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Feasibility of Introducing Hybrid Buses in Bus Rapid Transit Systems in Latin America:

The Case of Transmilenio Bogota

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Abstract

Bus rapid transit (BRT) systems have been recognized around the world by combining the advantages of urban rail transit systems with the flexibility and low cost of conventional bus systems. Although its introduction in different cities has helped to reduce greenhouse gas emissions and improve air quality, one of the major criticisms for these systems is that buses are usually powered by diesel, which is a pollutant and non-renewable energy source. Under this scenario, the feasibility to introduce hybrid electric buses for BRT systems in Latin America is evaluated, finding that hybrid buses have proven benefits such as 20-45% in fuel savings and reductions of up to 90% for some local air pollutants with respect to conventional diesel buses. However, there are some limitations for its introduction such as: the commercial unavailability of hybrid articulated buses, the higher life cycle cost of this technology and the lack of test data to determine if the fuel savings would be affected by operating at higher average speeds. Finally, a set of policies are suggested to promote introduction of hybrid buses in Bogota, these include: soft loans, specific policies for final disposal of buses, the introduction of regulatory standards to promote clean technologies and the establishment of a regulatory framework to monetize environmental impacts from propulsion systems for buses.

Keywords: hybrid electric buses, bus rapid transit, low carbon transportation technologies, sustainable transportation.

Executive summary

Despite the many advantages offered by BRT systems, one of the aspects that remain under analysis and constant improvement by bus operators and transit public authorities is the pollution generated from diesel engines. In the case of Bogota, where the first buses introduced in their BRT system known as "Transmilenio" are already completing their useful life, a growing interest has been generated in order to evaluate alternative propulsion alternatives to replace current diesel buses, in which hybrid buses are one of the options to be considered because of its potential to reduce fuel consumption and air pollution.

Under this scenario and utilizing the framework of innovation systems theory for the introduction of low carbon transport technologies (developed by E4Tech), this research seeks to determine if it is convenient to introduce hybrid buses for BRT systems in Latin America. This thesis also suggests a set of policies that would favour the introduction of hybrid buses in Bogota as a study case.

To assess the suitability of hybrid buses it should be noted that a BRT system uses two types of buses. "Feeder buses", which have similar characteristics of size and operation to a conventional bus; and "trunk buses", which are articulated and biarticulated buses with large capacity, that transit by exclusive lanes and have a higher average speed with respect to a conventional bus system.

The results obtained with hybrid buses vary significantly between different study cases analysed; for example New York implemented the first hybrid buses in 1998 and currently has 1,777 hybrid buses within its 5,560 bus fleet. Currently they have stopped their implementation due to higher maintenance costs and low reliability obtained with respect to a conventional modern diesel bus. Barcelona has a total of 1,064 buses of which 60 are hybrid buses and expect to expand this technology to 30% of their fleet. A key driver to increasing the number of hybrid buses in Barcelona are due to fuel savings but also to the existence of supportive policies to promote clean transportation technologies.

In the case of Latin America, the introduction of hybrid technology is limited to prior pilot tests and the recent tests conducted by the Clinton Foundation in Curitiba, Sao Paulo, Rio de Janeiro and Bogota. Overall the results of these tests have been positive for fuel savings and reduction of air pollutants. However, the introduction of this technology varies according to particular conditions in each city. For example, Sao Paulo and Curitiba have already ordered the first units of Volvo hybrid buses, while in Rio de Janeiro they are opting for Euro V buses powered with sugar cane diesel; since for them the financial evaluation of this option is more favourable than hybrid buses. In the case of Bogota, there is a strong interest from the government to accomplish the introduction hybrid buses; however, the cost in the life cycle is still higher than a conventional bus, so their introduction may only be carried out to the extent that there are enough incentives to offset the extra costs of this technology.

Based on the information obtained, it is possible to say that the feasibility to introduce hybrid buses for BRT varies according to the types of vehicles used in the system, on one hand the use of hybrid buses for trunk routes is still uncertain, since the supply of articulated and bi-articulated hybrid buses is limited, and there is no test data to estimate the fuel savings at high operating speeds. On the other hand, the use of hybrid technology on feeder buses is feasible because there is enough supply of standard size hybrid buses and test results have been positive.

However, the financial aspect remains the biggest limitation to introduce hybrid buses in Latin America, but considering that this is a low-carbon transport technology in pre-commercial stage it is perfectly feasible the use of support policies to favour its introduction. In the case of Bogota, the main policies suggested are: preferential loans for hybrid buses, specific policies for the disposal and sale of used buses, the introduction of regulatory standards to promote clean transportation technologies and the establishment of a regulatory framework to monetize the environmental impacts of different propulsion technologies for buses.

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Abbreviations

BRT	Bus Rapid Transit
CCI	Clinton Climate Initiative
CNG	Compressed Natural Gas
HEB	Hybrid Electric Bus
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
ITS	Intelligent Transportation Systems
MTA	Metropolitan Transit Authority
RIT	*Rede Integrada de Transporte* (Integrated Transport Network)
R&D	Research and Development
TMB	*Transports Metropolitans de Barcelona* (Metropolitan Transports of Barcelona)

1 Introduction

Bus Rapid Transit, referred to as BRT, is a public transport system originated in Latin America during the 70´s, which application and development have spread to several cities in North America, Central America, Europe, Asia, Australia and South Africa (Weinstock, Hook, Replogle, & Cross, 2011). Its innovation is based on combining some advantages of metro and light rail, with the lower operating and infrastructure costs of conventional bus systems. BRT differs from conventional bus systems by some characteristics like: dedicated bus ways, off-bus fare collection, high capacity buses and high frequency of service.

BRT systems can also help to improve air quality and reduce greenhouse gas emissions with respect to traditional bus systems or private cars. Such is the case of Bogotá (Colombia), whose BRT system was certified as a CDM (Clean Development Mechanism) by the UNFCCC because the reduction of 1.6 million tonnes of CO_2 equivalent during the period 2006-2012 (UNFCCC, 2012). However, BRT systems have been criticized because their buses are usually powered by diesel engines, whose emissions contain pollutants such as particulate matter, ozone precursors, benzene, arsenic, dioxins and formaldehyde. resulting in negative impacts for human health. Additionally, diesel emissions have been classified as carcinogenic[1] below certain levels of exposure that have not been determined yet (Ranganathan, n.d.).

In response to the need to improve air quality, cut carbon emissions and reduce dependence on fossil fuels, a growing number of transportation agencies around the world have been evaluating different alternatives to power their buses. Some of those are the use of CNG, biofuels, hydrogen cells, pure-electric vehicles and electric-hybrid technology. Between those options, a study from Frost & Sullivan indicates that hybrid technology will be the main propulsion technology for buses and medium weight trucks in the year 2020 (Kilcarr, 2011). Likewise, a report from the Environmental and Energy Study Institute highlights as a growing number of transportation agencies are implementing hybrid electric buses because their lower emissions and fuel consumption (Ranganathan, n.d.).

1.1 Problem definition

The Bogotá BRT system is called Transmilenio and started operations in 2000. Transmilenio is currently one of the largest BRT systems of the world, with a fleet of 1,906 buses and almost 200,000 passengers during peak hours (Transmilenio, 2012). Taking into account that the first buses introduced into the system are completing their useful life of one million kilometres, it is necessary to evaluate different alternatives to replace the current diesel-powered buses; among which the hybrid technology appears as an option that should be considered.

On the other hand, there are several studies about BRT systems and hybrid electric vehicles, but very little has been written about the feasibility to introduce hybrid buses in BRT systems, which is necessary if we consider that buses for BRT have particular characteristics such as operation speed or design, which requires specific analysis.

1.2 Research question

Although an increasing number of bus manufacturers in Latin America are including hybrid technology in their product portfolio and some cities have initiated tests with hybrid buses,

[1] Carcinogenic is a substance that under certain level of exposure is suspected or known to cause cancer.

there is still a high degree of uncertainty about the risks of this new technology and policies that could favour its introduction.

In order to clarify the uncertainties for bus manufacturers, public transport authorities and bus operators, this study seeks to answer the following two questions:

1. Is it feasible to introduce hybrid buses for BRT systems in Latin America? 2. Which policy instruments can help to carry out the introduction of hybrid buses in Bogota as a case study?

1.3 Methodology

Given that the use of hybrid buses on BRT systems is a relatively new topic in literature. Most of the collected information corresponds to primary sources, obtained during visits and interviews in the cities of Bogota, Sao Paulo, Rio de Janeiro, Curitiba, New York and Barcelona, complemented with academic literature about BRT systems and technical reports from bus manufacturers and transportation agencies.

The working schedule for this research is divided on the following five phases:

Figure 1-1 Research process stages

The initial phase defines the thesis scope and analytical framework, which corresponds to the innovation system theory for low carbon transportation technologies developed by E4Tech. Although this theory has been used during the entire research process, it is explained on detail in the analysis chapter for convenience of the reader.

The second phase corresponds to a literature review on BRT systems, with the idea of understanding its development and implementation in Latin America, also to identify specific characteristics that may influence the adoption of hybrid technology for buses. This phase also includes a literature review on hybrid electric technology for buses, mainly focusing on the buses available at commercial level in Latin America, leaving as a second priority, technologies that are currently under testing or development phase.

The third phase corresponds to the review of international cases, for which I visited the cities of Rio de Janeiro, Curitiba, Sao Paulo, New York and Barcelona. This phase also involved site visits to the bus factories of Volvo and Eletra in Brazil, which commercializes hybrid electric buses; complemented with phone interviews with representatives from other bus manufacturers.

The fourth phase focused on analysing the stages of the technological innovation process for hybrid buses in Latin America, and to identify policies that could promote the introduction of hybrid buses.

As a fifth and final phase, the set of policies previously identified will be evaluated for Bogota as a case study, with the purpose of defining conclusions about convenience to introduce hybrid buses for BRT, and provide some suggestions to carry out the introduction of hybrid buses in Bogota.

1.4 Limitation and scope

The evaluation of alternative propulsion technologies for a city bus fleet is usually conducted using the same evaluation criteria to different technologies available on the market; it means that different technologies such as diesel, biofuels, GNC, electric and hybrid are tested under the same criteria. However, the scope of this study is limited to evaluate the feasibility to introduce hybrid buses for BRT systems, leaving aside other potential technologies that should be also evaluated in complementary studies.

The information sources used for this study vary according to the type of data required, for example, supply of hybrid buses is limited to models that are currently available on the market or that could be offered in the near future; with respect to international cases studies, those are limited to three Brazilian cities that have similar conditions to Bogota and have conducted tests with hybrid buses, also to Barcelona and New York because those cities have some years of experience with hybrid technology in their bus fleet.

1.5 Audience

The intended audience for this research are stakeholders involved in the supply and demand of buses in Latin America; from the supply side it includes bus manufacturers, bus dealers and chassis manufacturers; and from the demand side it includes decision makers from BRT systems, transportation agencies and bus operators. Moreover, this study could be also relevant for an academic audience interested in sustainable transportation or low carbon transportation technologies.

2 Bus Rapid Transit

The bus rapid transit is a public transportation system which seeks to combine the functional characteristics of a metro or tram with the flexibility and low costs of the buses (Deng, 2010). The first BRT was developed in Latin America during the early 70´s, when the growth of cities demanded the creation of mass transit systems that could be developed with a limited amount of financial resources, and thanks to their success, these systems have been spread to more than 100 cities in almost all regions of the world (EvoBus GmbH, 2012).

2.1 Background

The modern concept of BRT emerged in the city of Curitiba, Brazil in 1972 when then mayor Jaime Lerner included in the development plan of the city, a transportation system known as Integrated Transportation Network (*Rede Integrada de Transporte)*. This system was designed as a metro above the surface that used buses instead of rails and wagons (Embarq, n.d.). One of the main components of the BRT is the use of exclusive bus lanes, although this concept had been developed since 1939 in the city of Chicago (Deng, 2010). However, the Curitiba system incorporated additional concepts such as the use of stations with platform and validation of a ticket previous to boarding the bus (Embarq, n.d.), which allows the boarding and unboarding of a large number of people in a few seconds, just as in a metro system.

The first bus corridor of Curitiba was developed in a low income area with high transportation demand, which later included other corridors and a bus feeder system to expand the coverage (Deng, 2010). To allow a greater passenger flow, the Integrated Transportation Network has articulated buses for 170 passengers and bi-articulated for 250 passengers, the boarding is done in the denominated tube stations, as seen in the picture on the right.

Bus station for BRT in Curitiba

Another city that marked a milestone in the development of the BRT was the city of Bogotá with Transmilenio system that began its operations in 2000. Unlike Curitiba, Transmilenio incorporated passing lanes to allow overtaking of express routes and replaced the stations on the sides of the road for central stations that allow two-way boarding. This system transports up to 46,000 passengers per hour in each direction (Peñalosa, 2008) and has been recognized as the only full BRT system, because of its wide coverage and characteristics (Pardo, 2009).

Bus rapid transit system in Bogotá

After the experience of Bogotá and Curitiba, BRTs have been consolidated as an efficient option to improve urban transportation systems, because of their lower infrastructure costs, faster construction, integration with existing systems and financial self-sustainability. BRT´s have been expanded to other cities in Latin America, Asia, North America, Europe, Oceania and Africa (Figure 2-1).

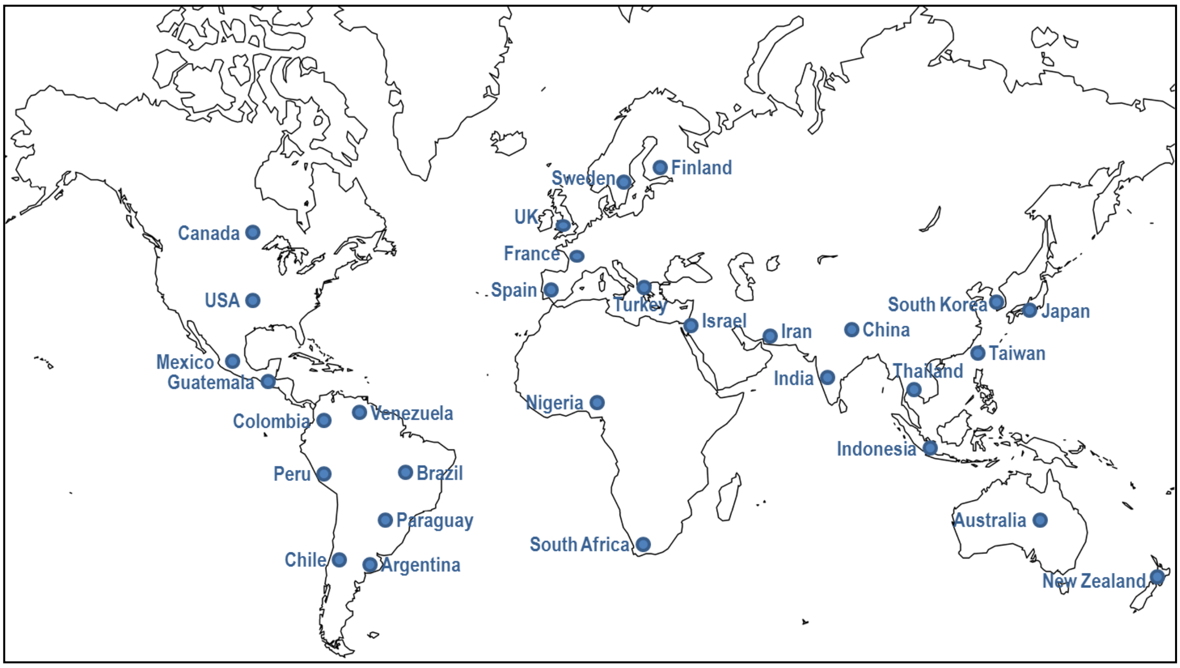


Figure 2-1 Countries that currently have BRT systems in operation. (Source: adapted from EvoBus GmbH (2012))

2.2 BRT Infrastructure

It is necessary to clarify that BRT emerged as a term after the implementation of the first system of this kind in Curitiba. For this reason, no one can speak of an initial model that has been implemented, but rather a set of experiences from several cities that have been improving the concept of BRT. Although not all BRT systems are equal, we can identify certain common elements such as bus lanes, bus stations, ticket validation systems, intelligent transportation systems (ITS) and specific vehicles; whose main features will be explained below.

