# Reintroduction of Trolleybuses in Colombia: An Opportunity for the Development of Sustainable Transport

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***Abstract*--Colombia is a country privileged in energy level: it has enough water, coal and renewable energy reserves to meet the electricity needs of future generations. However, it is a lagging country at mass transit in their cities, especially electric transit, because despite having five cities with over one million inhabitants, only one-Medellin- has an electrical system, while others favor the use of a few modes of transportation based on fossil fuels.**

**Although the country is known worldwide for BRT use, as the case of Bogota, in the use of electric transportation systems there are great opportunities, especially in the use of trolleybus system in such exclusive BRT corridors.**

**This article describes the opportunities in Colombia for the re-introduction of trolleybuses in electrical transportation systems through theses corridors, emphasizing its benefits for the optimal use of energy resources, the reduction of air quality impact of public transport in Colombian cities, and the opportunity for transport operators to reduce their operating costs with technology alternatives that are more economic and stable over time. Additionally, an analysis of a demonstration project with trolleybuses carried out at Universidad Pontificia Bolivariana in Medellin (Colombia) is presented, which demonstrated the applicability of this technology in the Colombian context.**

## I. INTRODUCTION

Pollution in cities and global warming are two of the most critical problems that our countries are facing nowadays. One of the roots for these problems is pollution caused by transportation systems, which comes in a big portion from the combustion engines that use diesel and gas as their energy source.

Colombia is not away from this situation. As it happens in almost all world, transportation in Colombia is basically a social segment that works with oil, and worse than this, mass transportation systems almost don't use electricity, which is the counterbalance for oil in this kind of systems. Only one mass transportation system in Colombia is fed by electricity, that is the Medellin's Metro, and the other transportation model that has been imposed in other Colombian cities, the Bus Rapid Transit (BRT), doesn't use electricity but oil.

This imposes a great question about future of environmental and country's energetic sustainability, and also about development opportunities that the country is losing because of their transportation policies.

In the field of operations, BRT systems are suitable to involve electric buses. They use exclusive right-of-way, which makes easier to trolleybuses to ride though the streets and avoid other vehicles surpassing, and they imply a station infrastructure that organize passenger input and output from the system. These operative advantages of BRT systems, and the good environmental performance of trolleybus vehicles (low noise, minimum air pollution on road, better energy efficiency and the use of a energy type –electricity- that is clean in most countries which have an important renewable energy mix) are a good solution for a Country with cities that need efficient mass transportation systems, at a relative low cost, and environmentally friendly.

## II. THE COLOMBIAN ENERGY CONTEXT

Colombia has an electricity generation mix composed principally by 8.525 MW of hydro sources (64.1%), 4089 MW of thermal sources (30.8%), and 675.5 MW of minor plants (generations plants of less than 20MW) and cogenerators (5.1 %), for a total electricity generation capacity of 13289 MW. Thanks to this generation mix, the emission factor for the Colombian´s grid (2010) is 0.28 kg/kWh, ideal for electrification, implying a net reduction of energy and greenhouse emissions. In terms of net generation, the hydro resources participate daily with more than 70% of the total, which implies that Colombian electricity comes from clean sources.

The projected expansion of electricity generation capacity maintains a good balance between hydro and thermal resources, being the hydro capacity the leader source of electricity generation in the next years. Currently, the Mining and Energy Planning Unit, government body responsible for keeping track of generation projects in Colombia, has recorded a capacity of 9121 MW (8269 MW hydro, 354 MW coal and 480 MW natural gas) in projects that will come in operation until 2025.

Taking into account that transportation in Colombia is responsible of consuming 35% of total energy consumed in the country, that is 85278 Tcal, and almost all energy consumed in this economic sector comes from fossil fuels, there are big opportunities for contributing to energy optimal usage incorporating electricity into transportation.

