Modern Trolleybuses on Bus Rapid Transit: key for electrification of public transportation

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***Abstract*— This paper presents the enormous advantages of applying modern trolleybuses on Bus Rapid Transit systems –BRT-, to ease the electrification of public transportation with all the consequences that this implies: reduction of energy consumption, substitution of fossil fuels, improvement of air quality on cities and travel experience. As a case of study the hypothetical consequences of the electrification of Transmilenio, one of the largest BRT in the world, are presented.**

Keywords—Electric Traction; Trolleybus; Bus Rapid Transit, Electrification of transport sector.

I. INTRODUCTION

In Colombia streetcars and trolleybuses were abandoned in the decade of 1950, and only a trolleybus system survived in Bogotá until 1990.

In 1996 a Metro system was inaugurated in Medellín, becoming the first and unique system of these features nowadays in Colombia. With its 40 km extension and almost 500.000 passengers transported on a week day, the “Metro de Medellín”, is the only electric traction based system in Colombia.

Unfortunately during the construction of the Metro of Medellín financial problems related to the currency of the Peso, corruption and the decision of president Barco to delay the project to attend other expenses of the country (this delay worsen the currency problem of the debt), brought massive over costs, and the idea that this kind of system are not suitable for a poor country as Colombia.

Other misguided “principles” surged from the over cost in Metro:

- Prohibited cost of electrical traction equipment.
- As corruption is inherent to the state, new systems have to involve privates as operators.
- To select which system should be use, infrastructure cost is the key factor for decision.

Those principles greatly defined the government politics to develop transportation system in Colombian main cities.

By the same time, a new transportation system implemented first in Latin America cities was gaining notability because of its much lower infrastructure cost involved, compared to other system of similar capacity. This new mode was called Bus Rapid System –BRT-, a bus system with many physical and operational elements that give them higher capacity, better performance and a stronger image than regular buses. [1]

A. BRT systems

A typical BRT system features:

- Exclusive or preferential bus lanes, so no traffic jammed is expected. This is right of way category B and C.
- Defined stations to board and get off.
- Pre boarding payment, avoiding delays associated with this transaction on board.
- Programmed and organized schedule, high frequency dispatch.

These features facilitate (see fig.1) the operation of electric trolleybuses because solve or minimize the major disadvantage of this kind of vehicles: inflexibility due the connection to the over head line; even though trolleybuses have operated without the benefits of preferential or exclusive lanes, undoubtedly their performance on mixed traffic is not the better.

A BRT system could be considered as an optimization of the usual bus mode, allowing increase both capacity and speed, and inherently comfort and safety. Taking into account those elements, in 1992 the government of the city of Bogota decided to solve the transit problems, by implementation of a large BRT system across the city, instead of a Metro. Bogotá is the capital of Colombia nowadays with more than eight million inhabitants.

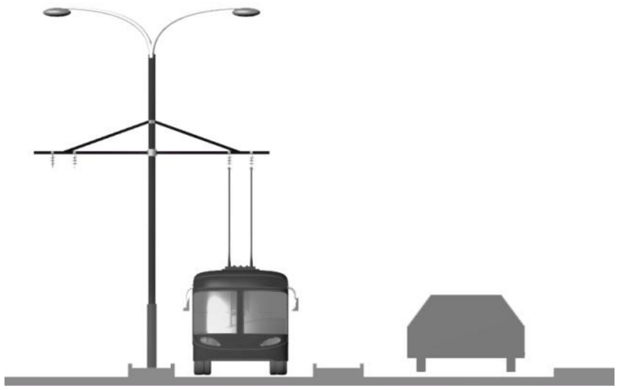

Figure 1. BRT right of way facilitate trolleybus operation and reduce visual impacts of the overhead line

The system was called Transmilenio and nowadays it transports around a million people daily trough 84 km of dedicated bus lanes, becoming one of the largest BRT system in the world, and being considered a reference in the world. Immediately the system was considered a success because the low cost and short time of implementation and construction compare to the Metro of Medellín; Transmileno became a reference to follow in the whole country, and even to other Latin-American countries.

Despite the richness of hydro power of the country, electric traction was not considered for the buses and instead, diesel technology was selected.

Since then the policy established in Colombia is to reproduce the Bogotá BRT experience in the main cities of the country, avoiding building either light or heavy rail Transit systems. Following this policy, in each case the National Planning Bureau designs a financial plan, where the Nation and the municipality are compromise to assume the expenses related to the lanes infrastructure, and a private operator is selected trough public bid, to operate the system for an establish period between 12 and 24 years. The costs of a BRT system are mostly associated to the infrastructure of the lanes, the stations, the repair and parking yards and the suppliers of combustible.

