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# Linking a transport dynamic model with an emissions model to aid air pollution evaluations of transport policies in Latin America

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**ABSTRACT**

Considering the key role of the transport sector in the economy and its contribution to greenhouse gas (GHG) and local air pollutant 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 $CO_2$ using an integrated Land-Use and Transport Interaction (LUTI) model in Bogota (Colombia) between 2010 and 2026. Two additional scenarios are modelled to illustrate the use of the model to evaluate the impacts of possible policy interventions. 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 transport subsystems. The emissions model considers 11 different vehicle categories in total and emission factors for $CO_2$, $NOx$, THC and $PM_{2.5}$ were established using local data collected with portable devices and from other available secondary sources. Adjustment factors were established in order to account for ageing of vehicles, technology improvements and changes in category distributions. 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 ageing and technology changes provides more reliable projections and helps identify important long-term trends in the emissions inventory. The scenarios proposed are meant to show the results obtained by the model to assist the decision-making process and do not represent current measures in the city or the best practices available. Due to an increase in the use of the private car transport, $CO_2$ emissions will continue to grow in Bogota despite possible technology improvements. Results show that the use of natural gas in the public transport fleet would imply considerable emission reductions in all studied species, being this an alternative technology while electric buses become financially viable.

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## Introduction and background

Road transport in Latin America is one sector in which policy change is needed to meet the emission reduction target for local air pollutants and several greenhouse gases (GHG). The topic generates great public interest, especially in big cities (Lutsey 2012, 179–190) and recent studies have shown that mobile sources play a key role in the emission inventories of air pollutants

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in urban centres, especially in congested roads (Gaffron 2012, 114–127). The link between travel patterns, vehicle technology and air pollution has received much attention in sustainable development discourses of policy-makers, particularly in developing countries. However, better tools to understand their behaviour and trends are needed in order to aid policy-makers in the decision process.

Air pollution associated with internal transport emissions have also gained importance in many developing cities due to their relationship with non-communicable diseases such as respiratory and cardiovascular disease (Bell et al. 2011, 57–66; Gallego, Montero, and Salas 2011; Kinney et al. 2011, 369–378; Wang and Mauzerall 2006, 1706–1721). GHG emissions inventories show that transport also has an important share in the responsibility to prevent significant climate change. In the last decade, Latin American transport policies have been implemented achieving reduction of mobility's environmental impacts especially through the operation of Bus Rapid Systems (BRT) in the region (Hensher 2007, 98–102), improving and increasing the use of public transport (PT) or restrictions on car use (Gallego, Montero, and Salas 2011). This study is a first step in assessing transport policies applied to technological changes in public transport fleets.

Bogota has done some efforts to reduce local pollutant emissions with the development of policies and plans for the reduction of particulate matter. According to Bogota's Air Quality Management Plan (Behrentz et al. 2011), the cost of having particulate matter concentrations above the national air quality standard in Colombia could mean around 15,200 deaths that imply economic costs of around $8 billion US dollars in the next 10 years. Considering that common emission control measures in mobile sources have typically been cost effective (Wang 2004, 155–169) and that large welfare gains can be obtained through well-known policies like reducing congestion or provision of free parking space (Proost and Van Dender 2001, 383–411), it is reasonable to consider the transport sector as a key player in the emission reduction processes.

Many cities have emission inventories (Gallardo et al. 2012, 12–19) 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, 483–493). However, with the rapid growth of developing cities and changes in technology and land-uses, these inventories can change quickly making past inventories of little or no use in a matter of years and releasing new versions may be very costly. In a recent publication by Lo and Sumalee (2013, 1–2), the authors mention that it is necessary to stop analysing the transport and its externalities as static entities, and begin to analyse them as a dynamic phenomenon. It is therefore important to have tools to estimate vehicle emissions in a way such that it considers transport patterns, ageing of vehicles and foreseeable technology changes.

Several 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 (Gallo 2011, 413–424; Guzman, de la Hoz, and Monzón, forthcoming; Shepherd, Bonsall, and Harrison 2012, 62–74). These considerations are crucial in order to help policy-makers take informed decisions that engage cities in a sustainable development trend. Despite significant efforts in developing these models, most still lack the capability of fully synthesizing vehicle emissions impacts (Hatzopoulou and Miller 2010, 315–325). This is a particular big challenge in developing cities due to particular characteristics of the vehicle fleet and travel behaviour.