Nowadays, great advance is happening in electric transportation technology. The development of energy storage devices is allowing the massification of electric vehicles for personal and familiar usage, but applications for

mass transportation with enough autonomy to work in a daily duty cycle without a charge is still being developed. That brings the opportunity for well developed technologies.

This opens the door for mature technologies such as trolley buses, which thanks to advances in electric traction systems (the use of AC motors with variable speed) and body design that facilitate users access, improve comfort and have a nice design that blends perfectly with the urban landscape of cities, are again considered in the development of new public transport systems and upgrading of transport routes with obsolete technology, which generally are also polluting.

To get an idea of what it means, by only substituting the articulated diesel buses of the BRTs systems of Bogota, Cali and Pereira (around 2000 units), the oil consumption of the country could be reduced by 2.2 %, and the CO2 emissions by 1 %, representing energy savings. The electricity consumption will increase only by 1.4 %, representing energy savings around 1500 Tcal. Now aware of this situation, the government included the electrification of public transportation among the policies to achieve a rational use of energy [1].

## III. MASS TRANSPORTATION SYSTEMS IN COLOMBIA

Public transportation in Colombia, over the past 50 years, has been starred mainly by diesel buses. Moving away from that technological scheme, we can only talk about the experience of electric trolley buses in Bogota, which operated until 1991, the Medellin Metro, which began operations in 1995, and the electrical cables scheme that began in 2004. At mass transport level, the capital city, Bogotá, is known worldwide for the scheme of Bus Rapid Transit (BRT) called *TransMilenio*, which started operations in 2000. This scheme was adopted by other Colombian cities, finding today such systems in the cities of Pereira, Cali, Bucaramanga, Barranquilla, Medellin and Cartagena.

Figure 1.Metro of Medellin. First generation (1995), second generation (2011)


Figure 2. Massive cable car systems in Medellin

TABLE 1: MASS TRANSPORTATION SYSTEMS IN COLOMBIA

| *Metro Systems* | **Length** | **Energy source** |
|---|---|---|
| Medellin | 23 km | Electricity |
| *BRT Systems* | | |
| Bogota | 84 km | Diesel |
| Pereira | 27 km | Diesel |
| Cali | 39 km | Diesel |
| Bucaramanga | | Diesel |
| Barranquilla | 13,3 km | Diesel |
| Medellín | 12.5km | CNG |
| Cartagena | 15.03 | Diesel |
| Cable System | | |
| Medellin | 4.6 km | Electricity |
| Manizales | 1km | Electricity |

## IV. BRT SYSTEMS: A BITTERSWEET STORY

*Transmilenio* system in Bogota rapidly became a transportation model in Colombia and many countries in the world, because of its fast implementation, low cost and apparent functionality.

Ten years later, it is evident that many *Transmilenio* corridors had to be designed like metro lines because of the high transportation capacity needed, while other lines of less capacity can be considered as well operated lines. In Colombia, the discussion between BRT systems and metro systems has been overtaken; so many academics and politicians consider that these systems, rather than competition, are complementary systems, discussion that has developed on last five years. In this sense, at the end of 2011 began to operate in Medellin a BRT system conceived like a feeder of a metro system; this system is called *Metroplus* and was precisely the system which opened the discussion of which energy source had to be used on this kind of systems.

At the beginning, *Metroplus* was conceived like Transmilenio in Bogota, so diesel was the energy source that would be implemented in this system. However, a strong debate began in the city, in 2008, between people that considered that electricity had to be used to move system's vehicles, and others that though that diesel had to continue. Among alternatives that were postulated at this time were the electric trolleybuses, hybrid buses, CNG buses and logically diesel buses.

The high pollution level in Medellin put the diesel alternative as the most unpopular, and high pressure was done to avoid implementing diesel alternative. The hybrid option was discarded for the high corridor's slopes, which are up to 14%, being the final options the electric trolleybuses and CNG buses.

