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Exploring Tools for Maximizing the Potential for Electrified Transit Buses in Mexico

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1 Introduction

Climate change is one of the largest and most urgent challenges facing humanity today. As people around the world continue to face the challenge of climate change, the reduction of greenhouse gas (GHG) emissions remains one of the most important and effective tools available to humanity to mitigate its effects. In 2019, it was estimated that the transportation sector accounted for approximately 22.1% of Mexico's GHG emissions, making transportation second only to electricity and heat generation in terms of its emissions contribution [1]. To address this challenge, many sectors of transportation are moving towards electrification.

One of the technologies that has enabled governments at many levels to affect both GHG emissions and local air quality has been the advent of zero-emission buses (ZEBs). The transition to ZEBs is a process that has been in motion for over a decade. The city of Shenzhen in China boasts one of the world's largest all-electric battery electric bus (BEB) fleets, at over 17,000 buses. The process of electrifying Shenzhen's bus fleet began in 2011 and was completed in 2017. The buses were deployed in stages, beginning with a demonstration phase in 2009, small-scale deployments from 2011 to 2015, and finally full electrification by 2017. The majority of these buses are Build Your Dreams (BYD) vehicles, and all are served by depot chargers around the city. Countries in Central and South America have also proven to be early adopters of BEBs. For example. Chile, Costa Rica, and Ecuador all have BEBs active in their cities, with more countries committing to follow their examples. India also placed an order for 1000 BEBs in 2019, representing the second largest such order at the time. The European Union has also adopted policies on transitioning transit buses to ZEBs, especially the Zero-Emission Urban Electric Bus System (ZeEUS). The Netherlands, France, and Sweden have emerged as early leaders in Europe, though many other nations are running demonstration-level deployments with scaling plans for the next decade.

In the United States, CALSTART estimates that in September of 2021, there were approximately 1287 ZEBs currently deployed with a total of 3533 funded or planned vehicles (including the currently deployed vehicles). Of these planned vehicles, CALSTART estimates that 3364 are BEBs, with only 169 FCEBs planned [2]. Despite this small number, there is growing interest in FCEBs due to certain operational advantages that the technology provides, if the obstacles of high cost and fuel availability can be overcome. Several transit agencies are planning or have begun pilot projects to determine the best ZEB type to suit their network and operations. These projects have been an invaluable source of data and information on ZEB operations and understanding the challenges of ZEB deployments.

This report explores a set of tools to help in electrification of the transit system by optimizing the type of path and infrastructure needed for each transit route using publicly available data. We demonstrate the benefits and cost of different battery electric buses setting and the use of optimization tool to pick the best solution for each use case. The report is first in a set of reports that will result in a publicly available software and a set of manuals that can be used in any city in Mexico.

2 Climate Policy in Mexico

2.1 Mexico's Global Climate Outlook

As part of the 195 nations that negotiated and adopted the Paris Agreement in 2015, Mexico along with each signatory country must present a Nationally Determined Contributions (NDC). NDCs are country-specific emission reduction goals and standards utilized by governments as guiding principles to develop climate change policy. Mexico's original NDC committed to reducing GHGs and short-lived climate pollutant (SLCP) emissions by 25% below business-as-usual (BAU) in 2030. A key goal for the country's NDC was the proposed pathway to position Mexico to reach a net emissions peak in 2026 [3].

Mexico's 2020 update of the NDC was not well received by the international community and was legally challenged by climate change advocacy groups [4]. The 2020 updates were less rigorous emission targets, and therefore breached the international climate agreement and domestic law. According to the Climate Action Tracker, a website that tracks the actions of Paris Accord signatories, "the BAU had been revised upwards and Mexico was using creative accounting in the BAU to produce higher absolute emissions levels." Other reports suggest that the 2020 NDC update also included unclear language for emission reduction targets across major sectors, while also removing specific language regarding a timeline for peak emissions [3].

During the COP27 Conference in Fall 2022, Mexican Foreign Ministry officials reaffirmed their commitment to global efforts to limit warming to 1.5° Celsius and to achieve net zero GHGs emissions by 2050. Mexican officials outlined an increase of GHGs reduction from 22% to 35% by 2030, as well as a reduction of black carbon emissions by 51% under a BAU scenario [5]. Additionally, Mexican officials reported aggressive investments in renewable energy, including the implementation of an ambitious strategy for energy efficiency, electromobility, and electrification of transportation [6]. However, progress in climate policy and goals have proven challenging under the current administration.

The current administration has rolled back a number of climate change policies and dismantled critical resources that aim to tackle climate change [4]. These actions are inconsistent with pledges to the United Nation, as a signatory of the Paris Agreement, and setting Mexico on a path to not reach its emission reduction goals. While there are some stakeholders (local governments and agencies) that are taking a more aggressive and proactive posture to climate change, overall is currently rated as Highly Insufficient by climate change watchdogs [3].

2.2 Policy Landscape for Electrification in Mexico

Mexico's climate policy strategies are defined and outlined by the General Climate Law (LGCC - *Ley General de Cambio Climático*) which was first passed in 2012 and has since been periodically amended, most recently in 2022 [7]. According to the World Climate Tracker, the LGCC includes the creation of climate-focused institutions, legal frameworks, and financing to move towards a low-carbon economy. Most importantly, the LGCC outlines emission reduction targets including a total GHG reduction of 50% by 2050, compared to 2000 levels [7].

In 2021, the Special Climate Change Program [8] was updated as a policy roadmap to reach the 50% by 2050 reduction goal set by the LGCC. In a previous version [9] the document outlined 5 Key Objectives, with 26 underlying strategies to meet each of those objectives. Individual strategies are supported by several lines of action with the purpose of advancing their respective strategies. Objective 3 in the PECC focuses specifically on emissions reduction, including Strategy 3.5, which points to the "Develop sustainable transportation and mobility models." The Lines of Action most critical to transit electrification in Mexico are outlined in the table below**.**

Table 1: The critical lines of action as outlined in the Special Climate Change Program

Action Line	***Objective 3:*** *Reducing GHG Emissions to orient Mexico towards a competitive economy and a development with low emissions*	Agency
3.5.1	*Design and implement a sustainable mobility policy for cities with 500,000+ inhabitants.*	SEDATU
3.5.2	*Reduce GHGs and pollutants under the Clean Transportation Program*	SCT
3.5.6	*Build passenger interurban railways with an integrated vision that considers the regional*	SCT
3.5.7	*Promote key massive transportation projects with lower travel times, socioeconomic profitability, and environmental impact criteria.*	SCT /BANOBRAS

Action Line 3.5.1 provides government bodies to develop and implement policies that advance clean transportation in Mexico's most urban environment. While Line of Action 3.5.5 is emphasizing the need for less polluting modes that ensure that Mexico is meeting its emission reduction goals. Both 3.5.6 and 3.5.7 focus on improving efficiency, connectivity, and planning, all while maintaining a commitment to the impacts of the environment. Overall, these actions provide regulatory and government bodies with a number of levers to advance and accelerate the electrification of Mexico's transportation sector.

2.3 Major obstacles and opportunities to Electrification

Emissions from the transportation sector in Mexico account for 20-24% of the national total[1]. The sub-sector of road transport is the largest source of emissions, generating 94% of the total emission of the sector[1]. As outlined in the previous section, Mexico has developed several of programs and targets that aim to reduce GHGs emissions reduction in transportation, including replacing fossil fuels in the sector, establishing urban public transport corridors, and the potentially implementing a National Electric Mobility Policy.

However, the agenda of the current administration has focused largely on energy security and austerity measures. In the last few years, the Mexican government has rolled back a number of climate policies, eliminated critical mitigation funds, and has prioritized securing and in some cases expanding Mexico's fossil fuel operations. Furthermore, the administration's energy agenda on energy focused largely on investments to modernize the country's aging coal, diesel, oil and gas plants - all of which were previously set to sunset [3].

In 2022, the administration approved a federal budget that included the construction and renovation of fossil fuel infrastructure, while also expanding the operations of state owned petroleum enterprise (PEMEX) in the United States [10]. Also in 2022, the governing party (MORENA) made an unsuccessful effort to eliminate the National Center for Energy Control (CENACE), a move that aimed to limit operations by private electricity producers. This came on the heels of policy changes that weakened the Clean Energy Certificate program, an incentive program for renewable energy production and one of the few policy mechanisms specifically designed to drive the clean energy transition [10].

Other political maneuvers that challenge the country's ability to achieve its climate policy goals include dissolving or diluting key climate change resources. For example the National Institute for Climate Change (INECC), which served as a nonpartisan think-tank and research institution that produced technical knowledge to aid decision making, has been largely integrated into the country's Secretariat of Environment and Natural Resources [3]. Also in 2021, the Climate Change Fund, one of the key sources of support for climate related measures was dismantled, making the currently available funding for climate change mitigation allocated primarily for the transport of natural gas [10].

