

# **LINKING A LAND-USE AND TRANSPORT INTERACTION MODEL WITH TRAFFIC EMISSIONS: TRANSPORT'S CONTRIBUTION TO AIR POLLUTION AND CLIMATE CHANGE IN BOGOTA**

*Luis A. Guzman. Ph.D. Grupo de Estudios en Sostenibilidad Urbana y Regional, Universidad de los Andes, Bogotá, Colombia.*

*Juan Pablo Orjuela. Research assistant. Grupo de Estudios en Sostenibilidad Urbana y Regional, Universidad de los Andes, Bogotá, Colombia*

## **ABSTRACT**

Considering the key role of the transport sector in the economy and its contribution to greenhouse gases (GHG) and local air pollutants emissions, the development of integrated techniques to evaluate long-term urban trends should be a top priority for creating a more sustainable society. This paper presents an integrated model for reliable estimation of passenger transport emissions of local pollutants and CO<sub>2</sub> using an integrated Land-Use and Transport Interaction (LUTI) model in Bogota (Colombia) between 2008 and 2038. An additional scenario is modeled which considers the increase in electric and hybrid private cars and its impacts are then discussed.

An alternative system dynamics approach is proposed as part of a structured decision making process. The methodology uses Causal Loop Diagrams (CLD) from systems dynamics to explain cause and effect relations, through linking the transport emissions and transportation subsystems. The emissions model considers eleven different vehicle categories in total and emission factors for CO<sub>2</sub>, NO<sub>x</sub>, THC and PM<sub>2.5</sub> were established using local data collected with portable devices and from other available secondary sources. Adjustment factors were established in order to account for aging of vehicles, technology improvements and changes in category distributions. Due to an increase in use of the private car transport, CO<sub>2</sub> emissions will continue to grow in Bogota (from 4.4 million t/year in 2008 to 10.5 million t/year in 2038) despite possible technology improvements. The green cars scenario suggests an important impact in CO<sub>2</sub> emissions but mild impacts in PM<sub>2.5</sub> that will only reduce about 10% of estimated emissions in 2038.

The development of a general framework based on dynamic systems for assessing long-term emissions estimations according with the particular transport systems is needed for effective sustainable transport planning. The inclusion of adjustment factors for aging and technology changes provides more reliable projections and helps identify important long-term trends in the emissions inventory.

*Keywords: developing countries, emissions inventories, transport modeling, green cars, long-term trends, integrated urban models*

## **INTRODUCTION**

Road transport is one of the key sectors in which policy change is needed in order to meet the reduction target for several greenhouse gases (GHG) and local pollutants emissions. Nowadays, this issue in big cities is one of the topics that generate greater public interest. Recent studies have shown that mobile sources play a key role in the emission inventories of air pollutants in urban centers, especially in busy roads (Gaffron 2012).

Although the Latin American region is responsible for only 12% of global emissions of GHG, it is already suffering the damage of climate change. A literature review suggests that damage from GHG emissions on climate could amount annually to 1-2% of world gross domestic product (GDP) by 2100 if temperatures increase by 2.5°C above pre-industrial levels (UNEP 2012). Hence, it is important that the region shows its commitment with reducing GHG emissions and sends the right message to the international community. Bogota as one of the region's mega-cities should be no exception. In order to evaluate these changes having tools to understand the long-term trends in emissions from road traffic, should be a priority, allowing researches and policy makers to quantify the severity of the problem and propose alternative scenarios.

Reducing GHG emissions from transport has now risen to be one of the priorities in the world's political agendas (Lutsey 2012). In the last decade Latin American transport policies have been, related to the reduction of environmental impacts associated to mobility in big cities, especially with the growth of Bus Rapid Systems (BRT) in the region (Hensher 2007). Many cities have emission inventories (Gallardo et al. 2012) that give information on current emission levels on both criteria pollutants and GHG based on local experimental data or international emission models such as IVE in Bogota (Behrentz et al. 2011) or COPERT IV in Buenos Aires (D'Angiola et al. 2010). However, with the rapid growth of developing cities and changes in technology and land-use, these inventories can change quickly making past inventories of little or no use in a matter of years. It is therefore important to have tools to estimate vehicle emissions in these cities in a way such that it considers land use, transport interactions, aging of vehicles and foreseeable technology changes.

Air pollution is a severe health problem in the urban areas. According to Bogota's Air Quality Management Plan (Behrentz et al. 2011) the cost of having particulate matter (PM) concentrations above the national air quality standard in Colombia could mean around

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15,200 deaths and induce economical costs of around \$8 billion US dollars in the next 10 years. Considering that emission control measures in mobile sources are in general terms cost effective (Wang 2004), it is reasonable to suggest that the transport sector play a key role in the emission reduction processes.

Transport emissions have become an important topic in many developing cities due to their relationship with health effects such as heart diseases and respiratory conditions (Kinney et al. 2011, Bell et al. 2011, Wang and Mauzerall 2006) as well as their role on GHG emissions inventories. However, many authors have acknowledged the difficulty in having complete emission models that account for the different vehicle categories and changes in vehicle composition or financial incentives (Shepherd, Bonsall and Harrison 2012, Gallo 2011). These considerations are crucial in order to help policy makers take informed decisions that engage cities in a sustainable development trend. This and other challenges have motivated the development of Land-Use and Transport Interaction strategic models (LUTI) as techniques for assessing the impacts of land-use and transportation changes over time. Despite significant efforts in developing LUTI models, they still lack the capability of fully synthesizing vehicle emissions impacts (Hatzopoulou, Miller 2010), especially in developing countries due to its particular characteristics of the vehicle fleet and travel behavior.

