Urban Pathways

ECONOMIC VIABILITY FOR ELECTRIC BUSES IN TWO CORRIDORS IN QUITO AND MONTEVIDEO

UN-HABITAT FOR A BETTER URBAN FUTURE

solutions plus

Wuppertal Institut

UN environment programme

Author: M.Sc. Alexandra Velasco

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The Urban Pathways project helps delivering on the Paris Agreement and the NDCs in the context of the New Urban Agenda and the Sustainable Development Goals. It has established a facility in close cooperation with other organisations and networks active in this area to support national and local governments to develop action plans and concrete implementation measures to boost low-carbon urban development. This builds on UN-Habitat’s role as “a focal point on sustainable urbanisation and human settlements including in the implementation and follow-up and review of the New Urban Agenda”. The project develops national action plans and local implementation concepts in key emerging economies with a high mitigation potential. The local implementation concepts are being developed into bankable projects, focusing on the access to urban basic services to create a direct link between climate change mitigation and sustainable development goals.

Project concept

The project follows a structured approach to boost Low Carbon Plans for urban mobility, energy and waste management services that deliver on the Paris Agreement and the New Urban Agenda. The project works on concrete steps towards a maximum impact with regards to the contribution of urban basic services (mobility, energy and waste management) in cities to global climate change mitigation efforts and sustainable and inclusive urban development. This project makes an active contribution to achieve global climate change targets to a 1.5°C stabilisation pathway by unlocking the global emission reduction potential of urban energy, transport and resource sectors. The project will contribute to a direct emission reduction in the pilot and outreach countries, which will trigger a longer term emission reduction with the aim to replicate this regionally and globally to make a substantial contribution to the overall emission reduction potential.

Project aims

This project implements integrated urban services solutions as proposed in the New Urban Agenda providing access to jobs and public services in urban areas, contributing to equality and social coherence and deliver on the Paris Agreement and the Sustainable Development Goals.This is the first dedicated implementation action oriented project, led by UN-Habitat to deliver on inclusive, low-carbon urban services. Securing sustainability and multiplier effect, the project aims to leverage domestic and international funding for the implementation projects that will follow from this initiative

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INTRODUCTION

In the context of the project Urban Pathways, this paper intends to give first inputs for the viability of electric buses in Latin American cities and to illustrate a methodology to evaluate sustainability and feasibility of electromobility in public transport on the continent.

The focus is on two cities, Quito (Ecuador) and Montevideo (Uruguay), that are pilot cities within the wider framework of the SOLUTIONSplus project. Both cities have proportionated information about costs structure of either selected BRT (bus rapid transit) corridors (Quito) or conventional bus lanes (Montevideo).

Terminology:

Many terms used in this report are explained along the document, however, we explain most frequent terms below:

Charging device: Equipment manufactured for recharging battery buses with a charging power of up to 150 kW, usually at bus depots.

Charging power: Electric power used to recharge a traction battery. The actual charging power depends on the state of charge. The maximum charging power, often described as C-Rate cannot be applied for completely recharging a battery.

Energy: Measured in kWh, is a quantity of work. For example, using a 50-kW bus charger for 2 hours consumes 100 kWh: 50 kW x 2 hours = 100 kWh. Using a 300-kW bus charger for 20 minutes also consumes 100 kWh: 300 kW x 0,33 hours = 100 kWh.

Power: Measured in kW, is the rate that energy is consumed or moved.

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VEHICLE TECHNOLOGIES

Hybrid buses

The hybrid electric buses (HEV) have two energy sources: the electric and the fuel-powered motor. Besides two or more motors, the HEV has a generator, a energy storage system, interconnected with a power electronic device. The direction of flow and the magnitude of the power in the system are managed by acceleration and braking control circuits that depend on commands received from the driver.

The braking system has two ways to decelerate the vehicle: the electrical way and the mechanical way. This allows to increase the cycles and, therefore, the useful life of the system, decreasing maintenance costs. Electric braking has an additional application that is fundamental to the definition of HEV: it is "regenerative braking". When the vehicle decelerates, the generator coupled to the traction sends energy to a bank of electrolytic capacitors. This stored energy can then be used to power an electric motor, which, depending on the hybrid configuration, will partially or fully drive the vehicle. The participation in traction depends on the arrangement of the energy sources, depending on their series or parallel configuration.

Battery Electric buses

Battery Electric Buses (BEB) are one of the best options from an environmental perspective, as they produce no emissions of local pollutants, including soot. In this way, they contribute reducing impacts on air quality, mitigating climate change, and improving the health of the population and users. BEBs are also quiet, which diminishes noise pollution in cities. Not only does the set consist of batteries and electric motors, but it also embraces integration technologies and connectors, hybrid systems – if applied – and other support systems, such as charging stations and their infrastructure. Vehicle electrification, for example, involves a completely new way of supplying the vehicle, which implies changes in the user's mindset as the supply model shifts from liquid or gas fuels to electricity from the grid. That results in different parameters, such as longer charging periods and directed accessibility for recharging infrastructure (Barassa, 2021).

The BEBs use onboard battery packs to power all bus systems. They are classified into two types depending on their charging system: 1) long range and 2) fast charge. Chargers can be plug-in, overhead conductive, or inductive. Any type of charger can be used at the depot or un-route (Linscott and Posner, 2021).

The long or extended range BEBs have larger battery packs for maximum range between charges and usually the power charging is lower. This arrangement allows buses to be charged one or two times per day and it would require up to 8 hours or more for a fully recharging. Buses of 11 -12 m length usually have battery capacity from 250 to 660 kWh and a charging power of 50 – 125+ kW. In most cases the reliable range in service is <240 km (Linscott and Posner, 2021).

The fast – charge BEBs have smaller battery packs suitable for high-powered charges. These buses typically charge on-route several times per day. If the charging system is well implemented, the buses will recharge at transfer stations after the completion of a running cycle or at long standing bus stops without stopping for an extended charging session. A 12 m long bus has a battery capacity between 50 and 250 kWh with a charging power of 150 - 450+ kW overhead or wireless charges (Linscott and Posner, 2021)

While the acquisition costs of electric buses are high, their operating costs are significantly lower than diesel buses. The battery-powered electric motor is much simpler and requires much less maintenance than a diesel or CNG engine. It is also much more efficient, reducing the amount of energy needed to run the bus by 70% to 80% compared to diesel. Finally, the cost of electricity in most of Latin American countries is lower than diesel (although not necessarily lower than CNG) (OLADE, 2020).

Electric buses are gaining more space in fleets around the world. However, there are still many barriers to their adoption, such as higher procurement costs, more complex route planning and the selection of a charging system. To overcome these difficulties, cities could add a smaller number of electric buses to their fleets (from 10 to 100 electric buses, depending on the size of the fleet) to understand and adapt to different operations. If possible, charging infrastructure plans should be designed to be scalable to accommodate a growing fleet of electric vehicles.

For route planning, it is important to consider elevation change and route length, as well as heating and cooling demand, which can significantly reduce vehicle range. With these details, the simulation model can determine the expected range of the buses under consideration and can help bus suppliers to determine the size of the battery needed. If the new electric buses do not have sufficient range to cover the full daily route, a greater number of electric buses will be needed, which could increase procurement costs.

All electric buses can be charged overnight, using either depot charging systems or on-road charging systems. To determine the best strategy, it is important to consider infrastructure, investment costs and electricity rates.

- Investment costs: To perform depot charging, the bus is required to have a larger battery to cover the full route for the day; however, larger battery packs will reduce passenger capacity which may result in more vehicles per route to supply the travel demand. The depot charging infrastructure is less expensive than on-road charging. However, on-road charging allows buses with smaller battery packs.
- Electricity tariffs: Tariffs generally include both usage charges and demand charges, both of which are charges, which are affected by the time of day, with nighttime rates being the lowest.

Nowadays various bus manufacturers offer full electric buses. However, for Latin America only a few manufacturers have a local or regional representative or have placed their buses on cities´ streets.

For the present study a list of flagship e-buses models from Asia, Europe and North America is included as reference (see Appendix 1).

Fuel Cell Electric Buses

FCEBs are electric propulsion buses powered by fuel cells, mainly hydrogen, instead of liquid fuels. Their cutting-edge technology is called fuel cell stack and is designed to produce electricity from hydrogen. Fuel cell buses are divided into vehicles in which the fuel cell serves either as a range extender to supplement an externally charged battery or as the sole energy source. Due to the high dynamic charges, fuel cells are only installed in buses in combination with electrical energy storage units, usually batteries. In its basic design, the drive train is like those in battery or trolley buses. The external supply of electrical energy via a charging station or charger is generally provided for vehicles in which the fuel cell serves as a range extender.

The powertrain is supplemented by the fuel cell's H2 supply system. At its core are compressed gas tanks in which the hydrogen carried is stored in compressed form. In fuel cell buses, the hydrogen is usually compressed to a maximum of 350 bar and carried in several pressure tanks located on the roof. Fuel cell buses thus combine essential features of an electric bus with those of a gas bus, which is reflected in the complexity of the powertrain.

CHARGING STRATEGIES AND CHARGING TECHNOLOGIES

Despite enormous progress in the development of battery technologies, battery buses are currently limited in terms of their range. As a result, battery buses can only be used with schedule plans with a short to medium range or be recharged during operation. In any case, an energy balance calculation must be carried out in advance to determine whether a line or a schedule is suitable for the operation of battery buses.

There are three options for BEB charging: plug-in charging, overhead conductive charging, and wireless inductive charging. Any of these types of chargers can be used to charge BEBs either at the depot or on-route. Typically, plug-in chargers are primarily used to charge buses at the depot, and overhead conductive or wireless inductive chargers are used to charge buses on-route. However, the appropriate charging technology and approach will depend on fleet size, charger power, route characteristics, and available space. Overhead or inductive charging may be necessary for large-scale BEB fleets with limited space at the depot for chargers, while high-power plug-in chargers may be suitable for on-route range extension (Linscott and Posner, 2021).

Full charging stations (also Depot charger)

This type of charging strategy is the most convenient, since buses are recharged at bus depots, usually at night and usually requires the lowest investments in the charging infrastructure as all installations are implemented inside the bus depots or maintenance yards. The advantage of recharging inside of the bus depot, at terminal stations and at stations where the bus usually stops for a longer period of time is that the range can be extended considerably without any impediments to the operating procedure, provided the battery has been designed appropriately.

It is important to consider an appropriate ratio of spare chargers for achieving desired service continuity, as charging stations can require maintenance. If space is limited, overhead pantograph or reel dispensers attached to gantries installed across the bus yard should be considered. However, these installations require additional planning and cost for the overhead structures. (Linscott and Posner, 2021).

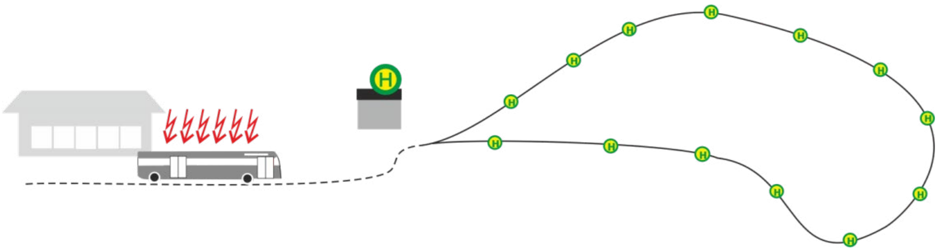


Fig 1. Depot charging

Overnight charging schemes employ plug-in technologies, perform conductive charging that can be AC or DC and relate to buses with high battery capacity (over 200 kWh, depending on the length of the bus). Charging times range from 2 (h) to 4.5 (h), depending on the power of the charger and the battery capacity of the bus. The power ratings of plug-in chargers range from 50 kW - 80 kW in AC to 90 - 170 kW in DC.