2.2.1 Corridors

The type of corridor is usually the most expensive component for the introduction of a BRT, and it becomes a key issue for city planning. Hinebaugh (2004) identifies three characteristics of the corridors for BRT: lanes exclusivity, road markings and the use of guidance systems.

Bus corridor for BRT in Bogotá

- <u>The exclusivity of the lanes</u> is one of the key aspects of the system, because while more independent is the bus lane to other vehicles, the BRT will have greater reliability and speed of operation (Martínez, 2009). According to Levinson (2003), there are five levels of segregation for lanes.

Table 2-1 Classification of lanes by level of segregation. (Source: Levinson (2003))

Type	Infrastructure	Description
I	Tunnels or elevated viaducts exclusive for buses.	Exclusive lanes with continuous traffic flow.
II	Exclusive lanes on highways.	Exclusive lanes with limited interruption of traffic flow.
III	Exclusive lanes on medium highways.	Exclusive lanes separated by a physical barrier of regular vehicles.
IV	Preferential use of lanes for buses.	Preferential use lanes for buses that do not have a physical barrier for separation.
V	Mixed traffic	Shared lanes between buses and regular vehicles.

- Road markings: prevents the invasion of exclusive bus lanes by other vehicles, and for that purpose, there are physical and visual techniques that can be combined to accomplish greater effectiveness. Physical barriers include curbs, bollards, paving ripple or lanes with different elevation; while the visual marking includes traffic signs, lines or pavements of different colour (Hinebaugh, 2004).
- Guidance systems: allow controlling the lateral movement of the vehicle similar to the railway of a train. Most BRT systems do not use this technology, and the vehicle control depends solely on driver skills. However, some BRT incorporate guidance systems as physical barriers similar to rails or optical or electromagnetic sensors which help the steering of the bus (Hinebaugh, 2004).

2.2.2 Stations

BRT stations may vary from a simple bus stop which only allows access to the bus, to complex intermodal transportation stations that connect users with other transportation services and provide information and commerce services (Hinebaugh, 2004). According to Levinson (2003) BRT stations must meet certain requirements as a high quality design that embellishes the landscape of the city, facilitates the identification of the system and respect the environment and surrounding community. Hinebaugh (2004) identifies five issues that must be noted in the design of the stations.

Bus station for BRT in Curitiba

- Base station: the type of stations may vary according to their complexity and include: simple stations which have a roof to protect passengers from the weather; upgraded stations include additional facilities such as glass walls, garbage baskets, phones or ATMs; specific BRT stations, include high access platforms and information services; and finally intermodal transportation terminals which are the most complex because they allow the transfer of passengers from the BRT to other transportation systems.

- Height of the boarding platform: the height of the station floor with respect to the door to the vehicle determines the boarding speed and access for people with reduced mobility. Its height for low floor buses is usually between 15 to 25 cm, and for buses with high access as those operating in Curitiba and Bogotá, the height is 90 (Moller, 2006). The use of high altitude platforms prevents the operation of conventional buses in BRT stations. The length of the platform can varies from 12 meters to allow the boarding of a single standard bus, up to 90 meters or more to allow boarding for multiple buses at the same time.
- Passing lanes facilities: one of the advantages of BRT over rail systems is the possibility of having express lines that do not stop at all stations, to carry out the overtaking there are two options: to have bay parking in each station thereby the bus that stops does not obstacle the traffic flow or to have passing lanes along the corridors (Hinebaugh, 2004).

2.2.3 Intelligent Transport Systems (ITS)

The ITS are a combination of technological developments aimed to improve comfort, safety and reliability of transport systems by collecting, analysing and disseminating information in real time (Deng, 2010). The BRT usually combine various applications and to this extent its optimum performance depends on proper integration and synergy obtained by combining different technologies such as those described below.

- Automatic vehicle location: is an application based on GPS technology that determines the location and the speed of the vehicles. This enables to optimize traffic flow and react to unforeseen events that disrupt the normal functioning of the system. It also provides information to users in real time about waiting times and suggested routes.
- Integrated control of traffic signs: this system gives priority to the movement of BRT vehicles at traffic light intersections. For example, increasing the time the traffic light is green to give priority to vehicles that are delayed or change traffic flow under unusual traffic conditions.
- Automated dispatch system: automated dispatch systems determine the number of buses which must be in operation, according to the established schedule and automated passenger counters at the stations.
- Support systems: it can incorporate other support systems such as video cameras, communication systems or alarm systems that contribute to improve safety for BRT users and operators.

2.2.4 Ticket Validation

The process of ticket purchase and validation is essential for a BRT system, because it determines the boarding time and complexity of the stations. Unlike conventional bus systems, most BRTs have validation systems before boarding the vehicle, thereby reducing the boarding time (Levinson, 2003). For greater detail, three different validation systems are identified by (Hinebaugh, 2004).

- Payment and validation on board: each user buys the ticket from a cash register or a ticket validation system inside the bus. Although the cost of infrastructure is relatively low, this system is only convenient for routes with a low passenger flow, because the boarding time is high, especially when is made by a single door.
- Entry control at stations: in this system the user must purchase and validate the ticket before entering the bus, for that purpose the stations require an additional infrastructure such as vending machines, turnstiles or operators who sell and validate the tickets.

Although this system has higher infrastructure costs, its greater advantage is the reduction in boarding time.

- Self-service or proof of payment: in this system the user must also purchase the ticket in advance, with the difference that there is no validation system that prevents access to the bus, but is subject to a validation system by agents that randomly get to the buses to ask passengers for the tickets. Its advantage is the lower cost of infrastructure, although is subject to evasion of payment from some users.

2.3 Vehicles for BRT

In a BRT system there are two types of vehicles according to their functions. The first type is trunk bus that travels along the corridors, stops only at BRT stations and has a higher passenger capacity. The second type is feeder bus, whose function is to transport passengers from additional corridors to BRT stations; those buses have less passenger capacity and are similar to a standard bus.

Trunk bus in Bogotá of 27,2 m

Feeder bus in Bogotá of 12m

A suitable bus for BRT must have certain characteristics such as high passenger capacity, adequate level of comfort, easy accessibility, easy identification and use of clean technologies (Deng, 2010). To this should be added other functional aspects such as facilities for people with reduced mobility, adequate lighting and the use of heating or air conditioning if weather conditions require it (Martínez, 2009). The following describes in more detail the main characteristics for BRT vehicles.

2.3.1 Dimensions

The size of the vehicle is often limited by local regulations and physical characteristics of traffic lanes. Generally, the bus has a width of 2.6 m and a height of 3 m approximately, but the bus length can varies from 12 to 28 m as is shown in Table 2-2.

Table 2-2 Main bus configurations for BRT in Latin America. (Adapted from SIBRT (2012))

Configuration	Length	Width	Passenger capacity
Standard bus	11 – 13,2 m	2.6 m	60 – 100
Three axis	15 m	2.6 m	80 – 120
Articulated	16 - 18 m	2.6 m	120 – 170
Bi-articulated	24 - 28 m	2.6 m	240 – 270

In addition to the vehicles described in Table 2-2, BRT systems also use small buses with a length of 9 m or less, which usually operate as feeder buses or in routes that are not connected to the BRT system.

2.3.2 Floor height

Previously most buses for urban transit used a body with high floor, low door and steps for its boarding; those buses have a high boarding time and limit access for disabled people, although in some cases may include lifting systems for wheelchairs or strollers. Since the introduction of the first low-floor bus by the manufacturer Denis in 1976 (MAN SE, 2010), this configuration has gained popularity in various countries, due to its benefits of accessibility for seniors, strollers and even wheelchairs. However, its limitation is its smaller passenger capacity due to the space occupied by the bus wheels and a higher cost in the manufacture of the body (Fioravanti, 2012).

A third configuration has been quite popular for BRT are high-floor buses with high doors, these buses combine the advantages of both systems, but require the use of stations specifically designed for these vehicles, since the access doors are located at a height of 90-100 cm.

2.3.3 Doors

In addition to floor height, another factor that influence on the boarding time is the size and number of doors. For a system with high flow of passengers is preferable the use of multiple access doors, which in turn requires that the ticket validation system is not performed by the driver. The number of doors varies according to the length of the bus, for example 12 m buses may have two or three doors, articulated buses have four doors and bi-articulated buses have seven doors.

BRT *bus with high door and high floor*

The position of the doors can also vary according to the configuration of corridors; doors are traditionally on the right side of the vehicle. However in corridors like in Bogota or Curitiba, doors can be on the right side or both sides of the vehicle (Levinson, 2003). This allows the use of central stations that operate in both directions and eliminates the need for stations in each direction of the lane.

2.3.4 Passenger capacity

The total passenger capacity is determined by the number of seated and standing passengers maximum load capacity. According to Levinson (2003) in a square meter can travel two seated passengers, while in the same space can be accommodated up to five passengers standing, for this reason the total passenger capacity is largely determined by the configuration of the seats of the vehicle, although it can be also limited by local regulations for maximum weight of vehicles, usually expressed as a maximum number of tons per axle. Weight limitations should be taken into account to evaluate new propulsion technologies that could increase the vehicle weight. For example, the additional weight of the batteries in an electric or hybrid bus could reduce the maximum number of passengers on the bus regarding a standard bus (González, 2012).

2.3.5 Aesthetics

In addition to the mechanical components of the vehicle, the visual appearance of the vehicle is equally important to achieve the identification of the system as well as to achieve user acceptance. Preferred buses for BRT have a modern body with large windows and paint patterns that help to distinguish different buses according to their kind of operation or configuration. On the inside, the use of high quality materials, lights, user information systems and temperature control systems help to improve user perception (Hinebaugh, 2004).

2.3.6 Propulsion

The propulsion system used in BRT buses determines the acceleration, top speed, fuel, emissions, autonomy and maintenance costs (Hinebaugh, 2004). Although there is a wide range of propulsion systems at commercial and developmental stage, the main propulsion system for buses still being the internal combustion engine (ICE) fuelled with diesel. Despite this, a large number of transportation agencies are adopting or evaluating other propulsion systems in order to reduce environmental impact and decrease dependence on fossil fuels.

While the scope of this investigation is limited to electric hybrid buses, the following briefly describes the most common propulsion systems available for BRT.

Internal combustion engine

The first vehicle powered by an ICE was patented in 1886 by Karl Benz. Its basic operating principle is the conversion of chemical energy to mechanical energy, to this end, it burns a compressed mixture of air and fuel into a chamber or piston; this generates an alternative movement of the piston which then turns into a rotary motion that is connected to the transmission system of the vehicle.

Although the most used fuel for buses is ultra-low sulphur diesel, it is also possible to use other fuel sources, both renewable and non-renewable:

- Diesel: is a fossil fuel obtained from petroleum, it is usually easier to refine than gasoline, so its cost is lower but contains more minerals and sulphur. Its main advantage is its low cost, low consumption and wide availability; while its main disadvantage are the emissions of CO_2 and polluting materials.
- Biodiesel: is a fuel with similar properties to conventional diesel, with the difference that this is obtained from animal or vegetable oil. It can be mixed with conventional diesel in different proportions which are denoted by the letter B followed by a number indicating the proportion of diesel in the mix. For example B100, corresponding to 100% biodiesel or B50 which corresponds to 50% biodiesel and 50% conventional diesel (Rozo, 2012). Compared with conventional diesel its main advantages are reductions of CO_2 emissions and particulate matter (Brincas, 2008); and in most cases it can operate directly in conventional engines without modifications; among its disadvantages are higher NOx emissions (Lorençon, 2012a) and possible impacts on food security due to the expansion of the agricultural frontier by the use of agricultural land for biofuels.
- Compressed Natural Gas (CNG): is a fossil fuel mainly composed of methane, although methane has an emission factor twenty times greater than carbon dioxide, when used in

an internal combustion engine, it usually has lower emissions of greenhouse gases that diesel (Nylund, Erkkilä, Lappi, & Ikonen, 2004). Its disadvantages are the additional weight of gas cylinders and modifications that must be made to the vehicle and fuel stations to supply the fuel under high pressure.

- Biogas: is a biofuel produced by anaerobic decomposition of organic matter such as agricultural waste, food waste or sewage. For use in an internal combustion engine, the biogas must be upgrade to remove polluting materials and increase the methane content in the mix. Its great advantage is its neutral CO_2 balance, while its major limitation is the regular availability of raw materials to carry out its large-scale production and in an economically feasible way (Dzene, 2009).
- Ethanol: is a fuel obtained from the fermentation process of sugars and yeast, it can be blended with gasoline in which case it is denoted with the letter E followed by the proportion of ethanol in the mixture, for example E10, E85 or E100. Its production is mainly obtained from plants like sugar cane and corn. Ethanol has also generated controversy as biofuels about its effect on food prices. In regard to operational aspects, ethanol has higher fuel consumption and engines require more frequent maintenance compared to diesel (Wilson, 2012).

Electric engine

The basic principle of the electric motor is transforming electrical energy into mechanical energy through the interaction of electromagnetic fields that generate the circular movement of a rotor. Some motors can operate in reverse, converting mechanical energy into electrical energy, which in vehicles is known as regenerative braking system.

There are two main types of electric buses, trolleybuses powered by external power cables and the autonomous which have an energy storage system such as batteries or ultracapacitors[2].

- Trolley: these vehicles have been in operation since the late 19th century, most are powered by power lines on the top of the vehicle, although some models also incorporate energy storage systems to operate for short distances in the case of a power outage. The main advantages of these vehicles are silence operation, reduction of local pollutants, decreased CO_2 emissions (when electricity comes from renewable energy sources) and more torque which allows better acceleration and performance on slopes. Limitations include the high cost of electricity infrastructure, visual intrusion caused by the cables and the inflexibility of the buses, as their traffic is limited to the lanes that have the necessary infrastructure (Levinson, 2003).
- Battery Bus: The introduction of these vehicles is much more recent, as it has only been in commercial operation since the 90´s; however, they have attracted great attention and resources for its development due to its potential benefits, as they promise to combine the advantages of a zero-emission vehicle with the flexibility of the buses powered by internal combustion engines. Its major limitation is the development of the batteries, as their high costs limit their competitiveness and the autonomy does not allow covering the distance travelled by most buses in a BRT system (Callaghan & Lynch, 2005).

[2] Ultracapacitors are electrochemical devices for energy storage that unlike conventional batteries have a longer life, are loaded and unloaded very quickly and their storage capacity is much lower.

Hydrogen fuel cell

Fuel cell powered buses combine hydrogen and oxygen to produce electricity without the need for an electric generator. Water vapour is the only emission of this type of vehicle during its operation and if the hydrogen is produced from renewable energy sources, it also helps reduce greenhouse gas emissions (Levinson, 2003). Despite their environmental benefits and silence operation, there are still limitations around their high costs and hydrogen production on a large scale, which for the moment limits its introduction to demonstration and testing phases in Latin America.

Hybrid electric

Although this type of technology will be explained in greater detail in the next chapter, the basic principle of hybrid vehicles is to combine two different technologies for its propulsion, in this case an internal combustion engine with an electric propulsion system.

2.4 Functional characteristics of BRT

The increasing population and its need for transportation has been a common factor in most cities during the last decades. This has led to the introduction of different mass transit systems, in which BRT systems have become more popular in Latin America and other regions of the world, thanks to the obtained results.

In this sense, it is convenient to describe some key features of BRT with respect to other systems such as traditional buses, trams, light train or heavy subway. But beyond falling into biased arguments to say that a transportation system is better than another, the most important aspect is that each system has its advantages and disadvantages, and for this reason the success in urban transport is usually achieved through the integration of different transportation systems.