In this study we focus in the emissions from road transport, in particular emissions from passenger's travel patterns, which have the largest share of emissions in road transport (Kwon 2005). More specifically, this paper projects emissions of carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), total hydrocarbons (THC) and particulate matter with aerodynamic radius of less than 2.5 microns (PM<sub>2.5</sub>) from passenger transportation in Bogota (Colombia) over the period between 2008 and 2038. Since there is considerable uncertainty about future changes in vehicle technology as well as travel behavior and urban form, this study relies on the development of a baseline based on a LUTI model. Under this model, an analysis of scenarios under different assumptions about future changes in travel patterns and technology was adopted. The construction of LUTI models linked to emissions data seems as a reliable and practical tool for such purposes.

An integrated process is presented, where a travel demand mode, activities location models and emissions models (car and public transport), are incorporated under a unified modeling framework. This methodology is followed in order to analyze transport policy packages intended to fulfill the emissions energy objectives in urban mobility. The proposed methodology comprises an alternative approach based on a dynamic framework for land-use and transportation systems. In this paper we focus mainly in the integration of travel demand and emission models.

This paper first builds a business as usual (BAU) scenario, which is based on the situation observed in Bogota in 2008, for the travel behaviors factors (veh·km and pax·km travelled) and technology factors respectively. With reasonable assumptions about future changes the current estate is then extrapolated to 2038. In the results section, the future trends of emissions estimated from car and public transport (PT) travel are presented and another

alternative scenario (increased fleet of electric and hybrid vehicles) is analyzed. Both of these are then compared in order to understand the implications related to a policy aimed at the increase of electric and hybrid private vehicles. Finally, the key implications of this analysis are outlined in the conclusions.

## **BACKGROUND**

The Bogota Mobility Observatory of 2010 (CCB 2011) shows that there are around 10.6 million motorized trips every day, out of which PT trips (including those in the BRT and transit buses) represent 53% of the total; 14% are made on foot or by bike, and only 22% are made on private vehicles. However, the rapid growth of car and motorcycles, and the poor state of road infrastructure have contributed to the increase in travel time in the city. Thus, relative to 2009, in 2010 the average trip time increased for all modes of transport. The most critical case is TransMilenio (BRT), which went from 43 to 53 minutes, including access time and waiting time. In TransMilenio, distances and travel times increased 21% and 4% respectively between 2009 and 2010. It is worth noting however, that in the last year the average travel distance of BRT passengers increased from 13 to 16 km.

Bogota is currently facing major challenges in the management of PT supply and vehicle fleet growth, causing air quality in Bogota become a sensitive element for the city. The air concentrations of PM often exceed the local air quality standards and tropospheric ozone levels are increasingly alarming due to a clear growth in emissions of total hydrocarbons (THC) and nitrogen oxides (NO<sub>x</sub>). The road transport emissions inventory for the base year (2008) is presented in Table I. Private vehicles contribute with the largest share in CO<sub>2</sub> emissions, and in 2010 they were responsible for 63% of total carbon dioxide emissions.

Table I – Emissions inventory for the base year (2008) in Bogota City [t]

Emission type	Car	Bus	BRT
PM <sub>2.5</sub>	50	510	35
NO <sub>x</sub>	9,600	12,000	850
THC	37,000	2,800	90
CO <sub>2</sub>	3,800,000	560,000	62,000

Source: Behrentz et al. (2011) and OMB (2011).

Road transport is one of the key sectors in which policy change is needed in order to meet the reduction target for CO<sub>2</sub> (Kwon 2005) and other substances' emissions. In Bogota as in many developing cities, particulate matter is the major pollutant in terms of public health effects. In mobile sources, PM<sub>2.5</sub> comes mainly from the heavy vehicle fleet.

Bogota has formulated an Air Quality Management Plan (Behrentz et al. 2011) for the whole city for the next ten years and it considers different scenarios for both mobile and fix sources within the city's metropolitan area. This information has become an important modeling tool in the city but has not been integrated to a transport model that allows modelers, policy

makers and decision takers to evaluate different policies in terms of their impact on air quality and climate change. The model presented in this paper enables the evaluation of the impact on main criteria pollutants (PM<sub>2.5</sub>, NO<sub>x</sub> and THC) and CO<sub>2</sub> emissions in a way that integrates land-use, transport interactions and technology changes allowing to obtain more reliable and easy to interpret results for evaluating futures policies or changes.

## THE DYNAMIC ASSESSMENT METHODOLOGY

This analysis proposes an evaluation framework using one long-term system dynamic (SD) that takes into account how a transport policy affects car and PT use, and therefore, distance-related impacts such as traffic congestion, emissions, travel time and other indicators. In this case, the SD approach was used to take into account the dynamic interaction between transport, territory and emissions in the Bogota Region. This approach is based in the use of a Land Use and Transport Interaction (LUTI) model. This system is considered to be a strategic and long-term SD. The model assumes that land-use is not a constant but is rather part of a dynamic system that is influenced by transport infrastructure, this interaction process is modeled using time-lagged feedback loops between the transport and land-use sub-models over a 2008-2038 period. The evaluation framework is showed in Figure 1.