The current political climate that favors fossil fuels has stalled the public release of a critical instrument for Mexico to set a pathway toward electrification. The National Strategy for Electric Mobility Vision 2030 has been in development since 2018 by the Secretariat of the Environment and Natural Resources (SEMARNAT) and is proposed as the country's electrification roadmap [11]. Although this National Strategy remains unavailable to the public, it has been widely reported that the document outlines a detailed work plan for the country to reach the country's electrification targets. These targets include a commitment to introduce 500,000 hybrid light-duty vehicles and 7,000 heavy-duty vehicles by 2030. Additionally, it is reported that Mexico aims to transition its 10 largest urban areas, including Mexico City, to all electric mobility by 50% in 2040 and 100% in 2050 [12].

As one of the main sources of transportation in urban areas, the electrification of Mexico's transit ecosystem will be key to reaching emission reduction goals [13]. Consequently, it is anticipated that sustainable public transportation will be one of the guiding principles in the National Strategy document. Transportation experts have also reported that the strategy will include efforts to establish more collaboration between regulators and transit agencies, as well as incentive programs to encourage greater adoption of electric vehicles in transit fleets. The latest reporting on this National Strategy points to the development of an aggressive infrastructure plan that aims to facilitate the deployment of an electrified fleet in geographies where the social, economic, and environmental impacts will be the greatest [14].

2.4 Policy Landscape for electrification in Mexico City

Mexico City (CDMX) is located in the Metropolitan Zone of the Valley of Mexico (ZMVM), the largest metropolitan area in the country with 7.5% of the national population [15]. CDMX serves as the country's primate city, dominating government, business, research, and social life [16]. Additionally, CDMX hosts one of the largest and most complex transit systems in Latin America. The ecosystem of transit in CDMX includes hard rail, light rail, rapid bus system (Metrobus), buses (Autobuses), micro-buses, taxis, ride-hailing, and shared micro-mobility. According to a report by the local CDMX government, transit is the most common mode of transport, specifically Microbuses and Combis with 35.7% and Metro, Metrobus, Trolebus, and Red de Transporte de Pasajeros de la Ciudad de México (RTP) with 29% of the share [16]. The report also indicates 23.3% of the population gets around the city by walking [16].

Overall, the city's transportation ecosystem generates close to 75% of the city's GHG emissions. In response to these figures, the CDMX government has outlined aggressive plans to encourage the mode shift from single-occupancy vehicles to public transit. Since 2018, the CDMX government has been planning several initiatives to improve transit and active mobility. These efforts included expanding transit corridors to total reach approximately 65 miles of travel (100 km) by 2024, developing 4 additional cable bus lines by 2024, improving the light rail system, expansion of metro lines, and the addition of new trains [17]. These plans also include initiatives to improve the city's biking infrastructure with the goal of attaining 3% of total rideshare by 2024.

The CDMX government views the transition to a cleaner, more efficient transit system as a key strategy for reducing GHG emissions and addressing the city's infamous poor air quality. In the recent Local Climate Action Program, the CDMX government defines, "Integrate and Sustainable Mobility" as the first of eight guiding principles towards a city-wide goal of net zero emission by 2050 [16]. Each guiding principle in the Local Climate Action Program includes subsequent action items.

Table 2: A list of action items presented in the Local Climate Action Program

Guiding Principle 1: Integrate and Sustainable Mobility *Objective: To transform and consolidate a low-emission mobility system that is accessible, integrated, inclusive, efficient, and safe, while prioritizing active mobility and public transportation.*	
Action Item 1.1	Encourage demand and promote the mode shift to clean mobility, active mobility and public transportation.
Action Item 1.2	Support the transition to new technologies in the public vehicle fleet and zero emission vehicles for private ownership.
Action Item 1.3	Consolidate a mobility system that is integrated and accessible by all

Action item 1.1. primarily focuses on "carrots-and-sticks" strategies for a greater modal shift away from personal vehicles towards zero-emission vehicles, active mobility, and/or public transit. The "sticks" in this strategy include low/zero emission zones in the city, premiums on private parking, congestion pricing, limited circulation of polluting vehicles, and greater enforcement of idling regulations. The "carrots" in this strategy focus on transportation ecosystem improvements and investments, with the purpose of making walking, biking, or using transit affordable, safe, and convenient.

Action Item 1.2. outlines the need for a technological transition of both private and public vehicles towards zero emissions vehicles. The action item sheds light on the role that Mexico plays in the overall supply line of vehicle manufacturing not just domestically but regionally, and the need to maintain this critical labor market. However, the action item fails to outline any policies or incentive programs that will propel the demand for these new mobility technologies from the local consumer market.

Action item 1.3. describes the need to develop a more integrated transportation network that improves accessibility, minimizes delays, and provides safe and secure mobility for all. The current challenges and inability to coordinate solutions are largely due to the segmented nature of the transportation system - physically, administratively, and financially. Consequently, the lack of connectivity in the transportation system has produced inequitable user experiences that cumulatively impact vulnerable populations, specifically women, disabled individuals, elderly, and children.

2.4.1 Environmental Goals for Mexico City

Mexico City is one of the many cities that have decided to join the C40 movement in which world-leading cities collaborate with one another to combat the climate crisis through science-oriented and collaborative efforts to limit global temperatures from rising an additional 1.5 degrees Celsius (34.7 Fahrenheit) (C40 Cities, 2021). C40 cities must meet leadership standards in order to continue being considered a C40 city, and these standards include efforts to create a climate action plan. Along with delivering their plan and applying it in real-world scenarios, they must maintain an equitable lens to enable a holistic approach to combat climate change.

One of the major aspects of cities involved in the C40 initiative is the mainstreaming of climate change management plans. Cities must use the necessary financial resources, policies, and social collaboration to help identify and address their city's needs in order to have a more immediate impact on their communities (C40 Cities, 2021). Mexico City’s plan to address climate change involves major innovation of their current transit system, primarily replacing their bus fleets with zero-emission vehicles (ZEVs), Mayor Mancera declared an obligatory measure in 2015 to replace 14,000 low-capacity buses for clean buses by 2018 and work with partners to produce zero-emission buses by 2025 (C40 Cities, 2021). While these goals are ambitious, they show Mexico City’s effort and intention to lead a clean transportation revolution to help improve public health and reduce transportation related emissions.

A significant challenge that Mexico faces is replacing its various vehicle fleets and identifying which fleets and which vehicles need to be replaced with ZEVs. This first begins with identifying the types of vehicles that are operating in each city, which has proved to be challenging in quantifying the various modes and types of transportation operating within Mexico City. Although the government of Mexico does provide a high-level breakdown of the number of federal vehicles operated in each municipality, more data and deeper analysis are required to make specific recommendations on fleet conversion.

2.5 Policy Analysis Conclusion

Mexico is currently falling behind on its domestic and international commitments to curve and reduce emissions to maintain the global temperature within the 1.5° Celsius threshold. The current administration continues to favor fossil fuel operations that further steer the country from its emission reduction targets. However, the concept of a clean, safe, and inclusive system of transport has gained significant momentum, particularly in large urban centers. Regional entities and local governments are synchronizing efforts and position plans to ensure that there is progress toward climate change targets. In the coming years, the challenge of an electrified system of public transportation will be focused on the lukewarm political will at the highest levels of government.

3 Modeling a Transition to ZEBs in Transit Networks

3.1 The Options for Electrifying a Transit Bus Network

3.1.1 Battery Electric Buses

At present, there are two types of ZEB technology available to transit agencies. The first of these is BEBs. Like other electric vehicles, these buses carry an on-board battery pack that is used as the primary energy storage on the bus. These packs are far larger than those found on cars, with pack sizes ranging from approximately 150 kWh to as large as nearly 700 kWh, with rumors of larger battery packs being developed for future vehicles. In general, the pack size of the buses can be affected by both the characteristics of the route(s) the bus is assigned to service, and by the charging strategy implemented for that bus. BEBs are manufactured in a variety of sizes, from small cutaway conversions and 35-foot small transit buses, to ordinary 40-foot buses most commonly used by transit agencies in North America and Europe, to double-decker and articulated buses for high-volume routes and bus rapid transit services (like Metrobús), with announcements of an extra-long biarticulated BEB from manufacturers like Van Hool and Solaris.

Deploying BEBs requires a corresponding deployment of charging infrastructure and recharging strategies. Currently, charging strategies can be categorized into one of two main strategies: overnight recharging in a depot, or opportunity charging along a route. Recharging overnight using a depot charger is typically done at power levels between 40-100 kW, with 65 kW being a typical value. This process takes approximately 3-6 hours depending on the size of the battery pack of the bus and the speed of the charger. These chargers tend to function similarly to consumer electric vehicle chargers: buses park in a spot and plug into a charging port. There are a few related charging standards that are in use around the world. In the United States, the Society of Automotive Engineers (SAE) typically sets the chargers. Depot charging typically takes place with chargers using the SAE J1772 charger. Although this is the same standard governing consumer EV chargers, bus chargers typically eschew the lower-powered AC charging options present in the standard in favor of the higher-powered DC Fast charging due to the overall size of the battery packs on these vehicles.