To make the BRT profitable to a private operator, it only assumes the cost of the vehicles; build the parking yards and the combustible suppliers. It is not expected that the cash flow return the investment related to infrastructure that the state built, but the system must be sustainable itself, the incomes must cover the expenses related to the operation such maintenance, energy, salaries and the investment on the vehicles.

Considering this, each new project requires a Financial, Legal and Technical Structure –FLTS-, usually afforded by the municipality, in order to get funds from the nation and international banks, who loan resources up to 70% of the investment on infrastructure; the other 30% is usually assumed by the municipality.

Unfortunately for Transmilenio, electric traction was not considered, and instead articulated diesel buses have been operating since the inauguration of the system. In this case the example was Curitiba, Brazil; considered the system that inspired BRT constructions in the entire world. All the other systems in Colombia were conceived also whit diesel buses. Pereira and Cali ones are operating now with diesel, and only in Medellin it is supposed to operate with compressed natural gas –CNG-, after a debate against diesel, and for the first time in Colombia, electric energy. The decision to operate with gas generated a polemic, and to support the decision local government argued that private operation should not be profitable considering the short time of the concession: 15 years.

II. Modern Trolleybuses

A trolleybus is an electric bus supplied by an overhead line circuit (AC or DC) through a collector system known as "trolley" (fig.1). The trolley is in contact with the airlines when the vehicle is in motion. Over the years the trolleys have undergone several transformations due to technological developments, which can be represented in three generations.

A first generation of trolleybuses (1890-1960) used for traction switchboard electric machines, usually fed by direct current, which thanks to its high torque characteristic and easy of speed regulation, were the undisputed best option. First, the starting and speed control systems consisted in variable resistors connected in series with the traction motor, until power electronics allowed the incursion of controls as the chopper, substantially more efficient because there was no energy wasted as heat.

Figure 2. On BRT operation visual impact of the overhead line is reduced

The successful raid by AC motors controlled by power electronic inverters could be considered the beginning of a second generation of trolleybuses. The machine preferred is the induction squirrel-cage rotor. Also, some trolleybuses have been equipped with energy storage devices such as batteries, capacitors and even flywheels, which allow operate the bus some miles unplugged of the overhead line, increasing the flexibility and reliability of the operation. With this system became possible to overtake another trolleybus or obstacles. This also is used in conservation areas (Rome is a good example) where is not desirable the overhead line, in complex crossroads and for workshops and facilities (fig. 3).

Some other models are equipped with combustion engine as a backup, usually less powerful than the electric motor, which can make traction in conjunction with the electric motor similar to how they operate so-called parallel type hybrid vehicles, or simply be used to produce electricity in a similar manner to operating a series type hybrid vehicle delivering greater robustness and reliability to the operation. In the case of serial operation, it requires an additional electric generator coupled to the combustion engine to generate electricity.

Figure 3. Trolleybus using his energy backup: batteries, ultracapacitor or thermal engine. Ideal to avoid overhead line where is undesirable.

Recently, the lower cost of magnetic materials and the development of high-speed electronic drivers have prompted the use of permanent magnet motors. These engines have a higher torque than the squirrel-cage rotor, in addition to being lighter and more efficient. They are designed so that did not require a transmission or gearbox, which can be coupled directly to the wheels, improving system efficiency and lowering significantly the weight of the bus.

Overall, trolleybuses offer the best dynamic performance to climb gradients, acceleration, comfort, less vibration and bring zero emissions on the streets. This feature is especially convenient for many of cities in Latin-America that are embedded in the Andes Mountains. As an example 18m trolleybuses in Quito have not problem to climb gradients up to 20% inclination. The key for this skill to climb gradients, besides the high torque of electric motors at any speed (thanks to the controller), is the use of tires, which have better adherence to pavement that a tram wheel with the rail. Usually large trams are limited to 11% gradients, but recently a tram on tires vehicles known as Translhor, from Lhor industries, features gradient ascension capability till 13% slope.

