates indicated that, although the permanent measure did not have a real impact, the additional measure reduced the use of cars by 5.5% in the short term. Additionally, on pre-emergency days, the flow of Metro passengers increased by 3%.

An alternative to being evaluated in LAC is implementing vehicle restriction policies with the possibility of paying for exemption. An example of these is the program called *"Pico y Placa Solidario"* (literally "Caring Peak and Plate" in Spanish), which was implemented on September 22, 2020, in Bogota. This program consists of including the option of paying economically and socially to avoid for a determined period the obligation of the traditional *"Pico y Placa"*. In the case of Bogota, the economic fee is 2,066,200 pesos (about US$590) to be exempted for a semester. The private vehicle user must also take a four-module course on the undesirable effects of improper use of the car and must not owe fines and/or subpoenas. The measure applies to all types of vehicles subject to the traditional "Pico y Placa".

The District Department of Mobility defined that the resources would be destined to finance the Integrated Public Transportation System. With the possibility of paying to circulate and using those resources to improve public transportation quality, this policy aims to avoid the purchase of an additional vehicle of lower quality by those users with sufficient economic means (Cantillo & Ortúzar, 2014). However, a criticism of this policy is that it has the defect of inducing more car trips due to this new cost to be amortized as it is a payment for a given number of months. Montero et al. (2020) propose an alternative: implementing a "day pass" vehicle restriction system to exempt from the restriction on one or more days of the week. One of the most critical challenges of this proposal is the need for an efficient system capable of collecting the money and monitoring compliance with the permit daily. Also, the authors recognize that there will be a welfare loss for the lower socioeconomic strata, which should be compensated by reducing public transportation fares (buses and subways) and improving bus service frequencies.

5.2.2 On-street parking limitations

The decision to use the car for regular trips is strongly conditioned by the availability of parking spaces at the trip destination. Roads are public spaces of the city and for all its inhabitants; therefore, a car that remains parked for many hours per day on the streets limit other users' potential to take advantage of that space. Marking out on-street parking areas has proven to be a good practice to reduce the use of private vehicles and road congestion. There are various ways of defining parking spaces, such as introducing resident-only spaces, mixed spaces (for residents and non-residents at the expense of non-residents), bus-only spaces (especially for tourists), motorcycle-only spaces, loading, and unloading spaces, and time-limited spaces.

International good practices show that in cities seeking to reduce the number of trips made in private vehicles, limit-

ing or eliminating the supply of parking spaces in real estate projects has been successful to that end. This has been proven by Guo (2013a) for the New York region, indicating that the number of parking spaces significantly determines the decision to own a vehicle. In fact, the parking supply variable is more relevant than income and other household demographic characteristics. The convenience of parking at the property is also related to more frequent use of the private vehicle and a higher number of miles driven in this way (Guo, 2013b). The results found by Shen et al. (2020) for Xi'an, China, are consistent with these findings, showing the correlation between parking supply-demand ratio, density, and land use with the level of congestion, as well as the positive association of parking availability with the spatiotemporal distribution of the traffic flows. Christiansen et al. (2017) analyzed the relationship between parking availability and commuting, finding that reduced parking is the most effective measure to discourage car use for such trips. Having free and plentiful parking can increase the likelihood of car commuting by up to four times. Auchincloss et al. (2015) collected data for 107 U.S. cities and showed that higher parking costs were associated with an increase in public transportation use.

5.2.3 Fuel taxes

Increasing taxes and withdrawing fuel subsidies is an instrument traditionally used to reduce the use of private vehicles and the resulting negative externalities. In particular, this instrument seeks to reduce polluting emissions. Most of the fuels used in today's cars and motorcycles (gasoline and diesel) come from fossil fuels. Their combustion causes the emission of polluting and greenhouse gases, which negatively affect human health and accelerate climate change, respectively.

Revenues from these taxes are an essential source of resources for the transportation sector, which are generally earmarked for the construction and maintenance of infrastructure and public transportation (see *Casos de financiación del transporte público: retos y buenas prácticas*) *(Cases of Public Transportation Financing: Challenges and Good Practices).* However, the effectiveness of the instrument in reducing car use is questioned in the literature, given the inelastic demand for fuels in the short term. Also, the tax magnitude is often far from being consistent with the environmental damage generated by fuel consumption (Miller & Vela, 2013). In this regard, several studies have been conducted in the region where the optimal fuel tax is estimated, calculating externalities related to air pollution, congestion, and the number of traffic incidents. For example, Parry & Timilsina (2010) calculated the optimal tax for Mexico City, Parry & Strand (2012) estimated it for Chile, and Antón-Sarabia & Hernández-Trillo (2019) indicated it for Guatemala.

Blackman et al. (2010) point out the importance of considering the redistributive effect of policies. While a direct tax on gasoline is progressive, an indirect tax on diesel (including public buses) implies a regressive component. Regarding the latter, Feng et al. (2018) analyze the distributional effects of energy price increases in 11 LAC countries, evidencing that high-income groups benefit more from lower prices than lower-income groups. Finally, this tax cannot allow targeting since it does not distinguish between urban and interurban trips, time of vehicle use, and congested or uncongested areas. For these reasons, and especially because of the increased adoption of electric vehicles, some countries are beginning to experiment with alternative charging instruments based on distance traveled, with dynamic elements that allow charging more during peak periods and/or depending on the type of vehicles (see 5.2.7).

5.2.4 Car taxes

The motorization growth rate in LAC is higher than in advanced economies (4.7% versus 0.5%, respectively) (Rivas et al., 2019). This is because cars have become much more affordable for a larger proportion of the population, based on financing schemes and other financial mechanisms. In this sense, despite its unpopularity, increasing the cost of a car by increasing purchase taxes or annual taxes for owning a vehicle, justified by the negative externalities it generates for society and the environment, supports decreasing motorization rate in the region.

In Singapore, car taxes have been used as one of the primary mechanisms to reduce congestion. Among them, the Additional Registration Fee (ARF) program and the Vehicle Quota System (VQS) were shown to be effective in reducing congestion (Willoughby, 2001). Between 1990 and 2002, the VQS program had succeeded in reducing the vehicle fleet's

growth rate to 2.8% from 4.2%. (Santos et al., 2004). A similar result was found in Hong Kong, where a sharp growth of the vehicle fleet was contained by a combination of a registration tax and an annual vehicle fee (Khan, 2001). However, the effectiveness of this measure depends on the value of the tax, which has to be high enough to discourage new acquisitions. Conversely, if it is too low, it would induce more trips on the acquired vehicle due to this new cost being amortized.

To learn more about how car taxes can contribute to the financing of public transportation, we recommend reading: *Casos de financiación del transporte público: retos y buenas prácticas (Cases of Public Transportation Financing: Challenges and Good Practices)* (Ariza et al., 2018a).

5.2.5 On-street parking charges

Charging for parking is one of the most effective actions to reduce the use of private vehicles. Most trips in LAC cities are for work, and people tend to stay there for up to ten hours a day. If users had to pay for parking in public places, they would probably look for other transportation alternatives, favoring private transportation modal substitution and reducing road congestion. In this regard, Kelly & Clinch (2006) found that a 50% increase in parking costs in central Dublin reduced parking demand and duration by 15% and 16.5%, respectively. Millard-Ball et al. (2014) evaluated the overall parking fee program in San Francisco, evidencing a higher vehicle occupancy rate and a 50% drop in parking search time relative to the two years prior to implementation. According to the Intelligent Transport Forum (ITF) (2019), changing the introduction of parking charging typically reduces solo travel by 10-30%.

However, it should be noted that these policies may be resisted by users, businesses, and neighborhood residents affected by the measures. For example, Gerrard et al. (2001) evaluated the attitudes of businesses to a parking charge in Cambridge, Norwich, and York, finding that, although users perceived a potential reduction in congestion and pollution, 72% of respondents expected a negative economic impact of the policy due to a decrease in consumers. Enoch & Ison (2006) analyzed the implementation of a parking license in Perth, Australia, and found that the search for parking had spread to the areas surrounding the old parking areas, generating more traffic in these areas.

In order to maximize the benefits and increase the effectiveness of this public policy instrument, the IDB (2013) published the *Guía Práctica: Estacionamiento y Políticas de Reducción de Congestión en América Latina (Practical Guide: Parking and Congestion Reduction Policies in Latin America)*, which presents detailed recommendations and guidelines for parking demand management.

5.2.6 Special taxes for on-street parking

Public parking facilities have proliferated in many LAC cities by diversifying their payment schemes and attracting many customers. As a result, many people pay monthly rates or maximum daily fees sufficiently affordable to make travel by private vehicle viable. Public parking lots promote the use of private transportation and, in many cities, occupy urban spaces that could be used for activities that benefit society, such as parks, public services, or housing. In this sense, requiring them to pay special taxes is a way to limit their presence in the city and thus their negative externalities such as the promotion of road congestion. The *Guía Práctica: Estacionamiento y Políticas de Reducción de Congestión en América Latina (Practical Guide: Parking and Congestion Reduction Policies in Latin America)* (IDB, 2013), provides recommendations and guidelines in this regard.