Opportunity charging works differently; these chargers operate at higher power levels (300-600 kW or more) and typical charging sessions take between 10-15 minutes. In that time, a bus isn't expected to fully recharge; instead, the charging takes place in such a way that the bus can complete its assigned duty cycle with a smaller battery pack than it would otherwise require. The physical implementation of opportunity charging varies somewhat compared to depot charging. Current deployments of opportunity charging have either been accomplished with overhead catenary chargers using the SAE J3105 standard, which allows for charging at the higher power levels discussed earlier. The other main implementation of opportunity charging uses wireless inductive charging, for which the SAE has recently published the J2954/2 standard in 2020. However, as both of these standards are relatively new, there are still several out-of-standard implementations of both technologies in use (such as the mono-blade charging system common on Proterra vehicles before 2018). When implemented correctly, opportunity charging can offset its higher cost by significantly shrinking the overall battery pack size requirements of the vehicles serviced[18]. This not only lowers the purchase price of the bus, but also improves the energy efficiency of the vehicle due to the weight savings of the battery pack. Typical implementations of both charging strategies are shown below.

Figure 1: An implementation of opportunity charging (left) and depot charging (right). Images credits: Electric Mobility Canada (left) and iTravel York (right).

3.1.2 Fuel Cell Electric Buses

Fuel cell electric buses (FCEBs) are a less mature technology than BEBs, with far fewer FCEBs being utilized by transit agencies today. FCEBs carry a tank of hydrogen that is used to generate electricity in a fuel cell. This electricity is used to charge a small on-board battery pack, which in turn is used to power an electric motor. There are several aspects of FCEBs that make them an attractive option for transit agencies. Primarily, FCEB refueling takes a very short amount of time. Refilling an FCEB is comparable to refueling a fossil-fuel powered bus, requiring very little change in operations after a transition is made. This is a significant advantage compared to BEBs, which can take several hours to recharge. However, there are several obstacles that make FCEBs a difficult proposition. Hydrogen fuel is not produced at a scale to support a large number of FCEBs entering service in the next decade, nor is distribution available at a scale to meet the new demand. Both of these factors and more contribute to the relatively high cost of hydrogen fuel, making transitioning to FCEBs a costly proposition.

3.2 Tools for Modeling a ZEB Transition

Transitioning a transit network from conventional fuels (such as diesel or compressed natural gas) to 100% ZEBs is a well-studied problem. Several studies have created tools using a variety of methods that have can model aspects of the transition to ZEBs, as shown in the table below:

Table 3: A table of example studies showing the breadth of tool types and results that can be found by modeling a transit network's transition to ZEBs.

Study Reference	**Location**	**Number of Buses in Agency**	**Methods**	**Primary Findings**

[19]	Park City, Utah, United States	45	Scenario Simulation	Uncoordinated use of BEB chargers may result in exceeding the voltage limit of the system, as well as abrupt current variation and high active energy loss. Introducing coordinated scheduling significantly reduces these losses.
[20]	Connecticut, United States	>400	Mixed-Integer Program	Optimal cost solution occurs at 79% fleet electrification. GHG can be reduced further with further electrification.
[21]	Shenzhen, China	16,359	Mixed-Integer Second-Order Cone Program with "No R" Algorithm	A set of locations to build 'mega-depots' around the city of Shenzhen was found.
[22]	Aachen, Germany and Roskilde/Copenhagen, Denmark	Varies (number of buses for 2 lines were optimized)	Grouping Genetic Algorithm with Mixed-Integer Non-Linear Program Formulation	Two scenarios (A and B) were developed. Scenario A found that BEBs could replace diesel buses 1-for-1 if they had enough range. In scenario B, this replacement was not possible. The optimal electrification is a heterogenous mix of the two vehicle types, with further savings possible through charger optimization.
[23]	Bangkok, Thailand	Varies	Drive cycle modeling in high-traffic environments, with and without opportunity charging	Including opportunity charging produced energy savings. Charging times and battery pack sizes were found to be more important than total range. Auxiliary loads have a significant impact on energy use.
[24]	Turkey	Varies (entire country is studied)	Mixed-Integer Program	130 of the 136 potential locations were selected to receive a charging

				station. Driving range of the buses had the largest impact on the overall cost of the system in a sensitivity analysis. The capacity of the charging system was dictated by the number of intercity routes converging on a certain node, not the population of the node itself.
[25]	Stockholm, Sweden	Varies (143 routes were studied)	Mixed-Integer Linear Program	Optimizing for costs results in 42 electrified routes and 101 biodiesel routes, with no cost increase relative to the 'business as usual' scenario. Energy use optimization results in 94 electrified routes, generally closer to the city center.
[26]	Greater Salt Lake City Area, Utah, United States	Varies (system operates 467 buses, different numbers were selected for electrification)	Bi-Objective Optimization Model	Tradeoff between cost and environmental equity works on a logarithmic scale. Bi-objective model formulation is flexible with many applications in a system like public transit with many different pressures

With the right data inputs, these tools can be used to understand the dynamics of a transit network, and provide key insights to a transit agency seeking to manage this transition and identify the best strategies to implement for their networks.

In the academic context, these tools can be very specific, often having been built as a bespoke model for the network around which the study centers. However, these methods can be generalized and applied more broadly to different networks

3.3 Understanding Transit in Mexico City

Mexico City is the largest city in Mexico, with a population within the city of almost nine million residents, and a population in the greater metropolitan area exceeding twenty million people (an area including the Federal District as well as the State of Mexico). In 2015, it was estimated that approximately 58.1% of trips within the metropolitan region were taken on public transit [27]. Mexico City is home to a variety of public transit options, including a robust subway train system, several systems of cable cars and trolley buses, and many different networks of transit buses to move the public around the city.

3.3.1 Fleets in Mexico City

In order to understand where to focus fleet conversion, the first step is to identify the fleets to develop a picture of what the environment has. The Diagnóstico Técnico de Movilidad CDMX contains a high-level view of the various fleets operating in Mexico City [28]. The data from this report includes 2019 fleet information for Metrobús, RTP, and Trolleybuses operating in Mexico City. Using this report, we gathered the 2019 fleet information for the number of vehicles, types, fuels, and capacity. These data are instrumental in developing a strategy for determining which buses to replace. One such method could be assessing the ages and fuel emission standards of the current fleets operating and determining which to phase out and replace.

Replacing older vehicles with lower emission standard rules could prove beneficial in terms of operating costs and public health. Removing the aging buses would make more room for the newer zero-emission fleets and could be less of an economic burden on the transit agency since they would continue to operate their newer diesel buses. The impact of this change would help Mexico City get closer to its emission goals laid out in its C40 climate action plan. To better visualize the variety of the buses, ages, and emissions standards we have included Metrobús, RTP, and Trolleybuses data in Appendix 1.

Metrobús operates over 7 routes throughout the city, serving primarily to cross the city and connect with other forms of transit. It is estimated that Metrobús serves over one million passengers on average weekdays. Metrobús has already begun the process of electrifying its service, with Line 3 being partially electrified in 2021 with a goal of fully electrifying the line in 2024. Additionally, plans have also been made to electrify Line 4. A map of the service is shown below:

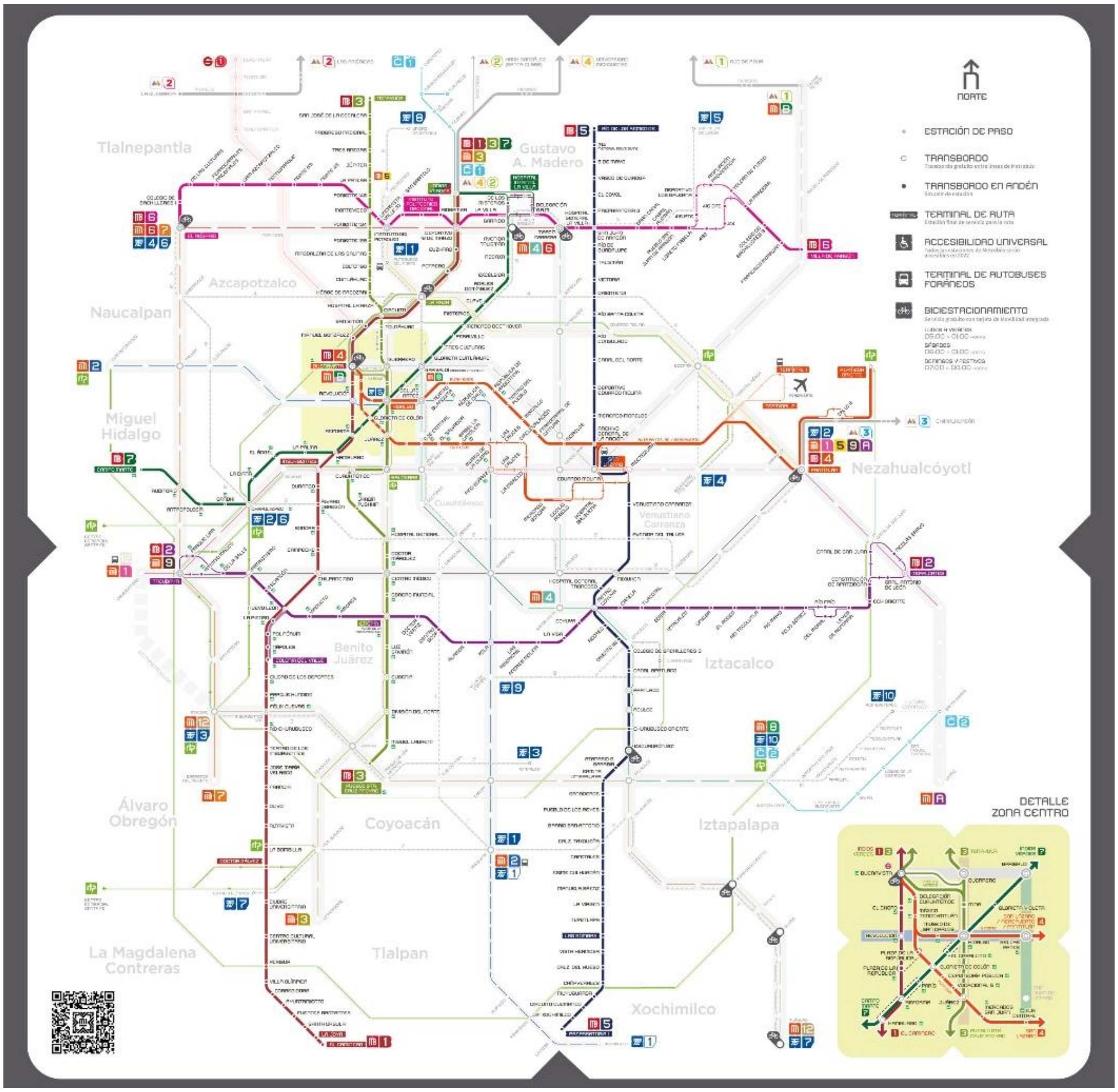

Figure 2: A map of Metrobús routes

Although the progress made by Metrobús in electrification is encouraging, it is only a small part of the larger picture of transit in Mexico City. Around 19 million daily trips are taken to Mexico City, with the most used mode being public transportation. These transit trips are made primarily with microbuses and combis, which together consist of 35.7% of the total trips per day (SEMOVI, 2019). With such a significant portion of trips using microbuses and combis, this mode of transportation would be a focus of the future investigation to electrify.

In addition to Metrobús and the independent operators, RTP is the major city-wide bus system of Mexico City. It operates over 100 routes with almost 1300 buses, servicing an estimated 400,000 passengers per day. RTP's service is subdivided into 6 service types: Ordinario (ordinary), Expreso (express), Ecobús (eco-friendly bus services using CNG vehicles), Atenea (Athena, a women-only bus service), Escolar (school), and Nochebús (night-bus service). In addition, its routes are split into 7 modules (Módulos) based on their location. A map of the service is shown below.

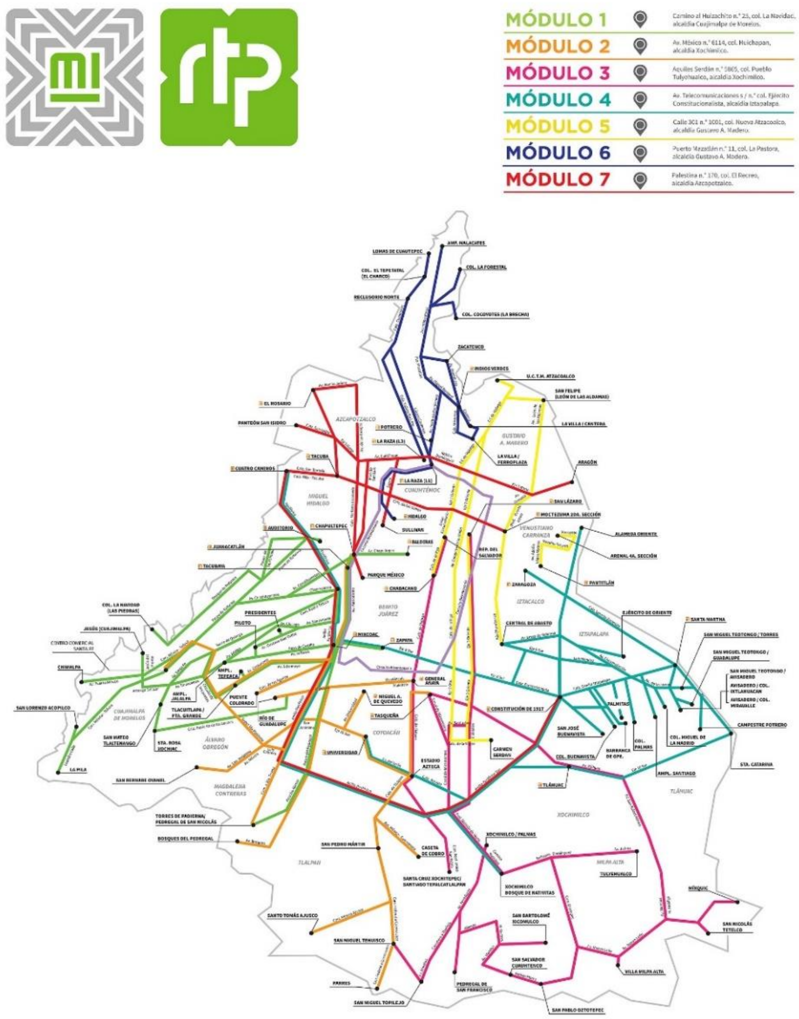

Figure 3: RTP's service map

The table below shows the breakdown of vehicles for passenger transport in Mexico City based on the vehicle classification.

Table 4: Inventory of vehicles for passenger transport in Mexico City by vehicle classification, 2021

Bus	Automobile	Truck	Midibus	Minibus	Total
22,927	2,717	663	7	452	**26,766**

A policy shift will be necessary for the proper transition and acceptance of zero-emission transportation, including a large undertaking of transforming the infrastructure to be able to accept the newer incoming fleets. While this will be a higher cost initially, the benefits from establishing the infrastructure first will translate into a more cohesive integration of the 2030 goal of having half of all cars sold domestically be electric vehicles (Reuters, 2023). This goal help can foster a relationship between electric public transport and the acceptance of electric vehicles within the country of Mexico.

3.3.2 Financial Aspects of a ZEB Transition in Mexico City

The high costs of ZEB fleet transitions have been examined as parts of demonstration-scale deployments [22], [29]–[31]. Most transitions have focused on the vehicles, as these represent the highest upfront cost of the transition and are central to the success of the network. These high vehicle costs and primarily due to the cost of the batteries in the buses. The cost of lithium-ion (Li-ion) batteries is a frequently researched topic, especially as the costs of Li-ion batteries have come down in the decades since the technology was first made commercially viable [32]–[34]. These falling costs have been identified as a key factor in the commercialization of transit buses and other heavy-duty vehicles [35], [36]. The cost of batteries has to be weighed against the cost of opportunity charging infrastructure, which can reduce the required battery pack size of the vehicles in the system under certain conditions [23], [37].

One way to mitigate the capital cost burden is to modify the structure of operating and purchasing new vehicles. In California, grants are available for manufacturers to produce and provide more ZEBs in the state [38]. This model can be implemented in Mexico City where the initial purchasing cost of the ZEBs can be offset by a grant provided by the Mexican government or in the form of subsidies for the ZEB manufacturers. Assisting the transit agency by alleviating the full brunt of the costs, rather the provider of the EV bus would be handling the monetary aspect of the EV purchase and the transit agency would handle only the operational costs [39]. This method would allow for a more integrated transit system that doesn't place so much weight on one agency or municipality; it distributes the costs and responsibilities to various agencies, which may improve the adoption and implementation of alternative fuel transit systems.

4 Case Study: Preliminary Analysis of RTP

To display the ways the model can be used, we carried out a preliminary case study analysis on RTP. An important aspect of any transition to ZEBs is understanding the energy consumption of vehicles in the network. Our model estimates the average energy use of vehicles on each route based on the general driving dynamics (primarily, the speed and acceleration) along with the physical characteristics of the bus to produce an estimate for an average energy use value. This value is presented as kilowatt-hours per mile (kWh/mi) throughout this report, which can be thought of as equivalent to "mpg" for conventional vehicles. The range of estimated energy use of 40-foot buses on the routes of the RTP network are shown below, organized by module. Most routes of RTP fall within the expected range of buses of this size (2 to 4 kWh per mile).