Table 2-3 Comparison of different mass transit systems. (Adapted from: [1]Wright (2005), [2]UITP (n.d.), [3] Peñalosa (2008), [4]Gonzáles (2012), [5]Géomez (2007), [6]Yarra Trams (2012))

	Standard bus	**Tram**	**Light rail**	**Metro**	**BRT**
Max Capacity (p/h/d)	6,000 [1]	15,000 [1]	36,000 [1]	72,000 [2]	46,000 [3]
Infrastructure costs (US million/km)	-	10 – 25 [1]	15 - 40 [1]	50 - 320 [1]	0,15 – 15 [1]
Average speed (km/h)	10 - 20 [4]	15 – 30 [6]	15 – 35 [5]	25 – 37 [5]	22 – 29 [1]

- Passenger capacity: one of the units of measure used to determine the passenger capacity of a transport system is the number of passengers per hour in each direction (p/h/d) in a specific route, whose maximum value is reached during peak hours. Transmilenio is the BRT with most capacity in the world and carries up to 46,000 (p/h/d); a number that according to Peñalosa (2008) is greater than the capacity of 95% of metros in the world and that otherwise could be expanded up to 50,000 (p/h/d) with the addition of some improvements.
- Costs: One of the aspects that have favoured the introduction of BRT systems have been its lower implementation costs compared to rail systems. Table 2-3 shows the range of costs in millions of dollars per kilometre. Based on that data it is possible to estimate that

at the same cost to build 426 km of BRT, could only build 14 km of elevated rail or 7 km of subway (Wright, 2005).

With regards to operating costs and unlike the vast majority of railway systems, BRT systems can operate without subsidies, it means that the value of the ticket can cover the expenses of operating the system, thereby freeing up resources that can be allocated to other sectors such as health or education (Pardo, 2009). However, it should be noted that BRT systems have subsidy for infrastructure to the extent that the stations and corridors are funded with public resources.

- Operating speed: Table 2-3 presents the average speed ranges of commercial operation for different transportation systems, where is observed how a BRT system can reach similar speeds to a tram but not as high as a metro or light rail. To estimate travel times for passengers, there should also be taken into account other factors such as boarding time, connection and travel time to and from stations.
- Construction: In addition to the significant differences in infrastructure costs, BRT systems require less construction time than rail systems, for example the time required to build a BRT can be up to ten times less than a metro system. On the other hand, it should be noted that a BRT system requires additional lane space for its construction with respect to rail systems (Pardo, 2009).
- Environmental aspects: BRT systems can contribute to improve air quality and reduce greenhouse gas emissions compared with standard buses or private car. Additionally, the use of high capacity buses helps to improve the use of public space, as a bi-articulated bus can carry as more passengers than 100 vehicles, thereby helping to reduce levels of congestion and noise.

  Traditionally it is considered that the rail systems reduce CO_2 emissions and air pollutants in greater proportion than BRT. However, this is not always true since the environmental impact of rail systems depend largely on the power source used to produce electricity. Such is the case of a study developed by the World Resources Institute, which showed how the adoption of a BRT system for a line in Maryland had lower CO_2 emissions than a light train, because the main source of energy in that region are the thermal coal centrals (Fuhs & Hidalgo, 2009).

  Despite the environmental benefits of the BRT, one of its biggest criticisms has been the use of diesel, whose emissions contain toxic elements. So much so, that a panel of experts from the World Health Organization ensured that prolonged exposure to particulate matter from diesel exhaust may cause lung and bladder cancer (Gallagher, 2012).

2.5 Business model scheme

Apart from the technical and infrastructure features, another aspect that may vary over a BRT or conventional bus system is the business model that determines the stakeholders and decision-making process. Figure 2-2 shows four different business models for the provision of public transportation bus system and the scheme for the purchase of vehicles, where each circle represents different agents as government, public transit authorities, operators (bus owners) and bus suppliers; and the arrows show the hierarchy and influence between those agents.

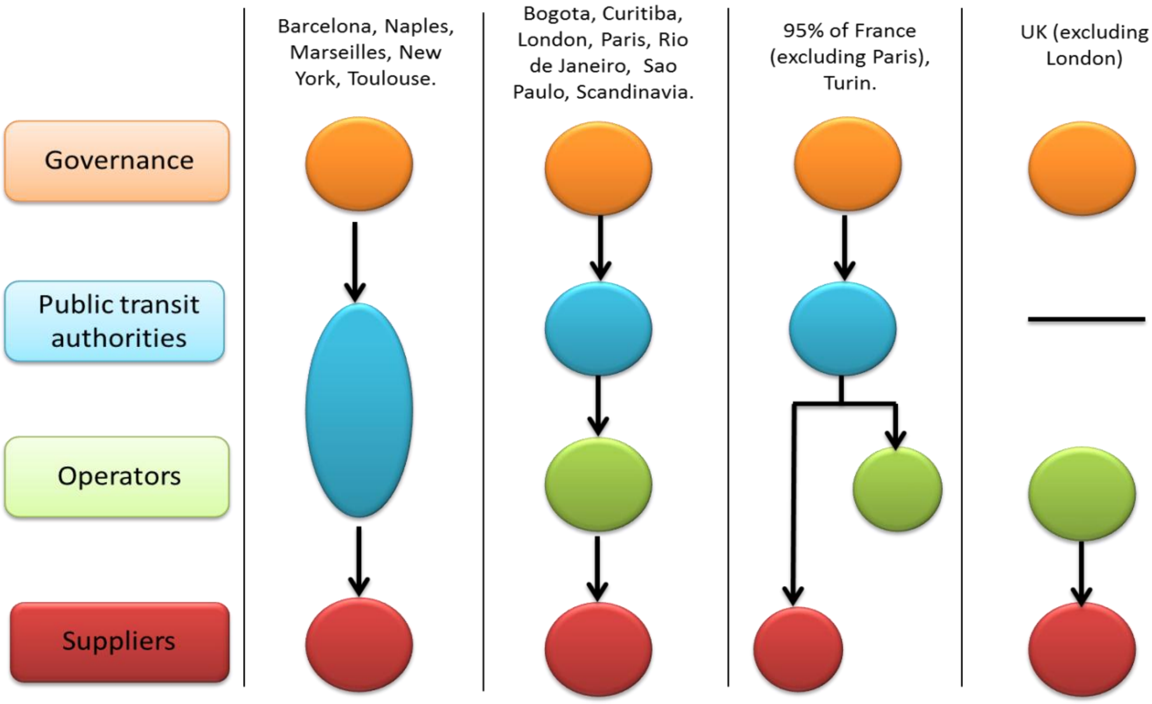


Figure 2-2 Business model for the provision of bus services (Source: adapted from UITP (2009))

In the study cases analysed in Latin America, such as Bogotá, Curitiba, Sao Paulo and Rio de Janeiro, the business model is characterized by the existence of a public transport authority that acts as an intermediary between the interests of local government and bus operators, considering that the buses do not belong to the transport authority but to the operators which are private companies; while in the cities of Barcelona and New York, public transport authorities are also the owners of the buses.

3 Electric Hybrid Buses

3.1 Background

Technology development for hybrid electric vehicles (HEV) dates back to 1900, when Ferdinand Porsche introduced the first car of this type during the Paris Exposition (Høyer, 2007), this vehicle had an internal combustion engine to spin an electric generator that transmit electricity to the wheel hubs and had a range of 40 km (Hybridcars.com, 2006).

From the beginning, these vehicles had regenerative braking technology and were known because combined the silent operation of an electric vehicle with the autonomy of a fuel-burning vehicle. Due to its high price, the concept of HEV disappeared from the automotive scene during the First World War and was only reconsidered again until the beginning of the 70´s. Initially the HEV´s were developed as an alternative that would improve the limited autonomy of purely electric vehicles and were usually produced by small manufacturers of electric vehicles. However, today these vehicles are manufactured by the main manufacturers of conventional vehicles and its current boom mainly obeys to the environmental awareness generated by the use of fossil fuels (Høyer, 2007).

Although the first hybrid electric bus (HEB) was developed in 1969 by Mercedes Benz, its production at a commercial level goes back to the early 80´s, when the first mini hybrid buses were introduced in the city of London, as a replacement for the aged double deckers (Thomas, 2011). During the same decade, different bus manufacturers as Iveco, Scania and Vossloh Kieppe among others began with the first HEB´s tests.

While the HEB´s have drawn the attention of operators and manufacturers of buses due to their environmental performance and fuel economy, its development has been slower than expected, as Anders Folkesson[3] mentioned, "Everyone wants to try them ... but few want to pay what they cost. Hybrids are not yet commercially attractive enough. Virtually all hybrids being sold today are heavily subsidised in different ways" (Scania AB, 2011).

Despite this, the future of the HEB´s looks promising, as most of the major bus manufacturers are offering electric hybrid technology in their product portfolio or are testing this kind of technology; likewise, a study by Frost & Sullivan indicates that hybrid technology will be the main propulsion alternative for medium weight trucks and buses in the year 2020 (Kilcarr, 2011), and a report of the Environmental and Energy Study Institute states that a growing number of transportation agencies are implementing HEB´s due to its lower fuel consumption and reduction of atmosphere emissions (Ranganathan, n.d.).

3.2 Hybrid electric technology

As mentioned above, a HEV seeks to combine the advantages of electric traction as silent operation, greater torque[4] and lower emissions levels, with the autonomy of other fuel sources. A hybrid system combines electric engine propulsion with another power source like an internal combustion engine, turbine or a fuel cell (Callaghan & Lynch, 2005).

The most used fuel for internal combustion engine is ultra-low sulphur diesel, although it is possible to use other energy sources such as gasoline, GNC, biofuels or biogas. For the

[3]Product Manager within Sustainable Systems at Scania Buses and Coaches,

[4]Torque is the rotational force that a engine can produce and in practical terms refers to the initial boost of a vehicle.

energy storage system are used batteries made of lead-acid, nickel-metal hydride or lithium ion; although in some cases can be also used a ultracapacitor that unlike a conventional battery has a longer life and provides a great deal of energy but for a short time period.

One of the biggest benefits of hybrid technology, which also applies to purely electric vehicles, is the recovery of the vehicle´s kinetic energy. This is accomplished by a regenerative braking system which transforms and stores as electricity the energy that is usually dissipated as heat when the vehicle stops. Although there are other technologies to store this energy as hydraulic systems or rotating flywheel, storing energy in a mechanical way remains being a complex technology to be implemented in commercial vehicles (TCRP, 2000).

Currently there are two configurations for HEV´s in series where traction is only generated by the electric engine and in parallel where both the electric engine and the combustion engine are connected to the drive system. While both systems offer advantages and disadvantages, in general terms the parallel system performs better at high speeds, while the series system offers advantages in operating conditions with low average speed and frequent stops and starts. However, Volvo ensures that its parallel hybrid bus can provide significant fuel savings at speeds ranging from 10 to 40 km/h (Lorençon, 2012b).

For a more detailed analysis, below are the basic characteristics of each of the systems, outlining their advantages and disadvantages.

3.2.1 Series Hybrid

As shown in Figure 3-1 a hybrid bus in series is powered exclusively by the electric engine, while the ICE is used exclusively to produce electricity through an electric generator; the electricity is used to power the electric engine, store energy in the batteries and to provide power for the auxiliary systems such as heating, air conditioning, lighting, air compressors and power steering, among others (Ranganathan, n.d.).

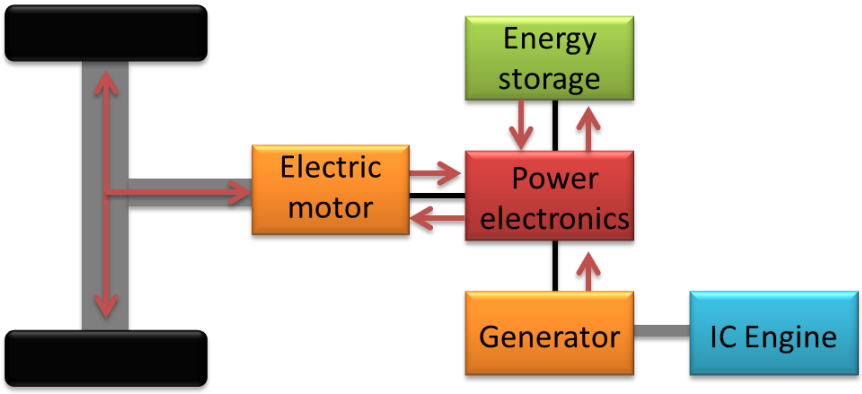


Figure 3-1 Diagram of a series hybrid vehicle (Source: elaborated by the author)

Advantages:

- The ICE can operate at an optimum rate of rotation because it is not connected to the wheels, which means an efficiency improvement of up to 40% compared to engines connected to the transmission (Callaghan & Lynch, 2005) and longer life for the diesel engine (González, 2012).

- In some cases the transmission system can be eliminated, due to the electric motor can be connected directly to the wheels, which means improved energy efficiency and reduced vehicle weight.

Disadvantages:

- Energy not used immediately should be stored in the batteries and this implies a loss of around 20%, since it always generates a loss between the energy loaded in the batteries and the one that can be subsequently used (Callaghan & Lynch, 2005).
- Transform all the ICE mechanical energy into electricity for the electric engine and then into mechanical energy to the drive system generate an energy loss of 15%, or even 35% when the energy also goes through the storage system (Callaghan & Lynch, 2005).
- In the absence of direct transmission from the ICE, the series system usually requires a large battery and an electric motor to move the vehicle (Lorençon, 2012a).

3.2.2 Parallel Hybrid

The parallel system is different from the series system, because both the combustion engine and the electric engine are connected to the transmission through a mechanical coupling (Figure 3-2). Additionally, the combustion engine can be also used to produce electricity for the electric engine, the storage system or the auxiliary systems.

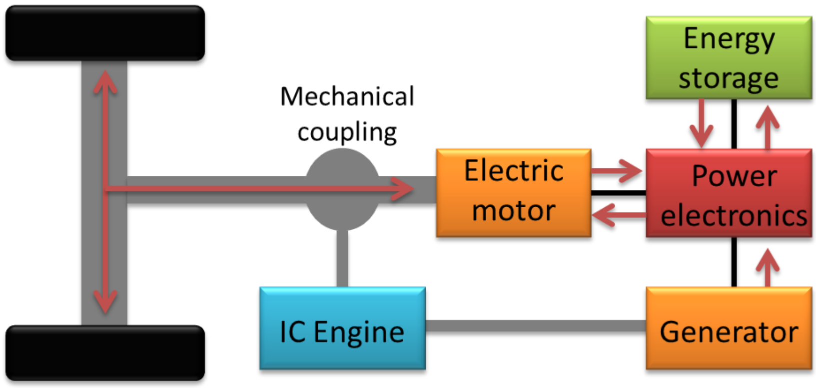


Figure 3-2 Diagram of a parallel hybrid vehicle (Source: elaborated by the author)

Advantages:

- It is possible to optimize the use of electric and diesel engines by switching or combining its operation; for example using the electric engine for starting, the combustion engine during steady speeds or using both engines when it requires more energy for acceleration or slopes (Ranganathan, n.d.).
- Compared to series system, parallel reduces losses of energy during the energy conversion process, since the ICE transfers a portion of the energy directly to the wheels, thus preventing its conversion and storage in form of electricity.
- In case of failure from the electric traction system, the vehicle can continue operating with the internal combustion engine (Lorençon, 2012a).

Disadvantages:

- As in conventional buses it always requires a transmission system connecting the ICE and the wheels, which means energy loss and increase in vehicle weight.
- This system is not compatible with non-mechanical engine systems as a hydrogen fuel cell, since it requires a mechanical energy source as an internal combustion engine (Ranganathan, n.d.).

3.3 Characteristics of hybrid electric buses

The introduction of a new technology to power buses requires the identification of the aspects that differentiate it from the conventional technology and likewise determine which of these factors could become positive or negative aspects for users and bus operators. For this purpose, in Table 3-1 are identified the main environmental, financial and operational aspects of hybrid propulsion compared to internal combustion diesel engines.

Table 3-1 Differential aspects of hybrid buses

Environmental aspects	Financial aspects	Operational aspects
• Reduction of greenhouse gases • Reduction or local air pollutants. • Noise reduction • Better performance during life cycle assessment. • Batteries contain toxic elements that require proper disposal.	• Less fuel consumption provide significant savings. • Uncertainty about maintenance costs • Batteries replacement involves additional cost. • The initial cost of the bus is usually 50% higher compared to a diesel bus. • Higher lifecycle cost.	• The useful life of the bus can be extended in 20% on average. • Fuel saving varies according to the average speed and frequency of stops • HEB´s are preferred by users due to its lower noise and vibration. • In pure electric mode HEB´s can operate in tunnels or underground stations. • HEB´s reduce dependence on fossil fuels. • The electric hybrid technology is compatible with biofuels. • Requires special training for operation and maintenance. • Resale of used HEB´s is limited by its technological barriers.