The applicability of depot charging strategies is widely hampered by the limited range of battery buses between recharging. Furthermore, depot charging will lead to higher depths of charge, which accelerates the degradation of batteries.

Opportunity charging

Opportunity charging systems are characterized by charging stations within the entire bus circuit or at the end stops. Recharging both in the depot and at the final stops or at stops with longer waiting times has the advantage that, if the electric energy storage system is correctly designed, a significantly greater range can be achieved without any significant restrictions in the operational process. There are multiple types of opportunity charging systems that vary in time and the amount of time and energy.

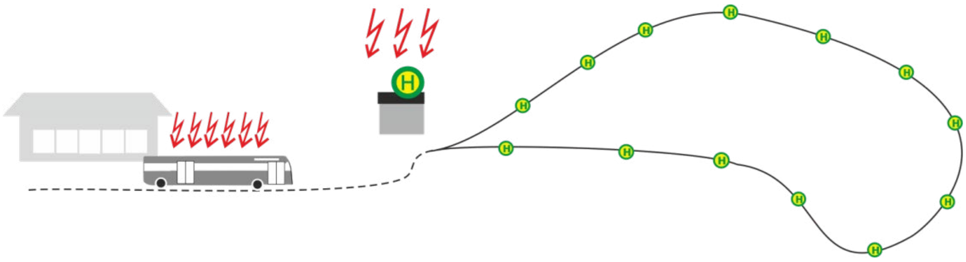
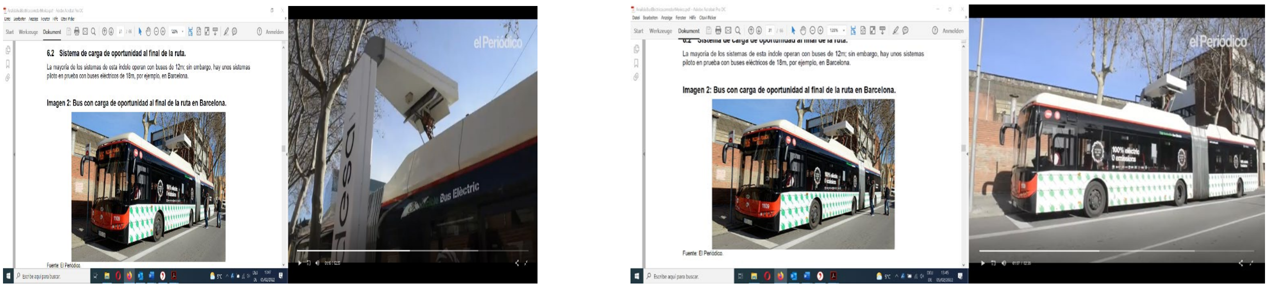


Fig 2. Opportunity charging

The majority of these systems operates with 12 m buses, however, there are some pilot projects with articulated buses of 18 m, i.e. Barcelona.



6.2 Sistema de carga de oportunidad al final de la ruta.

La mayoría de los sistemas de esta índole operan con buses de 12m; sin embargo, hay unos sistemas piloto en prueba con buses eléctricos de 18m, por ejemplo, en Barcelona.

Imagen 2: Bus con carga de oportunidad al final de la ruta en Barcelona.

Fuente: El Periódico.

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Imagen 2: Bus con carga de oportunidad al final de la ruta en Barcelona.

Fuente: El Periódico.

Fig 3. Opportunity charging station with pantograph in Barcelona

Source: El Periódico

If the ratio between

- total mileage per day
- journey time, and
- turn around or idle time at terminals with charging stations

is kept within certain limits, opportunity charging can facilitate significantly higher mileages per day of operation without changing the mode of operation, i.e. additional drivers or buses are not necessary. Furthermore, opportunity charging requires smaller batteries which increases the passenger capacity of the buses involved. However, opportunity charging requires additional charging infrastructure outside the bus depots (charging stations with high charging power) which makes the implementation significantly more complex and expensive. Furthermore, opportunity charging is not applicable on bus routes where long delays frequently occur. On the other hand, opportunity charging significantly reduces the amount of energy to be recharged at a bus depot and hence the grid connection power.

Flash Charging (or Ultrafast charging)

If, in addition to recharging at the depot and at terminal stops, energy is also supplied at on-route stops, even smaller electric energy storage units can be used. The charging times at the terminal stops can be reduced and thus the susceptibility to delays plays a lesser role. Since energy must be transferred in a short time, high charging power of 450 kW and more is necessary.

There are two types of ultrafast charging technologies: a) pantograph that which performs conductive charging by connecting the bus to a special device located on the roof; b) induction charger, which is wireless and recharges the batteries by electromagnetic induction from underneath the bus. Both charge in direct current (DC), in times ranging from 2 (min) to 10 (min), depending on the power ratings of the chargers and the capacity of the batteries. In the case of pantographic chargers, it is already possible to find power ratings ranging from 300 kW - 600 kW, while induction chargers are around 200 kW - 300 kW (Kane, 2019).

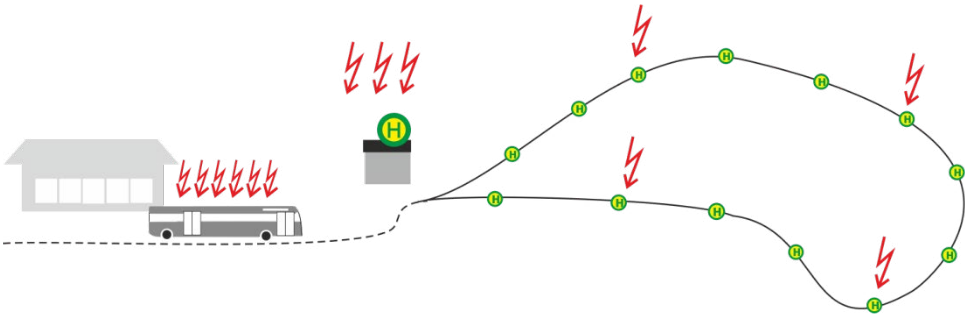

Fig 4. Ultrafast charging

The disadvantage is the further increased expense for the charging infrastructure as well as the requirements for the charging processes at the on-route stops, which can only be carried out with extremely high charging power. Thus, the recharging concept is only economically viable on lines with many vehicles. Another obstacle is the need to install charging stations at on-route stops in inner city areas. In addition, from a technological point of view, stops with charging stations must always be approached, which may result in additional stops during off-peak hours, and in the case of Latin American cities, additional training for drivers, which could be challenging to connect correctly with the pantograph. Another important point is that the buses must be specially equipped to receive pantograph charging or inductive charging, which not all suppliers offer in their electric model versions.

Hybrid trolleybuses (also In Motion charging – IMC)

Although hybrid trolleybuses are not battery-powered buses in the strict sense, some aspects of this form of energy supply will be presented in addition. Hybrid trolleybuses are trolleybuses with on-board energy storage that enables purely electric and at the same time fully catenary-free operation.

Hybrid trolleybuses are technologically based on conventional trolleybuses in which the auxiliary diesel generator has been replaced by an energy storage system. As a result, hybrid trolleybuses are characterized by durable and technically mature vehicle technology.

In contrast to conventional trolleybuses, hybrid trolleybuses require overhead lines only on part of their routes. Although each case requires individual examination, it can be said in general terms that hybrid trolleybuses will avoid overhead contact lines in sensitive urban areas (e.g. city centers) as well as expensive and complicated infrastructure installations such as crossings, underpasses and curves.

Fig 5. Electrified street in Spandau

Source: Urban-Transport-Magazine

Hybrid trolleybuses need ways to wire on and off overhead lines without driver action. While unwiring is easily accomplished using arrester cables, wiring on is a technical challenge. The simplest form of wiring is the so-called catch funnel. Automated wire-on systems (e.g. LibroDuct) are still in the development stage.

Charging infrastructure

The charging infrastructure for battery buses is inextricably linked to the charging strategy. The charging strategy is determined by the available charging time and the necessary charging power. A distinction is made between slow charging and fast charging. These, in turn, delimit the charging forms, which are divided into:

- Slow charging with a charging power of 150 - 180 kW and adapted for the so-called plug-in adaptors, and
- Fast charging with automated systems and inductive charging systems, with energy power more than 200 kW

Connectors

Plug-in charging is usually only suitable for lower charging powers. As a rule, plug-in charging is only used at depots, but there are also known applications in which smaller buses are recharged with plug-in charging at a terminal stop. Depending on the voltage of the battery system, the charging power can be up to 180 kW (in case of 750 V maximum voltage).

In Fig. 6 there are the types of connectors depending on the electric current used in the grid. The most used technologies in the market are the CCS connectors. In any case, the transit agency must ask interoperability in tendering contracts, where a bus with a determined connector can be charged with a different charging device.

Namely, all chargers are characterized according to three (3) main parameters:

1) **Level:** relates to the power level, with the semi-fast level in AC being the level that applies to buses (above 20 kW)

with three-phase electric start; and the fast or ultra-fast level in DC (90 kW or more). Power levels are related to recharging times, the higher the power (kW) the shorter the recharging time.

2) **Type:** refers to the type of physical connector used for charging (see Figure 6). These vary depending on the origin and are usually associated with charging modes. The most common types are the North American connector (SAE J1772 AC, CCS Type 1 DC), the European (IEC 62196 AC, CCS Type 2 DC); the Japanese (CHAdeMO DC); the Chinese GB/T AC and DC; and the iconic Tesla DC charger.
3) **Mode:** this parameter is the one that standardizes the communication protocol between the vehicle and the charger, normally associated with the type of charger, with four (4) modes according to the international standard IEC 61851-1. Mode 3 AC and mode 4 DC are the protocols used in electric buses where there is a high level of communication that manages safety, current and the charging process in general. In turn, these protocols vary by origin so it is necessary to be able to identify them to verify that they can communicate with the vehicles.

Fig. 6. Types of Connectors for E-Buses

Higher charging power rates require several plugs in parallel or automated contact systems which are subdivided into roof mounted pantographs and so-called inverted pantographs which are mounted on special poles. Opportunity charging is more popular in Europa and North America. Pantographs are large-scale infrastructure to be incorporated into the city's public space. They require access to three-phase power from 300 kW up to 600 kW and deliver power to the DC bus, which involves complex electronics to install, maintain and repair. This requires high skilled persons to be able to provide good technical support, which may be a barrier for the Latin American reality in the short term.

Regarding the operational aspects of the technology, a specialised training for drivers is necessary to effectively achieve fast loading. While the pantographs do charge between 2 to 10 (min) depending on the capacity of the bus battery, being able to properly position the bus under the pantograph so that charging can be initiated is not a trivial exercise for the driver to learn, representing a major cultural aspect for the set-up of the entire system.

Fig. 7. Schunk Smart charging contact system and inverted pantograph

Source: Siemens AG

Inductive charging systems are limited to approx. 200 kW and will most likely not stay in the market due to the high system complexity and cost.

All listed technologies have in common that buses must be positioned within certain tolerances regarding

- their position in the longitudinal direction,
- their position in lateral direction, and the angular deviation from the centre line of the roadside contact system or pantograph, which in most cases is parallel to the kerbstone line.

Charging devices

Regarding charging devices, the offer has increased significantly in the last years with charging devices. The power of the devices is limited by the plug. Non-cooled plugs are usually limited to approx. 150 kW, with the Foton charger being reported to provide about 180 kW charging power. In the following figures there are some examples of available charging devices in the market.