III. ENERGY DEMAND, OPERATIVE AND INFRASTRUCTURE COSTS

A. *Energy demand and operative cost*

To establish the energy demand of the vehicles, articulated buses TransMilenio system in Bogota, are taken as reference, with a capacity of 160 passengers. The electric bus considered equivalent corresponds to vehicles operating trolleybus system in Quito. As shown in the table, trolleybuses are by far the most efficient; consuming nearly half of the energy they consume hypothetically a hybrid bus in the best. The consumption of CNG (1.23 km/m3) bus is declared by the tests conducted by the National University [4] and diesel for the best performance data reported for Transmilenio (5.9 km/gl) operators. For the hybrid buses an optimistic performance 30% more efficient than diesel buses.

TABLE I. ENERGY CONSUMPTION AND MAINTENANCE COST

Topic	**Articulated Bus Technology**			
	Diesel	***Hybrid***	***CNG***	***Trolleybus***
Energy kWh/km	6.3	4.4	6.6	2.25
Energy cost USD/km	0.59	0.49	0.48	0.23
Maintenance USD/km	0.19	0.25	0.21	0.15

The maintenance costs were estimated using information provided by the operators of Transmilenio articulated buses, the engineering staff of the Metro de Medellin, and operative date from the trolleybus system in Sao Paolo, Brazil, and Quito, Equator.

The cost of the electrical infrastructure required to operate a BRT is very low in relation to civil infrastructure. Taking as a reference value 25 MUSD / km for the cost of a BRT way in Colombia (though they have reached values close to 40 MUSD / km), the worst case value of the electrification estimated is 1 MUSD / km (Quito electrification cost rounded 0.8 MUSD / km, covering medium voltage lines, substations, transformers, rectifiers, over head lines and poles); so the maximum increase in the total cost of infrastructure required for an electric BRT is just 4%.

A financial model was developed to assess if the operation of the Transmilenio system using modern Trolleybuses is profitable for a private operator, taking advantage that new concession periods are for 24 years, which is an acceptable lifespan for a trolleybuses, against 12 years of combustion technology buses. The financial results will be explained further.

B. *Energy outolook for electrification*

The transport sector demands a third of primary energy transformed by man, and if this remarkable participation is not enough warning, it must be the fact that almost all this amount of energy comes from the oil, a nonrenewable resource whose specific use in traction motors implies necessarily a combustion, and therefore the emission of greenhouse gases and toxic substances into the atmosphere. Logically, with such high demand for energy, transport sector has a significant weight in the emission of greenhouse gases (14%), weight similar to that of agriculture worldwide. Transport sector have more weight on global warming that change of land use, electricity generation and heating.

In Colombia, the share of transport sector's energy demand (36%) is higher than the global average (32%) and that demand share in the U.S. (29%). Virtually all of this energy comes from liquid fossil fuels, mainly petrol and diesel.

It's possible to conclude that the global economy and overall the country, depend largely on non-renewable resource, presenting a high vulnerability to the prices that these assets may have in the international market which is mired in an increasingly volatile geopolitical, but above it is alarming that the very use of these liquid fuels contribute substantially to global warming, considered one of the most serious problems facing humanity.

It is clear then why reduce the consumption of liquid fuels in the transport sector has become a global goal, regardless of how effective they can be, governments or international organizations actions have to be established for this purpose.

Likewise, the reduction in consumption has failed to be achieved by improving the energy efficiency of internal combustion vehicles, proving to be insufficient for the magnitude of the problem, and although much of the current efforts focus on particular vehicles, the opportunity of large-scale replacement of fossil fuels by electric power, is on mass transportation systems.

But it is convenient to review the source of the electric energy, to verify whether the substitution brings net benefits, and for this the primary sources used for electricity generation must be established.

Currently coal is the main resource for electric power generation by 42%, while renewable, mainly hydropower contributing only 20%. This can be considered bleak, but taking in account that there are more coal reserves, not linked to international cartels as the oil, and that electric-drive vehicles have a high efficiency, is becoming evident that the substitution is advantageous. From the environmental point of view can be argued also, that emissions of gaseous pollutants are concentrated generation centers to distant cities, where it is easier to control, and reduces the emission of gaseous pollutants within cities, improving air quality.

The outlook for electrification in Colombia is better than the world stage, because the share of renewable energy is much higher (33%) than the world average. It's quite remarkable that one third of primary energy currently consumed in the country comes from hydropower, a renewable source. Moreover, the installed hydro power capacity accounts 67%, and its annual share of total generation is about 80%.

The rest of the installed capacity is intended to ensure the power supply when the reservoir levels of hydro plants reach their limits in times of drought. Mainly thermal natural gas plants (28%) are used as backup, and minimally coal is used opposed to the world average.