3.3.1 Environmental aspects

- Greenhouse gases: HEB´s can achieve significant reduction in CO_2 emission that range from a 10% to a 45% according to the specific technology and handling conditions. In the case of Volvo 7700 hybrid bus, these savings are achieved mainly by the regenerative braking system, but also by additional factors such as smaller diesel engine, the "stop & go" system that turns the engine off when the car is stopped, improvements to the transmission system and optimum use of energy in the electric auxiliary systems (Lorençon, 2012b).
- Air pollutants: HEB´s also provide significant reductions in local air pollutants such as particulate matter (PM), nitrous oxide (NOx), hydrocarbon (HC) and carbon monoxide

(CO). These reductions are largely due to lower fuel consumption of hybrid electric technology, but are also favoured by other technological improvements that are also available in the most recent diesel vehicles, such as more efficient engines, filters and after-treatment systems of emissions.

- Noise reduction: a hybrid bus has a quieter ride, which improves comfort and reduces noise pollution in cities (Lorençon, 2012a).
- Life cycle assessment: according to Jobson (2010a) when a Volvo hybrid bus is compared with a similar diesel bus; the environmental impact of the hybrid bus is lower when are taking into account different stages as manufacture, use and disposal of the vehicle.
- Environmental impact of batteries: from the environmental point of view, batteries represent a challenge, for the use of toxic materials and proper disposal required. For the manufacture of batteries, the use of lead has been replaced by other less toxic materials such as Lithium Ion. The final disposal of batteries is usually delegated to bus manufacturers who use to sell used batteries for power backup systems for computers (Akashi, Oliveira, & do Nascimiento, 2012). However, it should be also considered how the battery is finally disposed once it has completely its full useful life.

3.3.2 Financial aspects

- Fuel savings: one of the most beneficial aspects of HEB´s is potential fuel savings. As with the reduction of CO_2 emissions, savings can vary among different manufacturers, but on average it is possible to get a 30% lower fuel consumption compared to a conventional bus. In the future these savings will become more important if it is considered that under one scenarios projected by the International Energy Agency (2011), oil prices will rising constantly until the year 2016-2017 when it will reach a peak price of $150 dollars per barrel (equivalent prices to 2010), which represents an increase of 60% over the current oil price.
- Maintenance costs: while some manufacturers claim that HEB´s reduce the wear of some mechanical components of the vehicle, as the engine or braking system; in practice it is still not certain how significant is the difference regarding maintenance to a conventional bus. For example, in New York which was one of the first cities to introduce hybrid buses, maintenance costs have resulted higher; while in Barcelona costs have been similar to a conventional bus (González, 2012). In the case of Latin America, it is not possible to obtain reliable information, because the first hybrid buses have been recently introduced.
- Initial cost of the bus: the price for a HEB is usually 50% higher compared with a conventional diesel bus. However, these higher costs are compensated directly by the lower fuel consumption and indirectly through positive externalities such as lower emissions of CO_2 and air pollutants.
- Lifecycle cost: although fuel savings and longer life of HEB´s contribute to reduce the initial higher costs, the entire life cycle cost for a hybrid bus in Latin America still been higher compared with a conventional diesel bus. For example, in Brazil the difference in the lifecycle cost is 8% higher (Lorençon, 2012a) and in Bogota is also 13% higher (Olivera, 2012).
- Cost of Batteries: batteries are a key component for manufacturing a HEV, such that they represent one of the biggest costs of the vehicle and one of the components that still requiring further technological development (Miamoto, 2012). Additionally, there is a higher degree of uncertainty about its lifetime and impact on the lifecycle cost of the vehicle.

3.3.3 Operational aspects

- Useful Life: in a similar manner as with pure electric vehicles, a HEV has a longer life compared to a conventional vehicle, for the case of the buses the difference is 20% higher on average. For example, in a hybrid series the ICE extends its useful life because it operates at an optimal speed of rotation which reduces its wear (González, 2012); additionally, the lower vehicle vibration extends the life of some mechanical components.
- Fuel saving varies according to the average speed and frequency of stops: since most of fuel savings in a hybrid bus are obtained from the regenerative braking system, those savings tend to decrease to the extent that the bus has a higher average speed and lower stops (González, 2012).
- Perception of users: in general terms, users have preferences for HEB´s, for example, in the city of São Bernardo do Campo in Brazil, some commuters wait up to 15 extra minutes to take a HEB instead of conventional diesel (Akashi, Oliveira, & do Nascimiento, 2012). This preference for HEB´s can be influenced by the three factors: smoother motion, lower noise and environmental awareness of users (Miamoto, 2012).
- Dependence on fossil fuels: currently the transportation sector is highly dependent on fossil fuels, for example, in the United States during 2005, 84% of the buses were powered by diesel engines (Ranganathan, n.d.). Which besides the environmental impact, it also generates a high dependence on a non-renewable energy source.
- Operation in unventilated areas: considering that some models of hybrid buses can operate only with the electric engine during a certain period of time; it is possible to use HEB´s in unventilated areas such as tunnels or underground stations, where diesel engine emissions are highly toxic for humans.
- Compatibility with different fuel sources: one of the advantages of hybrid system is its flexibility to use different types of fuel, although the most common fuel used today is ultra-low sulphur diesel, the electric hybrid system is also compatible with other energy sources such as natural gas, biofuels or even hydrogen cells. For example, Tata developed a hybrid bus that runs with gas, Volvo 7700 hybrid bus is compatible with biodiesel, and the hybrid bus developed by Scania runs with ethanol.
- Operation and maintenance: like any new technology, the process of adaptation to hybrid buses requires a learning and training for drivers and mechanics. For example, drivers must learn how to optimize the use of the bus during acceleration and braking, although once adapted to the new technology drivers tend to prefer HEB´s (Akashi, Oliveira, & do Nascimiento, 2012); likewise, maintainers should establish new standards for maintenance in accordance with information provided by bus manufacturers and results during operation.
- Sale of used vehicles: buses for urban transportation usually have an estimated life in number of years or kilometres, after which they must replace. In many cases these used buses can be refurbished to continue in operation or could be sold as a used vehicle to be used in another place. In the case of hybrid buses, resale is not so easy, because they have particular conditions which are not easily adaptable to other cities that do not have the required infrastructure to use this new technology. To solve this problem Volvo Latin America provides the conversion of used hybrid buses to conventional diesel, with the idea of facilitate the resale of those vehicles (Lorençon, 2012a).

3.4 Supply of hybrid buses in Latin America

Currently most of the major bus manufacturers include HEB´s in their product portfolio; also a considerable number of regional manufacturers are offering this technology for specific market niches. This boom is due in part to the growing interest from bus operators in this technology and the ease adoption of this technology by bus manufacturers (Akashi, Oliveira, & do Nascimiento, 2012). Table 3-2 shows in alphabetical order bus manufacturers that currently offer or could offer in the near future HEB´s in Latin America.

Table 3-2 Current and potential supply of hybrid electric buses in Latin America.

Brand	Model	Length	Hybrid configuration	Fuel saving	USD Price	Availability
Agrale	Hybridus	12 m	Series	30%	295,000	In testing phase
Eletra	Electric Hybrid	12 m	Series	10 – 20%	420,000	Commercial availability
Eletra	Electric Hybrid	18 m	Series	10 – 25%	650,000	Commercial availability
Foton	Hybrid City Bus	12 m	Parallel	30%	n/a	Commercial availability
MAN	Lion´s City Hybrid	12 m	Series	30%	400,000	Only available in Europe
Mercedes Benz	Citaro Blue Tec Hybrid	18 m	Series	30%	635.000	Only available in Europe
Scania	Omni Link Hybrid Ethanol	13.7 m	Series	25%	N/A	In testing phase
Tatsa	D12H body & chassis D12H chassis	12 m	Series	30%	270.000 215.000	Commercial availability
Volvo	7700 Hybrid	12 m	Parallel	35%	300,000	Commercial availability
Youngman	n/a	n/a	n/a	n/a	300,000	Commercial availability

3.4.1 Agrale

Agrale is a Brazilian company founded in 1962 that manufactures tractors, commercial vehicles, military vehicles and diesel engines; besides Brazil Agrale also has representation in other Latin American countries as Argentina, Chile, Colombia, Cuba, Uruguay and Venezuela. Its traditional business segment has been agricultural tractors, but also has a portfolio for urban and intercity buses, usually powered by diesel engines (Agrale, 2012).

The company introduced in 2009 a series hybrid bus known as "hybridus", developed with Agrale-Siemens technology. The chassis and the transmission as well as the ICE were developed by the Brazilian brand; while the electric drive system known as ELFA which represents 35% of the cost of the vehicle was developed by Siemens. The bus has a 73 passenger capacity and offers fuel savings of 30% compared with a traditional diesel bus. The estimated cost of the hybridus was $295,000 USD at the moment of its launch (Investe São Paulo, 2010).

3.4.2 Eletra

Is a Brazilian company founded 30 years ago, specialized in the manufacture of electric-drive buses as: hybrids, plug-in hybrids, trolleybus and pure electric; using different body versions as standard (12 m), articulated (18 m) and bi-articulated (27 m); with high and low floor. Although its main market is the state of Sao Paulo in Brazil, some of its buses have been commercialized in other countries like Mexico, Argentina and New Zealand (Eletra, 2012).

Eletra production plant in São Bernardo do Campo, Brazil

Representatives from Eletra ensures that its hybrid series buses with lead acid batteries can provide a reduction in fuel consumption of 10% to 20%, although they expect to achieve savings of 25% with the introduction of new technologies in the near future. In the same way, Eletra buses offers a cut of 90% for particulate matter (PM), 60% in hydrocarbon (HC) and carbon monoxide (CO) and 25% in nitrogen oxides (NOx).

The price of hybrid buses offered by Eletra are $420,000 USD for the standard bus of 12 m equipped with a diesel engine of 90 HP and an electric generator of 60 KW; for the articulated of 18 m, the price is $650,000 USD, which has a 160 HP diesel engine and an electric generator of 100 KW.

Eletra also offer the option of retrofit to transform a diesel bus to a hybrid bus, with an approximate cost of $168,000 USD for the bus of 12 m and $260,000 USD for the bus of 18 m; to these values must be added additional costs for mechanical and aesthetic refurbish of the bus (Akashi, Oliveira, & do Nascimiento, 2012).

According to previous experience, in the case of a significant bus order for another country, the best option would be to take the bus assembly process with an assembly plant in the buyer country.

3.4.3 Foton

Beiqi Foton Motor Co., Ltd is a Chinese company with mixed ownership, but whose largest shareholder is the state. It was founded in 1996 and its products portfolio includes buses, trucks and agricultural machinery. This company has fourteen manufacturing plants in China and five manufacturing plants abroad (Foton, 2012), by 2012 it plans to open a new assembly plant in Colombia to meet the growing demand for commercial vehicles in Latin America (EFE, 2010).

Foton offers in its portfolio the Hybrid City Bus, this vehicle was developed in partnership with American Eaton and has parallel hybrid technology. It is equipped with a 220 hp diesel engine and electric motor of 44 kW, for energy storage it has lithium batteries. The body is 12 m for 95 passengers, and the manufacturer claims fuel savings of 30% and a 40% reduction of greenhouse gases (Foton, n.d.). Unfortunately it was not possible to know the price for the HEB offered in Latin America, since this is still being defined by the parent company in China.

3.4.4 Man

The MAN SE Group is a German automotive industry which foundation goes back to 1758 in the Ruhr area in Western Germany. This company is one of the leading manufacturers of utility vehicles in Europe, as well as a world leader in production of diesel engines. Today the brand is undergoing an expansion process towards emerging markets as Eastern Europe, Asia and Latin America (MAN SE, 2012).

MAN Lion's City Hybrid in Rio de Janeiro

Among its portfolio of vehicles they include a HEB known as MAN Lion´s City Hybrid, which has been in commercial operation since 2010 in some European cities such as Munich, Paris and Barcelona. This bus has a length of 12 m and can accommodated up to 93 passengers; has a series hybrid configuration with a 220 HP diesel engine and an electric generator of 60 kW connected to a ultracapacitor of 220 kW. The manufacturer claims that it can get fuel savings of up to 30%, although during its operation in the city of Barcelona the savings have ranged from 20-30% (González, 2012); also offers significant reduction of CO_2 emissions and air pollutants into the atmosphere with respect to a conventional diesel bus (MAN Truck & Bus, 2011). The price of this bus in the Latin American market is unknown, but the estimated value in the European market is about $400.000 USD (González, 2012).

3.4.5 Mercedes Benz

Mercedes Benz is a German manufacturer of luxury vehicles, buses and trucks owned by Daimler AG group. Its origin dates back to the creation of the first gasoline car in 1886 by its founders Daimler and Benz. They were also the first creators of a combustion engine bus in the year 1895 and the first hybrid bus in 1969 (Daimler AG, 2012b).

Mercedes Benz Buses attend European, Asian and Latin America markets in Europe; but the automotive group Daimler AG has other brands like Orion and Setra buses to serve other regions, that together makes Daimler AG the largest manufacturer of buses worldwide (Daimler AG, 2012b). In the case of Latin America, Mercedes Benz has a manufacturing plant for buses and trucks in Brazil and assembly plants in Argentina, and a recent in Colombia which was driven by the growing demand of buses for Bogota during the coming years (Dinero, 2012).

The current offer of Mercedes Benz hybrid buses include hybrid, both electric and fuel cell, however, these models are only sold in some European countries. The Citaro Blue Tec Hybrid model presented in 2007, is an articulated 18-meter bus with a capacity for 150 passengers, it uses hybrid series technology with a 218 HP diesel engine and four electric motors of 80 kW each one, connected to a lithium ion battery that provides up to 240 kW. Under ideal topographical conditions, the Citaro Blue Tec Hybrid can transit up to 10 miles using only the electricity stored in the batteries and it can get fuel savings of 30% compared to the conventional model (Daimler AG, 2012a). This vehicle is only available for the European market and its price is approximately $635,000 USD.

3.4.6 Scania

Scania AB is a European manufacturer of buses, trucks and diesel engines for the maritime and industry sector. The company was founded in Sweden in 1891 and its origins date back to the steel industry. It is now part of the automotive group Volkswagen AG and is represented in over 100 countries and has several manufacturing plants in Europe and South America (Scania AB, 2012).

Since 2009 and with support from Swedish Energy Agency, Scania started operational trials with six hybrid buses in the city of Stockholm. The bus used for testing was the Omni Link ethanol hybrid, this vehicle is a series hybrid of 13.7 m, equipped with a diesel-ethanol engine of 270 hp and one electric generator of 220 kW; for energy storage it has four ultracapacitors of 125 volts each one. The manufacturer claims that it can get 25% fuel saving compared to a conventional bus and this is added to the environmental benefits of ethanol that allows reduction of CO_2 emissions by up to 90% (Scania AB, 2009).

Despite testing electric hybrid technology, Scania does not have a HEB in its current product portfolio, but the goal of the brand is to offer this kind of technology when hybrid buses become profitable on their own, which they estimated to be within three to five years (Scania AB, 2011).

3.4.7 Tatsa

Advanced Technology in Transportation (Tatsa in Spanish) is an Argentinian manufacturer of buses and trucks founded in 2005, currently has three production facilities in Argentina, USA and Uruguay; its representation extends to South America, Central America, the Caribbean and South Africa. In 2011 Tatsa established a cooperation agreement with the U.S. company Eaton Corporation, for the production of hybrid buses in Argentina, the value of this agreement is more than $100 million dollars and they expect to produce 1,500 hybrid vehicles over the next ten years (Tatsa, 2012).

The hybrid model developed by Tatsa is called D12H with parallel configuration; its length is 12 m, has low-floor body and is equipped with a diesel engine of 220 HP. The manufacturer claims that it can get fuel savings of 25% to 30% and 40% of greenhouse gas reductions (Tatsa, n.d.) It currently has six hybrid buses in operation in Argentina and the price of the vehicle for the Latin American market is $215,000 USD for single chassis and $270,000 USD for body and chassis (Garcia, 2012).

3.4.8 Volvo

AB Volvo is a Swedish company founded in 1927, manufacturer of trucks, buses and construction equipment; but also develops components for industry, maritime transportation and aerospace sector. The subsidiary Volvo Buses is one of the largest bus manufacturers in the world, it has production facilities in Europe, North America, Africa and Asia; and its commercial representation extends to over 80 countries (AB Volvo, 2011).