Charging power: 50 kW

Number of plugs: 1

Dimensions: 600 x 900 mm

Input voltage: 3 ~ AC

Protection level: IP54

Source: Heliox

Fig. 8. Heliox Bus Depot charger

Charging power: 2 x 40 kW/ 4 x 60 kW

Number of plus: 2/4

Dimensions: e.q. 690 x 400 mm (length x width) for 2 x 40 kW

Input voltage: 3 ~ AC

Protection level: IP55

Fig 9. BYD AC Charging Adapter at the London Waterloo bus depot

Charging power: 3 x 50 kW/

Number of plugs: 1 per charge box

Dimensions: 800 x 1,200 mm (length x width)

Input voltage: 3 ~ AC

Protection level: IP54 (power cabinet) / IP65 (charge box)

Source: ABB

Fig 10. ABB HVC 150 power cabinet with three charge boxes

Proterra Power Control System 60 / 125 kW

Charging power: 60/125 kW

Number of plugs: 1

Dimensions: 800 x 600 mm (length x width)

Input voltage: 3 ~ AC

Protection level: outdoor

Source: Proterra

Fig 11. Proterra Power Control System 60/125 kW

Charging stations

Charging stations provide a significantly higher charging power and therefore require more space. An example is shown in Figure 12 on the left-hand side. The necessary transformer (10 kV AC to 400 VAC) can be seen on the right-hand side.

Fig. 12 Charging station (Heliox charging station at Cologne – Germany)

Charging power: 2 x 18 kW

Number of plugs: 2

Dimensions: 800 x 950 x 2,000 mm (length x width x height)

Input voltage: 3 ~ AC

Protection level: indoor/outdoor

Source: Microvast

Fig. 13. Foton Ultra-Fast DC Charger

Charging power: up to 1 MW

Number of plugs: automated contact system

Dimensions: depending on charging power

Input voltage: 3 ~ AC

Protection level: IP44

Source: Eko Energetyka

Fig. 14. Eko Energetyka Quick Point City Charger

Charging power: 500 kW

Number of plugs: automated contact system

Dimensions: 2,200 x 600 mm (length x width)

Input voltage: medium voltage

Protection level: outdoor

Source: Proterra

Fig. 15. Proterra Power Control System 500 kW

Standardization

Standardization is a key process for scaling up BEVs fleet in developing countries. This would allow buses from different manufacturers to be charged with any charger. This has an impact especially when the terminal infrastructure is a public good and not the operator's. This consideration is also relevant in the planning and scaling up of fleets with phased purchases, so as not to restrict the best offers from manufacturers as procurement processes develop. As noted above, chargers can be used by several buses during the night-time charging day, normally 2 buses per 1 charger. Then, terminals have the potential to be able to receive more buses without the need to incorporate more chargers, as long as it is manageable within the charging schedules. Hence, it is important that there is compatibility and that the network of chargers is interoperable.

Interoperability involves both equipment (hardware) and connectivity (software) aspects. From the equipment point of view, it is important to plan and establish how the load is expected to be: DC or AC, and with which type of connector.

Also, the communication from the charger to the grid should be open and with OCPP (Open Charge Point Protocol) protocols. This is particularly relevant for charging management in large fleets, where there are multiple software packages offered by various dedicated companies, which can be freely changed without the need to change the charger. Flexible management of the charging infrastructure is very relevant to ensure the operation of the buses, but also to optimize fare costs according to timetable periods.

METHODOLOGY FOR BUS E-FLEET CALCULATIONS

The methodology includes two steps: 1) Passenger demand and local infrastructure analysis; 2) Costs analysis comparing different vehicles sizes.

Bus fleet and headway analysis

The capacity of a transport system results from the product of the frequency of journeys taken as a basis in the timetable design and the size (in the sense of the number of standing and seating places offered) of the vehicles used (Schnieder, 2018). The trip sequences (cycle times) are a key point for an attractive service offer for user and at the same time to optimize economic resources from the operator point of view.

For capacity planning the line load (number of passengers passing one or more adjacent cross-sections in a given time unit) is needed. The demand can be displayed separately according to weekdays and for both directions of travel, so that the temporal change in demand also becomes clear. If the service offer varies over the course of a day (change of cycle times, vehicle sizes or line variations), a representation in higher granularity (representation of demand in different time day ranges) may also be helpful (Schnieder, 2018).

The required maximum headway of each line depends on:

- the capacity (seating or standing) of the vehicles,
- a predefined maximum saturation level as a benchmark for comfort,
- the number of passengers on the line segment with maximum load.

The number of required vehicles results from

$$n = u/h = (s*u)/60$$

Where

n	number of required vehicles
s	service runs per hour
h	headway (min)
u	cycle time (min) (=Σ running time and layover time for both directions)

To calculate the service runs, we need to know the vehicle capacity and the travel demand per hour at a section with maximum load (p/h).

$$s = q/(qmax*xmax)$$

where

s	service runs (runs/h)
q	passengers per hour at section with maximum load (p/h)
q_{max}	capacity of vehicle (p/run)
x_{max}	maximum saturation level (-)

Then the headway (min) is determined by the number of service runs in one hour:

$$h = 60/s$$

Finally, the number of vehicles es determined by the service runs, the cycle time and the headway.

$$n = (s*u)/60$$

Where

n	number of vehicles
s	service runs (runs/h)
u	cycle time (min)

Then information about the types of BEBs suitable for Latin American markets with their technical characteristics, the length of the line or lines to be analyzed, the location of the depot and terminals and the dead kilometers were analyzed.

Analysis of costs with different vehicles

For this part is important to get information about current costs structure of the route, including administrative, operational and variable costs, energy costs in peak and valley hours, among other information. The calculations are shown monthly, yearly as well as the cost for operating one kilometer.

The annual cost of traction energy is defined by the consumption per kilometer of each bus in operation, the number of kilometers operated by the buses in the system and the rate per kwh charged by the local energy companies.

$$\textit{Energy cost} = \textit{Consumption per bus} * \textit{Cost kwh} * \textit{yearly km per bus}$$

QUITO CASE STUDY

Quito is the capital of Ecuador, a South American country located between Peru and Colombia in the pacific coast of the continent. Quito is located at 2.800 meters above sea level and has a population of 3 million inhabitants. The urban structure of the city is particularly a longitudinal form from north to south. Due to topographic, urban and transport development the transversal connections are partial. Therefore, the transport in Quito is characterized by a big public transport demand in both directions (north – south) with a growing demand coming from the eastern valleys to the city center in the last 10 years. The public transport system in Quito's Metropolitan District (DMQ) is called the Integrated Public Transport System (SITP). This system is structured by exclusive BRT corridors running north to south, the feeder lines to BRT corridors, running east to west, and conventional lines that have specific routes and provide urban services, as well as services within and between city districts intra- and interparochial routes. Additionally, a metro line was built parallel to the corridors, but is not operating yet. The Metrobus-Q (Metro-Q) is the trunk feeder system that connects the BRT segregated lanes services (trunk system) and the feeder lines. Metrobus-Q has 3 lines or "corridors": Central or Trolleybus, Oriental (Eastern) or Ecovía, and Occidental (Western). These corridors have several organized routes operated with articulated and bi-articulated buses on more than 71 kms of segregated bus lanes. The purpose of this project is to study the Central North Corridor at a pre-feasibility level, inaugurated in 2005 and running from La Ofelia Terminal to Playón de la Marín Terminal. The tariff scheme considers an integrated tariff of USD 0.25 normal value, USD 0.12 reduced tariff and USD 0.10 preferential tariff but with the recently built first line Metro the fare ticket will be USD 0,50 for the integrated system and USD 0,35 for the BRT corridors in the coming months (Logit Engenharía Consultiva Ltda., 2020).

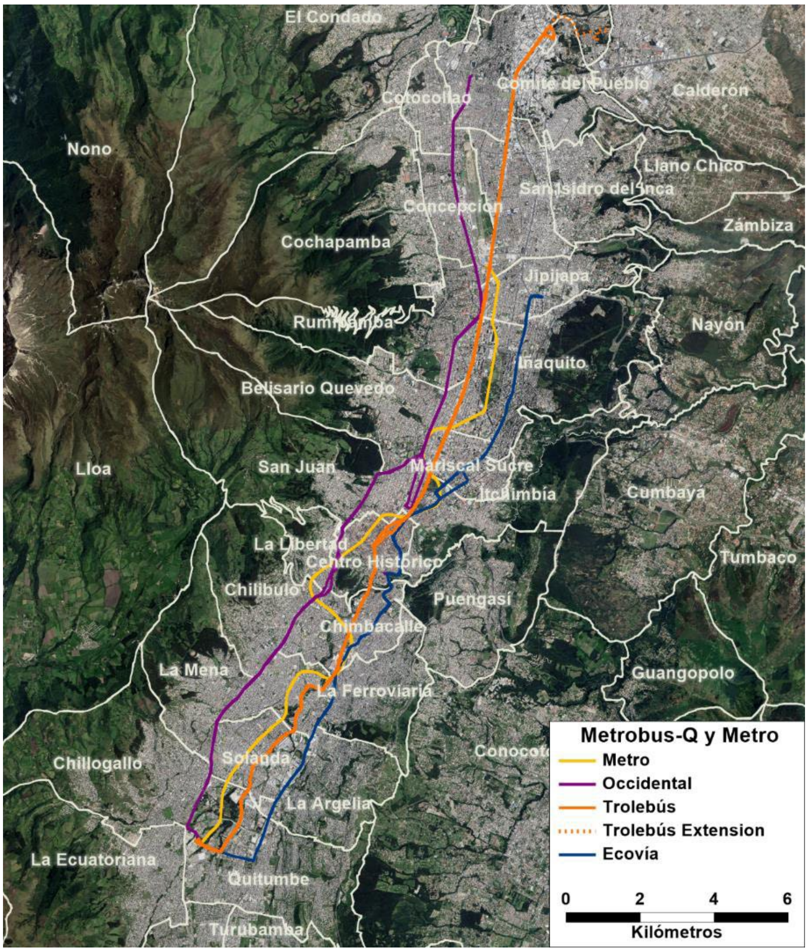

Fig. 16. Metrobus-Q BRT Corridor and first Metro line

(Finished but not operative)

Source: (Logit Engenharía Consultiva Ltda., 2020)

General characteristics of the selected corridor

The selected corridor has 36 stations including the 2 main transfers stations (one in the north and one in the south) with a distance between stops ranging from 460 m to almost 2km. The northern transfer station of the Central North Corridor (CCN) starts in La Ofelia sector and runs 14,84 km to the south in the heart of the historical center of Quito.