5.2.7 Road pricing

Road pricing is a policy for reducing negative (environmental, social, and economic) externalities produced by private vehicles. It consists of applying direct charges for the use of roads, thus increasing travel costs (Crotte et al., 2018). In this sense, a change in the costs associated with car use affects the number, frequency, and distance of trips made in this mode. The types of road pricing are: fixed points (parking meters), specific roads, cordon tolls, distance-based

fees, speed and/or time-based fees, and mixed. According to Lopez-Ghio et al. (2018), congestion pricing is considered the most effective measure to reach a social optimum, as drivers internalize the cost that congestion generates to society. By internalizing this externality, changes in individuals' behavior are achieved, encouraging trips to be made at off-peak hours or by other means of transportation.

Cities such as Singapore in 1975, Oslo in 1990, Durham in 2002, London in 2003, Stockholm in 2007, and Milan in 2012 have already implemented it. As a result of the measure, in Singapore, traffic volumes and emissions have decreased by 15%, and average speeds have increased from 30-35 km/h to 40-45 km/h, also generating annual revenues of US$100 million. In Stockholm, traffic volumes were reduced by 20%, traffic delays by 30-50%, and CO_2 emissions by 14%, generating revenues of US$155 million per year. The London cordon pricing scheme has also been successful in reducing congestion (30% reduction), improving air quality and public health (CO_2 emissions decreased by 16% and PM10 by 15.5%), and creating a long-term funding source for future transportation improvements (net annual revenues of US$182.1 million) (BID, 2020a; Lehe, 2019).

Although the potential benefits of congestion charging systems have been widely reported in the literature, their adoption rate worldwide is limited. Some authors point out that the implementation challenges and low acceptability of this policy are explained by concerns about the political cost, equity, and complexity aspects of executing this type of policy and uncertainty about the effects of the measure and the use of the revenues generated (Gu et al., 2018; Lopez-Ghio et al., 2018). From a political point of view, there is doubt about charging the public for something that has always been free, such as using the streets, although it would be the most appropriate, and because of the resistance that could be generated in the population (King et al., 2007). From an equity point of view, it has been argued that this policy would be detrimental to poorer car users, and it would benefit the rich, as for them, the time has more value than the increased financial costs of driving. Nonetheless, Basso & Silva (2014) argue that congestion pricing would be a progressive measure if public transportation systems were improved with the resources from fares and adequately covered the new demand.

Ortúzar (2013) conducted an exhaustive review of the main criticisms of the implementation of road pricing in LAC cities, such as low acceptability of the policy, opportunity cost, user inelasticity to charging, insufficient implementation technology, violation of privacy, earmarking of the tax revenues, and fairness of the policy. In his analysis, the author also presents a detailed response to the above criticisms and argues that, in order to introduce road pricing with majority public support, it would be necessary to convince the public and policymakers of the following four assertions: (i) action is needed to restrict current traffic levels; (ii) alternatives to road pricing are ineffective or insufficient; (iii) road pricing is a practical and effective measure, primarily through technological advances in traffic monitoring (see section 5.1.5); and (iv) it is possible to address the project's equity concerns. Ortúzar emphasizes that the latter is particularly important, as the regional context presents very different income levels and wealth distribution from the countries for which more information is available regarding the adoption and effects of measures such as road pricing.

Progressive implementation of such policies can help improve public acceptance, as in the case of Stockholm, where the measure was first introduced in 2006 on a trial basis. At the end of this period, a referendum was held to choose whether the measure would be maintained or eliminated, and continued implementation won. In the case of Milan, a traffic restriction was first applied to reduce emissions in the central area, and then a congestion charge was applied. Also, congestion charges should be conceptualized as a component of a broader transportation policy (supply and demand instruments), which should include, in the first place, actions to improve the quality and accessibility of public transportation services. Transparency and accountability in the use of revenues are also identified as key success factors in the case of London, while redistribution of revenues is critical to avoid the policy generating gains for higher-income groups and losses for lower-income groups (Cohen, 1987; Else, 1986).

Recent studies for the region analyze the applicability of a congestion charging fee in Mexico City, Santiago, and Bogota (Lopez-Ghio et al., 2018). With the implementation of an average toll per day between US$1.91 and US$3.33 in the selected area and depending on the city considered, significant benefits would be obtained in increasing the

average traffic speed in the area, which would be around 6 km/h in the three cities. The measure would generate a reduction in congestion of close to 28%, which would be in line with that observed in developed countries that have implemented this instrument. After its implementation, the congestion charge would raise significant resources, ranging from US$154,000 to US$611,000 net per day on average, depending on the city, which could be reinvested in the city's own transportation system. The annual revenue from this fare would be most significant for Mexico City and Santiago, where it would be equivalent to 97% and 40% of the vehicle circulation tax or would finance 53 km and 19.5 km of transportation system infrastructure, respectively. In the case of Bogota, a surcharge of $0.33/km would provide sufficient funding to cover up to 15% of the current costs of the integrated transportation system (Calatayud & Muñoz, 2020).

A specific case of road pricing is related to transportation network companies. Recent studies suggest that such companies are contributing to an increase in vehicle distances traveled and congestion: data for San Francisco, Boston, and Washington DC point out that on-demand travel vehicles account for 13%, 8%, and 7% respectively of all VMT in those cities, and one-third of those percentages correspond to distances traveled by empty vehicles (Fehr & Peers, 2019). For the case of LAC, Tirachini & Gomez-Lobo (2020) also show an increase in VMT in the case of Santiago. The potential adverse effects of this type of service call for policy measures (Calatayud & Muñoz, 2020). Under a permissive regulatory framework, by 2030, vehicle kilometers traveled, and CO_2 emissions in LAC could increase by 6% and 15%, respectively (ITF, 2019).

In contrast, with efficient regulation requiring high occupancy rates for on-demand travel trips, shared services could contribute to reducing total vehicle kilometers traveled by 24% and CO_2 emissions by 3% (ITF, 2019). In line with policies implemented by cities in other regions, some LAC cities have begun charging transport network companies for the use of road infrastructure. Sao Paulo imposes an initial fare based on an estimate of VMT, also known under the name of "credits", which can be used by its fleet of passenger vehicles over a two-month period, plus a surcharge if these credits are exceeded. In Mexico City, an additional charge of 1.5% per trip is applied to shared mobility services. The effectiveness of these policies is still to be assessed.

The publication *Tarificación vial: Una política para la reducción de externalidades negativas producidas por el congestionamiento vial* *(Road Pricing: A policy for the Reduction of Negative Externalities Produced by Road Congestion)* (Crotte et al., 2018) describes in detail the modalities of road pricing, successful experiences in the world, technology for vehicle identification and charges, among others. It also provides guidelines and recommendations for its implementation in LAC.

5.3 Policies that promote the use of public and active transportation

These policies **aim to increase the number of people using more sustainable modes of transportation**, including actions such as: (i) improving the availability and quality of public transportation; (ii) "park-and-ride" parking; (iii) bicycle and pedestrian infrastructure; (iv) school transportation; (v) institutional transportation; (vi) carpooling systems; and (vii) transportation supply for people with disabilities.

5.3.1 Quality and availability of public transportation

A key aspect of reducing congestion in cities is to encourage a modal shift to public transportation. In contrast to other modes of transportation, public transportation has the capacity to move large numbers of people, due to the carrying capacity of its vehicles, providing an efficient solution for mobility in medium and large cities and megacities. Indeed, a high-capacity corridor can carry approximately 40,000 passengers per hour. To achieve the same volume per car would require more than 20 parallel lanes, which is geographically impossible in urban contexts. However, as pointed out in Chapter 1, the quality of public transportation systems in the LAC region is limited, affecting the travel experience of those who use it and causing others to prefer not to use it. Thus, measures to attract people, mainly people who travel by car, to public transportation should aim to improve the quality of this mode of transportation.

This demands actions in different dimensions: availability of services, universal and transportation accessibility, information, travel times, customer service, comfort, safety, and environmental impact (Rodríguez et al., 2020), as well as the recognition of mobility patterns differentiated according to user type (Sánchez de Madariaga, 2013) and travel conditions different from those of the typical user (e.g., people with reduced mobility) (Olivares et al., 2019). For example, the development of mass transit systems, such as urban rail systems —including metros— or Bus Rapid Transit (BRT) systems, has been shown to improve the quality of transportation services by reducing travel times, with positive impacts in terms of access to job opportunities (Martinez et al., 2020; Scholl, Martínez, et al., 2018; Scholl, Oviedo, et al., 2018), emission reduction (Bel & Holst, 2018; Chenyihsu & Whalley, 2012; Gramsch et al., 2013) and traffic accident reduction. Likewise, improving the comfort, cleanliness, and safety of public transportation has been effective in increasing the number of trips: in the case of Chicago, the increase was 5%, equivalent to 15 million additional trips per day, after a long period of falling ridership on the subway (Foote, 2004).

Another critical aspect is providing information about services, including bus and subway schedules and delays, which is often evaluated more positively by users, as opposed to aspects such as level of service and transfer times (Dell'Olio et al., 2011) but rather what they desire, hope for or expect from their public transport system. This is why it is important to study the desired quality, knowledge of which gives local authorities the background information for personalised marketing policies based on the user's requirements rather than their daily perceptions. The methodology goes through several stages, such as the use of focus groups to choose the most important variables for the users, the design and use of unlabelled stated preferences surveys and the calibration of discrete choice models. All of these help determine the weight of the most relevant variables. The analysis is carried out with different categories of users and potential users (those people not currently using public transport. An evaluation for New York on the effects of real-time information provided through web and mobile devices reveals an increase in ridership per route of approximately 1.7% per weekday (Brakewood et al., 2015). An analysis on the implementation of Transport for London's open data policy shows that it generates annual economic benefits of up to US$175 million for users, the city, and the institution itself (Deloitte, 2017).