Volvo production plant in Curitiba, Brazil

The hybrid bus offered for the Latin American market is the Volvo 7700 Hybrid B215RH, this vehicle has a length of up to 13,2 m and is offered with high and low floor. The mechanical configuration is parallel hybrid that combines a 216 hp diesel engine with an electric generator of 120 kW, for energy storage it has lithium ion batteries whose useful life is estimated between three to five years. The manufacturer offers fuel savings of up to 35% and during operational tests conducted on various European and Latin American cities, the bus has achieved fuel savings of 29% to 43%, and emission reductions of NOx and particulate matter of 80% to 90% compared to the conventional diesel model (Lorençon, 2012b). They are currently manufacturing the first orders of these buses for the Brazilian market, including 50 units for Sao Paulo and 60 units for Curitiba; the selling price of this bus for the Colombian market is of $300,000 USD (Lorençon, 2012a).

Considering the great importance of articulated buses market in Latin America, it is expected in a near future to also offer the 18 m articulated bus with hybrid technology. This bus is in R&D process, but its release date is limited to the availability of resources and required personnel to support this project; but according to Miamoto (2012) it would be expected to have the articulated hybrid bus available on the market by 2015.

3.4.9 Youngman

Youngman Automobile Group is a Chinese auto factory founded in 2001, from its beginning the brand has maintained its leadership as the largest manufacturer of luxury buses in the Popular Republic of China. This brand has conducted several joint-ventures with some European automotive companies for the manufacture and assembly of automobiles and commercial vehicles in China, such as Neoplan, MAN and Lotus (Yougman, 2007). The company´s portfolio includes cars, trucks and buses for which also offers electric hybrid technology.

Although there are two Foton hybrid buses being tested in Colombian, Foton representatives for Colombia do not provide prices or technical data of the bus

3.5 Technical viability of hybrid electric buses for BRT

As explained previously, buses used in a BRT must meet certain design, capabilities and performance features that differentiate them from conventional bus systems. For this reason it is appropriate to assess various aspects such as size, design, passenger capacity, performance and fuel economy in hybrid buses that are currently commercially available in Latin America.

- Dimensions: bus fleet for BRT include a wide range of vehicles that varies from micro buses or standard buses that work as feeders to articulated and bi-articulated buses for main corridors. The current supply of HEB´s in Latin America is mainly limited to standard buses of 11-13.2 m which are offered by Eletra, Foton, Volvo and Youngman; with respect to 18 m articulated buses, only Eletra offers these vehicles although it is expected that by the year 2015 Volvo will also offer those buses (Miamoto, 2012); with respect to bi-articulated buses, it is also expected in the near future these are offered by Volvo, although Eletra of Brazil would also be able to produce them, but its production is restricted because bi-articulated chassis are only produced by Volvo, who limit their sale to other manufacturers that could manufacture hybrid vehicles with this chassis (Akashi, Oliveira, & do Nascimiento, 2012).
  According to Miamoto (2012) the benefits of hybrid technology are greater the larger the size of the bus is, so it is expected that articulated and bi-articulated buses with hybrid technology will have a greater fuel saving than a standard size bus. We should also keep

in mind that in the Latin American market no micro buses with hybrid technology were found, which according to Akashi, Oliveira, & do Nascimento (2012) is due to fuel savings in smaller buses are not enough to justify the extra cost of hybrid technology.

- Design: BRT buses require special design as the location of the doors or floor height. In this sense, it is possible to say that a HEB is fully adaptable to those design requirements and even high-floor buses offer an advantage since they have more space under the floor of the vehicle that could be used to storage power systems that are usually on the roof or rear of the bus (Akashi, Oliveira, & do Nascimiento, 2012).
- Passenger capacity: buses for BRT are characterized by having a high passenger capacity, which is one of the aspects taken into account in determining the system capacity and profitability for bus operators. In this sense it should be noted that HEB´s have some characteristics that may reduce passenger capacity, for example, in some buses the energy storage system is on the rear of the vehicle, thereby reducing the internal space; or in other cases additional weight of the batteries may decrease the load capacity of the buses (González, 2012).
- Aesthetics: overall the aesthetics of a HEB is similar to a conventional diesel bus except for the cases where the energy storage system is on the roof of the vehicle. Apart from this, it should be noted that hybrid vehicles tend to have a positive image among users, who usually identify them as vehicles with less environmental impact; for this reason, this feature might be used by bus operators to improve the city´s image through logos or colours that distinguish them from conventional buses.
- Performance: According to information provided by the various bus manufacturers, the performance of a hybrid bus can meet the same characteristics as autonomy, acceleration and top speed of a conventional diesel bus for urban transportation. However, the only way to verify this performance is through real testing operation, as in some cases the characteristics of each city as its topography or altitude can affect the performance of the bus.
- Fuel saving: According to several experts consulted, one of the main constraints to introduce hybrids in BRT systems is that fuel savings may be lower than in a conventional bus system because of the higher operating speed of trunk buses. This is due to the regenerative braking system of a HEB gets its power during the stopping of the vehicle and to the extent that the bus has fewer stops, the energy recovery will also be lower (González, 2012).

  In this sense Lorençon (2012a) indicates that the minor saving at high speeds is applicable to hybrid buses in series, but in tests made with the Volvo 7700 hybrid bus, this vehicle can get fuel savings of 30% even operating at similar speeds to a BRT system. However, it was not possible to access data from tests conducted in Latin America in this speed range, since the Clinton Climate Initiative tests were performed simulating driving conditions of a conventional bus system and not a BRT.

4 Study cases

It is common that successful transport experiences tend to be replicated from one city to another and that voluntary cooperation exists between the various transportation organizations for the implementation and evaluation of new technologies. Under this principle of cooperation and thanks to the voluntary collaboration provided by representatives from transportation agencies in different cities, this chapter describes the experiences of four Latin American cities that are testing hybrid buses; along with Barcelona and New York who already have several years of experience with this type of technology in their bus fleets.

4.1 Barcelona, Spain

The city of Barcelona and its metropolitan area comprises 4,000 km^2, with a population of about five million people, for a population density of 1,250 inhabitants per km^2. The main public transport operator is *Transports Metropolitans de Barcelona* (TMB), which operates different public transport systems available in the city, such as 102 km of Metro, 935 km of conventional bus networks, 50 km of tourist bus network , 1.2 km of tram, 0.7 km of tram and 0.7 km of cable car (TMB, 2011).

The bus network in the city of Barcelona is a conventional non BRT system and comprises a total of 1,064 buses, of which 600 are powered by diesel euro 4 and euro 5, 411 are powered by CNG and 60 have hybrid electric technology. The 60 HEB´s operated by TMB are 20 hybrid vehicles in series of the brands Denis and MAN with ultracapacitor, while the other 40 are diesel used vehicles that have been refurbished with Siemens hybrid technology. The retrofit process of these buses was made directly by TMB at a cost of 115.000 EUR per vehicle (González, 2012).

Conventional bus system in Barcelona

According to Gonzáles (2012) technical director of TMB buses, the hybrid buses used in Barcelona can help to reduce consumption, but only to the extent that the bus has a frequent number of stops. For example, when using these urban buses at an average speed of 12 km/h 25% of reductions are obtained, while a speed of 18 km/h reductions decreases to 15% and an average speed of 25 km/h as a BRT, fuel savings would just reach 10%.

In the case of Barcelona that has conventional bus system operating at a commercial speed of 12 km/h, hybrid buses in series have achieved 25% savings in fuel consumption and 25% in NOx emissions reduction. The maintenance costs are relatively lower than for conventional buses, because they operate with ultracapacitors and those no not need to be replaced during the life of the vehicle (González, 2012).

With regards to the limitations of HEB´s, Gonzales (2012) highlights the additional weight of the energy storage systems which can decrease the ability of the vehicle in about 10 passengers. With respect to the higher price of the vehicles that constitutes an entry barrier, those extra costs, it can be offset due to fuel savings and the use of current tax incentives in

Spain. Such as a subsidy of 40% of the extra cost of hybrid buses or the European Directive 2009/33 which establishes the methodology for calculating the environmental costs of public transportation vehicles, when comparing different propulsion technologies for buses, more polluting vehicles are affected with an extra cost over clean technologies.

In the future, the city of Barcelona plans to expand the use of hybrid technology to 30% of its fleet, and expands the use of CNG buses, which currently represent 40% of the fleet. They will continue implementing filters for particulate matter and NOx, which at a price of 15,000 Euros per vehicle, become in one of the most economical options to reduce these type of pollutants in diesel engines (González, 2012).

4.2 Curitiba, Brazil

The city of Curitiba and its metropolitan area have a population of 3.2 million inhabitants and an area of 15,400 km^2 for a population density of 207 inhabitants per km^2. This city is recognized internationally for its innovative urban planning model started during the 70´s, this model is based on a network of BRT and corridors that determine the growth and density of the city, so that the areas of greatest density are located around these corridors while limiting the expansion of the city to its surroundings for a more compact city (Sepúlveda, 2011).

The BRT of Curitiba is known as *Rede Integrada de Transporte* (RIT) and it was implemented in 1974 becoming the first BRT worldwide. The RIT comprises 81 km of road and 1,915 vehicles divided among articulated buses, bi-articulated buses, standard microbuses and double decker buses for sightseeing (URBS, 2012); current fuel for buses in Curitiba is diesel S50 B5[5].

Inside BRT station in Curitiba

Curitiba has always been at the forefront regarding testing and use of alternative fuels in Brazil, since 1995 they have been testing biofuels and the current regulatory framework establishes that for December 2012, each bus operator must have between 5% to 10 % of its fleet operating on biofuels, although this percentage also includes hybrid buses as they are considered a technology with lower environmental impact (Karas, 2012).

As part of the Clinton Climate Initiative (CCI) program to test hybrid and electric buses, in Curitiba was tested for 20 days a Volvo 7700 hybrid and compared with a conventional diesel bus Volvo B7R. The results of those tests can be seen on Figure 4-1, but overall the hybrid bus performed well in terms of fuel consumption and air pollutants compared to a Euro III diesel bus.

Thanks to the results of the tests, this city will incorporate 60 Volvo hybrid buses during the coming. Regarding the use of bi-articulated buses with hybrid technology, Curitiba hopes to incorporate the first Volvo buses of this type in 2014 (Karas, 2012).

[5] Diesel that emits 50 parts per million (ppm) of sulphur and contains 5% of biodiesel

Vehicle	NOx (g/km)	CO2 (g/km)	PM (1.5) (g/km)	Fuel consumption (km/L)
Diesel bus B7R	637	90870	12.6	2.03
Hybrid bus	164	58560	1.4	3.14
Reductions	74%	36%	89%	35%

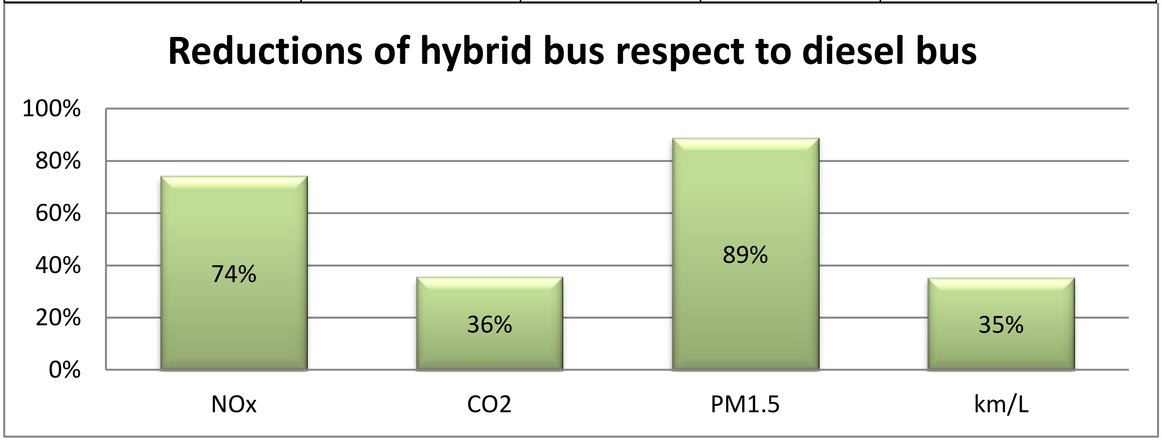


Figure 4-1 Comparison of air pollutants and fuel consumption between diesel and hybrid buses in the city of Curitiba. (Adapted from: Lorençon (2012b))

In order to facilitate the introduction of hybrid buses, whose price is usually higher than a conventional bus, the useful life for those buses can be extended from ten to twelve years (Karas, 2012). Additionally, bus operators can get soft credits from the National Development Bank of Brazil (BNDES) with lower interest rates and longer term compared with credits to acquire conventional buses (Fioravanti, 2012).

Finally, another aspect to emphasize on the management of the buses is the process of disposal of used vehicles. Usually used vehicles have a residual value of 10% and are received as a part of payment for the purchase of new vehicles, which can be scrapped or used in other cities for complementary services such as school transportation or in the case of articulated buses as computer schools, food sales, health systems or support programs for the community.

4.3 Sao Paulo, Brazil

The city of Sao Paulo excluding its metropolitan area has a population of 11.2 million inhabitants and an area of 1,522 km^2, for a population density of 7.383 inhabitants per km^2. The transport system of the city comprises 15,000 urban buses, 65 km of Metro and a complementary network of buses connecting the metropolitan areas of the city (Prefeitura de São Paulo, n.d.).

Trolleybus in Sao Paulo

From the 15,000 buses currently operating in the city, 1.200 use biodiesel B20, 160 use sugar cane diesel A10, 60 use ethanol, 190 are electric trolleybuses and the remaining operate with diesel S50. With respect to the use of hybrid buses, between 2006 and 2008 were conducting tests with fifteen Eletra hybrid buses, but according to de Souza (2012) the results of these tests were not satisfactory due to the high weight of the bus and that the hybrid technology of those vehicles were in an early stage of development.

In 2011, Sao Paulo also participated in the Clinton Climate Initiative program, in which was tested for 16 days, a Volvo 7700 hybrid bus of 12 m and two diesel buses of 12 m and 18 m. In Figure 4-2 you can see the values of emissions and fuel consumption for each vehicle, as well as a graph with percentage of savings terms between the Euro III diesel bus of 12 m and the Volvo hybrid bus powered with conventional diesel and diesel from sugar cane.

The values in Figure 4-2 correspond to local pollutants as total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), particulate matter larger than 1.5 microns (PM1.5); and fuel consumption, expressed in kilometres per litter (km/L). While the hybrid bus always obtained better results than Euro III diesel bus, some pollutants such as NOx may have significant variations according to the type of fuel used. Moreover, it was not possible to obtain values of THC for the hybrid bus operating with sugarcane diesel due to technical failures during testing (C40-CCI-IDB, 2011a).

In the future the city of Sao Paulo and in compliance with local law No 14933 which states that by the year 2018 all buses in the city must be powered by clean and renewable fuels, will continue implementing clean technologies such as biofuels and hybrid buses (De Souza, 2012), and they already ordered the first 50 units of Volvo 7700 hybrid buses (Lorençon, 2012a).