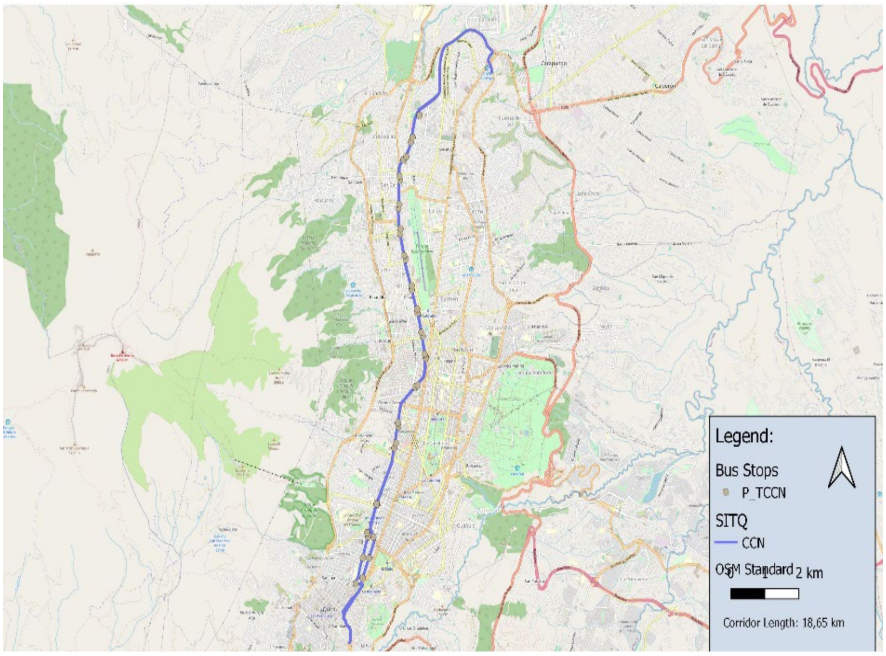

Fig. 17. Selected BRT Corridor for case study

Table 1. General characteristics of the Central North corridor in Quito

Parameters	Length (km)	Bus stops Terminals	Daily Travel Demand (pas-trips)	Distance Service run (km)	Pulling out/in km per veh	Pulling out/in time per veh (min)	IPK
Central North Corridor	14,84	36/2	132.391	29,68	14,84	17,8	4,5
Parameters	**Available periods for charging**	**Service Run Time (min)**	**Yearly mileage per bus** **(km)**	**Total daily mileage of fleet** **(km)**	Current bus fleet (articulated 18m)	Commercial speed (km/h)	**Current bus capacity**
Central North Corridor	00:00 – 05:00 total fleet/ 10:00 – 12:00/14:00 – 16:00 partial fleet	98	69.025	12.593,60	64	18	155 p

The average travel demand for direction North – South on a typical day (between Monday and Friday) is 76.413 passengers and from South to North is 33.187 passenger-trips. Adding weekends and holidays the total daily demand in the whole corridor is approx. 132.000 passenger-trips. The maximal load occurs between 07:00 and 08:00 hours and 17:00 – 18h00 hours, being direction north – south the most crowded (See Fig 18 and 20). Figures 21 and 22 shows an overload in both directions during peak hours, where the capacity of the articulated bus (155) is exceeded in around 25%. The total fleet stays in the depot located near the north terminal in La Ofelia. Therefore, at least 8 buses must drive in the morning before 5:00 to start the schedule on the other southern terminal in Playón La Marin. That is around 15 km of dead kilometers that should be added to the final cost calculation.

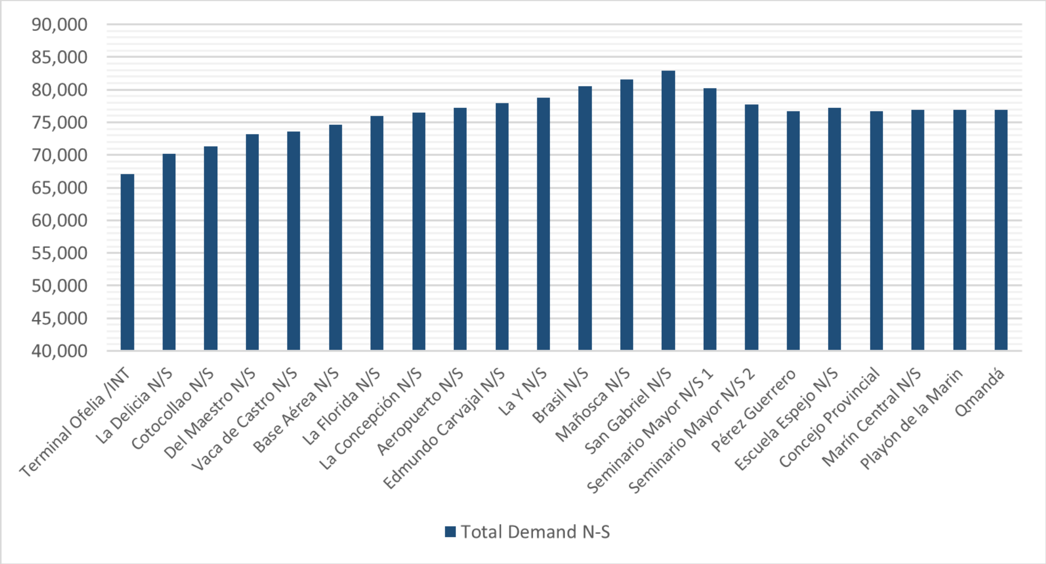

Fig 18. Travel Demand Typical Day North - South Direction CCN

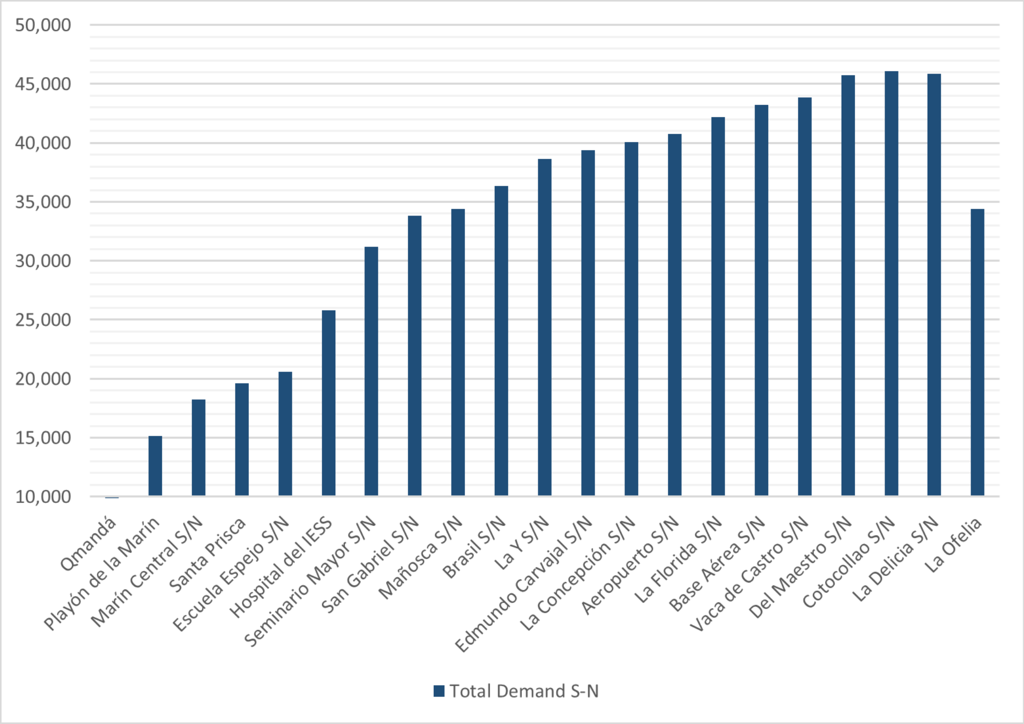

Fig 19. Travel Demand Typical Day South - North Direction CCN

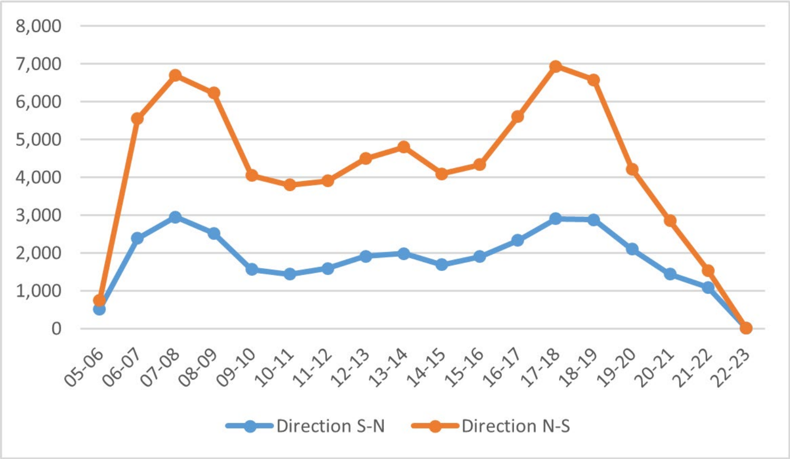

Fig 20. Hourly demand both directions CCN

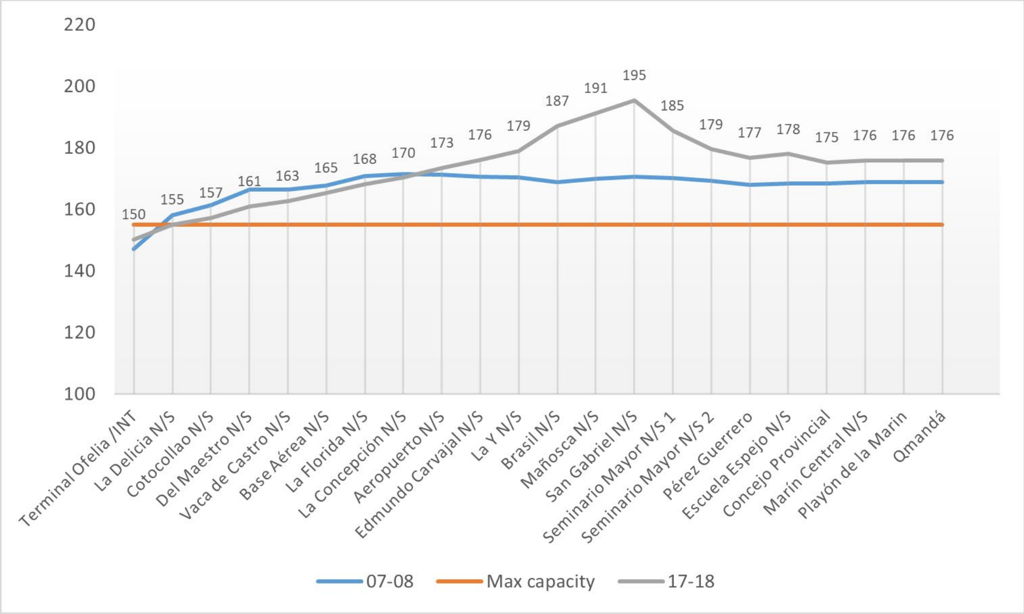

Fig 21. Occupancy rate per bus per peak hour North – South CCN

Calculation of E-Buses fleet

The definition of number of BEBs for a defined corridor depends on a variety of factors: financial costs sustainability, timetable, bus capacity and level of service required by a transit agency.

The calculations for bus fleet were made for five 18 – m bus models with different capacities, one model of 24-m capacity and one model of 30 meter large. In Table 2 the selected buses are presented.