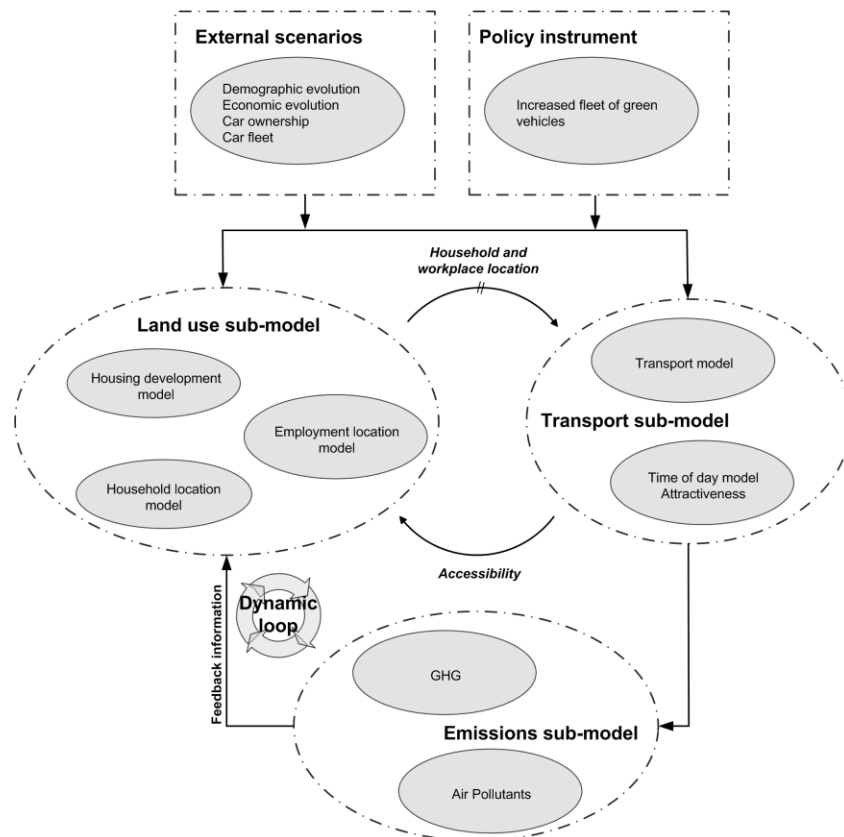


Figure 1 - Dynamic evaluation framework

Not too many integrated transport-emissions models have been developed using a system dynamics approach. Some examples are Hatzopoulou and Miller (2010), Kunsch and

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Springael (2008) and Piattelli, et al. (2002). This simulation technique stresses feedback dynamics of stocks and flows and the associated time delays in achieving objectives and learning mechanisms.

### **The LUTI strategic model**

The LUTI model used is based on Metropolitan Activity Relocation Simulator (MARS) model (Pfaffenbichler 2008). It includes a transport model, which simulates the travel behavior of the population depending on their housing and workplace location, a housing development model, a household location choice model, a workplace development model and a workplace location choice model. Changes in accessibility will affect both residential and workplace locations over the long-term, which may also have an impact on the attractiveness of car use (de la Hoz et al. 2008). The MARS model works at a high level of spatial aggregation. It was developed as an alternative to more traditional four-stage travel demand model in cases of strategic evaluation of land-use and transportation development in metropolitan areas for long-term assessments.

The MARS model is based on the concept of Casual Loop Diagrams (CLD) and is used to explain the cause-and-effect relationships in the model. The development of MARS started 13 years ago partly funded by a several EU-research projects (OPTIMA, FATIMA, PROSPECTS). To date, MARS has been applied to several European cities (Edinburgh, Helsinki, Leeds, Madrid, Oslo, Stockholm, Bari and Vienna), in some Asian cities (Chiang Mai and Ubon Ratchathani in Thailand and Hanoi in Vietnam) (Pfaffenbichler, Emberger & Shepherd 2008), Porto Alegre in Brazil (Becker Lopes 2010) and in Washington DC in the United States (Hardy 2012).

The transport model is broken down by commuting and non-commuting trips, including travel by non-motorized modes. Car speed in the MARS transport sub-model is volume and capacity dependent and hence not constant. The land-use model considers residential and workplace location preferences based on accessibility, available land, average rents and amount of green space available. The emission sub-model of MARS-Bogota uses base emission factors from the results reported by Behrentz et al., (2009) with some corrections to account for changes in time following a similar methodology to that described by Behrentz et al. (2011). Behrentz et al., (2009) used portable emissions measurement systems (PEMS) to determine local emission factors for gases (CO<sub>2</sub>, CO, THC and NO<sub>x</sub> for gasoline vehicles) and particles (PM<sub>2.5</sub> for diesel vehicles) in Bogota under real traffic conditions. They carried out a total of 202 tests and with their results they performed a complete mobile emissions inventory. Behrentz et al. (2011) used these results to design the baseline scenario and policy scenarios of the city's air quality management plan.

### **The Bogota Region model**

Bogota is the most important economic and industrial center in Colombia and is the largest and most populous city in the country. It is a dense and compact city with a rapidly growing

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population: having 7.57 million inhabitants in 2012 (1.27 million more than in 2000), spread over an area of 358 km<sup>2</sup>. This results in a population density of 21.145 inhabitants per km<sup>2</sup>, which makes it one of the most densely populated in the world. At the same time, the urban agglomeration outside the urban region had no institutional organization; each of the 12 contiguous municipalities still takes autonomous decisions. These other areas extend across 1,194 km<sup>2</sup>; with a population of 1.22 million of inhabitants (see Figure 2).