Vehicle	**Total HC** (g/km)	**CO** (g/km)	**NOx** (g/km)	**CO_2** (g/km)	**PM (1.5)** (g/km)	**Fuel consumption** (km/L)
Diesel bus	0.19	8.83	13.52	1442.13	0.321	1.57
Hybrid bus-diesel	0.08	1.02	7.38	995.34	0.097	2.81
Hybrid bus -sugar cane		0.65	13.31	877.97	0.008	2.68

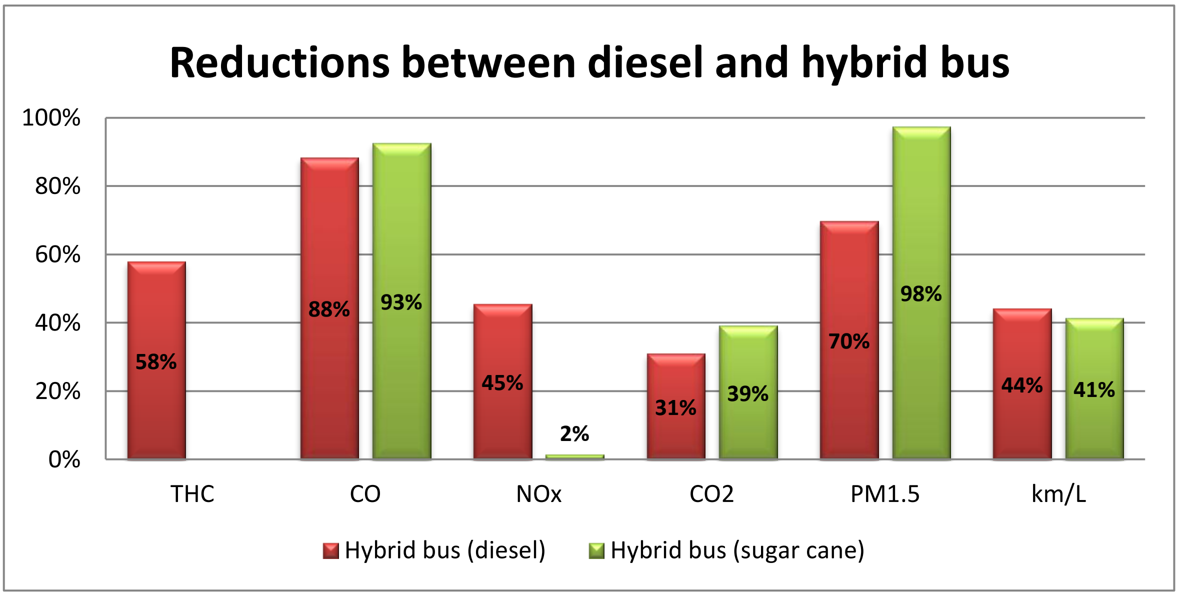


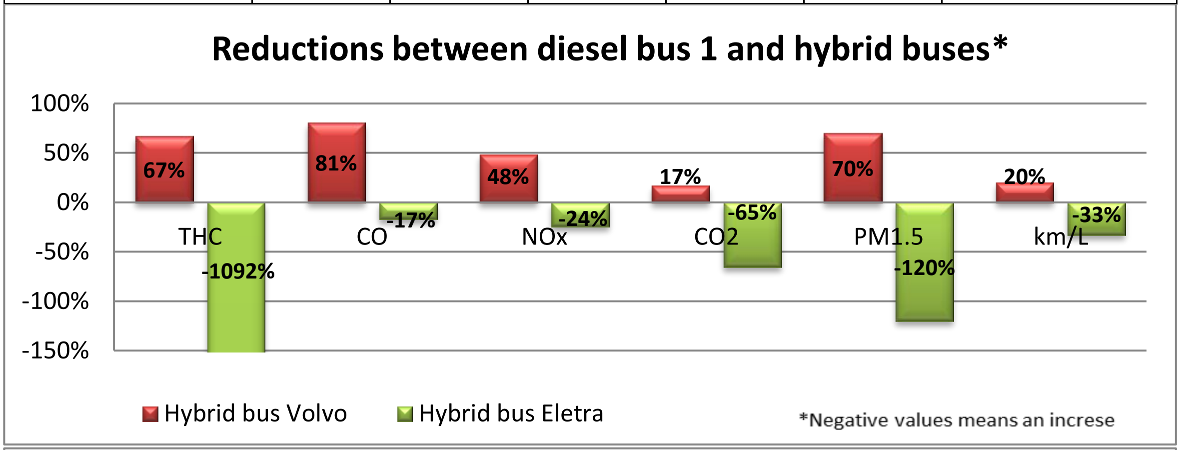
Figure 4-2 Comparison of air pollutants and fuel consumption between diesel and hybrid buses in the city of Sao Paulo. (Adapted from: C40-CCI-IDB (2011))

With regard to the possible limitations of the city for the introduction of alternative fuel sources, De Souza (2012) notes that when vehicles complete their useful life they are often resold to other cities, so the bus owners prefer those technologies where it is not required to perform further modifications for its resale, such as biodiesel. However, it is expected that towards the future, smaller cities begin to adopt renewable technologies for their bus fleets and this will facilitate the resale of vehicles operating with alternative technologies different to biodiesel.

4.4 Rio de Janeiro, Brazil

The city of Rio de Janeiro and its metropolitan area known as *Grande Rio*, has a population of 11.9 million inhabitants in an area of 5,645 km^2 for a population density of 2,108 inhabitants per km^2. The transport system of the city comprises 4.3 km of Metro (MetrôRio, 2012), a network of cable railway, 28 km of BRT and a fleet of 11.084 municipal buses and 5.688 intercity buses (Fetranspor, 2010).

Vehicle	Total HC (g/km)	CO (g/km)	NOx (g/km)	CO_2 (g/km)	PM (2.5) (g/km)	Fuel consumption (km/L)
Diesel bus 1	0.12	5.46	10.07	1073.41	0.1	2.54
Diesel bus 2	0.169	14.08	20.394	1255.172	0.073	2.155
Hybrid bus Volvo	0.04	1.06	5.19	891.61	0.03	3.05
Hybrid bus Eletra	1.43	6.39	12.52	1776.2	0.22	1.7



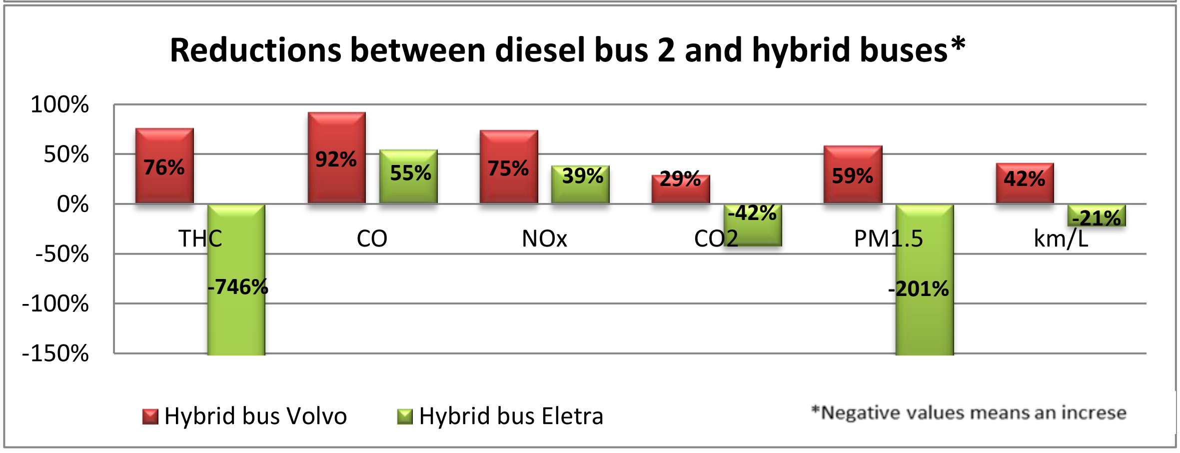


Figure 4-3 Comparison of air pollutants and fuel consumption between diesel and hybrid buses in the city of Rio de Janeiro. (Adapted from: C40-CCI-IDB (2011b))

The fleet of buses in the city is relatively new with 4.5 years on average and its propulsion technology is mostly diesel Euro III corresponding to 90% of the fleet, although it also has diesel Euro V in 1% of the fleet and 60 vehicles operating with ethanol. About the introduction of new propulsion technologies and alternative fuels in Rio de Janeiro, they have conducted tests with biodiesel, sugarcane diesel, ethanol, natural gas, hybrid electric technology and even hydrogen. Within these options and according to Wilson (2012), one of the most viable options is the use of diesel Euro V vehicles powered with sugar cane diesel, which provides reductions of 95% of particulate matter and 90% of CO_2, since this is a renewable fuel.

With regards to hybrid technology, this city also participated in the Clinton Climate Initiative program, with an Eletra hybrid bus, a Volvo hybrid bus and two diesel Euro III and Euro V buses. In Figure 4-3 you can see the values of the emissions and fuel consumption for each vehicle, as well as a graph with the percentage of savings between the two diesel buses and the hybrid buses.

As seen in the test results, the performance of the Eletra bus was in some cases inferior to the conventional diesel bus. According to Wilson (2012), the low performance of Eletra was because this bus was quite heavy and was not designed for operation in the city. On the other hand, the Volvo 7700 hybrid bus obtained significant reductions in fuel consumption and air pollutants.

Although Volvo hybrid bus had a good performance during the test; its potential introduction in Rio de Janeiro is limited by the higher life cycle of the vehicle. According to Wilson (2012) the adoption of this technology can only be given to the extent that there are economic incentives to compensate the extra costs of this technology. Additionally, there is no legislation in Brazil to monetize the environmental benefits provided by clean transportation technologies.

4.5 New York, USA

The city of New York has a population of 8.2 million inhabitants, being the most populated city in North America and its land area is 783.8 km^2 for a population density of 10.519 inhabitants per km^2. The mass transit system is operated by the Metropolitan Transit Authority (MTA) and includes one of the largest subway metro systems in the world with 468 stations and 21 interconnected routes. Additionally, it has a bus system comprising more than 300 routes covering the districts of Manhattan, Queens, Brooklyn, the Bronx, and Staten Island (MTA, 2011).

The average operation speed of the buses is relatively low 8 km/h, and the bus fleet consists of 5.560 vehicles with an age average of 8 years, most of which are powered by diesel engines with particulate matter filters. Emission standards vary according to the model of the bus and are regulated by the U.S. Environmental Protection Agency (EPA). With respect to the use of alternative fuels, they currently have 1,000 buses with CNG and 1.777 Orion hybrid buses in series (Sullivan, Higgins, & LaBouff, 2012).

Hybrid bus in New York City

New York´s experience with the use of hybrid buses go back to 1998, when they conducted the first tests with this kind of technology and in 2001 they ordered the first 125 units of HEB´s (Maynard, 2009). During the introduction, fuel savings were 40% with respect to diesel buses from the 80´s; however, when comparing the existing hybrid buses in the city with the most recent models of diesel technology there are no significant savings. Additionally, high maintenance costs and low reliability have led to stop the acquisition of new hybrids buses in New York (Sullivan, Higgins, & LaBouff, 2012). Regarding the low performance of HEB´s in New York, González (2012) believes that one of the main reasons is that during its introduction, hybrid technology was still under development and for that reason those buses have had many technical flaws.

In the future, the city contemplates the possibility to introduce pure electric buses, but only to the extent that this kind of technology could provide enough autonomy to operate during six hours and provide power to operate the heating and air conditioning systems, which in some cases require more energy than the vehicle traction system (Sullivan, Higgins, & LaBouff, 2012).

4.6 Bogotá, Colombia

Bogotá has a population of 7.3 million inhabitants and an area of 1,587 km^2 for a population density of 4,640 people per km^2. The collective public transportation system of the city has a conventional bus system, a BRT and is currently under discussion the future introduction of a rail system. During 2010 the collective public transportation system of the city mobilized 1,683 million passengers, of which 1,217 million were transported in the conventional bus system and 465 million were transported in Transmilenio (CCB, 2011).

The conventional bus system consists of more than 15,000 buses and micro buses (CCB, 2011), which are operated by more than 60 different companies (SDM, 2012). Those buses comprise about 500 routes transiting at an average speed of 19 km/h. Most of these vehicles have diesel engines, although some have been modified to operate on CNG. So far, the conventional bus system has been operating independently of the BRT, but both systems are being integrated and will become fully managed by Transmilenio S.A.

4.6.1 Transmilenio

Transmilenio began operations in the year 2000 and is now recognized as the full BRT model worldwide, thanks to its high capacity and performance. It has a fleet of 1,317 articulated and bi-articulated buses as well as 535 feeder buses; the average operating speed of the trunk routes is 26 km/h, and the system has an average of almost 200,000 passengers during peak hours (Transmilenio, 2012). Its administration is carried out by the transport agency known as Transmilenio S.A.

BRT corridor in Bogotá

One of the newest additions to Transmilenio is a differential tariff that varies during the day, where peak hours fare is 0.9 USD, while in non-peak hours is reduced to 0.76 USD. The money collected as fees is divided between 70.5% for trunk bus operators, 16.4% for feeder bus operators, 7.5% for the companies responsible for fare collection, 5.5% for Transmilenio S.A. and 0.039% for the trust fund that distributes the money (Semana, 2012).

When Transmilenio began operations in the year 2000, the duration of the contracts with the operators of the buses was defined by the distance travelled by the vehicle, so the contracts will be terminated when the bus fleet completes an average of 850,000 km and when a bus completes a million km it should be removed. Due to the incorporation of new vehicles, the average age of the bus fleet has decreased by up to 30%, which has also extended the duration of contracts, but is expected that by 2013 the first contracts with operators will expire and the first buses introduced into the system will be replaced (Semana, 2012b).

4.6.2 Alternative fuels testing

Transmilenio buses are powered by diesel engines whose emission standards vary from Euro II to Euro V according to the age of the vehicle; it can be emphasized that in 2010 Colombia was the first country in Latin America to introduce vehicles with emission standard Euro V, which were Mercedes Benz articulated buses for Transmilenio.

Vehicle	Total HC (g/km)	CO (g/km)	NOx (g/km)	CO_2 (g/km)	PM (1.5) (g/km)	Fuel consumption (km/L)
Diesel bus Euro II	0.53	6.4	12.19	1011	0.047	2.06
Hybrid bus Volvo	0.03	2.64	1.7	796.62	0.021	3.06
Hybrid bus Youngman	0.03	3.95	6.07	890.72	0.019	3.01

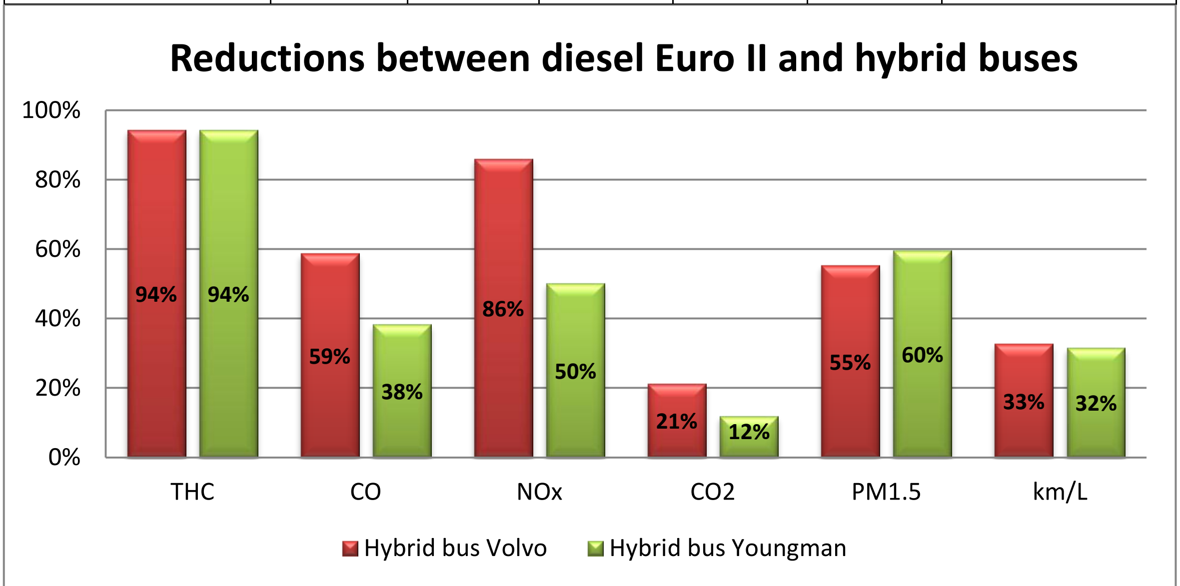


Figure 4-4 Comparison of air pollutants and fuel consumption between diesel and hybrid buses in the city of Bogotá. (Adapted from: C40-CCI-IDB (2011))

The fuel used for Transmilenio is diesel B5 S50 (Rozo, 2012), although Transmilenio S.A. and bus operators have also conducted tests with other types of fuels. For instance, in 2007 palm biodiesel was tested mixed in different proportions as B5, B10, B20, B30 and B50 (El Tiempo, 2007). Similarly tests with a CNG powered bus were held, but according to the results obtained, some modifications had to be done on the ignition system to allow the bus operate in Transmilenio, because Bogotá has an altitude of 2,600 m and the CNG bus lost power (Mantilla, Galeano, Acevedo, & Duque, 2008).