Surprisingly, supported by the city's utility -which owns hydroelectric plants that represent almost 25% of the installed power capacity of the country- CNG alternative was chosen.

This warmed up another discussion because city's mayor argued that trolleybus alternative had very high costs and their construction will late the project, but the electric alternative had to be considered in the future. At the end of his administration, the mayor acknowledged that in the future, a transportation system could not be envisaged that was not electric.

Currently in Medellin are operating twenty articulated CNG buses assembled in Peru, where operates another BRT system which uses CNG, the *Metropolitano de Lima*. The first comments about operation of these buses have been generally positive, with the exception of the slope climbing performance of vehicles. Even a station located in the middle of a big slope has not been habilitated to avoid that buses must stop in the middle of a climbing (there are also security arguments for handicapped). This kind of problems would not be present with electric buses, which have a good performance in slopes.

At national level, BRT are conceived to be privately operated, while Colombian State is in charge of building infrastructure. This has brought the false idea that systems like *Transmilenio* are good business for investors, besides not being subsidized by the state. However, in addition to state's contribution to infrastructure, significant resources must be spent to subsidize fuel because private operators do not buy fuel at international price, which has not been enough for operating companies at intermediate cities, that for not handle a passenger volume like Bogota, are reporting losses.It is noted that fuel has an increasing weight on operating cost of BRT systems.

BRT have proved to be appropriate when average capacity is approximately 8 kphs, but in saturated lanes, when is supposed to replace a Metro, BRT system demonstrates insufficiency, resulting problems such as:

- Reduced comfort and overall travel experience
- Accidents increase
- High dependence on human factor
- High susceptibility to strikes and sabotage

## V. OPPORTUNITIES FOR TROLLEYBUSES RE-INTRODUCTION

Trolleybuses operated in Colombia until 1991, when Bogota's trolleybus system closed due to administrative problems, after more than forty years of operation. Before that, Medellin had trolleybus systems, even with locally build body of the vehicles.

TABLE 2: ENERGY AND MAINTENANCE COST BY TECHNOLOGY

| | Articulated Bus Technology (18 m) | | | |
|---|---|---|---|---|
| | ***Diesel*** | ***Hybrid*** | ***CNG*** | ***Trolleybus*** |
| Energy kWh/km | 6.3 | 4.4 | 6.6 | 2.25 |
| Energy cost USD/km | 0.75 | 0.62 | 0.48 | 0.23 |
| Maintenance USD/km | 0.19 | 0.25 | 0.21 | 0.15 |

Operation of BRT systems in Colombia is conceived as profitable business, but the high oil prices are becoming a barrier for this premise and the main reason to electrify. A detailed financial assessment comparing the available bus technologies (CNG, Trolleybus, diesel, hybrid) [4] revealed great margin favorable to the trolleybus in terms of energy and maintenance costs, which are presented in Table 2, updated to 2012.

According to the costs of operation and maintenance shown in the above table, the trolleybus is over the other technologies in this aspect. However, investment costs for this technology are a disadvantage, since in today's market an articulated bus (18 m) of electrical technology can cost between 1.5 and 2 times the cost of a similar bus of diesel technology. This implies that the investment costs of the trolleybus compared with diesel buses are much larger, because we must add to the cost of vehicles, the cost of electricity infrastructure, which can be of 1 million USD / km.

This last fact is an entry barrier for implementing the trolleybus, because many investors are guided only by the initial investment costs. Despite this, it is important to emphasize that the operation of small fleets of buses (about 60 units [1]) is almost always favorable to diesel because of the low relative costs of the buses, regardless of the stage of permanent growth of diesel, but from approximately 60 buses, electric buses operation is economically more favorable, that is, in any period of time a higher net present value is achieved for the electric technology regarding diesel technology.

As is shown in figure 3, diesel cost has dramatically increased from 2012 threatening the sustainability of BRT systems, while electricity cost in the energy market has remained steady with exception of dry years as 2010.