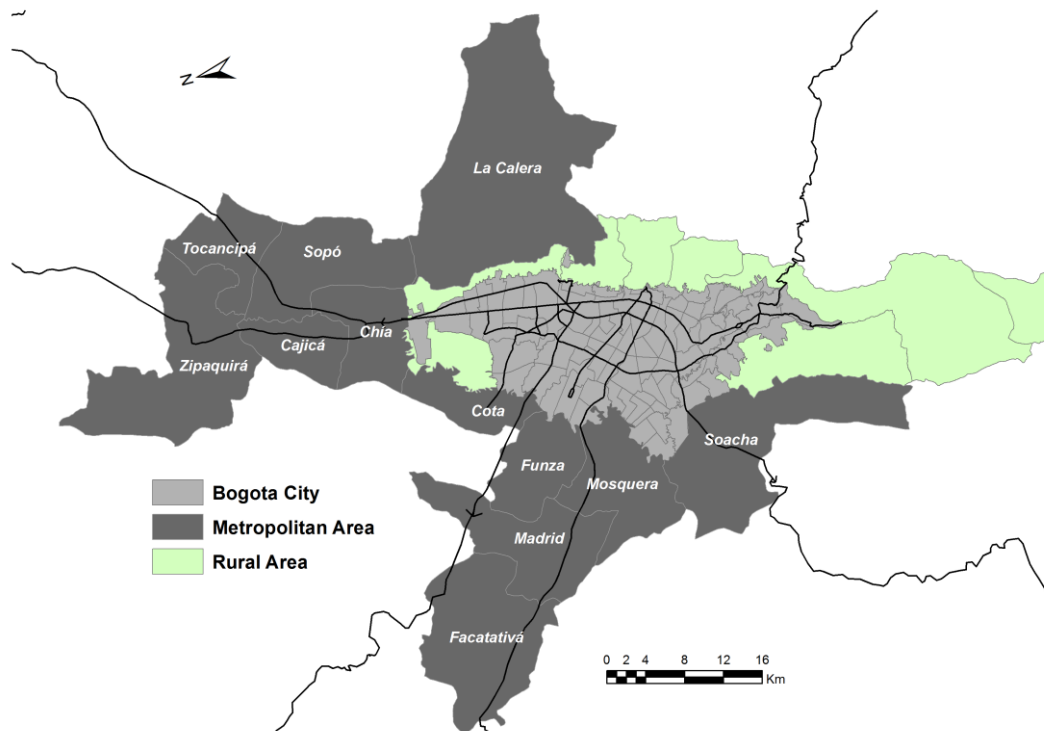


Figure 2 - Study area: the metropolitan area of Bogota, Colombia

The spatial distribution of population and activities shows important differences throughout the city. The densest sectors are located in the low-income zones, settled in the southern and western border of the urban area, which can reach densities of up to 60,000 inh/km<sup>2</sup>, both in consolidated zones and in new settlements, generally those of informal origin (Salazar Ferro 2011). On the other hand, northern and central locations are characterized by high-rise developments, lower population densities, and a high concentration of formal employment, where there are also commercial activities, services and offices, have densities of between 13,000 and 30,000 inh/km<sup>2</sup>. According to official statistics, 83% of households in the city belong to the low-income category (Bocarejo, Portilla and Pérez 2013).

The MARS-Bogota model represents the complete Bogota Region. It has 124 zones covering approximately 1,550 km<sup>2</sup> (see modeled area in Figure 2), 112 of which correspond to Bogota urban area. The remaining 12 zones correspond to neighboring municipalities. According with the last mobility survey (SDM 2011), the most used transport mode is walking with 46% of total daily trips. Second, public transport is reaching 30% (20% transit buses, 9% Transmilenio and 1% intermunicipal transport). The car catches 10% of daily trips and taxi

4%. External variable projections such as economic and population growth are estimated based on data for official statistics (SDP 2011).

## Emissions modeling in Bogota

The MARS-Bogota model was linked with a baseline that considers the inventory of emissions from mobile sources and data related to the main characteristics of the vehicle fleet. The main factors taken into consideration are vehicles ages (modeling begins with cars built in 1980, buses in 1971 and BRT buses in 2001), available technologies (Euro II, Euro IV and Euro VI for public transport) and fuel types (petrol, diesel, electric and CNG).

### *Emissions estimations*

The total car emissions of any given pollutant  $s$  are modeled through equation (1) shown below.

$$E_s = (1 \times 10^{-6}) \times \sum_{ij} \frac{trips_{ij}}{COc} \times distance_{ij} \times F_s^{vc} \times T_s^{vc} \times fleet^{vc} \times Ag^{vc} \quad (1)$$

Where  $E_s$  are the total emissions of a particular species  $s$  (in t/year),  $trips_{ij}$  is the total trips per vehicle from origin  $i$  to destination  $j$ ,  $COc$  is the vehicle occupancy,  $distance_{ij}$  is the distance travelled per vehicle,  $F_s^{vc}$  is the base emission factor of species  $s$  for the vehicle category  $vc$  used in each trip (in g/km),  $T_s^{vc}$  is the technology coefficient that accounts for technology improvements with in category  $vc$  (e.g. three way catalysts or other emission control device),  $fleet^{vc}$  is the vehicle fleet composition for the vehicle category  $vc$  and  $Ag^{vc}$  is the aging coefficient that accounts for changes in vehicle emissions as they get older. The sum is executed for all trips done during the year. To calculate the PT emissions, equation (2) was developed.

$${}^m E_s = (1 \times 10^{-6}) \times \sum_{ij} \frac{{}^m trips_{ij}}{m_{IPK}} \times {}^m F_s^{vc} \times {}^m Ag^{vc} \quad (2)$$

Where  $IPK$  is the index of passenger per kilometer travelled by mode  $m$  (transit bus or BRT) and all other variables are as stated above.

The base emission factors were obtained from the worked done by Behrentz et al. (2009). However, not all pollutants were measured for every category. In accordance with the expected dominant trends, they measured gases ( $CO_2$ ,  $CO$ ,  $NO_x$  and  $THC$ ) for gasoline vehicles but excluded the measurement of particles ( $PM_{2.5}$ ). On the other hand, for diesel vehicles, they measured particles but no gas emissions where considered. In order to have an estimated emission factor for the missing pollutants and GHG, they used secondary data from other international studies. Latter measurements in other Latin American cities have made available other sources of data (D'Angiola et al. 2010, Weaver, Balam 2006) so when possible these were used to replace the emission factors from secondary information. Measured emission factors were preferred over any other source. Base emission factors for



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transit buses for CO<sub>2</sub> and other buses are those reported by Weaver and Balam (2006). Some categories reported in Bogota were merged using a weighted ratio in accordance with the number of vehicles reported in each category. The vehicle categories used are showed in Figure 3.