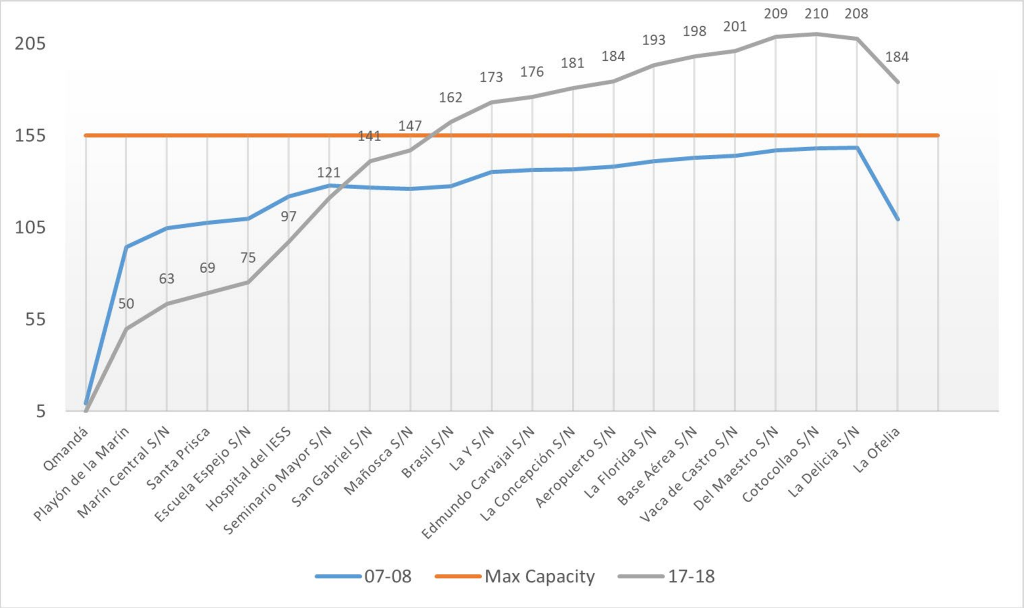

Fig 22. Occupancy rate per bus per peak hour South – North CCN

Table 2. Technical specifications of selected Asian and European articulated e-buses for fleet calculations

BUS BRAND	GVW* (ton)	Passengers' capacity	# Doors	Declared Autonomy (km)	Battery capacity (kWh)	Charging Power (kW)	Type of Battery	Orig	Cost ($USD)
Asian manufacturers									
BYD K11A	31	160	6	270-300	438	100 kW x 2	LiFePo$_4$	CH	660.000
YUTONG	28	160	3	300	563	150	LiFePo$_4$	CH	450.000
European manufacturers									
SOLARIS	31	140	4	220	550	up to 450 (plug in)	NMC	PO	855.000
eCITARO (NMC1 8/10/12 pcs) (NMC2 8/10/12 pcs) (Solid state battery, 6/7 pcs.)	30	142	3-4	200	194/243/292 264/330/396 378/441	Up to 150	NMC	GER	n/a
VOLVO 7900	29	150	3	180	396	400 (panto); 150 (plug in)	LiFePo$_4$	SW	n/a
Biarticulated Buses									
Sileo 25	39	210	4-5	300	450	150	LiFePo$_4$	GER-TUR	n/a

The travel demand data (Fig. 18 – Fig 21) was computed for bus fleet calculations with equations 1, 2, 3 and 4. The results are shown in the table 3. The saturation level factor indicates the occupancy rate of the buses. The current operation scheme uses 64 buses, that is the operator has chosen a saturation level of 1,25 with headways of 2 minutes in the peak hours. That means during peak hours the buses are exceeding their capacity by 25%, which is not so much, if taking that by standing people, the optimal occupancy rate is 4 persons/ m^2 and with 25% would be $5p/m^2$. In Table 4, we calculated different fleet sizes with different saturation levels. As expected, with a saturation level of 1,0 (100% of bus capacity) the operation scheme using buses with more capacity will require less vehicles. With a saturation level of 1,5 (50% capacity exceeded in peak hours) the required fleet is 53 e-buses with 160 passengers' capacity. For the biarticulated buses the capacity increase is 34%, that means 1 biarticulated bus replaces 1,3 articulated e-bus. With the AutoTram Extra Grand, a hybrid prototype designed by Fraunhofer IVI, the calculations shows that one bus of 256 passengers replaces 1.7 articulated buses in terms of passenger's capacity.

Table 3. Comparison of required bus fleet for different saturation factors

	Articulated E-Bus 18 m				Bi-articulated Bus 24 m		Extra-large Buses
Model and Passenger capacity	**eCitaro MB = 142 p**	**Volvo 7900 = 150 p**	**Solaris = 140 p**	**BYD K11A/ YUTONG = 160 p**	**SILEO S25= 210 p**	**HESS Light Tram 25 Tosa = 200 p**	**AutoTram ExtraGrand = 256 p**
Xmax = 1	90	85	91	80	61	64	50
Xmax = 1,25	72	68	73	64	49	51	40
Xmax = 1,5	60	57	61	53	41	43	33

Every manufacturer can offer different bus capacities by changing the battery size and thus, the cost for each bus will be lower. Table 2 shows how some BEBs models offer different battery capacities depending on the number of packs installed. The critical point for deciding which is the best electric solution depends on other factors like the declared autonomy in comparison with the real one, the battery capacity and the power consumption per km, the power charging capacity, and the life span of batteries. Therefore, the final decision of how many units should be acquired depends on other factors than only the capacity. It is obvious to mention that bigger buses will need less units to provide the same level of service in a given route. Notwithstanding, the current biarticulated buses are mainly manufactured for the European market that has other requirements than Latin American cities, i.e. they are low floor and their security standards are higher than their pairs in Latin America, therefore their costs are very high if totally imported.

Just for comparison we calculated the bus fleet considering the timetable and the bus capacity. The operational schedule for 2019 in the CCN corridor defined a bus fleet of 65 buses with 155 passenger capacity (currently 64 buses) with a X_{max} factor of 1,5 during peak hours, that means, passenger demand surpassed bus capacity in the peak hours. With same factor and changing the timetable to set in a suitable frequency intervals, the required fleet would be 49 buses of 160 p/each.

Table 4. Timetables with different bus capacities and occupancy rates

Timetable 2019 with buses = 155 p					Proposed timetable with BEB = 160 p			
HOUR	**Interv (min)**	**SR**	**Travel time (min)**	**Fleet**	**Interv. (min)**	**SR**	**Travel time (min)**	**Fleet**
05-06	10	6	98	10	15	4	98	7
06-07	1,5	40	98	65	3	20	98	33
07-08	1,5	40	98	65	2	30	98	49
08-09	1,5	40	98	65	3	20	98	33
09-10	2	30	98	49	4	15	98	25
10-11	2	30	98	49	4	15	98	25
11-12	2	30	98	49	4	15	98	25
12-13	2	30	98	49	3	20	98	33
13-14	2	30	98	49	3	20	98	33
14-15	2	30	98	49	4	15	98	25
15-16	2	30	98	49	3	20	98	33
16-17	1,5	40	98	65	3	20	98	33
17-18	1,5	40	98	65	2	30	98	49
18-19	1,5	40	98	65	2	30	98	49
19-20	2	30	98	49	3	20	98	33
20-21	2	30	98	49	5	12	98	20
21-22	4	15	98	25	10	6	98	10
22-23	15	4	98	7	30	2	98	3

N_{max} = *65 buses*

N_{max} = *49 buses*

Costs analysis for articulated buses

At the end of 2017 and beginnings of 2018, BYD tested its K11A articulated bus in the CCN. The results of the tests are shown in Table 4.

Table 5. Results of the BYD tests in the CCN 2017-2018

Month	Circuit	Mileage (Service + Dead Km)	% energy consumption	Energy (kWh)	Km per charge (km/kWh)	Energy consumption per km (kWh/Km)	Mileage (km)/month	Pass-Trips/ month
Dec 2017	C1	22,31	9,30%	40,72	0,55	1,83	1.299,2	10.121
Jan 2018	C2	30,62	12,77%	55,94	0,55	1,83	2.937,6	24.470
Feb 2018	C2	30,60	9,87%	43,25	0,71	1,41	2.265,0	18.711

Source: BYD Ecuador

For cost calculation we assumed the data given by the CCN operators of 2019 (before the pandemic) assuming that this condition would be return once the pandemic is over. The test results made by the BYD electric bus of 18 meters in the CCN in 2017-2018 were also included. The first variable to be calculated is the cost per kilometer comparing both a diesel bus running currently in the corridor and the BYD electric bus.

Parameters:

- Monthly mileage per bus: 5.866 km
- Diesel consumption of articulated bus: 1,1 l/km
- Energy consumption articulated bus: 1,83 kWh/km
- Diesel price: 0,5 $US/l
- Energy price[1]: 0,077 $US/kWh
- Energy used per month: 9.516,1 kWh

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[1] For electric vehicles charging between 08:00 and 18:00 is 0,08 $US/kWh, from 18:00 to 22:00 is 0,10 $US/kWh and from 22:00 to 08:00 is 0,050 $US/kWh. We took the average of all tariffs.

Table 6. Operating Cost per km for Articulated Diesel Bus ($USD)

Item	**Monthly Costs in $USD**	**$USD/ km**
Total Fixed Costs	**$4.947,86**	**$0,83**
Administrative Costs	$170,64	
Operational Costs	$170,72	
Maintenance and Mechanics	$174,37	
Staff	$2.310,60	
Services and Consumables	$217,62	
Registration fees	$101,13	
Insurance	$192,58	
Collection Costs	$1.408,78	
Extra administrative costs	$201,43	
Total variable costs (fuel, lubricants, spare parts)	**$6.554,68**	**$1,12**
Total Monthly costs per bus	**$11.502,55**	
Total cost per km		**$1,96**
Annual costs for diesel bus fleet with 64 vehicles	**$8.833.954,95**	
Annual costs for diesel bus fleet with 49 vehicles	**$6.763.496,76**	

Fig 23. Percentage Fixed and variable costs for Articulated Diesel Bus (%)

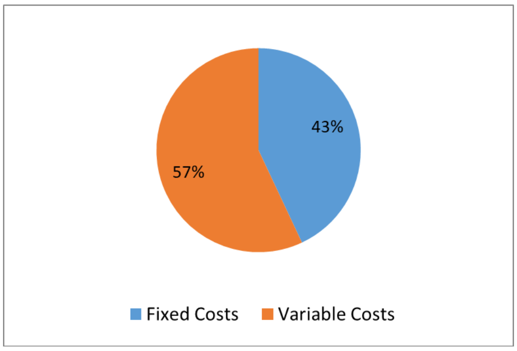
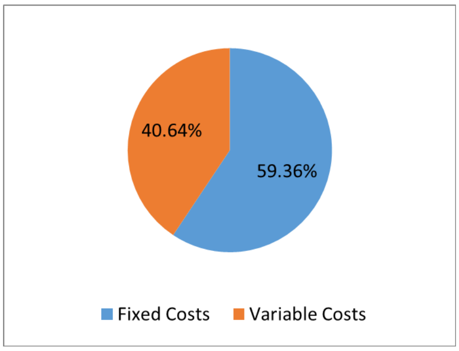


Table 7. Operating Costs per km for Articulated Electric Bus ($USD)

Item	Monthly Costs in $USD	$USD/ km
Total Fixed Costs	**$4.947,86**	**$0,84**
Administrative Costs	$170,64	
Operational Costs	$170,72	
Maintenance and Mechanics	$174,37	
Staff	$2.310,60	
Services and Consumables	$217,62	
Registration fees	$101,13	
Insurance	$192,58	
Collection Costs	$1.408,78	
Extra administrative costs	$201,43	
Total variable costs (energy costs, spare parts, maintenance)	**$3.506,17**	**$0,58**
Total Monthly costs	**$8.454,03**	
Total cost per km		**$1,42**
Annual costs for BEBs with 64 veh	**$6.492696**	
Annual costs for BEBs with 49 veh	**$4.970.971**	

Fig 24. Percentage Fixed and variable costs for Articulated E-Bus (%)



The operational cost for an electric bus is 28% lower than a diesel articulated bus for same size and same capacity. With a bus fleet of 49 buses the annual costs are reduced in As we can see in both pictures the operational costs for a diesel bus are more susceptible to variable costs than the electric bus, due to fuel costs, the higher number of parts to be replaced, repaired, and maintained.