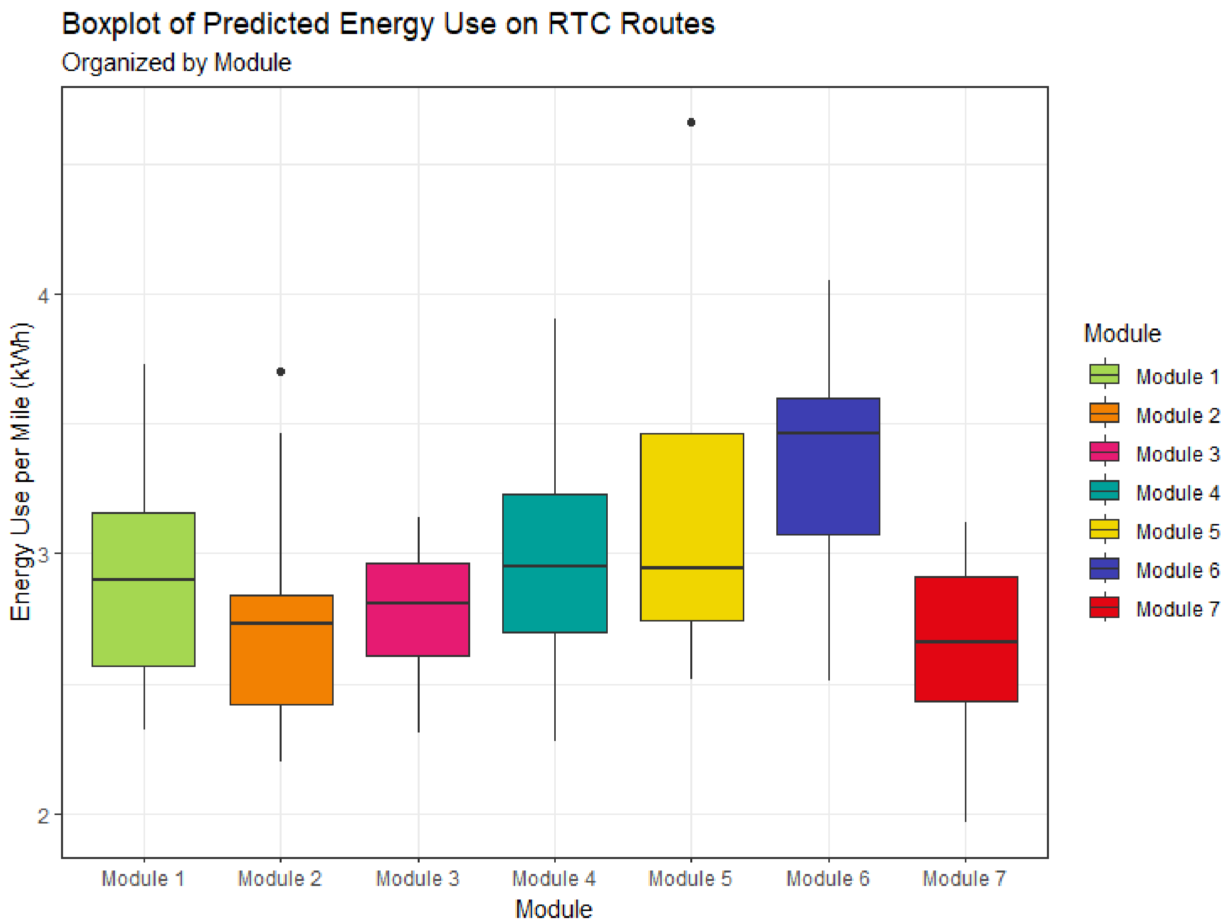

Figure 4: Estimation of energy use on routes for RTP, organized by module. Energy use is presented in kWh/mi (lower is more energy efficient).

When considering infrastructure decisions within a network, opportunity charging locations must be identified and selected. Our model selects bus stops as potential locations, using the criteria of frequency with which vehicles (from any route) arrive at that stop, as well as the number of individual routes that the stop serves. Although searching for more locations can be specified, the default behavior of the model is to search for stops until each route is served by at least one potential location (whether a charger is actually installed at these locations is determined later). For the initial analysis of RTP, 44 of these candidate locations were identified as suitable to serve all 117 routes in RTP. These locations are shown on the map below as blue pins on the map.

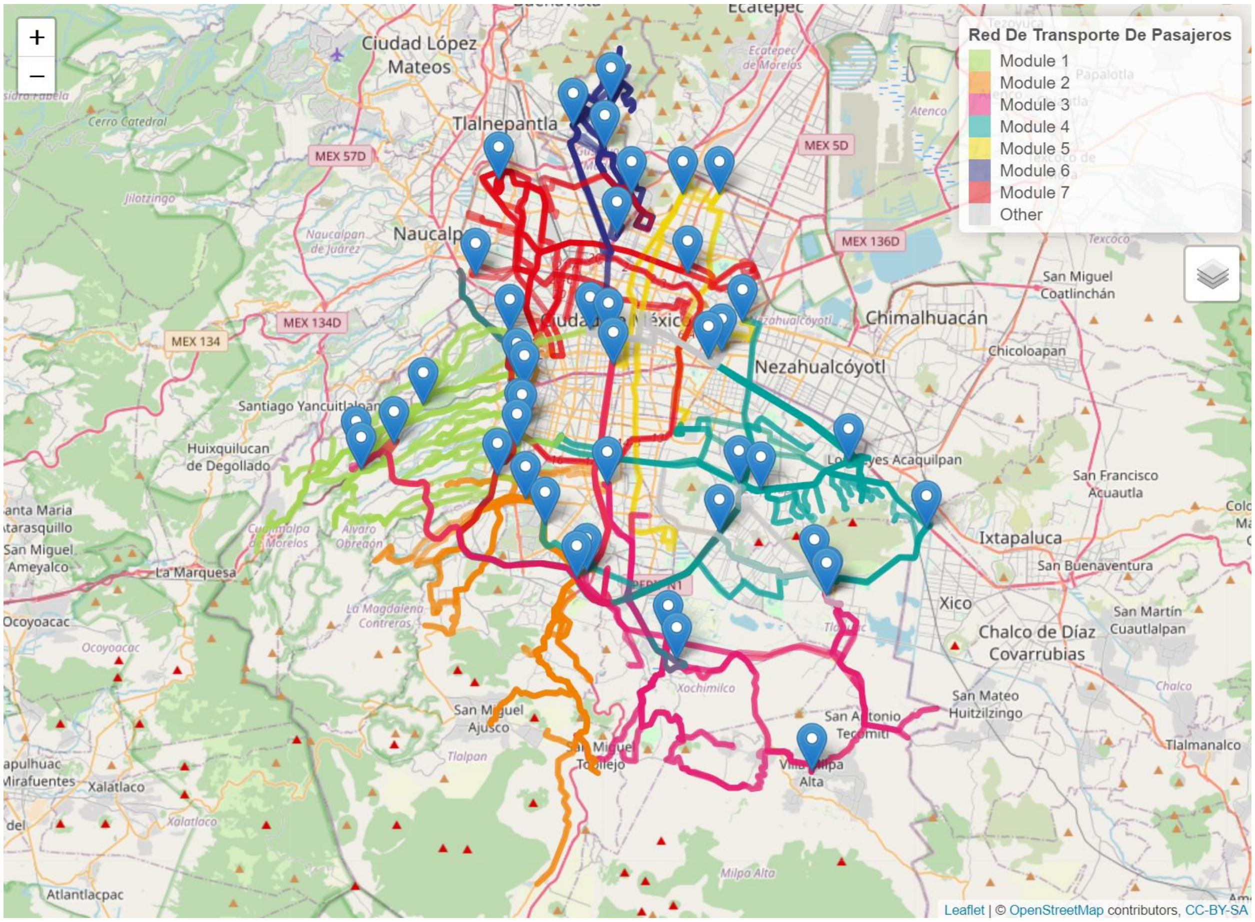

Figure 5: A map of RTP with blue pins identifying stops that are selected as candidate locations for opportunity charging. Routes are colored by module.