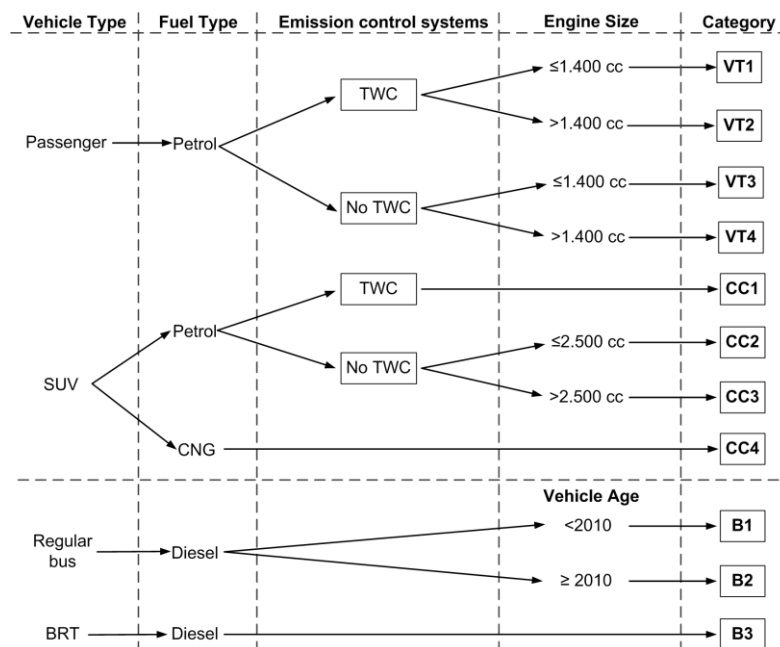


Figure 3 - Vehicle categories

Source: adapted from Behrentz et al. (2009)

The aging coefficients (Ag) were calculated assuming a lineal reduction in vehicle performance with time based on the results reported by Behrentz et al. (2009). For vehicles with three-way catalyst (TWC) a maximum life cycle of 10 years was estimated based on reported technical criteria (SynMax Performance Lubricants 2012). This means that a new private vehicle has a TWC with optimal performance that decreases annually and after 10 years it has basically no effect on the emissions of the vehicle. This assumption implies, for example, that a new vehicle in 2008 will have a THC emission factor of close to 0.9 g/km and that same vehicle year 10 years latter will be emitting something closer to 1.2 g/km. Considering maintenance practices in Bogota, this sounds like a reasonable estimate. Buses' aging was assumed to have a similar trend. Technology coefficients (T<sub>s</sub>) were calculated based on the assumption that Colombia's regulations face a 10-year lag with respect to European emission standards.

In order to have an approximation of the growth rate of the different categories, it was necessary to use the data reported by Acevedo et al. (2009). They suggest a motorization rate for Bogota between 2008 and 2040 based on the Gompertz equation based on the city's gross domestic product (GDP). Having the motorization rate and the age distribution for 2008 an extrapolation was made considering that no vehicle of more than 30 years of age is allowed to circulate. For the number of buses needed to supply future demand it was assumed that the IPK remains constant in time for both transit buses and the BRT. In this

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way, the kilometers traveled by such systems will be proportional to the trips in each mode. There are no buses older than 30 years of age and any additional bus needed will be brand new. The base emission factors used for each category are shown in Table II.

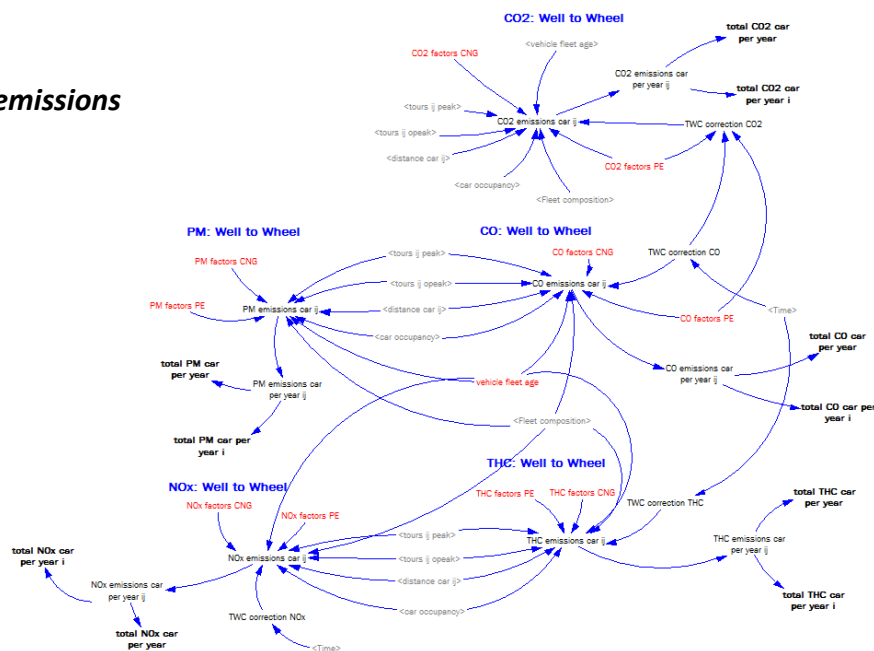
Table II – Base emission factors [g/km]

Categories		CO <sub>2</sub>	NOx	THC	PM
Petrol	VT1	232	0.7	0.9	0.003
	VT2	312	0.9	0.9	0.003
	VT3	218	1	7	0.003
	VT4	312	2	9	0.003
	CC1	379	1	0.7	0.003
	CC2	385	3	10	0.003
	CC3	460	4	8	0.003
CNG	CC4	390	4	4	0.02
Diesel	B1	1,160	11	1.5	0.6
	B2	1,160	6	0.6	0.3
	B3	685	7	0.7	0.3

*Linking emissions model and MARS-Bogota model*

The process by which travel demand mode, activities location models and emissions models was made using a causal loop structure and user-friendly software (Vensim®) that helps to improve the transparency, and hence the usefulness, of the modeling approaches used. This proposed SD approach consists of linking the subsystems of transport and an inventory of emissions from mobile sources in Bogota.