In this paper we explore the dynamic link between passengers travel patterns and their emissions in Bogota, Colombia, a city with high air pollution levels frequently exceeding local air quality standards for particulate matter and ozone (Behrentz et al. 2009a). For the purpose of this study, the term *dynamic* refers particularly to changes over time (travel patterns, ageing of vehicles and associated emissions). The application of system dynamics (SD) models applied in transport is well documented in the literature (Linton, Grant-Muller, and Gale 2015, 1–21; Shepherd 2014, 83–105). SD are based on the theory of nonlinear dynamics and feedback control developed in several scientific disciplines. The main reason behind the requirement for simulation-based analysis of the travel patterns-air pollution problem is the dynamic complexity of the urban systems, because as Forrester (1969, 332) puts it, 'the real world is a multi-loop, multi-state, non-linear feedback system that reacts to the decision makers' actions in ways both anticipated and unanticipated'.

Not many integrated transport-emissions models have been developed using a system dynamics approach. Some examples are Hatzopoulou and Miller (2010, 315–325), Shepherd et al. (2008, 19–40), Kunsch and Springael (2008, 1285–1299), and Piattelli et al. (2002, 47–69). This paper projects emission of particulate matter with aerodynamic radius of less than 2.5 microns ($PM_{2.5}$), nitrogen oxides ($NOx$), total hydrocarbons (THC) and carbon dioxide ($CO_2$) from passenger transport in Bogota between years 2010 and 2026. Since there are considerable unknown interactions and dynamics related to future changes in vehicle technology as well as travel behaviour, this study relies on the development of a baseline based on a dynamic land-use and transport model. Under this model, an analysis of scenarios under different assumptions about future changes in travel patterns and vehicle technology was adopted. The construction of dynamic transport models linked to emissions data seems as a reliable and practical tool for such purposes.

This approach is based on a research project for the Bogota Urban Planning Office, which involves the current development of a dynamic Land-Use and Transport Interaction (LUTI) model in Bogota as techniques for assessing the impacts of land-use and transport changes over time. This paper presents just an advance of this project: a travel demand model and emissions model (including private cars and public transport), which are incorporated under a unified modelling framework. The proposed methodology comprises an alternative approach based on a dynamic framework for transport systems. The methodology presented here can easily be replicated for other cities in the region as a means to quickly evaluate various policy scenarios and assessing their impacts in vehicle emissions.

Although future research will make more extensive use of the land-use component of the model, in this study it has been left aside on purpose. We did not want to lose focus of the main research question, which is the link between two models dynamically, where time plays an important role in the emission of pollutants and GHG. In short, the land-use module is present within the modelling and simulations, but it is not given much emphasis in this article.

## The Bogota context

Bogota is the biggest economic and industrial centre in Colombia and is the largest and most populous city in the country. It is a dense and compact city with a rapidly growing population having 7.6 million inhabitants in 2012 (1.3 million more than in 2000), over an urban area of 365 $km^2$. This results in a population density close of 20,820 inhabitants per $km^2$, which makes it one of the most densely populated in the world. The urban agglomeration outside the urban region has no institutional organization; all the 12 contiguous municipalities still take autonomous decisions. These other areas extend across 1194 $km^2$; with a population of 1.22 million of inhabitants.

Mobility in Bogota is characterized by high levels of congestion, low levels of service in public transport and a significant growth of private vehicles. In recent years, the economic growth in Colombia and its capital has caused the number of private vehicles to increase significantly: according to information available on December 2014, since 2008 the car fleet in Bogota has increased by 60%. In the same period, the motorcycle fleet tripled (see Figure 1). This has led, among other things, to a loss of share of public transport in the city's daily trips.