Natural gas is the second important resource for energy production (20%, coincidentally the same share that world average), and although it can be used directly in cars and buses for transport of medium capacity, it should be noted that conversion to the energy generation plants achieves power efficiency around 50%, while in the vehicles would only be around 25% at best, to levels as poor as 15%, taking into account the altitude of operation, poor engine maintenance and poor driving habits.

This indicates that it is preferable to convert gas into electricity, centralized in thermal generation plants, outside the cities, at a low altitude; and transport the energy to the cities to supply electric vehicles such trolleybuses and trams. This process can have an efficiency of at least 35% (assuming 10% losses in transmission and distribution system and 20% energy loss in the motor), much greater than if the gas is burned in the bus, at high altitude and where the people are exposed to the exhaust substances.

In cities like Bogota, which is at 2600 meters over the sea level, the use of electric motors is even better, because they are not affected so dramatically by the altitude as combustion engines, which increases fuel consumption and the emissions of polluting gases.

To assess the real impact of electrifying Transmilenio on greenhouse gas emissions, the annual energy consumption of the main routes are estimated for each technology. Main routes are those with exclusive way infrastructure, especially easy to electrify, nowadays the system counts 84 km of main routes, where 1080 articulated buses operate. As Table II presents, even if there are counted the emissions of the whole chain of the electricity, from generation to consumption, the reduction of CO2 are around 50.000 T each year.

TABLE II. ANNUAL EMISION AND ENERGY DEMAND

Topic	**Articulated Bus Technology**			
	Diesel	***Hybrid***	***CNG***	***Trolleybus (Electric Energy)***
Emission Factor	74.066 kg/TJ	-	56.100 Kg/TJ	0.28 kg/kWh[a]
Annual Emission in Co2 Tons	140.852	117.377	113.397	54.487
Annual energy consumption in TJ	1.902	1.585	2.021	689

a. Emission factor for Colombian Electric system

In the cases of technologies that operate with diesel or CNG, the emission factor is from the bus, the emissions related to production and transports of the fuel were not considered; obviously the greenhouse emission from the trolleybus is zero.

It is also important to highlight the enormous energy savings from nonrenewable sources, and their substitution for renewable ones. Also a contract between the operator of the buses and a utility to buy only hydro energy could be consider, is should be noted that the emission factor of Colombian electric system is increased because the thermal generation.

IV. FINANCIAL MODEL

A financial model was implemented to determine the advantages of Trolleybuses compared to Diesel, Hybrid and CNG buses. This model takes into account operative, administrative, infrastructure, vehicles and financial costs, as well as incomes for tickets selling, for all bus technologies.

The operative costs include energy, buses and infrastructure maintenance, and operative salaries. For energy costs, the model uses diesel and CNG scenarios published by Colombia's energy planning organization (UPME) [5], and electricity scenarios given by CODENSA, the Bogota's utility. The macroeconomic information used (as inflation and currency) is the official from the Banco de la República.

The administrative costs contain the insurances and vehicles taxes, the administrative salaries, and other taxes and costs related to tickets collection.

The infrastructure costs are only accounted for the Trolleybus technology, because it is the only one that needs overhead lines and substations to make possible its operation. The costs of service stations associated with Diesel, CNG and Hybrid buses are contained in the corresponding energy prices.

Infrastructure building and vehicles acquisition in BRT systems demand a great amount of money, so the investors need a financial leverage to make possible the system construction. The model takes into account this fact, including the interest and amortization of loans in the financial flux.

The bus system incomes are calculated multiplying the annual passenger quantity and the bus fares, and are the same for all technologies.

The financial model was applied to Transmilenio system. The calculation period was 24 years, as it is made in actual tenders for operating the public transport system in Bogotá. It is considered that all technologies, except trolleybuses, must be replaced at the 12th year, so they reach their service life (trolleybus service life is greater than 24 years, even there are trolleybus systems with vehicles older than 30 years). A sensitive analysis was also made taking as independent variables the Trolleybus cost and the annual travel of vehicles and as dependent variable the Net Present Value of the system in the evaluation period (24 years).

TABLE III. FINANCIAL SIMULATION DATA

System length	84 km
Number of buses	1.080
Bus travel per year	85.000 km/year
Passengers per kilometer index	5 passenger/km
Trolleybus cost	
Diesel bus cost	325.000 USD
CNG bus cost	422.500 USD
Hybrid bus cost	525.000 USD
Electric infrastructure cost	733.989 USD/km
Trolleybus service life	25 years
Diesel, Hybrid, CNG bus service life	12 years

As it shows figure 4, the trolleybus systems are represented in two ways, considering or not the electric infrastructure. When considering electric infrastructure, the trolleybus system is better than all other technologies with an annual travel greater than 78.800 kilometers per year, which could be easily achieved with actual Transmilenio system, whose vehicles travel more than 85.000 kilometers per year. When the electric infrastructure is not considered, this value decreases to 52.300 kilometers per year, a better case for Transmilenio.