With respect to the introduction of hybrid and electric buses, between 2011 and 2012, Bogotá took part in the programme of hybrid and electric buses of CCI. The vehicles tested were a Volvo 7700 parallel hybrid with capacity for 72 passengers, a Youngman parallel hybrid with capacity for 90 passengers, a BYD[7] electric bus with capacity for 49 passengers and one Euro II diesel bus. It should be noted that the tests were performed simulating operating conditions of a Transmilenio bus feeder at an average speed of 15 km/h and using mixed traffic lanes (C40-CCI-IDB, 2012).

As shown in Figure 4-4 during CCI tests in Bogotá, both hybrid buses had lower local pollutant emissions and lower fuel consumption compared to Euro II diesel bus. Comparing both vehicles shows that the Volvo bus performed better in reducing CO, NOx and CO_2, while the Youngman bus had a greater reduction in PM and both buses had similar performances in fuel consumption and THC emissions.

In the future it is expected that Bogota will conduct a major renovation on its fleet of buses, on one hand they should replace the first buses introduced in Transmilenio, and on the other hand the introduction of the Integrated Public Transportation System will involve the gradual renewal of over 5,000 buses and micro buses during the following years (Acosta, 2012). This future demand has generated a growing interest in bus manufacturers, as the case of Mercedes Benz who recently installed a bus assembly plant on the outskirts of Bogota. The local government also has a growing interest in evaluating alternative propulsion technologies to replace existing diesel buses, in which hybrid technology appears as an option to be considered (El Tiempo, 2012).

[7] Although electric technology is out of reach for this study, it is noteworthy that the BYD electric bus had a consumption of 1.15 km/kWh during CCI, by its kind of technology it does not generate emissions during the operation of the vehicle, has a range of 200 to 250 km between each charge and its FOB price for Colombia is of 440,000 USD (Zhang, 2012).

5 Analysis and discussion

As we have seen, hybrid buses brings some benefits that have been verified by both manufacturers and bus operators such as reduced environmental impact, lower fuel consumption and greater comfort for users and drivers. However, the higher lifecycle cost and constraints of any new technology make it necessary to have a set of policy instruments to facilitate their introduction for BRT and conventional bus systems.

For this purpose, this chapter uses the theory of innovation systems as an analytical framework to describe the different stages during the introduction of HEB´s in Latin America and to analyse public policy instruments to promote introduction of low carbon transportation technologies. Finally, it also includes some discussions to evaluate the relevance of the analytical framework used in this research.

5.1 Analytical Framework-Theory of Innovation Systems

The concept of innovation systems was developed during the 80´s, however, its widespread use and acceptance was achieved during the 90´s, when experts from international cooperation agencies like OECD, The World Bank and affiliated institutions to The United Nations, began using the term (Lundvall, 2005). This generalization has extended its application to different levels of local, regional and national analysis; as well as different study areas such as technology and communications, among others.

In the case of transportation, innovation systems theory was used by E4Tech consulting and Imperial College London Centre, during 2007 in order to evaluate the introduction of low carbon technologies for road transportation in the UK (E4Tech, 2007).

Overall, the systems innovation theory seeks to identify the different factors that influence the adoption of a new technology, and the extent to which each of these factors help or hinder the adoption of this technology. To this end, two aspects are considered: on one hand the different stages of an innovative process, ranging from research and development to the commercialization stage, and on the other hand the interaction between stakeholders, networks and institutions involved in developing this new technology, such as industry, academy, government and consumers.

When considering these factors, one of the main applications of this theory is that through an empirical analysis it is possible to identify flaws in the process of innovation and market mechanisms to incorporate new technologies. The theory also assists in understanding how to approach and reformulate public intervention policies towards a socially desirable objective, such as a better life quality and lower pollution levels (ICEPT & E4Tech, 2003).

In the case of technologies for low carbon transportation, it should be noted that there is less market pull, because the costs of carbon emissions are negative externalities that are not usually reflected in the prices of traditional technologies that generate higher carbon emissions (E4Tech, 2007). For this reason, the introduction of low carbon technologies require a higher level of intervention by the government; these interventions are known as policy instruments and include different alternatives such as regulatory standards, subsidies, market-based instruments, public investment or voluntary agreements that support the introduction of technologies with lower carbon emissions and/or internalize carbon emissions of traditional technologies.

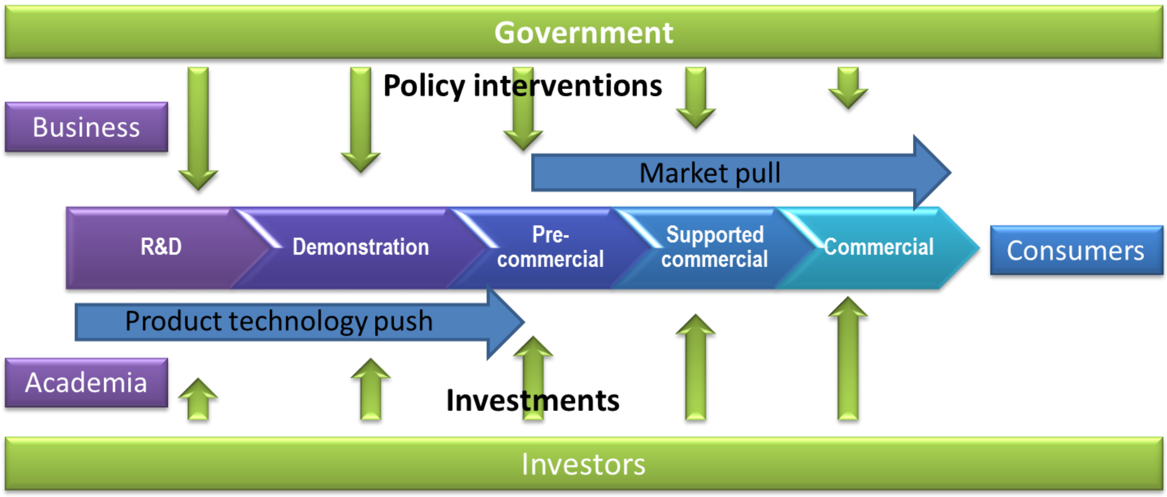


Figure 5-1 Stages in Innovation System (Source: adapted from ICEPT & E4Tech (2003))

As shown in Figure 5-1, the technological innovation processes involves a series of stages, each of which is influenced by a set of actors, driving forces and feedback processes between the different innovation (ICEPT & E4Tech, 2003), which are described below:

- Research and development: are activities mainly developed by universities and research centres that use applied scientific knowledge to develop technologies with practical applications.
- Demonstration: this phase ranges from the development of the first prototypes, until when they are fully functional prototypes. Usually this phase is funded with resources from the stage of R&D.
- Pre-commercial: is the sale of the first units of the product within a specific market niche and involves a high risk investment for first time buyers, for that reason is necessary to have public policies that help reduce the risk for early investors.
- Commercial supported: corresponds to a stage in which a new technology is marketed but still supported by the existence of public policies that favour the introduction of this technology.
- Commercial: in this last stage, the new technology can compete with other technologies within normal marketing conditions and with no need of specific support policies.

5.1.1 Technology Maturity and Policies

As seen in Figure 5-2, the process of market penetration for a new technology usually takes the form of an "S curve", which describes three stages during the introduction of a new technology: a first phase of slow market introduction, a second phase of accelerated diffusion and a final stage of market saturation. This curve was developed at the end of the 70´s and since then has been used to analyse the introduction of different products, from cars to cell phones (HS Dent, 2012).

The "S curve" traditionally uses the horizontal axis to measure the period of time during which the product is available on the market. However, ICEPT & E4Tech (2003) use this axis to show the different stages in innovation systems and related support policies to each of these stages, as described below:

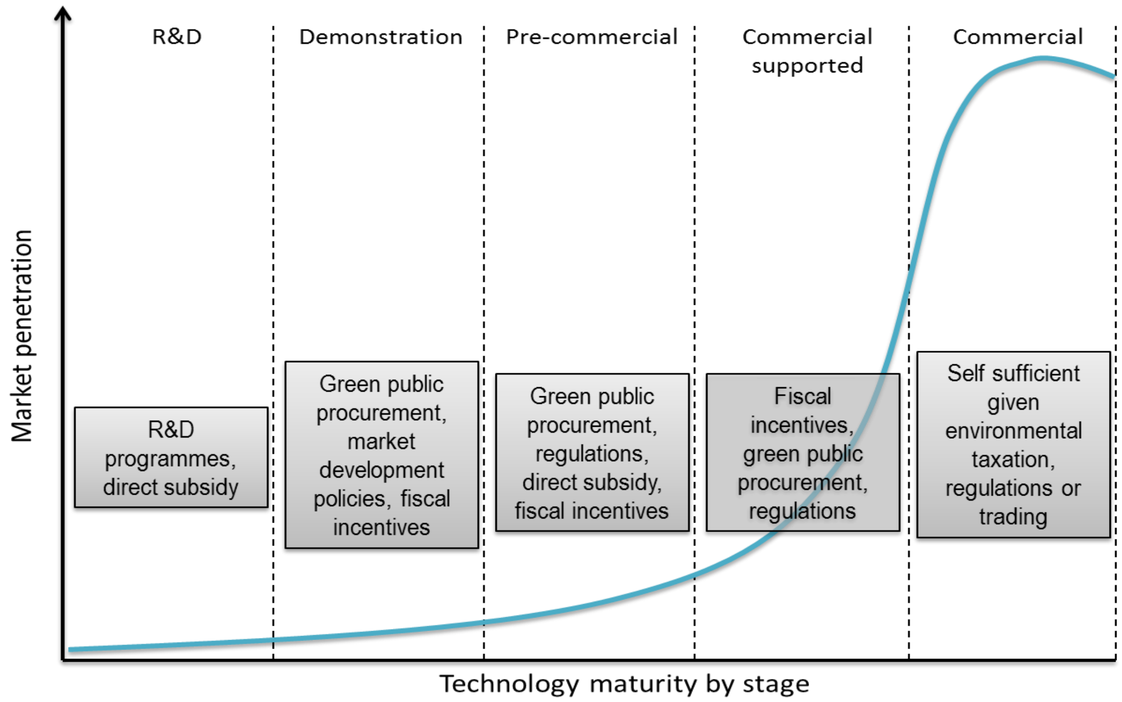


Figure 5-2 Market penetration and technology maturity (Source: adapted from (2007))

- R&D programmes: financing with public resources from the early stages of developing a new technology, can generate benefits in long term for society as a whole and is justified from the economic point of view because the social benefits from new technologies can outweigh the benefits obtained by private companies (Foxon, 2002).
- Market development policies: this type of policies allows the creation of specific market niches where technologies that are in pre-commercial phases can be implemented, thus achieving a learning process for stakeholders
- Green public procurement: is a process where public enterprises promote the acquisition of goods and services that throughout their life cycle can generate a lower environmental impact (Commision of the European Communities, 2008). To facilitate this process, the criteria of the triple base line (environmental, social and economic) is integrated to the processes of acquisition of new products, thereby moving from a private cost-benefit analysis to consider the long term benefits for society. For transportation technologies with low carbon emissions, green public procurement can support the creation of the first niche of markets and their application can be provided from the demonstration stage onwards.
- Direct subsidies: are incentives used by the government to encourage the consumption of a good or service in order to achieve certain social goals. Subsidies can be of two types, supply subsidy when is given directly to producers or service providers, and demand subsidy when the cost paid by the user is reduced.
- Tax incentives: are incentives granted by the state in the form of reductions or tax exemptions to promote the development of certain activities that are considered beneficial to society.
- Regulation: corresponds to technical specifications or requirements developed by state agencies for the development of an activity or service. An example for the transportation sector would be the implementation of maximum emission levels of greenhouse gases or

set a certain percentage of vehicles within a region that must use renewable energy sources.

5.2 Implementation of the innovation systems theory to introduce hybrid buses in Latin America

Based on the theory of innovation systems and according to the empirical information obtained during this research, below are described the different stages for the introduction of hybrid buses in Latin America and a set of policies applicable to each of these stage. It should be noted that many of those policies are also applicable to different low carbon transportation technologies, for that reason at the end of the chapter are also described a set of policies specifically aimed to promote hybrid buses.

Additionally, it should be highlighted that the set of policies identified are not only those previously defined by E4Tech(2007) but also complemented by other policies identified during the case studies, that could be object of further incorporation into this theory.

5.2.1 Stages of the technological innovation process for hybrid buses in Latin America

Below are described the stages of R&D, demonstration, pre-commercial, commercial supported and commercial for the introduction of hybrid buses in Latin America:

Research and development:
While electric hybrid technology vehicles have been around for over a hundred years and the first hybrid bus was developed in 1969, this technology still in development, especially to improve energy storage systems. Also, the development of a new hybrid bus involves a large R&D process, since the idea is conceived until the vehicle is available on the market.

For the case of HEB´s in Latin America, we can identify two categories of technology development; the first one is manufacturers like Agrale, Eletra, Tatsa or Youngman; who through trade agreements incorporate hybrid technology packages previously developed by other specialized industries as Siemens, Eaton or Vossloh Kieppe. And the second one is for brands like Volvo, Mercedes Benz or MAN, who develop the hybrid technology system by themselves.

Regarding the participation of the academy in the processes of R&D for hybrid buses in Latin America, this is usually quite limited, except for a hybrid hydrogen bus developed by the *Universidad Federal de Rio de Janeiro*, which has already been tested in the same city and has an approximate cost of USD 490.000 (Lavaquiel, 2012).

Demonstration:
The demonstration stage in the automotive industry usually occurs in specialized fairs where each brand presents its latest models, for the case of the HEB´s in Latin America it can be noted that during Rio +20 summit, took place presentations of three hybrid buses, the Volvo 7700 hybrid presented at the pavilion of the city of Curitiba, the Lion´s Hybrid city presented by MAN, and a hydrogen hybrid bus presented in the pavilion of the *Universidad Federal de Rio de Janeiro*.

In addition to the demonstration, it is also important to conduct testing of the vehicles to evaluate their performance under simulated operation. In Latin America the most important test for hybrid buses was conducted by Clinton Climate Initiative. This programme cost USD

1.49 billion and its aim was to promote the market of hybrid and electric buses in the region, for which comparative tests were performed between diesel, hybrid and electric buses in the cities of Curitiba, Bogota, Sao Paulo and Rio de Janeiro (C40-CCI-IDB, 2011a).

Pre-commercial:
Usually the introduction of the first hybrid buses in Latin America have been held in cities near to the place of manufacture, for example the first Volvo hybrid buses for Latin America will be introduced in Curitiba, which in turn corresponds to the city where these buses are manufactured; Eletra hybrid buses are in operation in Sao Bernardo, city in which it is also located the production plant, which is owned by the same operators of the transportation agency in the city. This closeness between the point of introduction of vehicles and its manufacturing facility is understandable by the logistics, but also because bus factories are great generators of employment and income for the city, therefore it is understandable that those cities provide support during the early demonstration stages of new buses.

The pre-commercial phase of buses with clean technologies can also be enhanced by the implementation of international events which seek to improve the image of the region, for example, Beijing Olympics in 2008 served as a platform for the introduction of electric buses in this city (Zhang, 2012), and Brazilian government has a growing interest to use hybrid buses during the football World Cup Brazil 2014.

Commercial supported:
In the case of Latin America, the use of hybrid vehicles in a supported commercial stage is not yet in place. However, there are a number of policies that have been used to support the introduction of other clean transportation technologies like biofuels that could be extended to HEB´s and will be explained in the next section.

Commercial:
Given that the lifecycle cost of the hybrid is higher for all case studies analysed, there are no conditions for a pure commercial stage without support policies. However, it is expected that in coming years the cost of a hybrid bus will be equal to, or is less, than the cost of a conventional bus (Miamoto, 2012), in which case this type of technology could compete without any incentives.

5.2.2 Identification of policies to promote low carbon transportation technologies for hybrid buses

Below a set of eight policy instruments to promote introduction of hybrid buses Latin America are analysed, each of those policies can be extended to different stages according to description provided in chapter 5.1.1 about technology maturity.