For each location, one or more opportunity chargers may be installed based on the overall effectiveness of that charger relative to its cost. In past analyses using this model, we have found that more central locations, and those which have higher overall utilization within the schedule, are locations where chargers are installed, even as costs get high. We expect these factors to hold true for networks like RTP as well. Figure 4, below, shows some of these results visually:

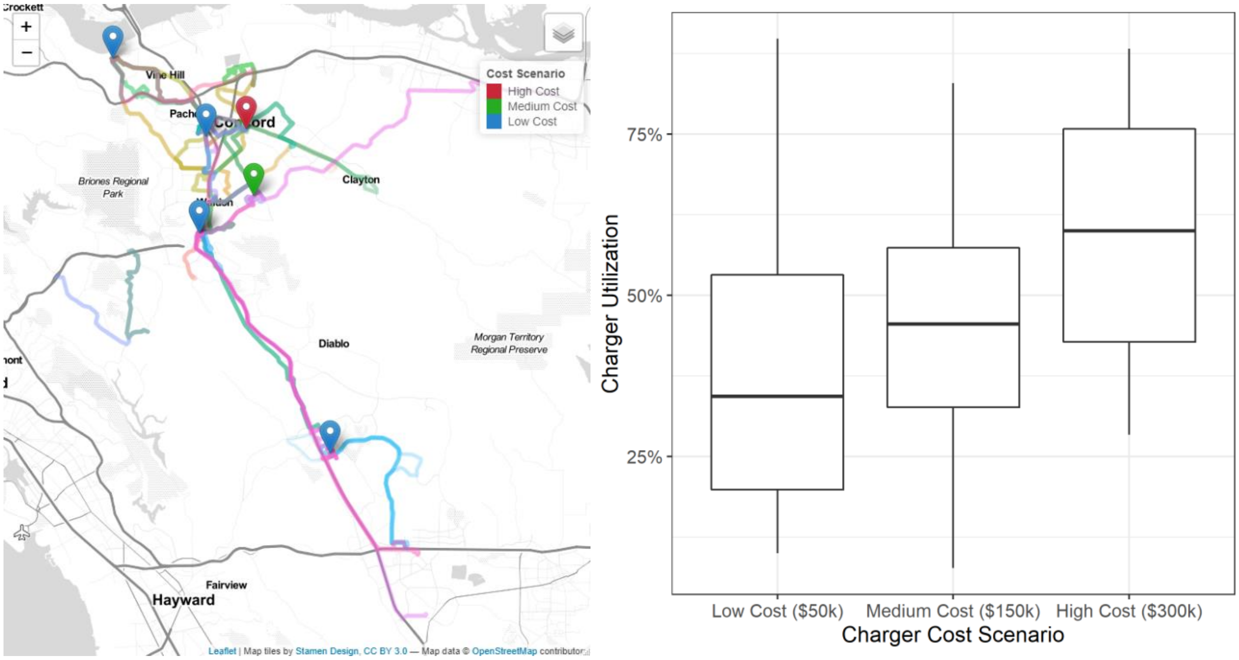

Figure 6: Left: A map of an example network showing the selected locations for charger installation when chargers had a low cost (all colors), a medium cost (red and green locations), and a high cost (red location only). Right: A boxplot of the amount of time opportunity chargers were used in the low, medium, and high-cost scenarios of a previous analysis. Notice that, as the cost of chargers increases, chargers must be used more frequently to be worth their increased cost.

Frequently, when large transit networks decide to begin transitioning to ZEBs, they will select a subsection of routes to introduce these vehicles into their operating environment. This serves a myriad of purposes; first, it allows a transit agency to understand the operation of these vehicles and gives individuals at all levels of the agency the ability to gain valuable experience without committing to a whole-fleet transition all at once. Second, these pilot projects introduce these vehicles to the public they serve, often creating public support for the new vehicles. Third, it allows transit agencies to understand the monetary costs of the technology, providing valuable information for planning the transition of the rest of the fleet. To assist in these decisions, we have studied the relative 'fitness' of different types of routes to electrification, helping to give these pilot programs the best chance of success possible. Our previous analyses have found that, in general, electrification (especially combined with opportunity charging) is best suited to routes that are low mileage and high frequency on a per-vehicle basis. These routes allow vehicles to make use of their battery pack most effectively as a capital asset, and when combined with opportunity charging to rapidly refill that battery pack, these routes tend to have the lowest time to meet their return on investment. To examine what routes might be good candidates at RTP, these two characteristics were plotted against each-other as a scatter plot:

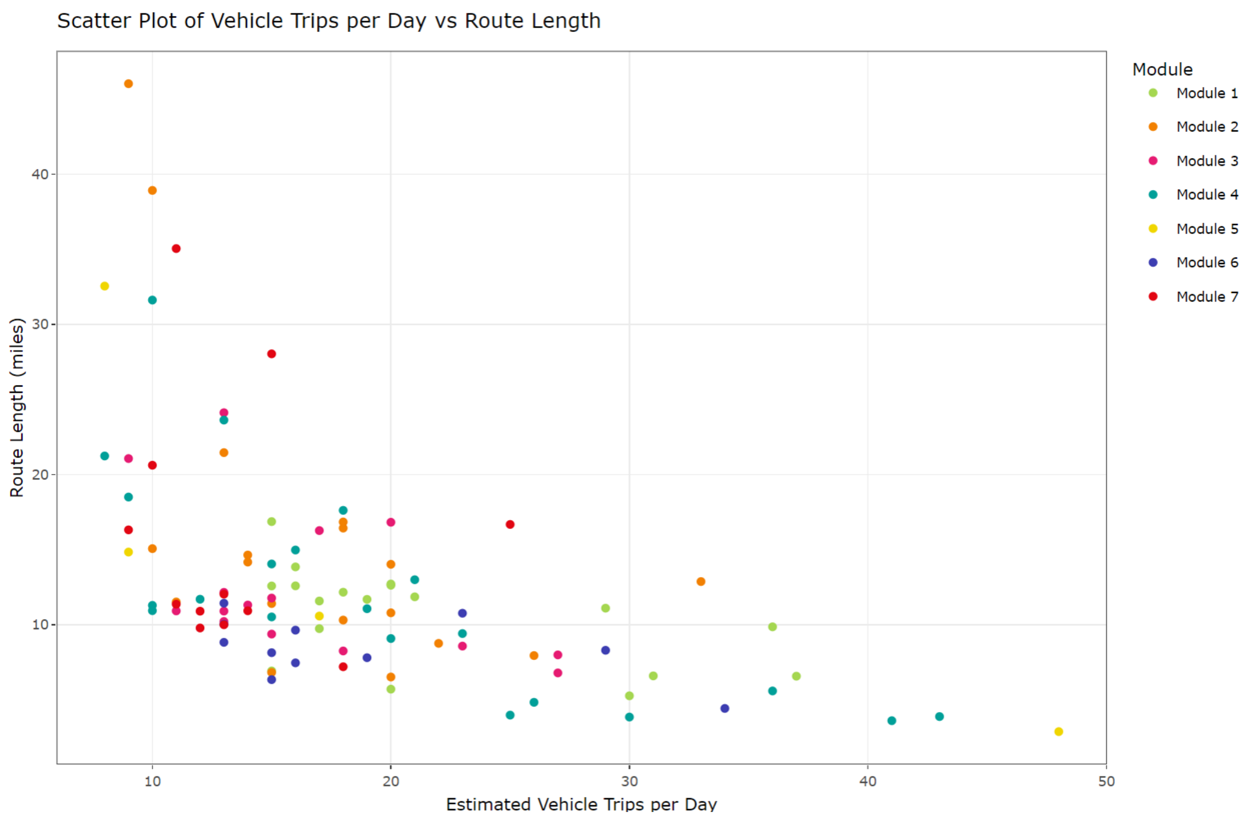

Figure 7: A scatter plot of estimated vehicle trips per day versus the length of the route for all routes in RTP, colored by module. Routes with low length and high frequency (lower left of this chart) are most suitable for electrification.

Based on this analysis, we can identify Modules 1 (the western branch of the network) and 6 (the northern branch) as the modules that are the best suited for this kind of pilot project for electrification.