**Car emissions**



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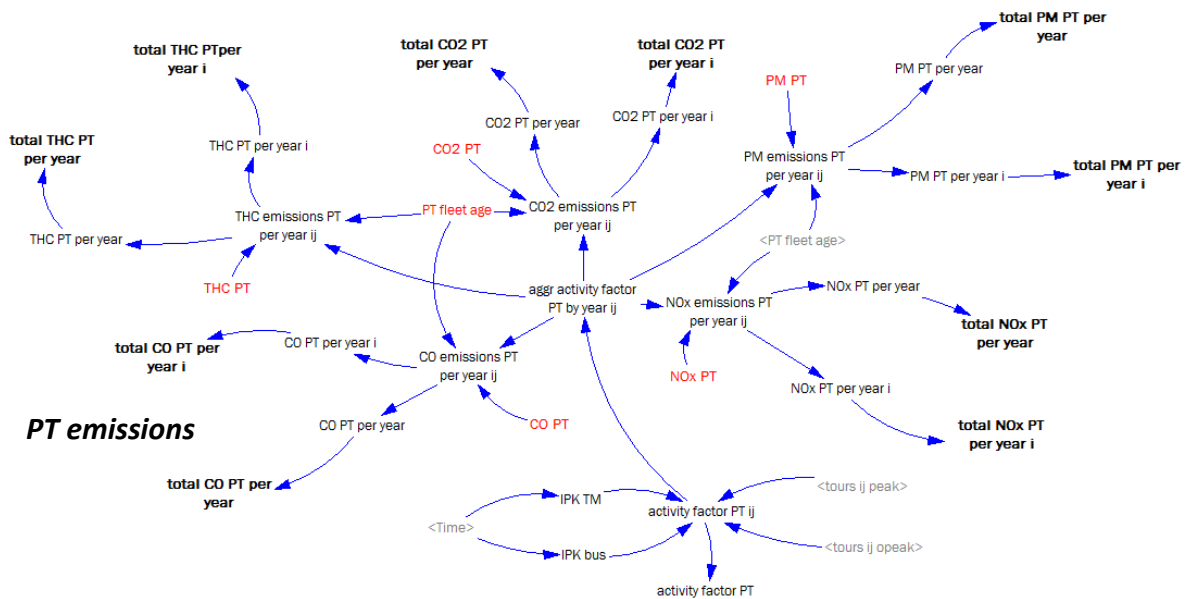


Figure 4 – CLD for vehicles emissions modeling

Figure 4 shows the interaction between the transport sub-models, the vehicle fleet (fuel type and vehicle category) and the coefficients. The MARS-Bogota model and the emission model are integrated by several variables, namely: number of trips, travel distance, speed and travel time. There is also a link between the land-use sub-model and the rest of the model through the accessibility and utility function for livability in each zone.

The resulting GHG and pollutant emissions are linked with time-travel patterns of individuals simulated within MARS-Bogota in order to estimate annual emissions for the Bogota Region. This approach is mainly concerned with exploiting the range of travel trends information generated by transport demand model for the purpose to estimate the emissions overall patterns over time.

### Scenarios

The BAU scenario includes only the infrastructure built in 2008 and does not consider any high impact intervention on infrastructure during the 30-year evaluation period (2008-2038). The alternative scenario is focused on technology improvements on car fleet. This scenario increases the number of clean technologies starting in 2018, growing exponentially until 2038, when the hybrid share of private vehicles reaches 28% and that of electric vehicles reaches 13%.

## RESULTS

The annual motorized trips (car and PT) are expected to grow due to an increase in population and economic growth in the city. In the BAU scenario this will evolve into a higher activity factor for all different modes. Also, as a result of poor public transport policies (the PT

supply has no significant changes from 2008) there is a clear shift in modal distribution where public transport loses part of its share (55%). This effect is shown in Figure 5.

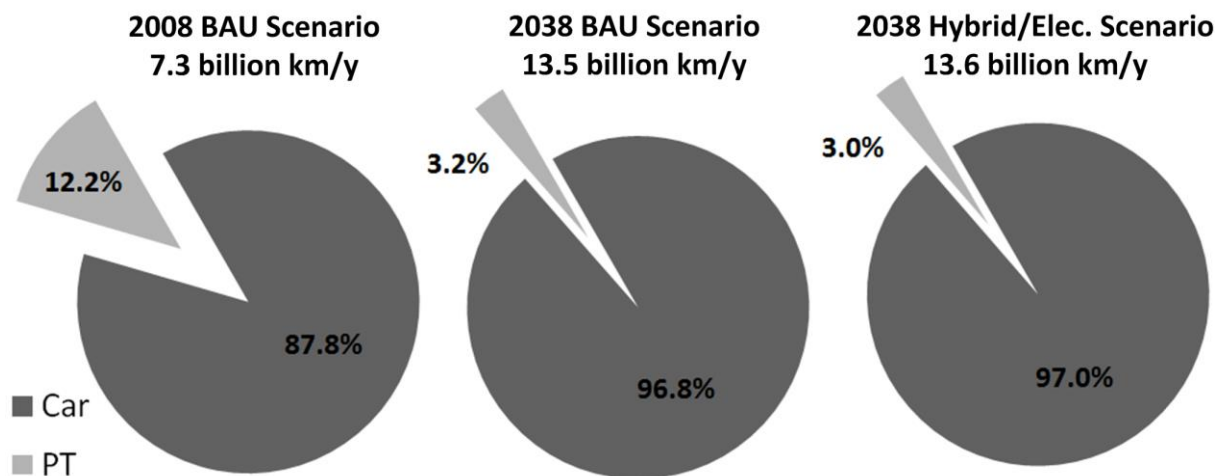


Figure 5. Change in distance traveled and modal share in 2008 and 2038 according scenario