A critical factor to improve in LAC cities is public transportation affordability (BID, 2020b). One measure usually adopted for this purpose is the provision of subsidies. In this regard, the literature has shown that demand-side subsidies are generally more effective than supply-side subsidies, as they allow a greater targeting of transfers to specific groups of beneficiaries (e.g., the elderly, people with disabilities) (Serebrisky et al., 2009). A successful case in the region refers to the subsidy mechanism implemented in Bogota since 2014, which has a similar approach to a direct cash transfer program. (Guzman et al., 2017). This scheme, based on the Colombian System of Identification of Social Program Beneficiaries (SISBEN as per its acronym in Spanish), provides subsidies to members of households with incomes below the poverty line, using a personalized smart card, which provides them with up to 30 trips per month at an average fare of US$0,30 [23], compared to an average fare of US$0.55. (Gwilliam, 2017). This subsidy increased beneficiaries' monthly trips by 56% (Rodriguez et al., 2017). It also increased the hourly income of informal workers (Rodríguez et al., 2016), positively impacting transportation accessibility and equity for beneficiaries (Guzman et al., 2017). The above confirms that, in addition to universal measures for reducing the basic public transportation fare, it is necessary to implement policies aimed at reducing the number of suppressed trips of low-income households (Falavigna & Hernandez, 2016).

While the investments needed to improve the quality of public transportation in LAC are significant, so are the social, environmental, and economic benefits derived from them. An essential instrument for raising the necessary resources for such investments is road pricing (see section 5.2.7). In addition to providing resources, the congestion reduction expected from road pricing contributes to improving the operation, level of service and, consequently, the quality of public transportation. Other sources of resources are discussed in detail in the publication *Mejores prácticas internacionales de fondeo y financiamiento para el transporte público urbano* *(Best International Funding and Financing Practices for Urban Public Transit)* (Crotte et al., 2017).

23. The policy was modified in March 2017 incorporating the following changes: (i) applies to people with SISBÉN scores from 0 to 30.56 points (previously applied to people between 0 and 40 points); and (ii) applies for a basket of 30 trips per month (previously covered 40 trips per month) (Veeduria Distrital Bogota, 2017).

5.3.2 Exclusive lanes for public transportation

One of the main factors why a person decides to use one mode of transportation over another is travel time. In this sense, to promote modal substitution from private vehicles to public transit, it is important that the public services have travel times equal to or less than those of private vehicles. One measure to achieve this is by installing exclusive lanes for public transportation that prevent buses from being affected by road congestion. Basso & Silva (2014) show that in Santiago and London the designation of exclusive bus lanes generated significant increases in public transit service levels and fare reductions without having to inject public funds. In the case of Bogota, Hidalgo & Huizenga (2013) found that the establishment of exclusive lanes for Transmilenio reduced travel time by 52%, generating savings for users valued at US$ 1,793 million. However, even though many BRT services in the LAC region already have this type of infrastructure in place, in the 29 largest metropolitan areas in LAC, less than 1% of the road system is dedicated exclusively to public transportation (Estupiñan et al., 2018).

5.3.3 Park-and-ride facilities

Private vehicles may represent a suitable alternative for first and last-mile trips, especially in cities with extreme topographies and climates. For this to be viable, it is essential to recognize the multimodal nature of the various trips and the needs of each mode of transportation. Park-and-ride (P&R) parking facilities represent an alternative for public transportation users who make their first and last mile in private vehicles to leave their vehicles near mass transit stations, with the longest part of their trip being made by public transportation. This reduces the intensity of use of private vehicles and their parking on public roads, promoting the reduction of road congestion and the re-appropriation of public space by other modes of transportation.

However, the literature suggests that the success of this policy depends on an appropriate design for the context in which it is implemented. If planned correctly, with sufficiently safe and well-lit parking, it can reduce congestion levels while also allowing non-users of public transportation to become familiar with this mode (Blainey et al., 2012). Other studies indicate that success will also depend on effective coordination and integration with urban policies, as well as the provision of a high-quality public transportation alternative (Batty et al., 2015). Moore et al. (2019) analyzed the impact of a P&R pilot in Tennessee, United States, estimating that the 44 P&R stations used in the study decreased daily VMT by 68% for the sampled workers. It also reduced energy consumption by 92% and gasoline use by 84%.

Nonetheless, Meek et al. (2011) evaluated one of the oldest applications of P&R implemented in the United Kingdom, reporting a counterproductive result in the number of VMT, with an increase of 14%. From there, an important discussion on modifications to traditional P&R has ensued. Indeed, this measure may have the disadvantage that an entire public transportation trip may be changed to a two-stage trip (car and public transportation), incentivizing an increase in VMT. Thus, Batty et al. (2015) point out that P&R is more effective for metro and urban rail services than for buses. In turn, congestion could be shifted to areas surrounding mass parking. In this regard, Liu et al. (2018) propose "Remote Parking & Ride (RP&R)", in which parking is not located at major mass transit stations, but in the suburbs with lower costs for car users, while supplying a bus service connecting these parking lots to major mass transit stations. The results of their simulation promise significant benefits for congestion mitigation in metropolitan areas.

5.3.4 Bicycle and pedestrian infrastructure

The construction of bicycle and pedestrian infrastructure generates an induced demand for this type of users, and it encourages a modal substitution of the private vehicle. The study by Song et al. (2017) evaluated the distance to new walking and cycling infrastructure facilities (a measure of potential use) and the actual use of this infrastructure in the United Kingdom. The analysis showed a significant association between these measures and modal shift from cars to active modes.

It is worth noting that cycling infrastructure consists not only of bicycle lanes, but also of bicycle parking facilities at public transportation stations and sites of interest, bicycle space on urban buses, workplaces equipped with show-

ers, and public bicycle systems. Regarding the latter, international evidence shows that programs focused on developing public bicycle sharing systems increase the frequency with which a personal or shared bicycle is used (Ricci, 2015; Ríos Flores et al., 2015). For example, bike-share systems reduced car use by approximately 90,000 km per year in Melbourne and Minneapolis/St. Paul, and 243,291 km for Washington, D. C. (Fishman et al., 2014).

Likewise, pedestrian infrastructure goes beyond sidewalks to include rest and recreation spaces, and areas with trees that lower the temperature. Pucher & Dijkstra (2003) note that in the Netherlands and Germany well-lit pedestrian crossings, refuge islands, raised intersections, in addition to visible and active signals, created a safe environment that encouraged walking and cycling. The design of this type of infrastructure must recognize that pedestrians, cyclists, and users of other micro-mobility vehicles are the most vulnerable road users; therefore, their safety must be a priority. In addition, the design must consider the diversity of road users, so all interventions must be made following universal accessibility principles. The British Department of Transport estimated that the number of pedestrian fatalities was 53% lower in the neighborhoods where appropriate pedestrian infrastructure was in place. The study by Pucher & Dijkstra (2003) shows that environments that are not safe for pedestrians and cyclists discourage the use of these modes.

To find out more about this topic, we recommend the *Guía para planeación e implementación de sistemas públicos de bicicletas en LAC* *(Guide for Planning and Implementation of Public Bicycle Systems in LAC)* (Crotte & Arvizu, 2018) and the *Guía de vías Emergentes para Ciudades Resilientes* *(Emerging Roadways Guide for Resilient Cities)* (Aguirre Benítez et al., 2020).

5.3.5 School transportation

The second most common reason for travel in many LAC cities is studying. Students of certain ages, specifically those under 18 years of age, in many cases, depend on another person to travel to their place of study. This phenomenon leads to road congestion when the mode of transportation they use is the private vehicle. In this sense, the implementation of school transportation services is a best practice to make it easier for all students to travel from their homes to their study places. School transportation not only benefits students, but also all the other people who used to make escort/care trips to drop off students at their study sites. However, it is worth mentioning that this type of transportation can be a solution only if students travel within their area of residence. This is the case in U.S. public schools, where school enrollment depends on the students' residence location.

5.3.6 Institutional transportation

There are various economic activities, such as industrial and corporate enterprises, which employ a large number of people and therefore attract a large number of trips. To prevent a high percentage of these people from using private vehicles which contributes to the city's road congestion, or wasting long periods of time and money using other modes of transportation, the implementation of institutional transportation services is recommended. The implementation of routes and schedules should be carefully designed to meet the needs of employees. It is considered good practice for the cost of this service to be absorbed entirely by the institutions or for a fare to be charged to employees so that the service is self-sufficient rather than revenue-raising.

Another institutional initiative to discourage car use is to charge for parking in the organization's buildings. The study led by Guzman et al. (2020) shows that a substantial increase in parking cost is an effective disincentive to reduce the use of private vehicles for commuting, leading to a significant migration to public transportation, carpooling, cycling, and walking.

5.3.7 Carpooling systems

Many private vehicles spend most of their time at a standstill, occupying a large amount of public and private space. This generates negative externalities for the city, including contributing to road congestion and the cost overruns of many

infrastructures to provide parking spaces. Therefore, carpooling schemes are considered a good practice to reduce the negative impacts of private vehicles by generating a shared economy and a better use of the car, considerably reducing the demand for parking. Moreover, recent studies indicate that carpooling systems postpone or discourage the decision to buy a car by those who do not own one (Aguilera & Cacciari, 2020). They also contribute to the decision to sell one or more cars for people who already own them (Cervero et al., 2007; Nijland & van Meerkerk, 2017).