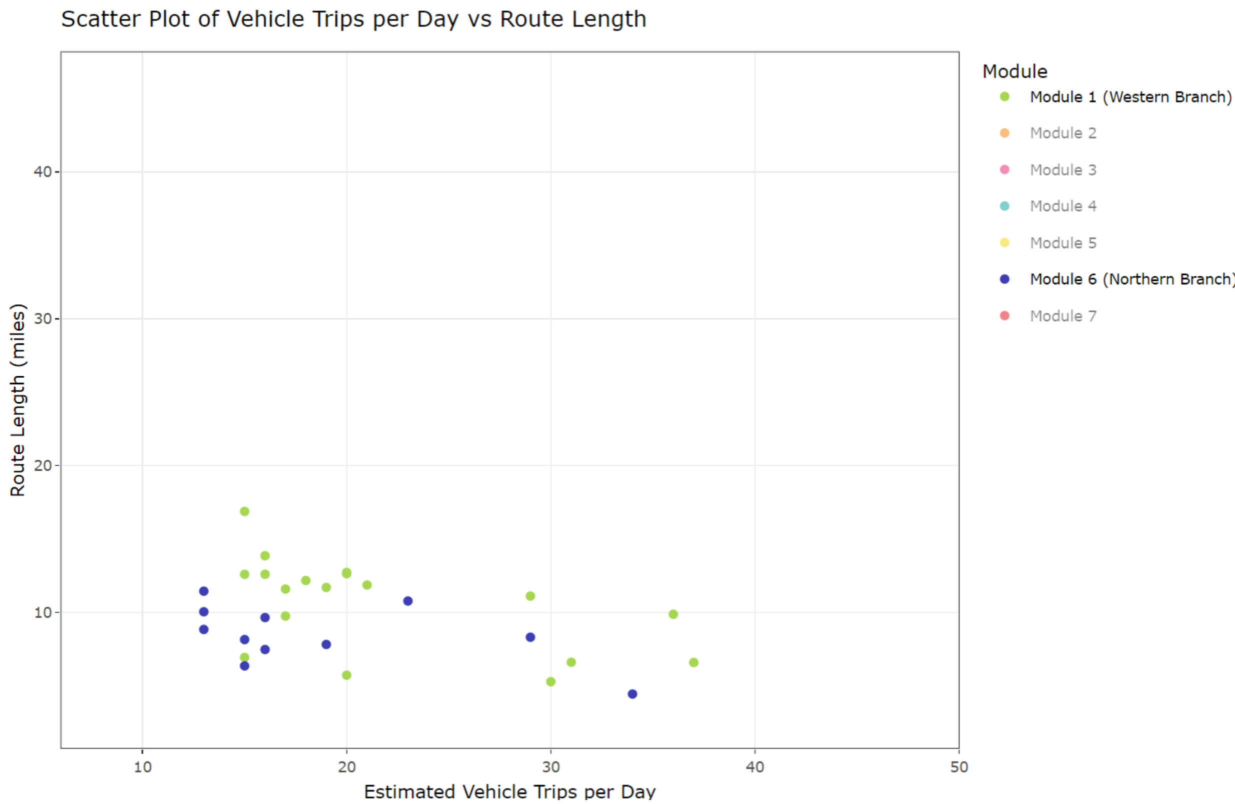

Figure 8: The same plot as Figure 7, with Modules 1 (western branch) and 6 (northern branch) isolated as the best candidates for electrification pilot projects.

Preliminary analysis on the effects of electrifying these routes shows that they represent a combined savings of (depending on certain assumptions about the way the network is operated) between 1000-5000 gallons of diesel fuel per operational day. Based on fuel costs and electricity costs in Mexico City, this represents a savings in fuel costs of almost 6000 USD per day on these two modules alone. Given the average market prices of BEBs, that results in an average payback time of less than 4 months per vehicle. In our previous analyses, we have found that the replacement rate of the vehicles is slightly higher than 1-to-1; typically, between 10% to 30% additional vehicles are required for full replacement at the existing level of service. This replacement rate is generally based on the relative lengths of the routes being transitioned, as well as the overall energy use on those routes. As Modules 1 and 6 are identified as ideal candidates for transitioning to BEBs, we estimate that approximately 10-15% more buses will be required on these routes relative to the current size of the fleet servicing those modules. Transit agencies have also reported long-term operational savings, primarily due to the significantly reduced maintenance that BEBs require relative to their conventionally fueled counterparts (though these savings are beyond the scope of the model).

5 Conclusions and Future Work

Overall, there is a great deal of potential for electrifying transit agencies in Mexico City and around the rest of the country. There are some missing data that could be collected to better augment these analyses that will be discussed momentarily, but these data are relatively easy to procure with the cooperation of the agencies in question. For Mexico City's RTP, we have identified routes that have a high potential for success in electrification, especially if combined with an opportunity charging system. Although these findings are too preliminary to make specific recommendations for how to electrify these routes, we have presented the kinds of findings that will be produced by our analysis tool, and described how these results may translate and apply to RTP.

The next stage in this analysis is to finalize the optimization model and produce a version that can be used generally by transit agencies in Mexico. The tool will be made available for public use, assisting transit agencies in Mexico and elsewhere in their analysis of electrification options. At present, there are only plans to make a 'development' version of the tool available, though a more feature-complete version may be made available at a later time. To utilize the tool, it will be necessary to develop a General Transit Feed Specification (GTFS) data feed for the transit network to be analyzed. Although these feeds exist for the transit agencies within Mexico City, we were unable to identify fully suitable data for any other agency in the country of Mexico. The model is based on the static GTFS feed of a transit agency. The data for this feed is likely already being collected by most agencies, as it primarily relies on timetable information about a network's stops, routes, and trips. There are several free tools to help agencies produce these feeds, and these data are also useful for producing the real-time directions through apps like Google Maps to customers wishing to use the bus system. After developing these data feeds, the analysis possible with the tool can be used to provide a guide on how an optimal form of transitioning may be accomplished. These results, in turn, can either be used as a roadmap, or as another form of guide in helping transit agencies determine the best way to transition to ZEBs.

In addition to developing the model we would like to offer learning sessions with Mexican transit operators and Californian transit operators walks on transit electrification. These workshops will include all level of walkers from technicians and drivers to managers and decision makers you can learns from the successes and failures of Californians operators in the last decade. In interviews with these California agencies, collaboration and sharing of knowledge has repeatedly been cited as one of the most helpful actions for agencies seeking to electrify their networks. Agencies like Foothills Transit and

Antelope Valley Transit Authority in the Los Angeles area already operate on mostly BEBs, while agencies like the San Joaquin Regional Transit District and Unitrans of Davis also operate significant numbers of BEBs with a mixture of charging agencies. The exchange of information can be beneficial to all parties in expanding the general knowledge base of electrifying transit routes.

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Appendix 1 – A Breakdown of Fleets in Mexico City

Metrobús fleet, as of 2019

Quantity of Buses	Model	Model Year	Rule
90	Alexander Dennis Enviro 500	2017	EURO 4
9	DINA BRIGHTER	2014	EURO 5
10	DINA BRIGHTER	2015	EURO 5
3	Mercedes Benz Gran Viale	2008	EURO 3
16	Mercedes Benz Gran Viale	2009	EURO 3
54	Mercedes Benz Gran Viale	2011	EURO 5
11	Mercedes Benz Gran Viale	2012	EURO 5
4	Mercedes Benz Gran Viale	2014	EURO 5
49	Mercedes Benz Gran Viale	2016	EURO 5
4	Mercedes Benz Gran Viale	2019	EURO 5
2	SCANIA Mega Articulado	2014	EURO 5
12	SCANIA Mega Articulado	2016	EURO 5
2	SCANIA Mega Articulado	2017	EURO 5
2	SCANIA Mega Biarticulado	2015	EURO 5
1	SCANIA Mega Biarticulado	2016	EURO 5
1	Volvo 7300 Articulado	2006	EURO 3
15	Volvo 7300 Articulado	2008	EURO 3
34	Volvo 7300 Articulado	2008	EURO 4
12	Volvo 7300 Articulado	2009	EURO 5
1	Volvo 7300 Articulado	2011	EURO 4
7	Volvo 7300 Articulado	2011	EURO 5
3	Volvo 7300 Articulado	2012	EURO 5
9	Volvo 7300 Articulado	2013	EURO 5
29	Volvo 7300 Articulado	2014	EURO 5
4	Volvo 7300 Articulado	2015	EURO 5
39	Volvo 7300 Articulado	2016	EURO 5
10	Volvo 7300 Articulado	2017	EURO 5
3	Volvo 7300 Articulado	2018	EURO 5

25	Volvo 7300 Articulado	2019	EURO 5
1	Volvo 7300 Biarticulado	2007	EURO 3
8	Volvo 7300 Biarticulado	2008	EURO 4
4	Volvo 7300 Biarticulado	2012	EURO 5
10	Volvo 7300 Biarticulado	2013	EURO 5
16	Volvo 7300 Biarticulado	2015	EURO 5
12	Volvo 7300 Biarticulado	2016	EURO 5
10	Volvo 7300 Biarticulado	2017	EURO 5
37	Volvo 7300 Biarticulado	2018	EURO 5
9	Volvo 7300 Biarticulado	2019	EURO 5
10	Volvo 7300 Biarticulado	2020	EURO 5
10	Volvo 7300 Biarticulado	2020	EURO 5 Plus
1	Volvo 7700 Articulado	2011	EURO 5
46	Volvo 7700 Articulado	2012	EURO 5
8	Volvo 7700 Hybrid	2012	EURO 5
1	Volvo Access	2014	EURO 5
13	Volvo Access	2017	EURO 5

2019 Distribution of Metrobús vehicle fleet by transport company, quantity of buses and lines serviced.

Quantity of Buses	Company	Lines
109	Corredor Insurgentes S.A. de C.V.	1
37	Rey Cuauhtémoc S.A. de C.V.	1
20	Vanguardia y Cambio S.A. de C.V.	1
32	Red de Transporte de Pasajeros	1, 2, & 5
16	Corredor Oriente Poniente S.A. de C.V.	2
36	Corredor Tacubaya - Tepalcates S.A. de C.V.	2
25	Transportes Sánchez Armas José Juan S.A. de C.V.	2