The total emissions in the BAU scenario will depend on the emission factors of each mode (Table II), the distance travelled by each mode (Figure 5) and the correction coefficients associated to technology changes and aging of the vehicles. There is a clear decreasing trend over the years for ozone promoters (i.e. NO<sub>x</sub> and THC) as shown in Figure 6. In the case of CO<sub>2</sub> there is an important increase in the annual emissions, which suggests that the growth in the distance traveled, the modal shift and car ownership have a greater influence in emissions than the foreseeable technological improvements. The growth shown for PM<sub>2.5</sub> emissions is associated to the aging process of public transport vehicles. Even though there are some reductions in the total distance travelled (due to a modal shift toward the private vehicle) and that there are new buses with better technologies, the aging process has a greater impact in total emissions.

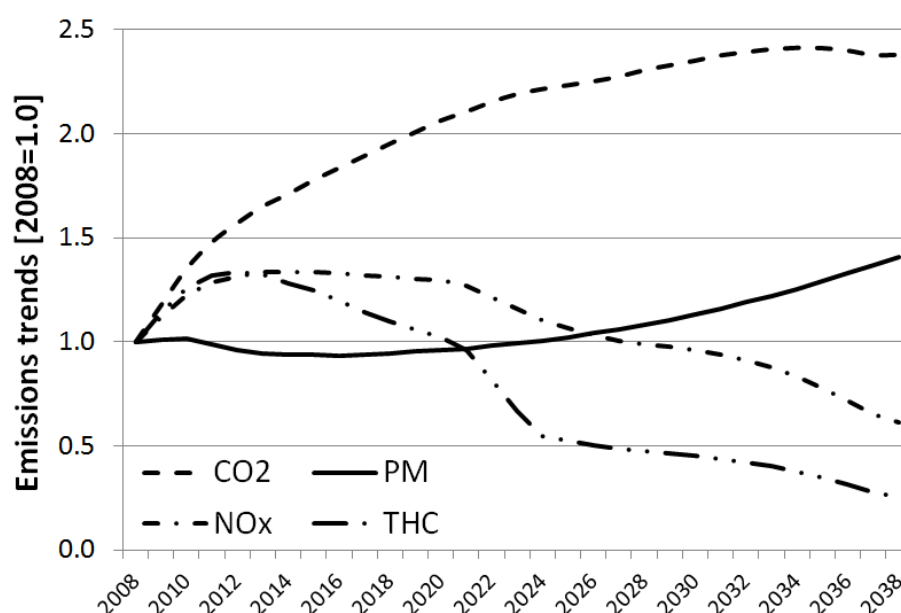


Figure 6 - Emissions trends in Bogota Region

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According with the BAU scenario results, private cars are responsible for 86% of the CO<sub>2</sub> emissions considered here at 2008 and mainly due to a population growth and car ownership combined with the modal shift, after 30 years private cars are responsible for 93% of the passenger transport emissions inventory. This implies that in order to reduce CO<sub>2</sub> emissions in the city policies should be directed towards private cars. Although there is a clear benefit associated to the introduction of new technologies, the results suggest that CO<sub>2</sub> emissions will still grow in the city in the following years if private cars continue to have a big share of the modal distribution. If Bogota wishes to move towards a sustainable development path consistent with international demands, additional policies reducing car usage are needed.

The behavior of particulate matter is different to that of CO<sub>2</sub> stressing the importance of evaluating measures from an integral perspective. Public transport accounts for 92% of the PM<sub>2.5</sub> emissions in 2008 (Table I). Colombia's current legislation makes mandatory for new buses to be Euro IV compliant and thus, these PM<sub>2.5</sub> emissions will be lower than traditional buses. However, the aging process has a stronger effect on the overall emissions so the total effect will probably be a net growth of emissions as shown in Figure 7. This growth is far from achieving the city's goals as Bogota's Air Quality Management Plan suggests that in order to reach the desired concentrations fixed by the city for 2020, PM emissions have to be reduced to 60% of current levels (Behrentz et al. 2011). It is also clear from the results that the current public transit buses system is not effective in terms of moving passengers. While the BRT has in average an IPK of more than 5.1, transit buses have never reached more than 1.6, which translates into more distance traveled and thus, more emissions, than what could be expected.