The last mobility survey (SDM 2011) shows that there are around 17.5 million trips every day (8.8 million motorized), out of which 46% are made on foot and 3% by bicycle. Public transport trips represent 30% of the total (including those in the BRT 9%, regular buses 20% and inter-municipal transport 1%). Private cars contributed with 10% of daily trips and taxis and additional 4%. Of motorized trips, public transport is the most important with 60% of daily trips; cars move 20% of trips followed by taxis with 7% and motorcycles 5%. The growth in motorcycle ownership is becoming a cause of concern due to its high accident rates and increased emissions. For this study, this transport mode was not included due to lack of reliable data.

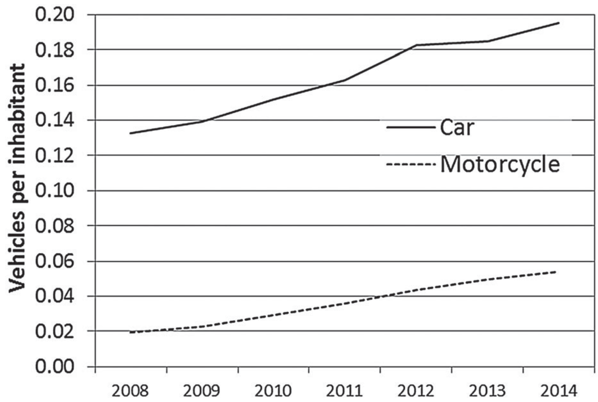


**Figure 1.** Growth in car and motorcycle ownership.

**Table 1.** Emissions inventory in Bogota city from transport (t).

| Emission type *s* | 2003 | 2005 | 2007 | 2010 |
|---|---|---|---|---|
| $PM_{2.5}$ | – | – | – | 1100 |
| NO*x* | 13,651 | 12,000 | 55,000 | 43,400 |
| THC | – | 25,000 | – | 60,000 |
| $CO_2$ | 1,873,545 | 3,000,000 | 5,100,000 | 8,100,000 |

Source: CCB ([2010] 2011).

Relative to 2010, in 2011 the average travel time increased for all modes of transport, mainly because the rapid growth of car and motorcycles, and the poor state of road infrastructure. In Transmilenio (the BRT system), 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.

The public transport in the city traditionally worked with private bus companies, where there was no effective control on the quantity and type of vehicles, routes and schedules. This resulted in a chaotic and unregulated public transport system for many years. In 2000, the Transmilenio system began to operate, revolutionizing public transport in the city under clear rules and regulations, organizing and formalizing part of the public transport offer. However, many traditional buses were still operating at the same time. In 2009 the Integrated Public Transport System (SITP) was created and though not fully implemented to date, aims to reach 100% coverage in the public transport supply in the years to come, integrating the operation and fares while improving the current fleet.

Mobile sources play a key role in total emissions in Bogota although car ownership is comparatively low (136 vehicles per 1000 inhabitants (SDM 2011)), when compared to other cities in Latin America and the world. Bogota's rapid growth will probably result in higher concentrations and higher mitigation costs if a clear policy shift towards cleaner technologies and more efficient modes is not promoted. This paper focuses the emissions from road transport, in particular emissions from passenger trips, which have the largest share of emissions in road transport (Kwon 2005, 175–184).

Given this context, Bogota is currently facing major challenges in the management of public transport supply and private vehicle fleet growth, causing air quality to 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 THC and NO*x*. The historical road transport-emissions inventory is presented in Table 1.

The reduction in NO*x* emissions from 2007 and 2010 has been explained as a result of the introduction of new emission standards in 2008 (Resolution 910 of 2008 of the Ministry of Environment, housing and territorial development). This resolution did not include $CO_2$ as part of the regulated gases.

In mobile sources, $PM_{2.5}$ comes mainly from the heavy vehicle fleet (diesel combustion). In Bogota's Air Quality Management Plan (Behrentz et al. 2011) different scenarios for both mobile and fix sources within the city's metropolitan area are considered. This information has become an important modelling tool but has not been integrated to a transport model that allows modellers, policy-makers and decision-takers to evaluate different transport or mobility policies in terms of their impact on air quality and climate change. This is normally the case in other Latin American cities, slowing down the implementation and evaluation process of sustainable transport policies. The model presented in this paper enables the evaluation of the impact on main criteria pollutants ($PM_{2.5}$, NO*x* and THC) and $CO_2$ emissions in a way that integrates transport interactions and technology changes obtaining more reliable and easy to interpret results for future policies or changes. The Bogota case study may be replicated in other cities of the region promoting more comprehensive evaluations of transport systems in Latin America.