72	Movilidad Integral de Vanguardia S.A. de C.V.	3
70	Conexión Centro-Aeropuerto S.A. de C.V.	4
23	Corredor Integral de Transporte Eduardo Molina S.A. de C.V.	5
18	Corredor Antenas-Rosario S.A. de C.V.	6
25	Curva-Villa-Ixtacala S.A. de C.V.	6
93	Corredor Eje 4 - 17 de Marzo S.A. de C.V.	1, 2, & 6
48	Operador Línea 7 S.A. de C.V.	7
42	Sky Bus Reforma S.A. de C.V.	7

Metrobús fleet for diesel vehicles by type, emission standard and line on which they operate

Quantity of buses (780 total)	Type	Length	Capacity	Fuel
438	Articulated high floor	59 feet	160	Diesel
153	Bi-articulated high floor	78 feet	240	Diesel
90	double decker low floor	39 feet	130	Diesel
70 (including 9 hybrid diesel electric)	Low floor	39 feet	100	Diesel, hybrid diesel electric
20	Low floor	49 feet	100	Diesel
9	Articulated high floor	59 feet	160	Electric

Detailed breakdown of Metrobús lines 3 and 4

Parameter	Line 3	Line 4
Number of buses	81	70
Bus typology	59 feet, high floor, articulated	39 feet, low floor, standard
Model 1	Mercedes Benz Gran Viale (diésel)	Volvo 7700 (diesel)
Model 2	Volvo 7300 BRT (diésel)	Volvo ACCESS (diesel)

Model 3	Yutong (eléctrico a batería)	Volvo 7700 (diesel hybrid)
Capacity	160 pasajeros por vehículo	90 passengers per vehicle
Trip Demand	180 mil viajes / día	68 thousand trips per day
Passengers per kilometre and miles (IPK)	10.2	4
Daily kilometers and miles	245 km / 152 miles	250 km / 155 miles
Yearly kilometers and miles	80 thousand km / 49,709 miles	81.5 thousand km / 50,641 miles
Length of the route	22 km / 13 miles	30 km / 18 miles
Average Speed	18.8 km per hour / 11 per hour	19.0 km per hour / 11 miles per hour
Terminals	5	4
Intermediate Stations	33	32
Hours of service	4:30 - 01:00	4:30 - 01:00

2019 RTP Vehicle fleet quantity, model, year, fuel and EPA/EURO rule

Buses	Model	Model Year	Fuel	Rule
20	AYCO 3000 RE	2001	Diesel Ultra Low Sulfur	EPA 98
16	AYCO 30030 RE	2002	Diesel Ultra Low Sulfur	EPA 98
3	AYCO DISCAP	2002	Diesel Ultra Low Sulfur	EPA 98
6	AYCO SUSP DEL MEC.	2002	Diesel Ultra Low Sulfur	EPA 98
89	Mercedes Benz Torino 2002	2002	Diesel Ultra Low Sulfur	EURO 3
80	Mercedes Benz Torino 2004	2004	Diesel Ultra Low Sulfur	EURO 3
220	Mercedes Benz Torino 2006	2006	Diesel Ultra Low Sulfur	EURO 3
17	Mercedes Benz Torino 2006 Equipped	2006	Diesel Ultra Low Sulfur	EURO 3
71	Mercedes Benz Torino 2009	2009	Diesel Ultra Low Sulfur	EURO 4

72	Mercedes Benz Torino 2009 Equipped	2009	Diesel Ultra Low Sulfur	EURO 4
2	Hyundai Hybrid	2012	Gas Natural / Electric	EURO 5
40	Hyundai CNG	2014	Gas Natural	EURO 5
30	MASA Volvo	2016	Gas Natural	EURO 5
41	AYCO Mercedes Benz Cosmopolitan	2016	Diesel Ultra Low Sulfur	EURO 5
8	AYCO Mercedes Benz Cosmopolitan C/Rampa	2016	Diesel Ultra Low Sulfur	EURO 5
147	Volvo PROCITY Diesel	2016	Diesel Ultra Low Sulfur	EURO 5
44	Volvo PROCITY C/Rampa	2016	Diesel Ultra Low Sulfur	EURO 5
130	DINA LINNER Expreso	2017	Diesel Ultra Low Sulfur	EURO 5
34	DINA LINNER C/Rampa	2017	Diesel Ultra Low Sulfur	EURO 5
70	Volvo Access	2020	Diesel Ultra Low Sulfur	EURO 5

2019 RTP Vehicle Fleet by bus quantity, model, and capacity breakdown

Quantity	Model	Passengers Sitting	Passengers on Foot	Unit Capacity
20	AYCO 3000 RE	28	72	100
16	AYCO 30030 RE	28	57	85
3	AYCO DISCAP	21	79	100
6	AYCO SUSP DEL MEC	28	57	85
89	Mercedes Benz Torino 2002	28	62	90
80	Mercedes Benz Torino 2004	28	62	90
220	Mercedes Benz Torino 2006	28	62	90
17	Mercedes Benz Torino 2006 Equipado	28	62	90
71	Mercedes Benz Torino 2009	28	62	90

72	Mercedes Benz Torino 2009 Equipado	27	62	89
2	Hyundai Híbrido	53	53	106
40	Hyundai GNC	53	53	106
30	MASA Volvo	34	66	100
41	AYCO Mercedes Benz Cosmopolitan	28	62	90
8	AYCO Mercedes Benz Cosmopolitan C/Rampa	28	62	90
147	Volvo PROCITY Diesel	31	69	100
43	Volvo PROCITY C/Rampa	31	69	100
130	DINA LINNER Expreso	31	69	100
34	DINA LINNER C/Rampa	31	69	100
70	VOLVO Access	33	67	100

2019 Distribution of road network by borough

City	Miles	% of primary roads	% of secondary roads
Álvaro Obregón	679	10	90
Azcapotzalco	340	10.9	89.1
Benito Juárez	333	19.8	80.2
Coyoacán	555	9.5	90.5
Cuajimalpa	242	4	96
Cuauhtémoc	381	20.7	79.3
Gustavo A. Madero	1005	8.2	91.8
Iztacalco	297	11.5	88.5
Iztapalapa	1396	5.9	94.1

La Magdalena Contreras	243	4.3	95.7
Miguel Hidalgo	430	13.3	86.7
Milpa Alta	294	0.5	99.5
Tláhuac	446	4	96
Tlalpan	836	3.9	96.1
Venustiano Carranza	371	13.4	86.6
Xochimilco	596	3.2	96.8

2019 Trolleybus fleet information

Quantity	Series	Fabricator	Passengers Sitting	Passengers Standing	Total Passengers
2	3200	New Flyer	18	68	86
34	4200	MASA Toshiba	35	50	85
76	4300-4400	MASA Toshiba	38	55	93
14	4700	MASA Mitsubishi	32	68	100
80	9700	MASA Mitsubishi	36	54	90
84	9800	MASA Mitsubishi	36	54	90
63	20000	Yutong	28	57	85

2019 Trolleybus information regarding series, fabricator, and model year

Series	Manufacturer	Model Year
3200	New Flyer	1975
4200	MASA Toshiba	1981
4300-4400	MASA Toshiba	1984
4700	MASA Mitsubishi	1988

9700	MASA Mitsubishi	1997
9800	MASA Mitsubishi	1998
20000	Yutong	2019

2019 Distribution of vehicle fleet by concessioned brokers

Corridor	Authorized	Existing	In Operation	Percent	Previous Route(s)	Microbuses Substituted
ACASA	90	90	86	95.6	2	220
AMOPSA	74	66	58	87.9	11	53
ATROLSA	85	85	81	95.3	2	103
AUISA	36	21	20	95.2	78	144
CASSUR	25	25	25	100	1	25
CEUSA	112	80	75	93.8	1	207
COAVEO	123	90	84	93.3	1	398
CONGESA	102	82	78	95.1	3	224
COPATTSA	112	108	90	83.3	1, 28, 118	282
COPESA	224	165	145	87.9	2, 98	502
COREVSA	72	79	75	94.9	2	214
COTANSAPI	70	70	60	85.7	99	229
COTOBUSA	58	50	45	90	28	108
COTXSA	228	218	190	87.2	1, 26, 111	882
COVISUR	34	34	8	23.5	25	75
COVITENI	46	38	38	100	1	38
ESASA	59	43	41	95.3	58	208

ITEC	20	20	18	90	1	20
SAUSA	69	69	66	95.7	86	105
SIMESA	90	84	80	95.2	2	214
TREPSA	87	66	53	80.3	2	136
TRESANTAFE	30	30	23	76.7	Bicentennial Corridor and Route 5	0
TRIOXA	53	53	50	94.3	10	186
Corredores Concesionados	1899	1666	1489	89.4	NA	NA