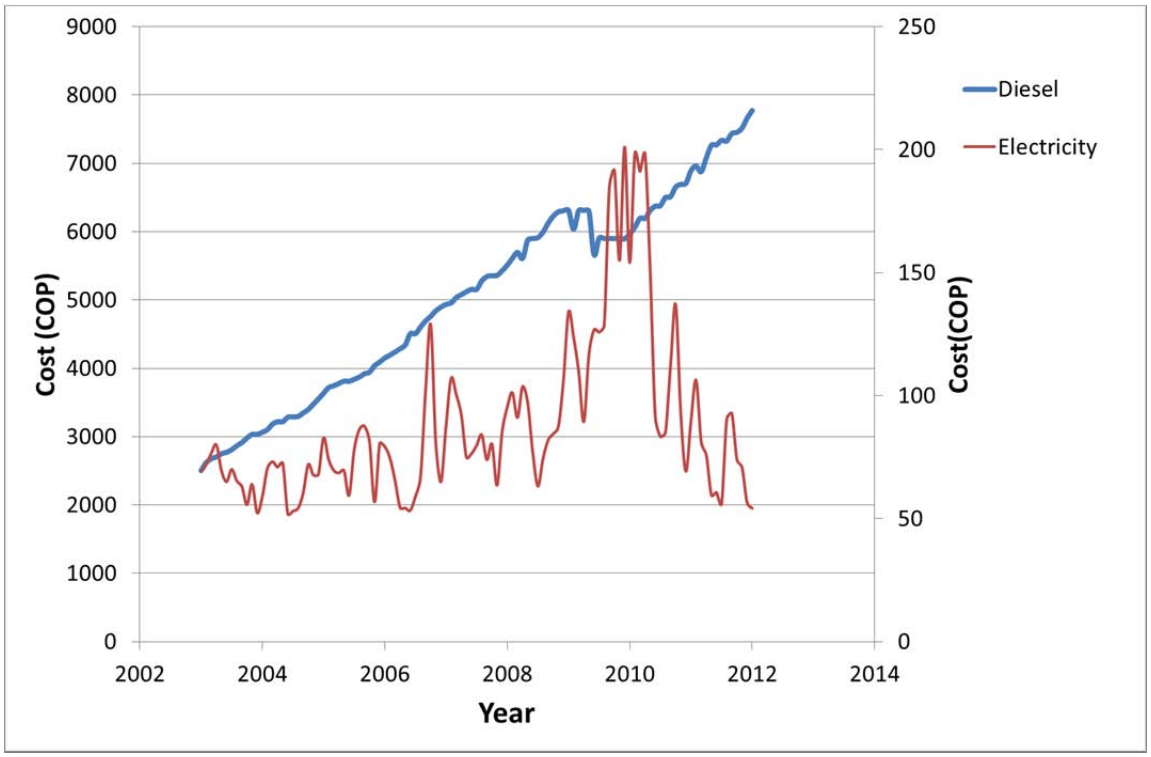


Figure 3. Diesel and electricity cost trends in Colombia

[1] This number is a reference and is based upon the experience of the authors. To determine an exact point at which the trolleybus has a higher NPV than diesel, it is necessary to know the length of the routes and the actual costs of technologies.

In terms of emissions, the hydropower prevalence implies a low emission factor of Colombian´s grid (0.28 kg/kWh), and then an articulated electric trolleybus could save around 100 Tons of CO2 tons respect to a diesel bus (only considering on street emissions), and 80 Tons saved respect to CNG buses.

In terms of energy consumption trolleybuses have a remarkable performance when compare also with battery buses. There is only two electric buses currently in Colombia, both of 12 m, a BKM 42003, and the well know BYD Fe battery bus. As table 3 presents, the energy consumption per passenger of the battery bus is almost twice of the trolleybus, due the 2.9 Tons overweigh of the batteries.