Costs analysis for biarticulated and extra-large buses

For costs comparison with larger models, we used a biarticulated electric bus with passenger capacity of 220 p, and the hybrid model of AutoTram® Extra Grand (IVI Fraunhofer, 2014), with a passenger capacity of 256 p. The AutoTram® Extra Grand is a extra-large bus of 30,7 m long, and it could be manufactured either hybrid, full electric or its trolley version. Since there is not maintenance and spare parts costs for biarticulated electric buses and the AutoTram® Extra Grand, we omitted this item in the cost comparison. The following parameters were assumed:

Yearly mileage per bus (km)	70.393
Diesel consumption articulated bus (l/km)	1,32
Diesel consumption hybrid Autotram (l/km)	0,8
Diesel consumption biarticulated bus (l/km)	0,93
Energy consumption hybrid Autotram Extra Grand (kWh/km)	3,5
Energy consumption articulated E-bus (kWh/km)	2,7
Diesel price in $USD	$0,50
Electricity cost for electric vehicles $/kWh	$0,07
Number of drivers per bus	2,4
Average Salary per driver/month	$962,75

Table 8. Partial comparison of yearly costs for different bus technologies

	1.7 articulated diesel bus	1.3 biarticulated diesel bus	1.2 biarticulated electric bus	1 AutoTram® Extra Grand Hybrid
Mileage (km)	119.668	91.511	84.472	70.393
Diesel consumption (l)	93.112	65.179	-	56.314
Diesel Costs ($USD)	$46.742,42	$32.719,69	-	$28.269,81
Energy consumption (kWh/y)			190.061	246.375
Number of drivers	4,08	3,12	2,88	2,4
Staff personal (drivers)	$47.136,24	$36.045,36	$33.272,64	$27.727,20

By replacing 1,7 articulated buses with a bi-articulated electric bus there are annual savings of $USD60.606, and with the hybrid AutoTram® Extra Grand the savings are $USD37.882. The final decision should be by means of a financial model considering a base price of $USD 362.880 for a new articulated bus, $USD700.000 - $USD 800.000 for a new biarticulated electric bus, and $1.1 for a full electric AutoTram. The TOC (total costs of ownership) should include the grid infrastructure and charging stations.

Fig 25. AutoTram® Extra Grand - 2014

Source: (IVI Fraunhofer, 2014)

Charging strategy

The tests performed by BYD K11A in the CCN showed that the electric articulated bus covered partially the 230 km (see Fig 25) that a diesel bus drives currently in a typical day. That means with the highest passenger load, opportunity charging would be needed during the route, moreover, if the entire bus fleet is intended to be electric. The applicability of only depot charging is limited by the required availability of buses and the dead mileage involved in travel to depots for charging. In the case of CCN, all buses overnight at La Ofelia depot, in the northern end of the route.

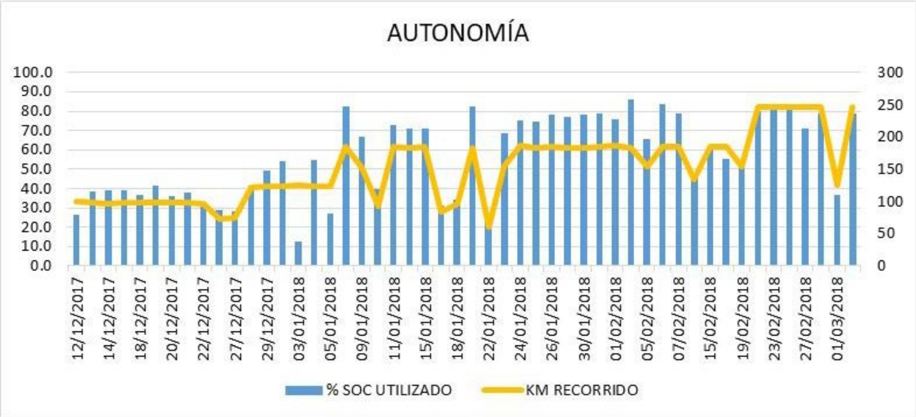


Fig. 26. Autonomy of BYD K11A and % SOC vs. mileage covered

Therefore, opportunity charging can facilitate significantly higher mileages per day of operation without changing the timetable. The layover times between peak and valley hours has been calculated to determine how much time is available during operation for opportunity charging. For maintaining costs at minimum, opportunity charging should be carried out between 08:00 and 18:00 h since the cost for one kWh is $USD 0,08 compared to $USD 0,10 between 18:00 and 22:00 h.

Table 9. Layover times and Time Span at peak and valley hours for CCN corridor

Time span	Average Layover time (min)	Average # service runs per bus	Opportunity charging
07:00 – 09:00 h	03:21	2	Not recommended
09:00 – 12:00 h	22:23	2+1	Recommended for 15% of the bus fleet
12:00 – 15:00 h	20:44	2+1+2	Recommended for 15% of the fleet
15:00 – 17:00 h	39:51	2+1+2+1	Recommended for 25%
17:00 – 19:00 h	20:09	2+	Not recommended
19:00 – 22:00 h	28:41	8	Not recommended

Now to define how many minutes are needed for different bus technologies for opportunity charging, we assumed different rates of energy consumption either given during real time tests of the mentioned models or by taking 1,5 kWh/km as a proxy when data is not available.

Table 10. Battery capacity, charging times and charging power for different bus models at the CCN corridor

	Battery Capacity (kWh)	% SOC Battery Capacity (kWh)	Charging Power (kW)	Required charging time to cover one run (min)	# Chargings to finish daily operation
BYD K11A	438	350,4	200	15,81	2
YUTONG ZK6128BEVG	563	450,4	150	17,05	2
SOLARIS URBINO 18E	550	440	450	5,76	1
Volvo 790	396	316,8	150	17,28	2
Sileo 25	450	360	150	19,01	2

Table 11. Energy consumption and reached autonomy for corridor CCN with different bus models

BUS MODELS	km		28,8	57,6	86,4	115,2	144	172,8	201,6	230,4
BYD K11A	kWh	1,83	52,7	105,4	158,1	210,8	263,5	316,2	368,9	421,6
YUTONG ZK6128BEVG	kWh	1,48	42,6	85,2	127,9	170,5	213,1	255,7	298,4	341,0
SOLARIS URBINO 18E	kWh	1,5	43,2	86,4	129,6	172,8	216,0	259,2	302,4	345,6
Volvo 790	kWh	1,5	43,2	86,4	129,6	172,8	216,0	259,2	302,4	345,6
Sileo 25	kWh	1,65	47,5	95,0	142,6	190,1	237,6	285,1	332,6	380,2

From the models mentioned above only the Yutong ZK6128BEVG and the Solaris Urbino 18 E could fulfill a daily service without a need for charging in the intermediate times. The adoption of opportunity charging would require manufacturers to adapt pantograph system. The Solaris Urbino 18E and the Volvo 7900 E present this option in their official websites. However, opportunity charging requires additional charging infrastructure outside the bus depots (charging stations with high charging power), which makes the implementation significantly more complex and difficult. Furthermore, it is not applicable on bus routes where long delays frequently occur. On the other hand, opportunity charging significantly reduces the amount of energy requirement for recharging at a bus depot and the grid connection power that is required. In the case of Quito, a technical study should be required to estimate the feasibility of opportunity charging in Playón de la Marín, Seminario Mayor and in La Ofelia terminal. In the case of La Marín, the charging infrastructure would be useful for other lines and operators that also end or start their service there.

For the models that only have plug-in systems (only for slow charging), a change in the timetable might be needed to couple with the %SOC frontier, either by serving only for the C1 schedule (LA Ofelia – Seminario Mayor) or by larger layover times during the day at the depot while diesel articulated buses replacing the service. Therefore, the final strategy for electrification of the CCN bus fleet should be conservative starting with few units and increasing the acquisition of buses depending on the trials and errors pilot phase. Different scenarios should be analyzed as well including delay times, layover times, and the operation of the recently constructed metro line. When the metro starts operating there will be a reduction in the travel demand of the CCN, in about 25%, that means only 50 new articulated bus will be needed for the service in the CCN.

The decision of whether only plug-in strategy or a mixed strategy with opportunity charging (either at La Ofelia or in La Marin or in intermediate station Seminario Mayor) depends on a variety of factors, i.e. the available space at depot and terminal stations, the layover times, the drivers change, and the TOC with different technologies. Since the available technical and economic information about biarticulated buses is scarce, further research should be needed to include them in a feasibility analysis and see if their acquisition is cost-effective or not.

MONTEVIDEO CASE STUDY

Montevideo is the capital city of Uruguay, situated on the southern coast of the country, on the northeastern bank of the Río de la Plata. The estimated population for 2022 in the metropolitan area is of 1.76 million inhabitants. It is home to approximately one-third of the country's total population. Montevideo's city proper has a population of 1.3 million inhabitants.

The lines that are analyzed in this report are lines 169 and 143 operated by CUTCSA, a renowned bus operator in Montevideo. Line 169 is 20,8 km long while line 143 was 7,9 km long in 2019. For the line 169 there are three types of services: 1) 169: Ciudad Vieja - Toledo Chica (Direction A: 19,95/Direction B: 23,51 km), 2); 169-2: Aduana – Toledo Chico (A: 21,38/B:21,97 km), and 3) 169 SD: Terminal Ciudadela – Instrucciones (A:16,25/B:16,74 km). Line 143 runs between Ave Battle and Terminal Ciudadela.