However, from the point of view of the overall efficiency of urban mobility, it is important essential to mention that carpooling should be a mobility alternative for the first and last mile (complementary to other sustainable modes), or exceptional cases that require the characteristics offered by a vehicle, but not for long trips, as this does not boost the reduction of road congestion.

5.3.8 Transportation supply for people with disabilities

Transportation users vary, ranging from young people to people with disabilities that radically limit their ability and autonomy to move around. As a result of the design flaws of public transportation systems in terms of universal accessibility or the absence of flat and homogeneous sidewalks in the city to walk comfortably, many of these people are forced to limit their mobility to private vehicles. In this sense, rethinking transportation systems and modes to make them inclusive and universally accessible can motivate people with disabilities to use more sustainable modes of transportation.

To find out more about this topic, we recommend reading the publications *Accesibilidad e inclusión en el transporte: Análisis en ciudades latinoamericanas (IDB, 2019 & 2020). (Accessibility and Inclusion in Transportation: Analyses of Latin American Cities)*

5.4 Integrated mobility and land use planning

Urban planning paradigms have varied over time in order to respond to the changing social, economic, and environmental needs of cities. The contemporary urban agenda seeks to transform cities into sustainable and resilient environments. To this end, it is important to move from cities of large extensions and low densities to cities at human scales and human needs. Mobility and land use play a fundamental role in this, since focusing on promoting more sustainable and resilient cities implies thinking about **moving people and not vehicles**. To this end, a systematic approach should be applied to the planning of cities, through the developments of connectivity networks based on mixed land uses and an integrated and efficient transportation network. In this way, the population as a whole is encouraged to have access to the various opportunities offered by their cities.

Integrated planning of transportation systems and land use is essential to control the accelerated expansion of the urban sprawl (Suzuki et al., 2013). In this context, a policy little used in the region is the Transit-Oriented Development (TOD), which prioritizes a model of planning and development of cities around nodes of the public transportation system (motorized and non-motorized) (Martínez Salgado, 2018). The experiences of Curitiba, Denver and Hong Kong, for example, have shown that these types of policies contribute to dense, compact and multimodal cities, resulting in reduced congestion and increased ridership of public transportation systems, opportunities for joint public-private infrastructure development, the number of affordable housing, land value and real estate rents (IDB, 2020a; Medina-Ramírez & Veloz-Rosas, 2013).

The development and implementation of urban mobility master plans is another measure to facilitate comprehensive planning. These instruments consolidate a long-term vision for the development of sustainable transportation systems. To this end, they usually incorporate actions to achieve a more efficient use of road space, prioritizing public transportation as a mode for expeditious, reliable, and safe travel (Arsenio et al., 2016; Lefevre et al., 2019), also promoting the coordination of transportation and land use policies. The experience of European cities shows that these instruments are correlated with modal shifts in favor of a higher use of public and active transportation (Bueno et al., 2019).

For more details on the new planning paradigm proposed from the perspective of urban accessibility and policy guidelines for LAC cities, please refer to the publication *¿Qué implica la accesibilidad en el diseño e implementación de políticas públicas urbanas?: Concepto, instrumentos para su evaluación y su rol en la planificación de la movilidad urbana* *(What does Accessibility Imply in the Design and Implementation of Urban Public Policies? Concept, Instruments for its Evaluation and its Role in Urban Mobility Planning)* (Hansz et al., 2018).

5.5 Policies for urban logistics management

Every day, millions of products are moved in LAC cities. Indeed, the economic and social activities that take place in a city usually require the provisioning of a varied set of goods. Supermarkets, pharmacies and basic necessities stores, businesses selling various products, hotels and restaurants, health centers, construction companies, public administration and inhabitants, in general, are the main demanders of goods and, consequently, of logistics activities. In recent years, urban logistics has become particularly important due to the increase in e-commerce. In contrast to purchases made physically in stores and department stores, new consumer trends require the delivery of products directly to consumers, in smaller quantities but with greater frequency. This implies an increase in the number of trips for the distribution of goods, particularly in high-density areas with limited space and increasing traffic congestion (Calatayud & Montes, 2021). Considering that, in the decade 2020-2030, e-commerce growth projections for LAC are around 650%, it will be essential to implement measures to mitigate the impact of this increase on the already high levels of road congestion there and to achieve **sustainable integration between the mobility of people and goods** (IDB, 2020b). Among these measures, the following stand out: (i) off-peak delivery of goods; (ii) allocation of special areas for loading and unloading; and (iii) congestion and/or parking charges.

5.5.1 Off-peak delivery of goods

Off-peak delivery of goods is a policy that has been tested in several cities around the world to prevent logistics vehicles from circulating during peak infrastructure demand hours and contributing to increased road congestion. In order to be effective, this policy requires businesses to have personnel available to receive goods and to comply with low noise standards, especially at night. Studies in New York and Sao Paulo show that, depending on the magnitude of the change in delivery hours, these types of measures are effective in reducing environmental pollution, achieving decreases between 45%-67%. (Holguín-Veras & Sánchez-Díaz, 2016). Other economic benefits derived from these measures include the reduction of operating costs and parking fines; of inventory levels, thanks to more frequent deliveries; and of drivers' stress and working hours (Holguín-Veras et al., 2020). Pilots conducted in the city of Bogota showed that these programs could reduce costs per trip by 32%, CO_2 emissions by 42%, and unloading time by 60% (SdM, 2016).

5.5.2 Allocation of special areas for loading and unloading

Dedicating roadway areas for loading and unloading is a low-cost and easy-to-implement infrastructure solution to facilitate logistics operations (Merchán & Blanco, 2016). It also helps prevent double-parking or other forms of illegal parking that generate congestion and hinder the mobility of pedestrians and other road users (McLeod & Cherrett, 2011), positively influencing traffic flows and the efficiency of urban logistics (Sosik et al., 2019). For example, a study conducted in Oslo concludes that the implementation of loading bays reduces carbon monoxide emissions by 5%, hydrocarbons by 3%, and nitrogen oxide emissions by 4% (Sosik et al., 2019). Pilots conducted in Querétaro, Mexico, showed that transit and parking time of delivery vehicles could be reduced by 30% with better use of loading/unloading zones (Calatayud & Millan, 2019). The literature suggests that the main limitation of loading/unloading bays lies in reserving the parking area and in inspection and supervision to ensure that the maximum allowed parking time is not exceeded and that the reserved space is not used by other vehicles. Artificial intelligence and video detection tools can improve inspection and supervision (Miranda-Moreno et al., 2020). The pilot developed jointly by the IDB and the mayor's office of Bogota showed that the effective use of loading and unloading bays in the city is hampered by the inappropriate use that motorcycles make of such spaces, providing critical information for better management of

traffic flows and parking in urban space.

5.5.3 Congestion and/or parking charges

These regulations seek to correct, through pricing, the negative externalities of urban logistics. Measures built on market-based instruments such as congestion and/or parking charges, accompanied by technological innovations to make the use of urban space (sidewalks, parking lots, etc.) more efficient, have proven to be successful in reducing urban congestion. A pilot conducted in Washington, D.C. that evaluated the effectiveness of implementing dynamic parking pricing in commercial loading zones resulted in a 7-minute reduction in finding parking space, reduced congestion and pollution, and improved safety. The number of double-parked vehicles decreased by 43% and fines by 55%. Other examples of "smart" public space management have been observed in Amsterdam, Barcelona and Helsinki with reservation systems that provide real-time information on parking spaces (IDB, 2020a; Calatayud & Millan, 2019).

5.6 Considerations for the implementation of measures in LAC

Road congestion creates economic, social, and environmental challenges for cities and their inhabitants. In this sense, it is essential to reduce private car use through strategies such as boosting public transportation, increasing the cost of owning and driving a car, encouraging the use of other modes of transportation, and reducing the need to travel. In this chapter, we have presented frequently used policy measures for congestion reduction. In general, these measures can be classified into **five categories**: (i) traffic management instruments; (ii) policies that restrict the use of private vehicles; (iii) policies that promote the use of public transportation, active transportation, and ridesharing; (iv) integrated mobility and land use planning; and (v) policies for urban logistics management. We have also included empirical evidence on their effectiveness and mentioned how easy or difficult they are to implement.

Among these measures, it is now worth reflecting on which ones should be implemented by the large cities and megacities in LAC studied here and in what sequence they should be implemented to be effective. First and foremost, reducing congestion on a permanent basis depends on **better coordination between land use planning and transportation planning**. Policies to promote densification and optimal land use are crucial to prevent territorial expansion, when new areas are not equipped with mass transit systems, leading to an increase in miles traveled. In this regard, planners should require, for example, that development in a given location meets a minimum density and contains sufficient dedicated infrastructure to ensure sustainable transportation, and promote development orientated to public transportation. They should also put in place mechanisms to capture increases in property values resulting from transportation improvements. For all this to happen, cities need **strong planning departments** with adequate powers to ensure compliance.