## The proposed emissions dynamic assessment methodology

The models presented are based on the concept of casual loop diagrams (CLD) and are used to explain the cause-and-effect relationships. The usefulness of a CLD is that it connects entities by causal relationships, which mean that the input variable has a causal influence on the output variable and as the diagram develops then feedback loops become evident. These loops are either negative (balancing) or positive (self-reinforcing) feedback loops. When a model contains reinforcing and balancing loops then a dynamic equilibrium may be reached (Shepherd 2014, 83–105). Several examples of dynamic models and CLD in a system are shown in Sterman (2000).

Dynamic problems are characterized by variables that change over time. The proposed model simplifies the real world using the main variables that are believed to be important for the emissions accounting problem and shows causal relations among them. Thus, this approach links qualitative and quantitative models: the first ones are useful in describing the structure (causal relationships) of the transport-emission model and its dynamic hypothesis; and the second ones, allow the results to be shown in a quantitative manner, a desirable characteristic for decision-makers (Shepherd 2014, 83–105). The SD approach allows these two types of models to be merged into one.

### *The transport model*

The transport model used is based on the Metropolitan Activity Relocation Simulator (MARS) model (Pfaffenbichler, Emberger, and Shepherd 2008, 183–200) with several own modifications. It uses data from the 2011 Bogota Household Travel Survey (SDM 2011) to estimate models of the total number of tours generated and attracted by each zone of the study area. Linear regression methods were used to estimate the number of productions and attractions associated with each of two home-based trip purposes. Thus, this strategic transport model simulates the travel behaviour of the population depending on their housing and workplace location. This model is broken down by commuting and non-commuting trips (trip purposes), including travel by non-motorized modes. Car speed in the Bogota transport model is volume and capacity dependent and hence not constant.

The dynamics of transport interactions is critical to understand cause–effect relationships and the appearance of unintended outcomes. Figure 2 illustrates the CLD for the factors that affect the number of motorized trips in Bogota.

For example, 'car trips' depend on variables such as 'population' and 'car attractiveness', and it contributes to others as 'car speed'. Figure 2 shows loops of balancing (−) and reinforcing (+) interactions. The attractiveness of car use depends on availability, costs and times, not only for private car but also for the other transport modes. However, attractiveness itself also varies according to the intensity of car usage, as congestion may balance the time used for car trips in relation with the other modes (L1: balancing causal loop). On the other hand, congestion may affect public transport performance (if the road is shared) that can improve car attractiveness, in this case configuring a reinforcing loop (L3).