R&D programmes:
The development of a hybrid bus requires a lot of financial resources which in many cases cannot be funded entirely by private companies. For instance, the development of articulated and bi-articulated hybrid buses in Volvo Brazil, require additional investments by USD 16 million (Olmos, 2011) which are expected to be financed 50% by the Swedish government, 25 % by Volvo, and 25% by the Brazilian government. However, there is uncertainty about obtaining resources from Brazilian government, in which case the development of this project could be transferred to other countries like China or India, where Volvo also has manufacturing plants (Lorençon, 2012a).

It is important to understand that the investment of public funds for low carbon transportation technologies brings social benefits, not only for the environmental impact of these new technologies, but also for the creation of jobs and foreign investment that involves a project of this type. Additionally, when a bus is manufactured in a Latin American country its introduction to neighbour countries can be easily extended, because lower transportation costs and international trade agreements.

Direct subsidy:
Given the higher initial cost for HEB´s the use of subsidies to promote the purchase of these vehicles is one of the most attractive alternatives for bus operators. For example, in Barcelona there is a mechanism that allows subsidizing 40% of the extra cost of HEB´s with public funds, which represents USD 50,000 per vehicle. While this subsidy model is quite effective, its major limitation is that it requires a large amount of public resources that are usually limited in Latin America countries.

Cross subsidies:
It is a subsidy strategy where part of the profit from a product is used to promote the introduction of a new product that usually cannot compete in normal market conditions. This subsidy model does not require the use of additional public funds to promote the new product, but these resources are obtained indirectly by the tariff paid by users, which in some cases could be increased.

An example of cross-subsidy is the one used in Sao Paulo, where the transportation fees are always the same regardless of bus propulsion technology, but the payment received by bus operators varies according to the bus technology, being higher for those buses powered with clean technologies.

Soft loans:
Another type of incentive that is currently used to promote the introduction of clean technologies for buses are soft loans, which have preferential characteristics regarding loans used to purchase conventional buses. For example, a diesel bus for Rio de Janeiro is financed within a period of 10 years, with an interest rate of 10% and 6 months of grace period; while a hybrid bus is financed to 12 years, with an interest rate of 7%, and 24 month grace period (Wilson, 2012).

Because these loans have better terms than those offered by traditional financial market, its necessary to have an additional source of funding which are usually second floor banks, international financial institutions or international cooperation agencies.

Market development policies:
Regarding policies to promote the introduction of hybrid buses and other clean technologies for urban transport, can be highlighted the municipal law No 14933 of Sao Paulo, which states that by 2018 all buses in the city must be powered by clean and renewable fuels. Also there were identified other local and national policies in Latin America countries that aims to reduce air pollution and greenhouse gas emissions, which can be used as a basis to promote the introduction of less polluting transportation systems.

Green public procurement:
Although environmental aspects sometimes are included in the tender process for the purchase of buses in Latin America countries, in many cases the importance of the environmental component is arbitrarily defined by the transit agency or city hall.

For this reason, it is necessary to have regulations to promote the concept of green public procurement, which is not yet sufficiently widespread in Latin America; and likewise to have a regulatory framework to quantify in monetary terms the environmental impacts of different propulsion technologies for buses, which often represent direct costs to the society. For example, higher emissions of air pollutants involve higher costs for the health system due to increased respiratory diseases, and higher CO_2 emissions involve additional resources for climate change.

Tax incentives:
Given that public transportation vehicles are subject to some taxes during its acquisition and use, tax exemption can be an effective measure to promote the use of clean technology vehicles. In the case of Colombia, Decree 2629 of 2011 allows reducing the import tariff from 15% to 5% for electric, hybrid or GNC vehicles (Pearl, 2011). Also the mayor of Bogotá is promoting the 220 Agreement of 2011, which provides tax exemption for five years for electric and hybrid electric vehicles for public transportation (Secretaría General de la Alcaldía Mayor de Bogotá, 2011).

Regulation:
The use of regulatory standards to promote the introduction of clean transportation technologies can be applied by setting maximum emission standards or by rules that favour the use of a specific technology. The introduction of HEB´s can be promoted by emission standards that cannot be met by conventional diesel buses, but only by hybrid buses (Olivera, 2012); or by regulations that promote the use of clean transportation technologies, as in Curitiba, where the regulatory framework establishes that between 5% to 10% of the bus fleet should be powered with biofuels or electric hybrid technology (Karas, 2012).

5.3 Specific policies to promote the introduction of hybrid electric buses

Given that the policies described above can be used to promote various clean transportation technologies, it should be noted that there are also certain specific characteristics of hybrid buses, as longer lifetime that require the use specific policies to promote its use.

Fuel taxes and subsidies:
Fuel Savings of HEB´s can vary from 20 to 40% and are one of the main alternatives to offset the extra costs of this technology. However, the monetary value of those savings can vary significantly according to fuel prices in each country. For this reason, taxes and surcharges on diesel, favour indirectly the introduction of hybrid vehicles, while subsidies to fossil fuels have an opposite effect.

Additionally, when those monetary saving are estimated, future fuel prices should be taken into account, since according to the International Energy Agency (2011) it is expected that oil prices continue to rise over the coming years, thus the savings of hybrid buses will be also be higher.

Extension of lifetime of the buses and contracts with bus operators:
Due to the wear of a HEB is usually less than a conventional bus; its useful life is typically 20% greater. This means that the operating time and depreciation should be extended in the same rate, whereby the higher initial costs can be partially compensated for the longest time during which the bus is in operation. According to this, it is also convenient that contracts with bus operators have equal or more duration than the useful life of the buses.

Final disposal of vehicles:
Given that the resale of used vehicles can be an additional source of revenue for bus operators or transit agencies, it is advisable to have mechanisms to facilitate resale of hybrid buses; such as retrofit for used vehicles or regulations that allow and promote the sale of used vehicles to other cities or countries. Similarly, the sale of used batteries can be also an additional source of incomes (Olivera, 2012), because once replaced on buses, batteries can be used for cell phones or power backup systems (Lorençon, 2012a).

Leasing contracts:
One of the biggest limitations for the introduction of HEB´s is the uncertainty about maintenance costs and batteries lifetime. An alternative to reduce this uncertainty for bus operators and transit agencies are leasing contracts, in which a fixed fee covers both bus rental and maintenance costs. Additionally, bus operators can return the vehicle at the end of the contract if they are not satisfied with its performance.

These contracts can be used for the entire vehicle, as in Copenhagen where they are testing for two years BYD electric buses under leasing contracts (Als, 2012), or only for hybrid bus batteries as is currently offered by Volvo in Latin America (Lorençon, 2012a).

5.4 Discussion

After completing this analysis stage, in which the innovation systems theory was used as analytical framework to assess and apply the information provided by representatives from bus manufacturers and public transportation authorities; it is convenient to evaluate the relevance of this analytical framework and the legitimacy of research questions initially proposed.

Although innovation system theory for low carbon transportation technologies was initially developed by E4Tech to be applied in the United Kingdom, its application to other scenarios such as Latin America is totally convenient. For example, this theory allow us to understand that introduction of hybrid buses in Latin America is not merely a process of commercialization of technologies previously developed in other developed countries, but also involves stages of R&D carried out directly in the region: such as hybrid buses manufactured by Eletra, Agrale, Tatsa and Volvo; whose development is subject to the existence of the necessary conditions to carry out a technological innovation process.

Furthermore, and as shown in Figure 5-3, support policies for the introduction of low carbon transportation technologies identified by E4Tech, served as a starting point to analyse policies applicable to the HEB´s in Latin America. However, those policies initially described in the analytical framework were supplemented by additional policies identified by the author during the analysis of the study cases; for example cross subsidies are available in Sao Paulo for bus operators, soft loans are found in Brazil and Bogota, the methodology to monetize environmental benefits from transportation technologies is suggested by the International Association of Public Transport (UITP, 2009), fuel taxes are currently used in Sweden to cut carbon emissions, extension of contracts with bus operators was suggested by a bus manufacturer, and policies for final disposal of and batteries are related to similar experiences on electronic waste.

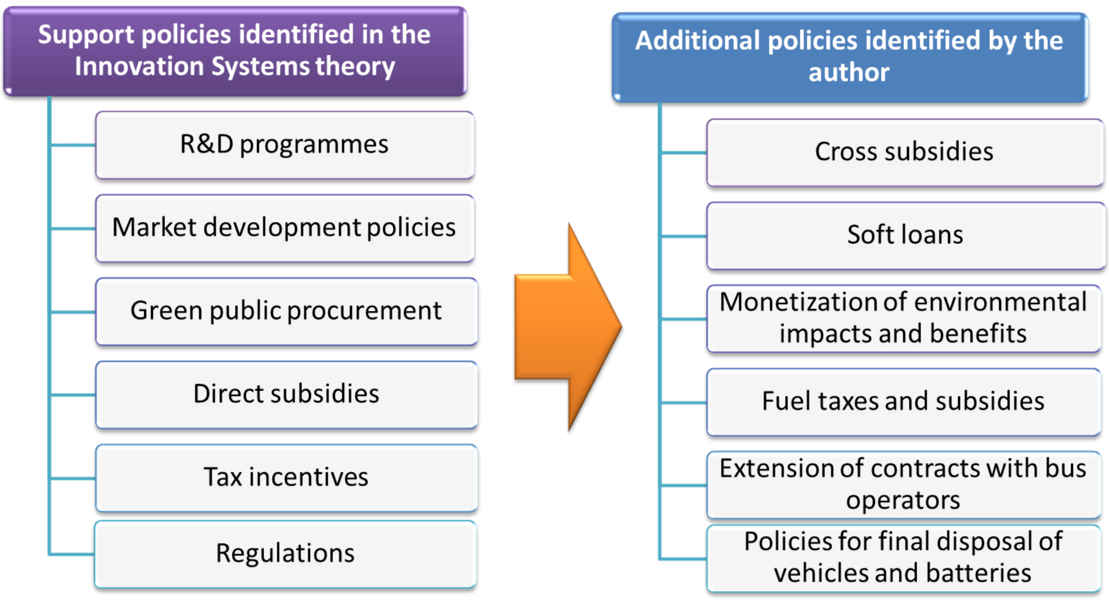


Figure 5-3 Support policies to introduce low carbon transportation technologies (Source: adapted from E4Tech (2007))

It is useful to understand that there are some policies that can be extended to different kinds of technologies for low carbon transportation, but there are certain features of each technology that require specific support policies.

Respect to the legitimacy of the research questions initially proposed, it can be said that the first question about the feasibility of hybrid buses for BRT in Latin America, was defined in a very general way without a specific evaluation criteria to evaluate the feasibility of this technology. However, during this research it was possible to establish that the assessment criteria most commonly used by governments and transportation authorities, includes three components (environmental, economic and financial), which are used in the final chapter to answer the research questions initially proposed.

As for the second question on support policies to promote the introduction of hybrid buses in Bogota, this question is also justified, since there is a great interest to promote the introduction of HEB´s in Bogota, but this could be carried out to the extent that there are enough incentives to offset the extra lifecycle cost of hybrid buses.

Finally, although the results of this analysis were developed specifically for Latin America, some findings could be also extended to other regions that have BRT systems or cities that are currently evaluating the convenience of introducing low carbon technologies in their bus fleets.

6 Conclusions and recommendations

As was explained in the first chapter, the main objective of this research is to assess the feasibility to introduce hybrid buses for BRT systems in Latin America and likewise identify a set of policies that contribute to promote the introduction of hybrid buses in Bogotá. To this end, this chapter answers the two research questions initially proposed and then give some suggestions for future research related to this topic.

Is it feasible to introduce hybrid buses for BRT systems in Latin America?

To answer this question we must start from the fact that BRT systems in Latin America have two different types of buses: high-capacity buses such as articulated and bi-articulated which ride on trunk routes and standard sized buses that operate as feeders or complementary routes; each of which requires a different analysis.

On articulated buses there is not enough information yet to determine whether or not it is convenient, as only Eletra currently offers this type of buses in Latin America and there are no tests performed on this vehicle. Moreover, one of the potential limitations to introduce hybrid buses on trunk routes is the higher operating speed, which could increase fuel consumption for HEB´s since the vehicle reduces the number of stops and braking energy recovering. However, Volvo says that its hybrid bus can offer significant savings even at high operational speeds, but there are no results of tests conducted in Latin America with this bus at high operating speeds to prove this assumption.

Additionally, it should be noted that several manufacturers agree that the larger size of a hybrid bus would get better fuel savings, but this can only be proven through tests for hybrid articulated buses in BRT trunk routes.

With respect to standard size hybrid buses and taking as evaluation criteria the environmental, operational and financial, we can say that its use Latin America is feasible for the following reasons:

- On the environmental side, HEB´s allow fuel savings, lower pollutant emissions and quieter operation compared with conventional diesel buses.
- On the operational side, although there is still a high degree of uncertainty about their maintenance costs, this uncertainty can only be resolved to the extent that first hybrid buses are introduced.
- In terms of financial viability, the lifecycle cost for hybrid buses is higher than a conventional bus, but considering that HEB´s are a low carbon transportation technology that is still in pre-commercial stage, it is entirely feasible the implementation of support policies to promote its introduction and offset those extra costs.

Which policy instruments can help to carry out the introduction of hybrid buses in Bogota as a case study?

In the city Bogotá there are certain conditions that favour the introduction of hybrid buses, on one hand there is great interest from part of the government, headed by the mayor to undertake the introduction of these vehicles, and moreover the tests with hybrid buses showed positive results in terms of fuel savings and reduction of air pollutants. However, during the financial evaluation for the Volvo hybrid bus in Bogotá, its estimated lifecycle cost is 13% higher compared to a conventional diesel bus, so its adoption may only be carried out if there are enough incentives to offset those extra costs. For this end, below are some recommendations and supporting policies that may encourage the introduction of hybrid buses in Bogotá:

- Soft loans: this alternative is already on implementation, since Bogota has approved funds for $ 40,000,000 USD from the Climate Trust Fund to grant preferential credits to encourage the purchase of HEB´s. However, it necessary to define the specific conditions for those loans to compensate all the extra costs for bus operators.
- Disposal of vehicles: the used buses from Transmilenio, once complete their useful life, must be scrapped. But in the case of hybrid buses, it will be convenient to establish policies to allow their refurbishment or sale as pre-owned vehicles, which would constitute an additional source of incomes for bus operators or Transmilenio.
- Regulatory standards: something that is already in uses in other Latin American cities and does not exist in Bogotá is the existence of regulatory standards to promote the introduction of buses with clean technologies. In this sense, it would be convenient introduce a regulation that require operators to have in their bus fleet a certain percentage of vehicles with clean technologies.
- Extension of contracts: considering that the lifetime of HEB´s is 20% higher, it is necessary for future contracts with bus operators to extend their duration according to the technology used, so that operators can use the vehicles during their whole lifetime.
- Monetization of environmental benefits: the lower emissions of CO_2 and local pollutants provided by hybrid buses are positive externalities that provide benefits to the society. However, in Bogota as in other Latin American cities, there is no regulatory framework to estimate what are the social impacts or benefits from different transportation technology. In this regard it would be useful to establish a regulatory framework to monetize positive and negative externalities from different propulsion systems for buses.

In addition to those support policies that are mainly focused on government and public transport authorities, the following describes a series of recommendations for bus manufacturers to promote the introduction of HEB´s in Bogota.

- Introduce hybrid articulated buses: considering that in 2013 will take place the renewal of the first trunk buses introduced in Transmilenio, the replacement of these buses with hybrid propulsion may only be carried out to the extent that hybrid articulated and bi-articulated will be available on the Latin America, because otherwise this implementation could only be carried out for future bus renewals or extensions of the current bus system.
- Demonstrations: Although tests for hybrid buses have been already conducted in Bogotá, there is still a high degree of uncertainty about the convenience of this technology; therefore it would be desirable to carry out additional tests with hybrid buses according with requirements from bus operators and Transmilenio S. A.
- Testing at high speeds: In order to explore feasibility to introduce HEB´s for trunk routes, it is also convenient to conduct tests with hybrid buses at high average speeds.

Suggestions for further research

Given that the assessment about the feasibility to introduce a new transportation technology cannot rely just on the benefits over the current technology, but also on the comparison with other technologies available on the market. The final decision about the adoption of a new propulsion technology for buses in Bogota must be carried out by a cross evaluation which incorporates the criteria of the triple bottom line (economical, environmental and social) to compare different technologies available on the market such as diesel, CNG, biogas, ethanol, biodiesel, electric and hybrid technology, to determine which is the most convenient option for Bogotá.

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