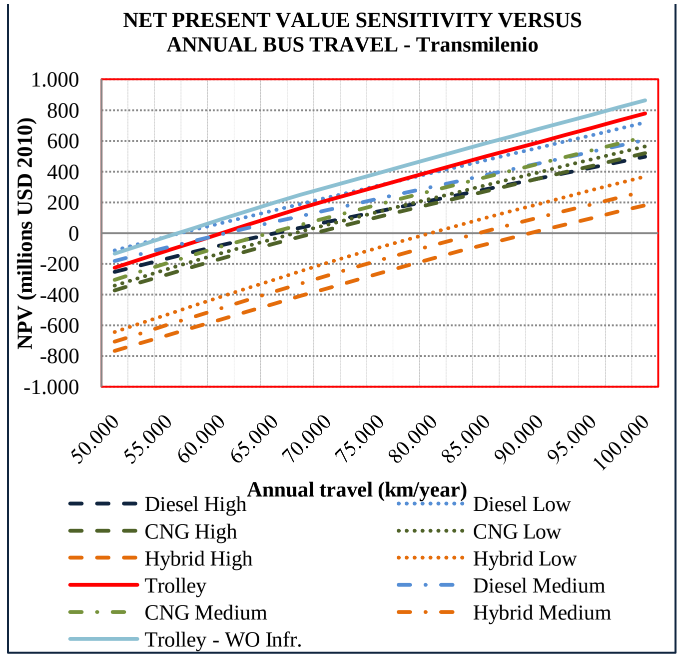

Figure 4. Financial results varying annual bus travel

In the sensitivity analysis varying trolleybus cost (figure 5), the results show that a trolleybus system including electric infrastructure for Transmilenio is financially better than all technology scenarios if the bus cost is less than 606.000 USD.

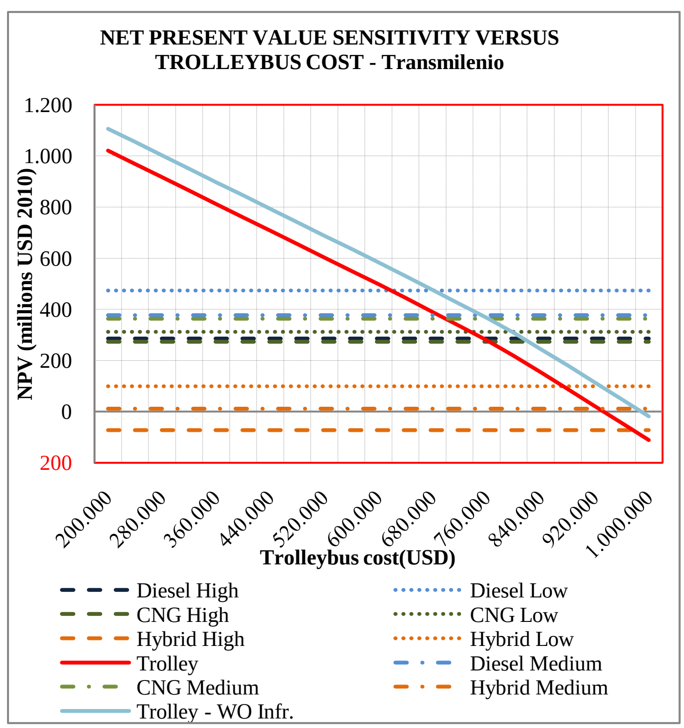

Figure 5. Financial results varying trolleybus cost

If the electric infrastructure is not included, this value increases to 668.000 USD. As an example, Brazilian articulated trolleybuses cost around 560.000 USD.

Despite that even if the private operators expends the infrastructure required for the electrification, the project is profitable, it should be recommended that the state assumes the investment, as a part of the whole infrastructure of the BRT. This because the lifespan of the equipment related to substation and overhead lines, usually surpasses the concession period (in some cases with good maintenance practices this equipment have reach more than 50 years in many cities), and taking in account external benefits to the society related to electric traction such:

- Reduction of noise levels, because trolleybuses are by fare quieter than the other buses.
- Reduction of pollutant that affects the health.
- Increase of the comfort, because less vibration and finest acceleration.