At the same time, the **quality, accessibility and flexibility of the public and active transportation system should be improved** to provide efficient, reliable and responsive service to accommodate the diverse demands of citizens. The question that arises from this is how to generate the necessary resources for these investments. International experience shows that **stable funding structures** are required for public transportation systems (IDB, 2020a). However, LAC countries usually finance their systems through fare revenues and have evidenced greater difficulty in developing alternative sources, such as land value capture tools and infrastructure usage charges (Ariza et al., 2018). International good practices suggest that good financial planning for transportation systems requires four main components: quantifiable long-term objectives, funding mechanisms aligned with strategic mobility principles, institutional control and monitoring mechanisms to estimate funding gaps, and resource management that guarantees the flow of resources in the long term (Ariza et al., 2018). These elements are aligned with the strategic planning exercises mentioned in the previous paragraph. An interesting example in the region regarding the implementation of alternative funding instruments comes from Bogota and Cali, which are using the payment to exempt themselves from the "pico y placa" to raise additional funds to finance their public transportation systems.

This example leads us to the third measure to be implemented. An important source of resources for public transpor-

tation improvements can come from **appropriate pricing of the use of road infrastructure** by private vehicles, cabs or similar, and freight vehicles, including parking spaces, loading and unloading bays, sidewalk curbs, and the streets themselves. This is based on the idea of infrastructure as a service that should be paid for through fares that cover the costs to provide it and reflect its value to users (Calatayud & Muñoz, 2020). By allocating fare revenues to improving public transportation systems, equity in resource allocation would also be improved: subsidies for private car users who have higher income are eliminated and resources are used to improve the quality of the public transportation most used by the lower-income population. The new technologies of the Internet of Things, digitalization, and artificial intelligence facilitate the application of this concept, since they allow the monitoring of compliance with the measures, as well as the adjustment of fares in real time to the conditions of infrastructure demand. Payment for infrastructure use thus joins **other measures already in place** that have been effective in reducing the use of private vehicles in the medium term, such as parking restrictions, and in improving traffic flow, such as the use of adaptive and synchronized traffic light cycles.

However, setting the right fares for mobility decisions is no easy task. There are numerous externalities involved and the debate can generate social unrest, as seen in Paris (sparked by a diesel tax increase) in 2018, Ecuador (fuel price hike) and Santiago (metro price increase) in 2019. By themselves, price increases can penalize low-income citizens or those who lack other mobility options. Therefore, it is essential to consider the **sequencing of policy measures** (see Table 5.3) and to **combine the setting of these new prices with other measures**. For example, London substantially increased its bus fleet before implementing road pricing. Another important measure is the **subsidization of public transportation for low-income citizens**, for whom mobility consumes an important part of monthly income. The cases of Stockholm and London show that piloting solutions such as road pricing and conducting a public consultation before large-scale implementation should also be considered. This can help to increase citizens' knowledge about the benefits provided by the measures and help public policymakers to make the necessary adjustments to increase the effectiveness of these measures (Calatayud & Muñoz, 2020). Another way to generate support for these policies is to provide flexibility to users in terms of the fare to be paid according to the time and mode of travel. The most innovative proposals, although not yet tested, include systems of points or mileage credits for private vehicle travel, which individuals can use according to their preference, and can sell or buy from other users (Basso et al., 2020).

Given that urban space, especially in the case of large cities and megacities, often includes more than one level of government, **coordination between planning and mobility agencies** at all levels is critical to develop and implement comprehensive land use and transportation plans that are effective in increasing sustainability and reducing levels of road congestion. To reinforce this coordination, there are international (e.g. Madrid and London) and regional (e.g. Lima) experiences where a transportation agency has been established at the metropolitan level, which has the prerogatives of planning, regulating and supervising public transportation services, with the ultimate goal of providing users with an integrated transportation experience independent of the administrative divisions that may exist in a metropolis. In this regard, improvements resulting from the creation of the Madrid transportation authority led to an increase in the use of public transportation of 45.8% (Vassallo et al., 2019).

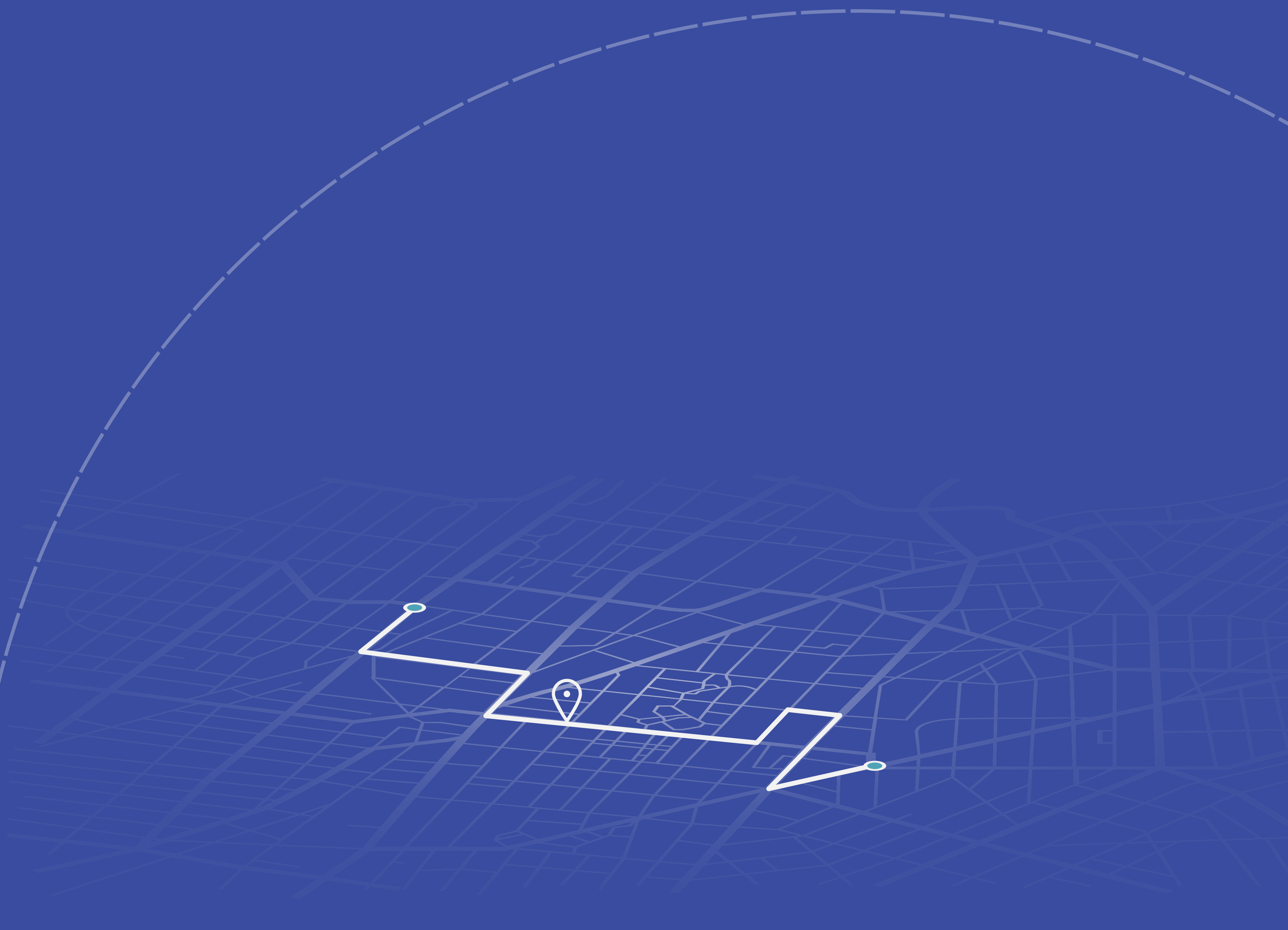
Finally, it is worth noting the existence of **measures that are external to the transportation sector** and that can also contribute to setting adequate prices. An obvious example is the elimination of subsidies for the purchase of cars, which are part of some industrial policies in the region. Such subsidies encourage motorization and generate unfair competition for public and active transportation.

Table 5.3 presents the recommended measures to reduce congestion in the large cities and megacities of LAC analyzed, including guidance on their sequencing in terms of their implementation in the short, medium, and long term. In addition to those mentioned in the preceding paragraphs, measures related to the **adoption of technologies** for improving traffic management and urban logistics planning are presented.

Table 5.3 Sequencing of Public Policies to Reduce Congestion

	Short term	Medium term	Long term (2030)
Improving public, active transportation, and ridesharing	• Improving the quality of public and active transportation (frequency, cleanliness, comfort, safety) • Allocation of road space to public and active transportation • Alternative funding sources for public transportation • Digitalization of services and provision of real-time information	• Integration of public and active transportation and ridesharing services • Increasing accessibility and improving the affordability of public transportation • Promotion of carpooling in institutions to reduce solo travel.	
Discouraging car use	• Parking charging • Parking restrictions • Car restriction with payment for its exemption	• Road pricing • Re-evaluation of car purchase subsidies	• Dynamic road pricing and full implementation of infrastructure as a service
Traffic management	• Traffic calming and road access control • High-occupant vehicle lanes • Enforcement of traffic laws and regulations	• Real-time traffic management • Reduction of travel demand • Infrastructure supply	
Urban logistics management	• Allocation of loading and offloading bays • Pilots of traffic management measures	• Off-peak delivery of goods • Congestion charges • Smart management of loading and unloading bays	
Integrated planning	• Integrated planning of land use and transportation (incl. logistics) • Institutional capacity strengthening (e.g., digital and logistics) • Strengthening of inter-institutional coordination with the private and academic sectors and civil society	• Transit-oriented development • Densification and mixed land use • Metropolitan transportation authorities	

CONCLUSIONS



This study estimates, for the first time, the direct and indirect costs of congestion in ten major LAC cities. To do so, we start by estimating the aggregate delay at the city level, per inhabitant, and vehicle user. Our results indicate that, in absolute terms, the cities with the highest delays are those with the largest number of inhabitants, namely: Sao Paulo (21.8 million inhabitants and 702 million hours lost in 2019) and Mexico City (21.6 million inhabitants and 647 million hours lost). San Salvador, the city with the smallest number of inhabitants among the ten analyzed (1.1 million), was the city with the lowest number of hours lost to congestion, reaching 37 million hours in 2019.