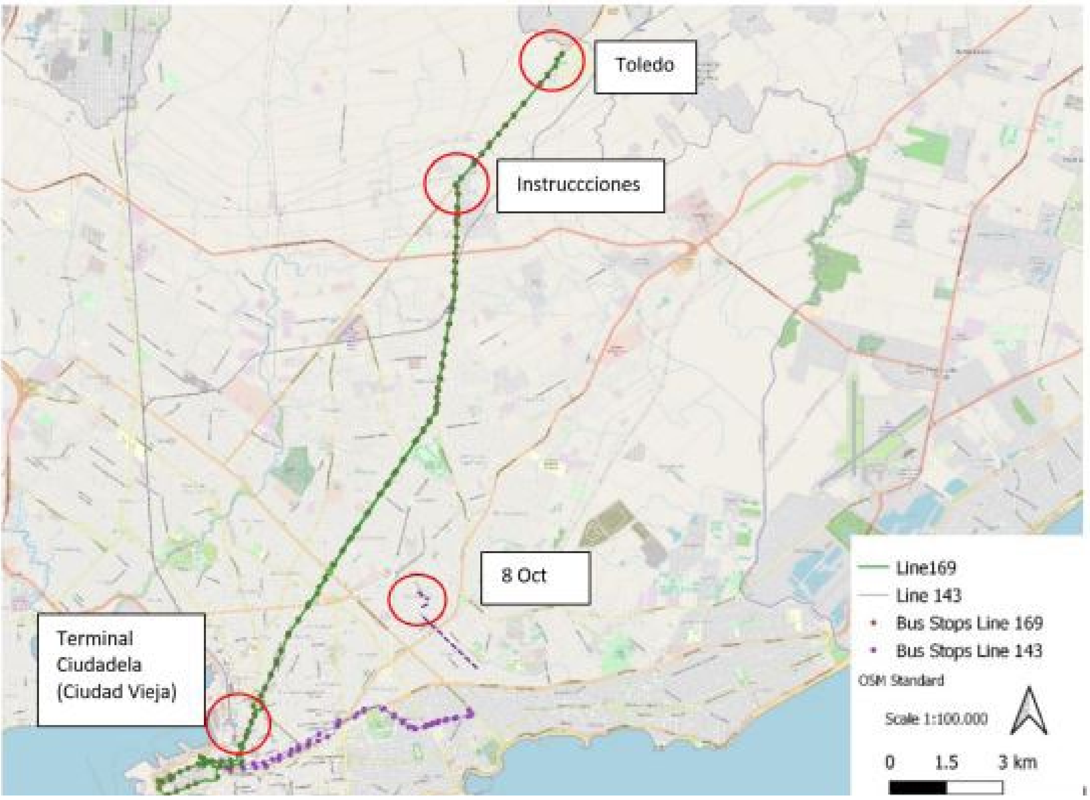


Fig 27. Lines 169 and 143 in Montevideo

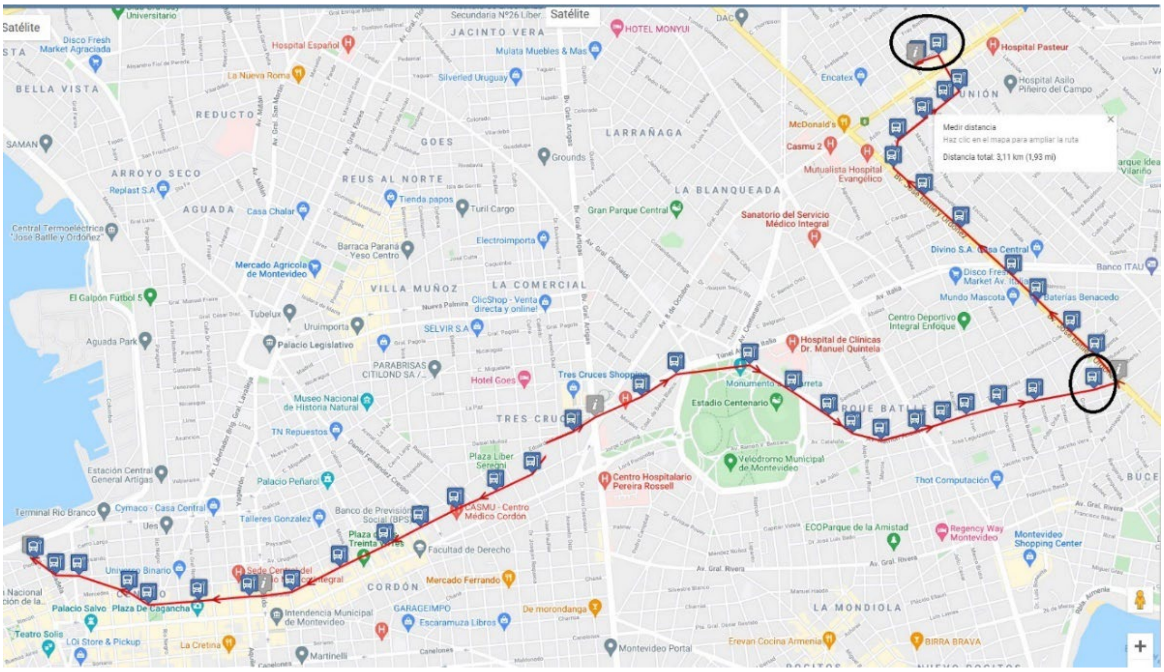


Fig 28. Line 143- 2019

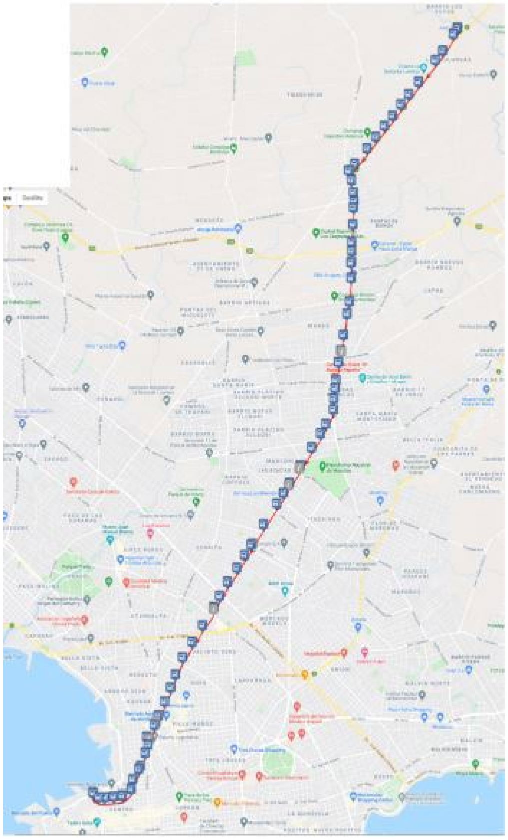


Fig 29. Line 169 - 2019

The following table shows some general parameters for both lines obtained by the operator and the municipality of Montevideo. The data used for the cost and operational analysis was from year 2019, since they were taken before the pandemic, and it is expected that travel demand and operation conditions return to the former status.

Table 12. Operational parameters of Lines 143 and 169 – Montevideo - 2019

Parameters	**Length Km**	**Bus stops Terminals (both directions)**	**Yearly Travel Demand (pas-trips)**	**Service run km**	**Average occupancy per bus (A/B)***	**Max occupancy per bus (A/B)**	**Current bus fleet (12 m)**
Line 169	20,80	73/76	5.172.106	41,01	22,7 (SD:32,5) /21,85 (SD:29)	78/81	29
Line 143	11,01	33/32	1.233.131	22,02	13,6/14,1	57/67	11

Parameters	**Daily mileage of fleet Km**	**Monthly mileage of fleet km**	**Yearly mileage per fleet km**	**Daily Mileage per bus km**	**IPK (2018/19/20)**	**Daily average hours-fleet h**	**Commercial speed km/h**
Line 169	4.144,43	128.477,29	1.909.085,32	123,33	3,72/3,76/3,03 (SD: 5,11/5,21/4,7)	261 (max: 304; min: 177,8)	18
Line 143	1.176,44	32.940,19	438.388,89	86,98	3,22	80,41 (max:95,47; min: 23,34)	20

**Direction A: one-way/B: way back; Source: CUTCSA – Intendencia of Montevideo*

The travel demand shows that L169 has five times more passengers than L143. In the case of Line 143 the peak hour in the morning (7:00 – 11:00) occurs from José Battle y Ordóñez (JBO) to Terminal Ciudadela, that is from northeast to southwest, and in the afternoon is the opposite, being a high peak between 16:00 and 19:00 h direction southwest to northeast (Terminal Ciudadela – JBO).

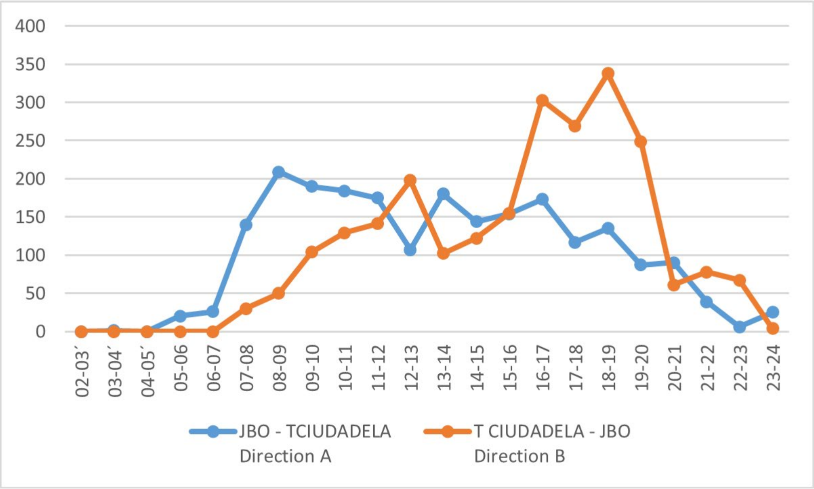


Fig 30. Hourly Travel Demand Line 143

For Line 169, the peak hours are from 07:00 – 10:00 direction Toledo Chico – T Ciudadela, and from 16:00 – to 18:00 hours and at 20:00 h direction T Ciudadela – Toledo Chico. This is consistent with the distribution of land use where the northeast is more residential and the southwest has a tourist, financial and commercial character.

In total both lines transport 24.097 passenger-trips in one day.

Operational feasibility of fleet electrification for Line 143 and 169

By checking the travel demand per peak of each route the electrification with articulated or larger BEBs is not recommended since it would increase the operational costs exponentially. The most suitable BEBs are 12 m-buses. We compare different models (European and Asian models) that are suitable for the Latin American market in terms of price and battery sizes. In table 9 general features of well-known brands are included.

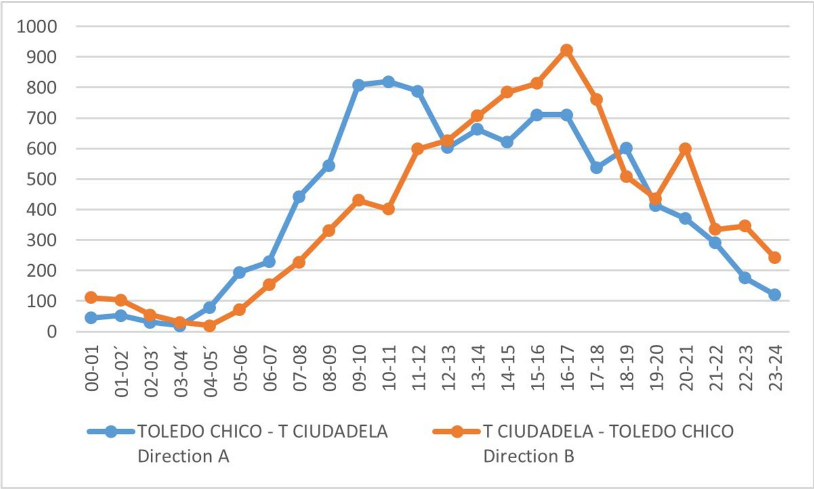


Fig 31. Hourly Travel Demand Line 169

Table 13. Examples of 12-m BEBs for Montevideo case study

BUS BRAND	GVWR* (ton)	Passengers capacity	Declared Autonomy[1] (km)	Battery Capacity (kWh)	Charging Power (kW)	Charging time (h)	Engine (power in kW; torque in Nm)	$USD K	Max Speed km/h
Asian manufacturers									
BYD K9A	19	87	250	324	80 (at depot)	4-5 h using 80 kW	AC synchronous; 2 x 150 kW; 2 x 550 Nm	370	70
GOLDEN DRAGON PIVOT E-12	19	79	Not found	345	75 (at depot)	4-5 h	Max P: 258 kW; Max T: 3,500 Nm	-	69
YUTONG E12	18,5	90	250	375	≥ 60 - ≤150 (at depot)	4-5 h, depending on charging power	240 kW; 2850 Nm	360	69
European manufacturers									
SOLARIS URBINO 12E	19	65	200	125 (high power); 396 (high energy)	450/200/80 kW (at depot)	2 - 6 h	220 kW; max power 300 kW	615	80
VOLVO 7900 E	19,5	90	180	470	250 (at depot); 300 (panto)	depending on charging power	Max P: 200 kW; Max T: 19,000 Nm	-	80
SCANIA CITYWIDE LFE	20	100	180	240/330 (8/10 Battery Packs)	150 (at depot); 300 (panto)	depending on charging power	Max P: 300 kW; Nom T: 2,100 Nm	652	100

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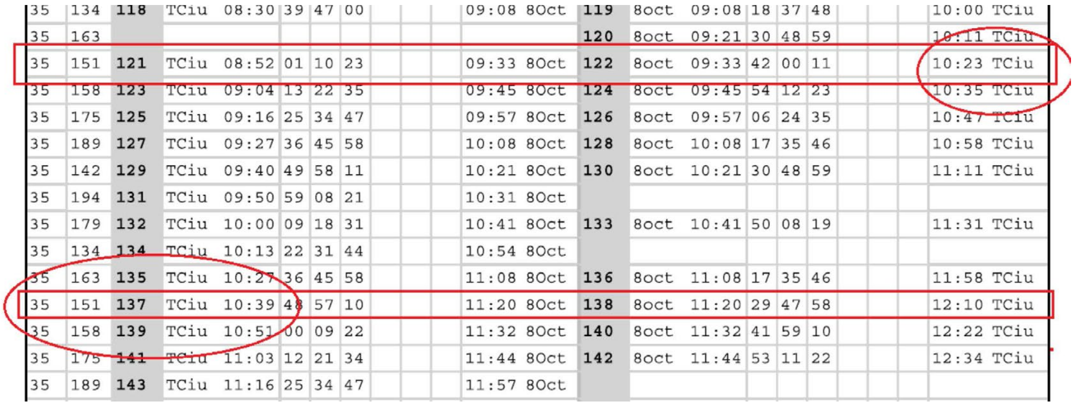
[1] The declared autonomy is not a determining feature for the selection of the best technology because it depends on the driving cycle, the local conditions, i.e. air conditioning needed, load, slopes, type of charging, among other factors.