TABLE 3: ENERGY CONSUMPTION COMPARISON

| | ***Trolleybus BKM*** | ***Battery bus BYD*** |
|---|---|---|
| Lengh (m) | 12 | 12 |
| Empty weight (kg) | 11.900 | 13.800 |
| Maximun weigh (kg) | 18.000 | 18.000 |
| Available Passenger capacity | 6.1 | 4.2 |
| Passengers (65 kg/passenger) | 105 | 64 |
| Energy consumption (kWh/km) | 1.2 | 1.2 |
| Energy consumption per passenger (Wh/km-passenger) | 11.4 | 18.75 |

## VI. A DEMONSTRATIVE CASE: PONTIFICAL BOLIVARIAN UNIVERSITY ELECTRIC TRANSPORTATION LABORATORY

The Pontifical Bolivarian University (Spanish: *Universidad Pontificia Bolivariana*) of Medellin, in alliance with the company Sytecsa and CIDET (Center for research and technological development of electricity sector), have developed an Electric-Traction Laboratory inside the campus, intended to demonstrate the benefits of electric transportation systems, train engineers and technicians on the installation of the overhead line, register variables as energy consumption to establish the performance of the electric vehicle, and evaluate the integration of overhead lines with existing infrastructure in Colombian cities. A modern trolleybus owned by the company Sytecsa is operating in the pilot line.

With the Project it is developed the first modern trolleybus line in Colombia; modern because these buses, unlike those that already operated in the country, have high-efficiency alternating-current motor technology, as well as a battery backup system for autonomous off-grid operation.

With this experience, trolleybuses have returned to the collective imaginarium in Colombia, after disappearing for more than 30 years. In fact, mostly of Medellin´s citizens ignored the existence of trolleybuses, and many of the visitors to the exhibition in UPB´s campus have astonished by the quietness of the trolleybus, the smooth acceleration, the absence of exhausts and emissions, and overall, superior travel experience.

The exhibition also has been very useful to demystify many ideas as:

- Prohibitive cost of electric systems: many of the components used as the traction transformers, poles, brackets, among others accessories of the overhead line, are from local manufactures, lowering the installation costs dramatically.
- High complexity of electric systems: all the designs where performed by teachers and students of the University, and only a supervisor from Switzerland was required to the installation of the overhead line. The installation was made by Colombian technicians from the company Sytecsa.

Figure 4. Demonstrative trolleybus line in the campus of UPB

## VII. CONCLUSIONS AND FURTHER PROJECTS

It is possible an operational equivalence between a BRT with modern trolleybuses and one that operates diesel buses as *Transmilenio*. Express routes can be achieved by taking advantage of systems that allow autonomous operation of the buses, in combination with automatic overhead line switches.

The cost of the electrical infrastructure required to operate a BRT is very low in relation to civil infrastructure costs required. If a reference value of 25 MUSD / km for the cost of a BRT trunk in Colombia (though they have achieved values close to 40 MUSD/km) is taken, and the largest value that can make the electrification of 1 MUSD/km is chosen; the maximum increase in the total cost of infrastructure required for an electric BRT is just 4 %.

Modern trolleybuses unquestionably are an option to be considered for operating 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 it is possible and even attractive to a private company the operation of transportation systems based on electric traction.

Electric trolleybuses are more efficient by far than buses (3:1 ratio) with internal combustion engine, whether diesel or gas, and even hybrids, and also presents the lowest cost of energy to operate. Currently in Colombia, the electrical energy required for moving an electric bus costs about half of the diesel and natural gas required for the same effect, with a trend to increase the difference in the short term, favorable to Trolleybuses .

The trolleybuses are the only alternative that offers zero emissions in the streets, and by far it is the quietest. It is the only real option to reduce noise pollution, and a key to improve air quality in cities, especially for residents near to main routes.

A mass production of trolleybuses will reduce the cost of the vehicles, but it 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.