However, when estimating the delay per inhabitant and car user, the positioning of the cities changes significantly. Thus, in 2019, the inhabitants of Montevideo, for example, lost 51% more time in congestion than those of Mexico City, even though the population of the Mexican capital city is 11 times greater than that of Montevideo. The same goes for San Salvador, where its inhabitants lost 33 hours idling in traffic in 2019, above megacities such as Bogota (31 hours), Rio de Janeiro (25 hours), and Buenos Aires (20 hours). Similarly, if we consider only private vehicle users, Bogota was the city with the highest congestion losses, amounting to 186 hours per user. This figure is 1.7 and 1.8 times greater than the losses of private vehicle users in Sao Paulo and Mexico City, respectively.

The value of time in each city has an important impact on congestion losses. Thus, while 647 million hours were lost in Mexico City in 2019, compared to 305 million in Buenos Aires, the value of each hour lost in Buenos Aires is higher. Consequently, while the delay cost US$ 1,168 million to Mexico City, the cost for Buenos Aires was 45% higher, amounting to US$ 1,691 million. The same can be said for Santiago (US$ 1,045 million) with respect to Rio de Janeiro (US$ 943 million) and Bogota (US$ 612 million). It is interesting to look at these costs in comparison with the level of wealth of the cities. Thus, congestion losses in 2019 represented: 1.1% of the GDP of Montevideo; 1.1% of Sao Paulo; 1.1% of Buenos Aires; 1.0% of Santiago; 0.9% Bogota; 0.9% Rio de Janeiro; 0.8% Lima; 0.7% Santo Domingo; 0.5% Mexico City; and 0.5% San Salvador. To put into perspective what these losses imply, by way of example, congestion costs to Buenos Aires and Mexico City, respectively, 1.9 and 2.3 times what the local government invests in education. Sao Paulo's investment in health is equivalent to what congestion costs the city. Similarly, Bogota's investment in care for the vulnerable population is equal to two-thirds of its losses due to congestion.

At the individual level, the cost of congestion per person in 2019 was highest in the cities of Montevideo (US$ 177), Santiago (US$ 156), and Buenos Aires (US$ 112). If the cost per private vehicle user is considered, the most significant losses were in Montevideo (US$ 474), Santiago (US$ 409), and Bogota (US$ 341). Again, the difference in the value of time explains the lower costs for cities such as San Salvador and Sao Paulo, even though the delay is longer in those cities. If we look at how much congestion costs per day, Montevideo and Santiago are the cities with the most discouraging figures: in a working day, drivers lose US$ 1.2 and US$ 1.3 in congestion, respectively. This figure is worrisome considering that the median hourly wage is US$ 3.7 and US$ 3.4, respectively. Among all the major cities analyzed, Santiago had the record of the maximum congestion cost in 2019 in one day, reaching a loss of more than US$ 3 per driver. This was recorded on October 18, when different road and public transportation closures occurred due to demonstrations in the city. San Salvador and Santo Domingo are the cities with the highest relative volatility among the cities analyzed. Finally, if we compare the time lost in congestion with the number of weekly hours worked per person, we can see that a driver in Bogota, for example, loses in congestion the equivalent of 9% of the hours worked. In Lima and Montevideo, these figures correspond to 8% and 6%, respectively.

Regarding the indirect costs of congestion, we analyze the relationship with the rate of traffic incidents in the selected cities. Our findings suggest that, if the aggregate delay on an average working day were reduced by 10%, then traffic incidents would decrease by 5.5% in Sao Paulo; 4.7% in Mexico City; 2.8% in Lima; 2.4% in Rio de Janeiro, 2.2% in Bogota; 2.1% in Buenos Aires; 1.6% in Santiago; 0.6% in Santo Domingo; 0.4% in Montevideo; and 0.3% in San Salvador. Notably, this means that if congestion in 2019 had been 10% lower, the number of reported traffic incidents would have been reduced by 3.5% on average for the region. This equates to a reduction of more than 137,500 traffic incidents. The most significant proportion of this reduction would have taken place in Mexico City and Sao Paulo, with 26,600 and 22,300 fewer traffic incidents, respectively; followed by Bogota (11,100); Lima (4,100); Rio de Janeiro (3,500); Santiago (2,200); Buenos Aires (1,900); San Salvador (200); Santo Domingo (150); Montevideo (120).

In summary, congestion in the cities analyzed generates significant economic and social losses for their inhabitants and the cities themselves. The general trends in mobility in the region, with an increase in motorization rates and a reduction in public transportation use, together with an increase in urban population, do not suggest that the current congestion levels will be reversed shortly. Moreover, the distrust of public transportation caused by the COVID-19 pandemic could increase private vehicles' use. There are already some signs of this shift in cities such as Shanghai and Madrid. In the latter case, public transportation went from being the most used mode in the pre-pandemic period to being the third (25% of trips), after the private vehicle (44%) and active transportation (32%) (El País, 2020).

In this context, the design of effective public policies will be vital in moving towards more efficient and sustainable mobility in our cities. Thus, in the last chapter of the publication, we have included various instruments used internationally to manage road congestion better and mitigate its risks. These solutions can be grouped into five categories: (i) traffic management instruments; (ii) policies that restrict the use of private vehicles; (iii) policies that promote the use of public transportation, active transportation, and ridesharing; (iv) integrated mobility and land use planning; and (v) policies for urban logistics management.

It is important to emphasize that, for congestion reduction initiatives to be successful, they must be contained within a comprehensive framework that, on the one hand, promotes the improvement of alternative modes of transportation to the private vehicle and, on the other, discourages the use of cars. Above all, these measures must be contained in integrated land use and transportation plans that promote more sustainable and resilient cities focused on moving people and not vehicles. To this end, it is crucial to plan the city from a systemic approach that generates greater accessibility to job, health, and education opportunities based on mixed land uses and an integrated and efficient transportation network.

Likewise, the level of acceptance and effectiveness of the measures will depend on their proper sequencing. International experience shows that improving the quality, accessibility, and flexibility of the public and active transportation system is paramount to provide an efficient and reliable service that attracts trips once made by car. Thus, quality improvement should begin before implementing measures such as road pricing and should continue in parallel to it, now leveraged on the resources that come along road pricing. In turn, the reduction of congestion expected from the implementation of road pricing will reinforce the improvement in the quality of public transportation services, which will now be able to operate with greater predictability and speed.

In general, the paradigm that the use of road infrastructure is free of charge —including parking spaces, loading and unloading bays, sidewalk curbs, and the streets themselves— must be changed. Instead, infrastructure is a service that must be paid for through fares that cover the costs to provide it, and its value must be reflected for users (Calatayud y Muñoz, 2020). By allocating fare revenues to improving transit systems, equity in resource allocation would also be enhanced: subsidies for higher-income private car users are eliminated, and resources are used to improve the quality of public transportation most used by the lower-income population. Another aspect to consider is piloting solutions before large-scale implementation. This can help increase citizens' awareness of the benefits of the measures and help policymakers make the necessary adjustments to improve their effectiveness.

Finally, given that urban space, especially in the case of large cities and megacities, often includes more than one level of government, coordination among planning and mobility agencies at all levels is critical to developing and implementing comprehensive land use and transportation plans that are effective in increasing sustainability and reducing levels of road congestion. This objective also requires coordination with agencies outside the transportation sector. Fuel subsidy policies and car purchase subsidies are examples of some of the external measures that encourage motorization and generate unfair competition for public and active transportation, to the detriment of more globally efficient and environmentally sustainable mobility.