The first two benefits are also associated to the implementation of a BRT itself, because of the rationalization of the amount of buses, but clearly in cities with high population density this is insufficient. A study conducted by the university Los Andes of Bogota found that the particulate matter ambient concentrations in the air of Bogotá tend to be much higher than the levels suggested by international air quality standards [6]. The study also points the diesel buses as one of principal sources of this particulate matter, and states that Bogota´s inhabitants during significant periods of time, are been exposed to toxic pollutants levels considered inadequate by the World Health Organization and the United States Environmental Protection Agency.

Table IV presents the estimated yearly emission of the articulated buses of Transmilenio, considering different technologies of engines according to the European emission standards. PM is the particulate matter, HC, the hydrocarbons, and NOx the Nitrogen oxides. It is important remark that meet higher requirements will imply higher cost of the buses, with special engines and filtering devices, and also the over cost of the fuel should be consider. Vehicle aging and maintenance practices also have effects on the emissions, and for a private operator is not clear the incentive to these additional expenses. These standards are progressively stricter, as science establishes the relationship between this pollutants and a wide range of diseases.

TABLE IV. TRANSMILENIO YEARLY EMISSIONS OF POLLUTANS

Articulated bus EngineTechnology	Yearly Tons		
	PM	HC	NOx
Euro III	3966	26180	198333
Euro IV	793	18247	138833
Euro V	793	18247	79333
Euro VI	396	4297	13222

The electrification is an overwhelming measure to make zero these emissions on street and effectively reduce the exposure of population to toxic and carcinogen substances. Further studies should asses the economical this impact on the public health in Bogota.

V. CONCLUSSIONS AND RECOMENDATIONS

Modern trolleybuses are unquestionably an option to be considered for operate medium capacity transportation systems in Colombia. When vehicles are used intensively (bus covering more than 60,000 km per year), fuel and maintenance cost makes trolleybuses more attractive than other buses. Even assuming a conservative growth of fossil fuel prices, now is possible and even attractive to a private the operation of transportation systems based on electric traction.

Remarkable is that financial results show that even if the private operator expends the cost of the infrastructure required, and the additional cost of the bus; electric trolleybuses becomes an opportunity to significantly increase profits, if the span of concession is larger than the life cycle of the combustion vehicles. Also is important to point the fact that a relation cost of almost 1:2 between diesel bus and trolleybus is compensated by maintenance and energy cost, which means that diesel system, is greatly dependent of variable costs in contrast to the electric project. A mass production of trolleybuses will reduce the cost of the vehicles, but is recommended that local manufacturers participate assembling the buses as an strategy to lower the production costs, and avoid any undesirable impact in local industry.

Should be a matter of concern the risk associate to the volatility of oil prices due the fuel share in total cost nowadays is close to 40%

In systems of rapid transit buses (BRT) as the Transmilenio, where the infrastructure has a dedicated lane or exclusive to the movement of buses, trolley-type technology is ideal, the visual impact of supply networks is minimal, and poles required for it can be used for street lighting or vice versa.

This kind of assessment should be applied in every city which intends to implement a BRT system, using local information about energy prices. If the result shows that the use of electricity is not profitable to a private operator, because of the low prices of natural gas or diesel locally, then is recommended that the state help with the additional expenses related to the change of technology, in return to the social benefits associated to the use of clean buses.

It is important to develop a standard methodology that allows assessing the social cost of the external benefits that brings the electric traction as reduction of pollutants, energy savings, reduction of noise levels, and increase of travel comfort.

Even though there is an effort to improve the capacity of energy storage devices such batteries, fuel cells and ultra capacitors that eventually will make unnecessary the use of the overhead line, this expectation should not be use to delay the electrification of transportation systems. This because the same trolleybuses acquired nowadays, could be easily equipped in the future with this devices as many of the trolleybuses already have it, such batteries in the case of Rome and Vancouver, and even ultra capacitor in China.

Is most likely that systems in the future will still retain some of the overhead line, for example in high slope gradients where the consumption of energy is important. Also the remained overhead line could be used as a charge system with the advantage that the bus is working and is not parked. The decision to withdraw a section of the overhead line, have to consider the extra cost related to the reduction of the life span of the batteries, the energy losses related to the process of charge and discharge, and the extra cost of the infrastructure required for rapid charge. This also must be considered for hydrogen and plug-in hybrid technologies.

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