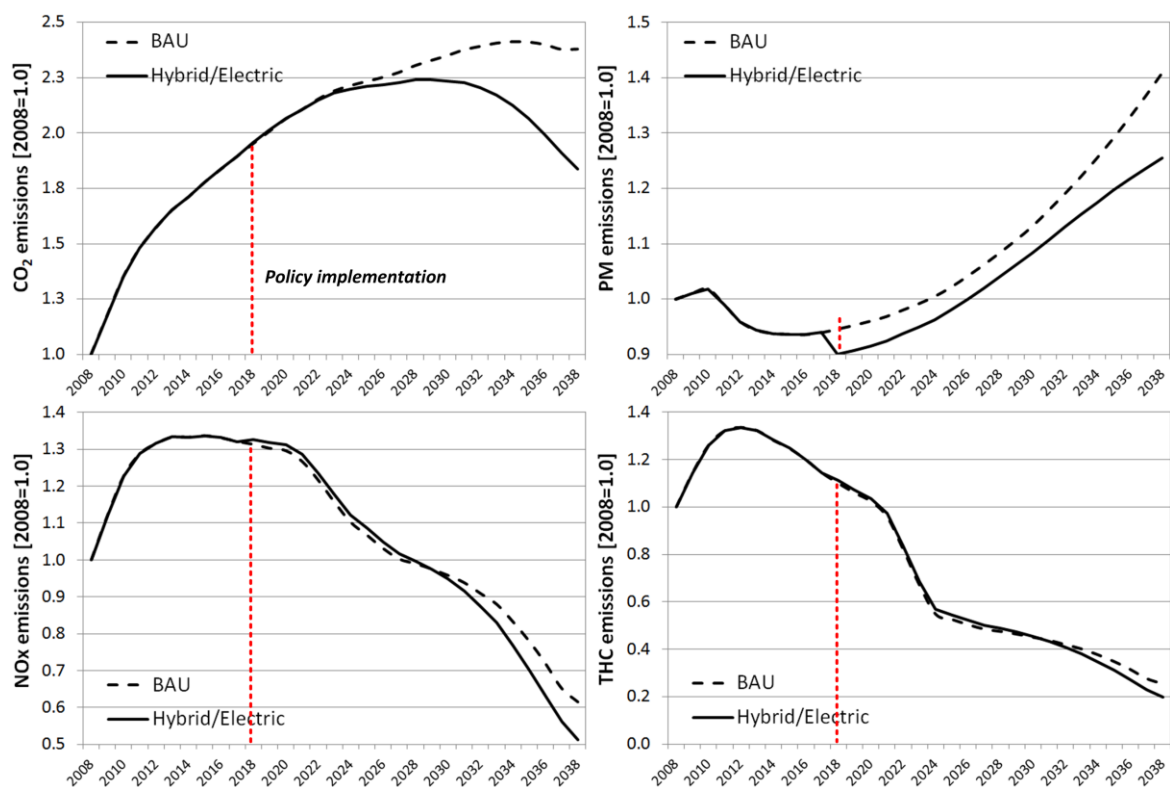


Figure 7 - Results for emissions type in the baseline scenario and the scenario with green cars

The slow processes of fleet renewal in Bogota make the average age of buses around ten years of age and this slows down the impacts of technology improvements. This situation has caused that currently PM<sub>2.5</sub> emissions per passenger are lower for private cars than buses. Although the modal shift from public to private transport would in this sense seem as a good policy to reduce PM emissions, the mentioned increase in CO<sub>2</sub> and possible greater mobility problems would arise from this fact. It is important then to consider other policies such as the proposed public transport integrated system (SITP in Bogota) that not only renews the fleet but also reduces the distance traveled and should promote the use of public transport. Figure 7 shows the impacts over all emission trends of including a policy which results in a greater share in electric and hybrid cars in the city.

Finally, in terms of NO<sub>x</sub> and THC, results show a trend towards a decrease of the emission of these substances. The reduction is mainly due to the expected technology improvement over the years. The promotion of electric and hybrid cars could result in even greater reductions as shown in the Table III.

Table III - Emissions results at 2038 according scenario (car and PT)

Pollutant	2008 [t]	BAU	Elect./hybrid cars	BAU	Elect./hybrid cars	Difference scenarios
		2038 [t]	2038 [t]	Δ2038-2008	Δ2038-2008	
CO <sub>2</sub>	4,422,000	10,522,00	8,130,000	+140%	+84%	-23%
PM <sub>2.5</sub>	595	838	750	+40%	+25%	-11%
NO <sub>x</sub>	22,450	13,800	11,500	-38%	-48%	-17%
THC	39,890	10,160	7,900	-75%	-80%	-22%

Although in the alternative scenario the emissions are reduced, the car use increases (less fuel costs). Additionally, the average travel distance increases 8% for car trips and 7% for bus trips. The average travel speed decreases by 27% in private transport and by 29% in PT. In general, after 30 years the city has more motorized trips, which are also slower and longer.

## CONCLUSIONS

This research paper evaluates a transport energy conservation strategy using a SD framework that can consider different planning objectives, and accounts for emissions impacts from changes in private car and PT use. The study provides a comprehensive treatment of vehicle emissions by explicitly representing the most important variables affecting the level of emissions in addition to their spatial and temporal variation.

The use of a LUTI model in order to generate trip patterns inputs has enabled the achievement of more comprehensive emission results over time, that have into account the transport mode, vehicle and fuel types, and geographical zone. Another advantage of this

approach is that it is possible to test different policies to reduce emissions, like technological improvements, pricing instruments or promoting alternative transport modes.

Its main purpose is not to forecast precisely the amount of emissions in the future. Considering the huge uncertainty of changes in future travel behavior and transport technology, a precise forecast of the emission trend would be quite difficult, especially in Bogota where in recent years there have been major changes related to mobility and urban structure. However, important policy guidance can be extracted from the results.

Although the expected technology improvements in the private vehicles will probably mean a considerable decrease in THC and NOx emissions from mobile sources, the high level of PM<sub>2.5</sub> emissions will continue to be a problem in the next 30 years if no action is taken. In order to reach the city's goals defined in Bogota's Air Quality Management Plan, relying only on technology improvement will not be enough and additional measures will have to be considered. The aging of buses seems to have a considerable effect and faster renovation schemes should be considered in order to avoid excessive emission factors on the operating fleet.

Due to an increase in use of the private car transport (70% in 2038), CO<sub>2</sub> emissions will continue to grow in Bogota despite possible technology improvements. Results suggest an increase of 105% by 2020 and emissions will almost triple in a BAU scenario, growing from 4.4 million t/year in 2008 to 10.5 million t/year in 2038. The modal shift from public to private transport will probably mean an increase in travel times and congestion.

The green cars scenario suggests an important impact in CO<sub>2</sub> emissions but mild impacts in PM<sub>2.5</sub> that will only reduce about 10% of estimated emissions in 2038. In case this policy is promoted, an increase in the private transport share of the modal distribution should be expected due to lower operation car costs (e.g. lower fuel costs). Considering current congestion problems this seems inconvenient.

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