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Appendix

Appendix 1

Development of a congestion calculation model:

Scenario 1 :

$$D_{ts} = D_{ts}^{stock} + D_{ts}^{flow}$$

$$D_{ts} = OR * La_s \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\gamma=1}^{\Gamma_{ts}} \gamma \; + \; OR * La_s * \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\gamma=1}^{\Gamma_{ts}-1} \gamma \; + \; OR * La_s * (\Omega_{ts} - \Gamma_{ts}) * d_{ts}^{max}$$

Developing algebraically, we obtain:

$$D_{ts} = OR * La_s * d_{ts}^{w} * \left(\frac{1}{\Gamma_{ts}} * \left[(\Gamma_{ts} + 1) * \left(\frac{\Gamma_{ts}}{2} \right) + (\Gamma_{ts} - 1) * \left(\frac{\Gamma_{ts}}{2} \right) \right] + \; \Omega_{ts} - \Gamma_{ts} \right)$$

$$D_{is} = OR * La_s * d_{ts}^{w} * \Omega_{ts}$$

Once this equation is achieved, the aggregated delay of specific area will be the aggregation of the different segments in all time intervals:

$$D = \sum_{t}^{T} \sum_{s}^{S} D_{ts} \qquad (14)$$

Scenario 2:

$$D_{ts} = D_{ts}^{flow} + D_{ts}^{stock}$$

$$D_{ts} = OR * La_s * \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\omega=1}^{\Omega_{ts}-1} \omega + OR * La_s * \frac{d_{ts}^{w}}{\Gamma_{ts}} * \sum_{\omega=1}^{\Omega_{ts}} \omega + OR * La_s * (\Gamma_{ts} - \Omega_{ts}) * d_{ts}^{max}$$

Developing algebraically, we obtain:

$$D_{ts} = OR * La_s * \left(\frac{d_{ts}^{w}}{\Gamma_{ts}} * \left[(\Omega_{ts} - 1) * \left(\frac{\Omega_{ts}}{2} \right) + (\Omega_{ts} + 1) * \left(\frac{\Omega_{ts}}{2} \right) \right] + (\Gamma_{ts} - \Omega_{ts}) \right)$$

$$D_{ts} = OR * La_s * \left(d_{ts}^{w} * \frac{\Omega_{ts}}{\Gamma_{ts}} * \Omega_{ts} + \Gamma_{ts} * d_{ts}^{max} - \Omega_{ts} * d_{ts}^{max} \right)$$

$$Note: d_{ts}^{max} = d_{ts}^{w} * \frac{t}{t_{ts}^{ef}} = d_{ts}^{w} * \frac{\Omega_{ts}}{\Gamma_{ts}}$$

$$Note: \frac{t}{t_{ts}^{ef}} = \frac{t}{L_{ts}} v_{ts}^{ef} = \frac{t}{L_{ts}} * \frac{q_{ts}}{k_{ts}} = \frac{\Omega_{ts}}{\Gamma_{ts}}$$

$$D_{ts} = OR * La_s * d_{ts}^{max} * (\Omega_{ts} + \Gamma_{ts} - \Omega_{ts})$$

$$D_{ts} = OR * La_s * d_{ts}^{max} * \Gamma_{ts}$$

As in Scenario 1, the aggregate delay of a specific area will be obtained as the addition of the different time intervals and segments:

$$D = \sum_{t}^{T} \sum_{s}^{S} D_{ts} \qquad (15)$$

Algebraic derivation of the vehicle count

For the purposes of aggregate flow estimation, the values of k-j(k^j) or point of maximum saturation of road use equal to $\frac{1}{6}\frac{veh}{m}$ and k-critical (k^c) or point of highest possible vehicle flow are calibrated as $\frac{1}{6}$ of k^j. Based on this, Ω_{ts} is calculated as follows: q_{ts}^{max} is the highest possible flow of vehicles per second on the road and is the point at which the flow of vehicles becomes zero as a consequence of excessive road use, i.e.:

$$q_{ts}^{max} = V_{ts}^{ff} * k^c$$

$$q^j\left(k^j\right) = 0$$

$m_{ts}\ (q)$ is, on the other hand, the slope of the function of in its decreasing section:

$$m_{ts}(q) = \frac{q^j - q_{ts}^{max}}{k^j - k^c}$$

Once you have this, you can obtain the function of q in its decreasing part,

$$q_{ts} - q^j = m_{ts}\left(k_{ts} - k^j\right)$$

$$q_{ts} = m_{ts}k_{is} - m_{ts}k^j$$

On the other hand, the gray function can be easily calculated as:

$$q_{ts} = V_{ts}^{ef} * k_{ts}$$

Finally, the estimated value for q_{ts} be obtained from the intersection between the gray function and the decreasing section of the black function of Figure 2.3.

$$q_{ts} = \frac{-m_{ts}k^j}{V_{ts}^{ef} - m_{ts}} * V_{ts}^{ef}$$

Subsequently, the number of vehicles that will enter the traffic jam can be estimated as follows:

$$\Omega_{ts} = q_{ts} * t \qquad (16)$$

Appendix 2

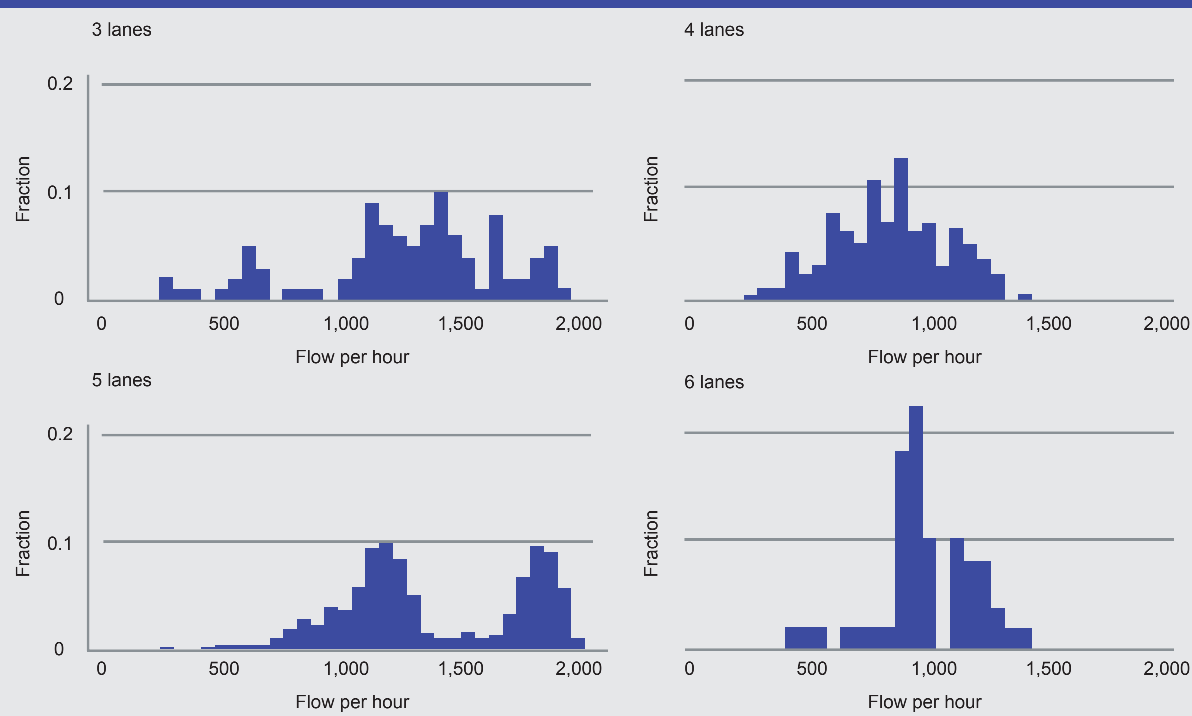
Data validation

In this section we describe the process to validate the number of vehicles per lane, estimated through the triangular relationship explained in Chapter 2. Indeed, the main challenge presented by the Waze database is that it only reports traffic conditions in congested situations, making it impossible to calibrate a triangular relationship following the traditional methodology. Thus, we proceeded to estimate the number of lanes and approximated a general triangular fundamental relationship for all roads in the city.

In order to certify the validity of the congestion model and the data obtained through Waze, we contrasted the flow estimates of the proposed model for the city of Buenos Aires, with the data provided by the highway company of Buenos Aires: Autopistas de Buenos Aires S.A. (as per its Spanish acronym: AUSA). These data are captured through radars, which perform a vehicle count per hour of the day, in 27 locations of the different urban highways of the Metropolitan Region of the argentinian capital.

Due to possible entry errors, the data obtained from AUSA have been filtered to consider a minimum of 200 vehicles and a maximum of 2,500 vehicles flow per lane (Varaiya, 2005). Once these data were filtered, we cross-checked them with the information coming from Waze, conditioning on: (i) that the traffic jams recorded by Waze have taken place throughout a full hour, this in order to ensure that the flows of both databases are comparable; (ii) that the traffic jams recorded by Waze intercept the radars that perform the vehicle count throughout the recorded hour (spatial cross). Based on these criteria, we obtained 12 geographic points where it is possible to make a contrast between the AUSA data and those estimated by us from the data. Each geographic point contains about 150 moments on average, amounting to a total of 1,827 observations.