The risk associate to the volatility of oil prices should be a matter of concern because the fuel share in total cost nowadays is close to 40 %, and the gasoline and diesel subsides are gradually being eliminated.

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 it 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 also desirable to develop plans that aim for the gradual electrification of existing BRT systems, and that the alternative power traction should be considered as a priority for the next steps to develop such systems.

Regarding to systems of trams and light rail, it can be concluded that they must be taken into account when the mobility studies show that the passenger demand cannot be served by double-articulated trolleybus systems. In this context it is interesting to research and develop models for selecting the optimal transportation mode in accordance with demand and growth projections.

## VIII. BARRIERS DETECTED

The following barriers to the electrification of transport can be observed:

- The higher cost of electric buses and more restricted market than diesel buses. As alternative options Brazilian companies offers trolleybuses whose cost and quality are consistent with national requirements, and European companies, which while offering high-cost buses, also expressed the possibility of getting prices for the Colombian market, provided via agreements with chassis manufacturers and local body builders, also the Asian market, with a mass production of low-cost trolleybuses should be explored.
- Cost of overhead line, substations and related infrastructure. Although it is very low compared with the associated civil infrastructure (bus lanes and real state), represents a problem if it is supposed to be assumed by the operator of the BRT system. One way to break this barrier is to include this cost in the infrastructure component in charge of the state, taking into account all the benefits to society thatelectric transport involves.
- Electric Buses cost similar to that of diesel buses, they are offered in markets in Eastern Europe and Asia, the success of its implementation in Colombia depends on establishing a good channel for knowledge transfer and support.

## IX. OPPORTUNITIES DETECTED

The following opportunities for the electrification of transport were identified:

- Possibility of mounting and assembly of electric buses by domestic companies, in a similar way as it is done for gas and diesel buses.
- Better use of national energy mix, increasing the enjoyment of power sector infrastructure.
- To wean an important component as transport sector off the oil, reducing the risk, to ensure stable and affordable rates to the public.
- To decrease consumption of high quality diesel, for use in areas where it is now possible replacement, such as inter municipal transportation and collective (smallest buses) public transport.

Figure 5. Conceptual images of the green corridor of *Carrera Séptima* in Bogotá

- To reduce state contributions such subsidy to keep down the price of diesel, while in the case of electricity, increasing consumption, increases the resources corresponding to contributions in the price.
- Usually in European cities public transport ridership has increased when it is electrified. There is a greater motivation to leave the private car feels like it actually helps the environment by using electric buses. Also, in a country like Colombia, new technologies have proved attractive foci, as demonstrated by the Metro de Medellin and cable cars.
- Most of the infrastructure associated to the electrification, as substations, could also be used to charge small Electric and Plug-in Buses during the night, allowing a faster recovery of the investment. These small buses are called "feeders" of the main routes of BRT systems, and they could be battery powered.

Concrete results of this effort to electrify transportation are projected Ayacucho green corridors starting in Medellin, and the recently announced interest in the *Carrera Septima* of Bogota. Now, the electric transport systems are already on the agenda of the national and local governments plans.

## REFERENCES


[1] Republica de Colombia, MINISTERIO DE MINAS Y ENERGÍA. *Balances Energéticos Nacionales 1975-2006.* Bogotá 2007.ISBN 978-958-98138-3-6

[2] Republica de Colombia. *Diario oficial.* Año CXLIV No. 47.728. Bogotá DC, 2nd of June 2010.ISSN 0122-2112

[3] Diez, A.E.; Bohórquez, A.; Velandia, E.; Roa, L.F.;Restrepo, M.; Modern trolleybuses on Bus Rapid Transit: Key for electrification of public transportation. ANDESCON, IEEE

[4] Díez, A.E.; Bohórquez, A.; Velandia, E.; Roa, L.F.; Restrepo, M.; "Modern Trolleybuses on Bus Rapid Transit: key for electrification of public transportation" . ANDESCON, 2010 IEEE.