Then the layover times were calculated for both lines, to see how much time is available for charging during the timetable. In Fig 32, for example, service #151 arrives at 10:23 to Terminal Ciudadela and starts its service at 10:39, that means 16 minutes of layover time.

By analyzing timetable of both line 169 and line 143, the time windows average 16 minutes with some units having more than 3 hours of dead time. It is not clear if these buses serve to other lines or if they remain at a terminal.



35	134	118	TCiu 08:30	39	47	00				09:08 8Oct	119	8oct 09:08	18	37	48				10:00 TCiu
35	163										120	8oct 09:21	30	48	59				10:11 TCiu
35	151	121	TCiu 08:52	01	10	23				09:33 8Oct	122	8oct 09:33	42	00	11				10:23 TCiu
35	158	123	TCiu 09:04	13	22	35				09:45 8Oct	124	8oct 09:45	54	12	23				10:35 TCiu
35	175	125	TCiu 09:16	25	34	47				09:57 8Oct	126	8oct 09:57	06	24	35				10:47 TCiu
35	189	127	TCiu 09:27	36	45	58				10:08 8Oct	128	8oct 10:08	17	35	46				10:58 TCiu
35	142	129	TCiu 09:40	49	58	11				10:21 8Oct	130	8oct 10:21	30	48	59				11:11 TCiu
35	194	131	TCiu 09:50	59	08	21				10:31 8Oct									
35	179	132	TCiu 10:00	09	18	31				10:41 8Oct	133	8oct 10:41	50	08	19				11:31 TCiu
35	134	134	TCiu 10:13	22	31	44				10:54 8Oct									
35	163	135	TCiu 10:27	36	45	58				11:08 8Oct	136	8oct 11:08	17	35	46				11:58 TCiu
35	151	137	TCiu 10:39	48	57	10				11:20 8Oct	138	8oct 11:20	29	47	58				12:10 TCiu
35	158	139	TCiu 10:51	00	09	22				11:32 8Oct	140	8oct 11:32	41	59	10				12:22 TCiu
35	175	141	TCiu 11:03	12	21	34				11:44 8Oct	142	8oct 11:44	53	11	22				12:34 TCiu
35	189	143	TCiu 11:16	25	34	47				11:57 8Oct									

Fig 32. Example of layover times calculation based on timetable

The layover times analysis will be analyzed later when the battery capacity is compared with the service run.

As a second step, we calculated different bus capacities, to see how many buses are required by using an X_{max} factor of 1,0. We just took some examples of the table above. The results show that with current supply the service is more than satisfied (40 buses instead of 24). The

Table 14. Comparison of different bus capacities and required BEBs for Lines 143 and 169

Bus Type	Current bus 75 p	B1 65 p	B2 79 p	B3 90 p	B4 100 p
Number of buses needed Line 143	7	8	6	6	5
Number of buses needed Line 169	17	22	18	16	14
Total amount of vehicles needed	24	30	24	22	19

This table is a first comparison that shows the relationship among the passenger capacity of a bus and the travel demand: the higher the capacity, the less vehicles needed. However, the final decision should be taken by the vehicle costs, the changes in the operation schedule, the charging strategy, among other factors.

Costs analysis for electric buses

From an economic point of view, the use of battery buses only makes sense if the vehicles cover the longest possible distances per day. For fully charged buses, therefore, target driving must be covered by a vehicle per day as a minimum to classify its use as economically acceptable. The upper limit is determined by the maximum range that can be achieved on a sustained basis. The lower limit is set at around 75% of the range of a given time horizon.

Both lines are connected in Terminal Ciudadela, therefore the prefeasibility analysis took both lines as one feasible network, since for line 143 the travel demand does not justify the operation with electric buses only for this route.

Table 15. Current operational costs for lines 143 and 169 in a yearly basis

Costs for both lines		**Unit**	**Costs in $USD**	**USD$/km**	**USD$/per bus-month**
Total Costs per month per bus					**$ 11.824,56**
Operation cost veh/km	Month	$ 523.371,00	$ 12.037,53	$ 1,838	$ 4.493,925
Operation cost veh/hour		$ 523.371,00	$ 12.037,53	$ 30,263	$ 4.694,334
Cost rate maintenance veh/km		$ 27.226,00	$ 626,20	$ 0,609	$ 1.489,526
Variable cost per veh/km		968	$ 919,19		$ 919,188
Monthly mileage per bus (km)		2.445			
Daily mileage per bus (km)		163			
Administrative costs per month	$318.060,00	$ 26.505,00	$ 609,62	$ 0,093	$ 227,585
Total Costs per Year both lines					**$ 5.675.788,134**

**data provided by the operator*

The parameters taken for the cost calculation for electric buses are as follows:

Average energy consumption of 12 m BEBs (kWh/km)		1,03
min kWh/km		0,82
max kWh/km		1,14
Cost rate per kWh for BEBs	Peak hour	$0,363
	Flat hour	$0,139
	Valley hour	$0,075

The total costs for energy were calculated with a valley hour price. Therefore, the monthly (and yearly) costs are just for reference and some adjustments may be required via a feasibility analysis. However, the table below shows that the operation of a electric fleet might be cheaper in terms of variable costs, which includes less expenses in spare parts and maintenance than diesel buses. Also, the kWh price is lower than the gasoil price per liter. However, for a complete overview of expenses, the costs of electric infrastructure, connection to the network, etc should be included.

Table 16. Monthly and annual costs for electric buses in both lines with current bus fleet

Costs for both lines		**Unit**	**Costs in $USD**	**USD$/ km**	**USD$/per bus-month**
Total Costs per month per bus					**$ 10.259,636**
Operation cost veh/km	Monthly cost	$ 523.371,00	12037,533	$1,838	$ 4.493,925
Operation cost veh/hour		$ 523.371,00	12037,533	$ 30,263	$ 4.694,334
Cost rate maintenance veh/km				$ 0,268	$ 655,581
Variable cost per veh/km		2.519	$ 188,21		$ 188,211
Yearly mileage per bus (km)		115.303			
Monthly mileage per bus (km)		2.445			
Administrative costs per month	$318.060,00	$ 26.505,00	$ 609,62	$ 0,093	$ 227,585
Total Costs per Year both lines					**$ 4.924.625,180**

Table 17. Monthly and annual costs for electric buses in both lines with 24 BEBs

Costs for both lines		**Unit**	**Costs in $USD**	**USD$/km**	**USD$/per bus-month**
Total Costs per month per bus					**$ 10.258,986**
Operation cost veh/km	Monthly cost	$ 523.371,00	$ 12.037,53	$1,838	$ 4.493,400
Operation cost veh/hour		$ 523.371,00	$ 12.037,53	$ 30,263	$ 4.694,334
Cost rate maintenance veh/km				$ 0,268	$ 655,505
Variable cost per veh/km		2.518	$ 188,19		$ 188,189
Yearly mileage per bus (km)		115.303			
Monthly mileage per bus (km)		2.445			
Administrative costs per month	$318.060,00	$ 26.505,00	$ 609,62	$ 0,093	$ 227,559
Total Costs per Year both lines					**$2.954.587,883**

1.1. Charging strategy

By calculating the different parameters given by the manufacturers, the range was calculated

Table 18. General performance for selected BEBs

Bus models	Nominal energy content (kWh)	Usable energy content (kWh)	Range* (km)	Charging Power (kW)	Required time with slow charging (h)
BYD K9A	324	243	236	80	2
GOLDEN DRAGON PIVOT E-12	345	258,75	251	75	2
YUTONG E12	375	281,25	273	150	1
SOLARIS URBINO 12E	396	297	288	400 (plug-in); 200 (panto)	0,42
VOLVO 7900 E	470	352,5	342	250 (plug-in); 300 (panto)	1
SCANIA CITYWIDE LFE	330	247,5	240	150 (plug-in); 300 (panto)	1

**Calculated with a 1,03 kWh/km as an average given by operators running the 31 electric buses in Montevideo*

For both lines, the average mileage per bus in a day is 163 km, which is covered by all the different models. However, the final range will also depend on other external conditions such as the driving style, air conditioning during hot seasons, slopes, the daily load, among others. Only with specific simulation programs introducing the variables above mentioned, can be determined exactly the range of the bus. With this first overview, opportunity charging might be not required. Furthermore, the only models with pantograph technology that allows opportunity charging are the European models, which are a more expensive technology not only per unit but for charging infrastructure. However, the final decision for the purchase of a determined bus and its correspondent charging infrastructure will depend on the financial model that justifies the electrification of both lines, the available space at Terminal Ciudadela or at the depots were the buses overnight among other factors.

For a first electrification of lines 143 and 169 a progressive purchase of units is recommended to see the impacts in the operation and financial schemes. The total required fleet is of 24 vehicles to meet the demand and service needs. For the electrification strategy a financial and technical feasibility should be carried out, including subsidies, operation methods, and capacity building.

GENERAL RECOMMENDATIONS

The electrification of Latin American bus fleets is recommended with lines with high passenger's demand to be economically feasible. A very important factor for both the technical and the financial feasibility is the ratio between the number of buses per charging station. To have a certain degree of operational safety and stability, this factor should not exceed 1:6. The lower limit is more or less defined by economic considerations and should not fall below 1:3.

If the buses are only to be recharged at the bus depots, it is strongly recommended to select routes on which

- buses do not travel for more than 200 km per day, if a return to the bus depot for recharging in between is not possible or very inefficient (dead kilometres),
- traffic conditions should allow for a relatively high journey speed, and
- passenger demand varies during the day significantly which allows for longer crew changes and less mileage per bus and day.

Short distances between the terminals and the bus depots facilitate the fast recharging at bus depots but this must also be considered when the service schedules are designed.

For opportunity charging the following conditions should be met:

- recharging takes place during the 20 – 30 minutes breaks and the crew is changed.
- A bus must find a vacant station immediately upon arrival.
- Both breaks and change of the crew should take place at the same terminal or bus depot.
- Long routes with many buses and long headways between consecutive buses maximises the number of buses per charging station.

Bus depot equipment

In general, bus depots and workshops are already equipped to maintain, repair and clean battery buses. However, additional equipment is required as follows:

- high voltage tools
- measurement and testing equipment
- special diagnosis software
- protective equipment (e.g. safety glasses and gloves)
- working platform and a crane as more components are mounted on the roofs.

Washing installations do not need to be replaced as battery buses should be suitable for automated washing.

Staff training

In the case of Quito, since there is not yet any experience with BEBs both drivers and depot staff need to be trained for battery buses and the charging infrastructure, as the voltage level is higher than 60 VDC. Montevideo already has some experience with the 31 electric buses running in the city. CUTCSA, the operator that provided the data for their lines, already has 20 e-buses in their fleet. In both cases, the following training courses might serve as a general guideline:

- Step A: starting the buses, driving the buses, switching off, safety aspects
- Step B: safety aspects, prerequisites for towing away, switching off, safety aspects
- Step C: non-high voltage work (e.g. safety aspects, especially for welding and repair after major accidents)
- Step C2: high voltage work with high voltage being switched off, accident prevention

Additionally, fire fighters and rescue workers need to be involved as battery buses pose other risks and hazards than e.g. diesel buses, which primarily stem from the high voltage system.

The implementation of battery buses will involve higher costs compared to diesel buses, which must be compensated with public funds. Different support schemes should be discussed among all stakeholders. A competition-based compensation using adapted vehicle-km costs will presumably be the most efficient way to support this new technology on Quito and Montevideo's routes.

APPENDIX

Major Battery Bus Manufacturers and their flagship models

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