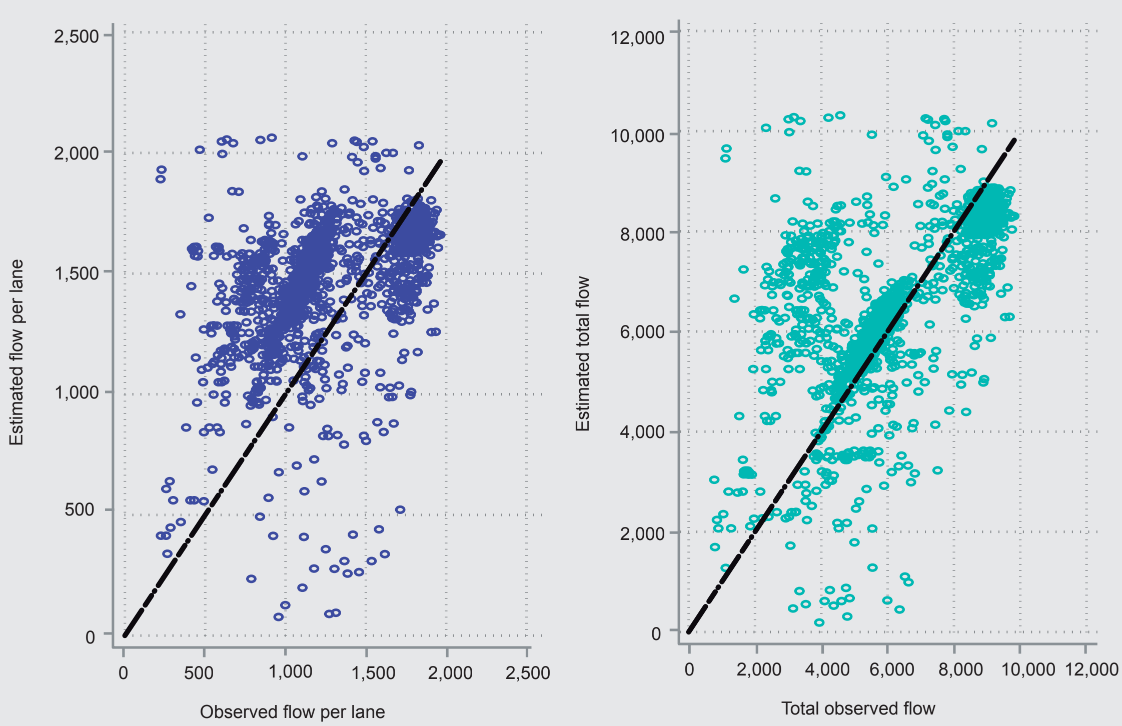
Figure A.1 Flow per lane – hour (selected points, Buenos Aires)



Source: Own calculations with data obtained from AUSA

Figure A.2 shows the results obtained by the proposed model from the Waze data, checked with the observed data from AUSA. In this graph, the ordinate axis represents the observed value from AUSA, while the abscissa axis is the one estimated by the proposed congestion model. The dotted line represents is a 45-degree slope function, i.e., this represents the perfect fit of the flow value of the AUSA data and that of the model proposed here based on the Waze data. In the left panel, the results of flow per lane are presented, showing that the fit of the estimates made with the proposed triangular model replicates quite well the observed flow of vehicles per lane using the AUSA radars, as most of the calculated flows are mostly between 1,000 and 2,000 veh/h, with a maximum flow between 1,800-2,100 veh/h. Both values are quite in line with what is proposed by theory (Varaiya, 2005). The prediction coefficient of the observed value, based on the AUSA data, amounts to 1.07 and presents statistical significance at 1%, in addition to an R^2 greater than 0.92. The right panel, on the other hand, shows the results of the total flow considering the lanes estimated by the neural network model. This graph shows a similar dynamic to the one presented in the previous graph, with a small margin of difference in the central points of the graph. The linear prediction coefficient in this case is 1.00 and is statistically significant at 1%, with an R^2 of 0.92.

Figure A.2 Comparison estimated by model vs. observed AUSA

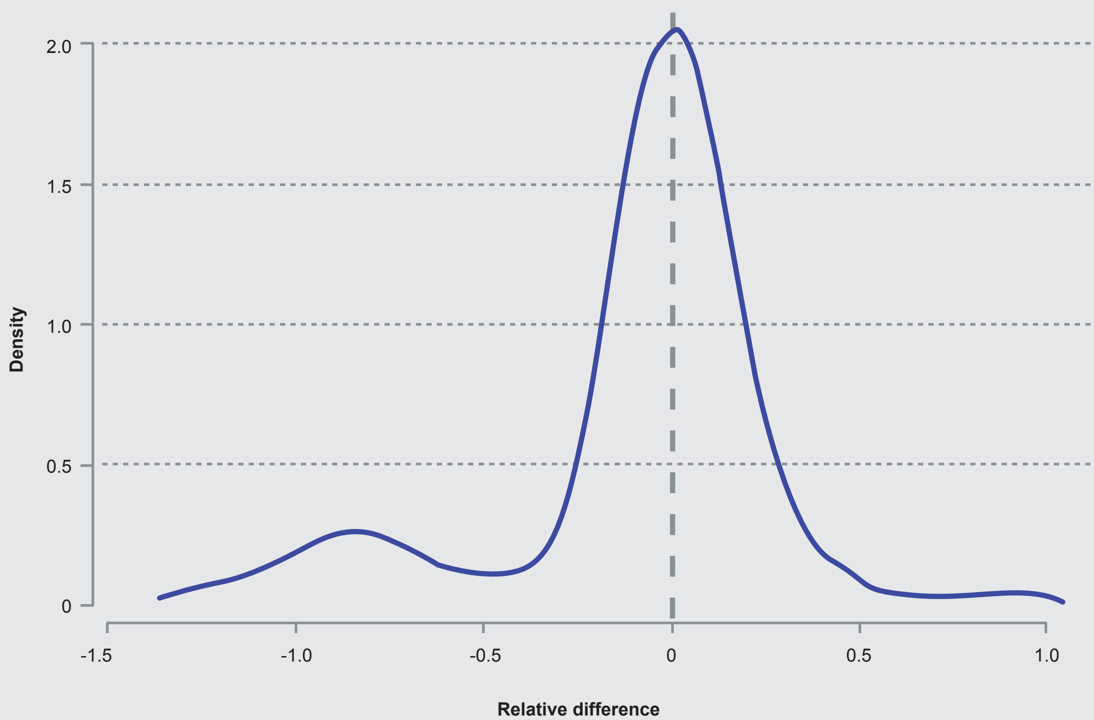


Source: Own calculations with data from Waze and AUSA.

In order to determine the quality of the adjustment to a greater degree, we analyzed both the trend and the bias of the estimates. For this purpose, we used the relative adjustment indicator, calculated as the linear difference between the observed and estimated flow, relative to the observed flow. From this indicator, we observe whether there is a relevant mismatch of the estimates, which should be considered, or an evident bias.

Figure A. 3 shows the distribution of this indicator. It shows that, although the mean is -0.17, the median value is -0.02. In other words, there is a margin in the distribution of this indicator. That is to say, there is a margin in which the flow of vehicles may be overestimated, but this may be guided by the margin of error of the observed data, since the median of this indicator is approximately zero, which is an indication of the good adjustment of the congestion model.

Figure A.3 Relative adjustment



Source: Own calculations with data from Waze and AUSA.

Finally, it is worth including a small comment regarding the accuracy of the data. As shown in Figure A.2, there are points where the model underestimates the flow, and others where it overestimates the flow observed in the AUSA data. Considering that this is not a permanent trend for all observations, it is valid to question the accuracy of the AUSA sensor data, since, if they were absolutely accurate, using the same method for all data should result in an underestimation or overestimation of all AUSA flows. On the other hand, it is acceptable to question the assumption that the flow is homogeneous along the segment, and therefore corresponds to the flow observed at the specific point where the sensor is located. Beyond these questions, the robustness analyses performed show that the flows calculated by our model from the Waze data, especially considering the number of lanes, are a good approximation to the real congestion experienced on the analyzed streets.

Appendix 3

To estimate the effect of cruise ships on congestion in the port area, an initial approximation has been proposed based on an analysis of covariance (ANCOVA) to determine the differences in the distribution of total delay in the presence of cruise ships. There it is found that the average time lost in congestion is higher in the presence of at least one cruise ship and statistically significant. This difference rises to almost 20% after controlling for road closures, road hazard warnings and discrimination between working days.

Once the existing differences in terms of congestion in the presence of cruise ships are determined, a panel data model is designed with fixed effects by port and an autoregressive error process:

$$D_{NTx1} = Z_{NTxL} + X_{NTxK}\beta_{Kx1} + U_{NTx1} \qquad (17)$$

$$U_{NTx} = \alpha U_{NT-\ x} + \epsilon_{NTx} \qquad (18)$$

Where the subscripts N, T and L are the number of ports, periods of time and no-observed effects per port. D represents a vector containing the aggregate delay information in the port area; Z is a matrix of no observed fixed effects; U represents the assumed independent and identically distributed error term and ϵ the error of the autoregressive process. X is the matrix containing the control variables used in the regression, i.e., time of day, morning and afternoon; the effect of being a workday; road closures; road hazards of various kinds; and, most importantly, the number of cruise ships arriving/departing from the port. From the equations (17) and (18) we derive:

$$d_{it} = z_{it}^{1} + \cdots + z_{it}^{l} + \beta_0 + \beta_1 x_{1it} + \cdots + \beta_k x_{kit} + u_{it}$$

$$d_{it} - \bar{d}_{it} = z_{it}^{1} + \cdots + z_{it}^{l} + \beta_0 + \beta_1 x_{1it} + \cdots + \beta_k x_{kit} + u_{it} - \left(z_{it}^{1} + \cdots + z_{it}^{l} + \beta_0 + \beta_1 \bar{x}_{1it} + \cdots + \beta_k \bar{x}_{kit} + \bar{u}_{it}\right)$$

$$\ddot{d}_{it} = \beta_0 + \beta_1 \ddot{x}_{1it} + \beta_2 \ddot{x}_{2it} + \ldots + \beta_k \ddot{x}_{kit} + \left(\alpha \ddot{u}_{it-1} + \ddot{\varepsilon}_{it}\right) \qquad (19)$$

The two dots above the variables indicate that it is the difference of the observed variable with respect to the mean in the port area $(\overline{y_t})$, i.e.: $(\ddot{y}_t) = y_{it} - \overline{y_t}$

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