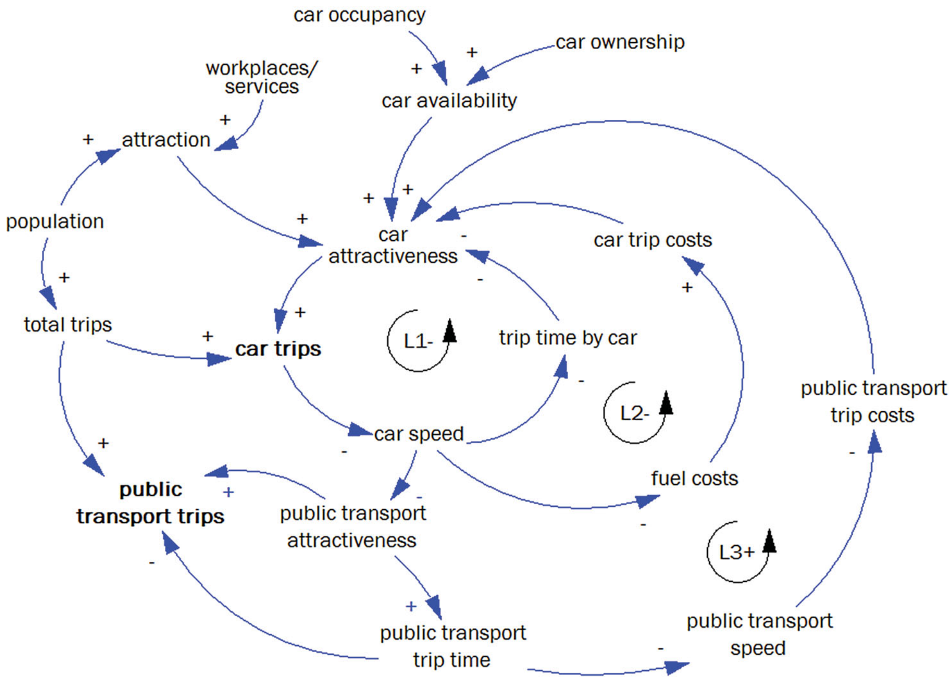


**Figure 2.** CLD for the transport model – basic relations.

This must be added to a third loop (balancing loop L2), as fuel consumption is related to travel speed. Similar configurations can be extended through all the subsystems, establishing a complex system of interrelated variables.

The desire to minimize travel time coupled with inadequate public transport in Bogota increases the attractiveness of car use which in turn reduces patronage of public transport services. In other words, the inadequate public transport supply and the growth of motorization rates, converge into an increased traffic volume, in a similar way as Sterman (2000) describes in *The Mass Transit Death Spiral*. The problem presented in this paper arises when emission levels increase due to the increases in traffic volume over time.

### *The emissions model*

The emission model uses base emission factors from the results reported by Behrentz et al. (2009b) with some additional factors (see Table 2) to account for changes in time following a similar methodology to that described by Behrentz et al. (2011). Behrentz et al. (2009b) used portable emissions measurement systems (PEMS) to determine local emission factors for gases ($CO_2$, CO, THC and NO*x* for gasoline vehicles) and particles ($PM_{2.5}$ 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. Considering the limited amount of information from primary sources in the Latin American region, this is one of the most reliable sources available today for emissions modelling.

The transport model was linked with an emissions model that considers only mobile sources using information from the emissions inventory and data related to the main characteristics of the vehicle fleet. The main factors taken into consideration are vehicles ages (the model starts by assuming that the older model circulating in 2010 is 1980 for private vehicles, 1971 for public buses and 2001 for BRT

**Table 2.** Base emission factors by vehicle category (g km$^{-1}$).

| Categories | | $CO_2$ | NO*x* | THC | PM |
|---|---|---|---|---|---|
| Gasoline | VT1 | 232 | 0.7 | 0.9 | 0.003 |
| | VT2 | 312 | 0.9 | 0.9 | 0.003 |
| | VT3 | 218 | 1.0 | 7.0 | 0.003 |
| | VT4 | 312 | 2.0 | 9.0 | 0.003 |
| | CC1 | 379 | 1.0 | 0.7 | 0.003 |
| | CC2 | 385 | 3.0 | 10.0 | 0.003 |
| | CC3 | 460 | 4.0 | 8.0 | 0.003 |
| CNG | CC4 | 390 | 4.0 | 4.0 | 0.02 |
| Diesel | B1 | 1160 | 11.0 | 1.5 | 0.6 |
| | B2 | 1160 | 6.0 | 0.6 | 0.3 |
| | B3 | 685 | 7.0 | 0.7 | 0.3 |

Source: Behrentz et al. (2011).

articulate and feeder buses), available technologies (Euro II, Euro IV and Euro VI for public transport) and fuel types (gasoline, diesel, CNG and electric).

We propose two different equations to calculate emissions from passengers road transport: the first one calculates emissions from cars using number of trips and travel speed and distance; and the second calculates emissions from public transport, using an activity factor (IPK). The estimation of emissions of several chemical species (from private and public transport) is of interest in the short and long term as well as the main factors that influence those emission levels. The total car emission of any given chemical species *s* is modelled through Equation (1) shown below.

$$E_s = (1 \times 10^{-6}) \times \sum_{ij} \frac{\text{trips}_{ij}}{\text{CO}_c} \times \text{distance}_{ij} \times F_s^{\text{vc}} \times T_s^{\text{vc}} \times \text{fleet}^{\text{vc}} \times \text{Ag}^{\text{vc}} \tag{1}$$

where $E_s$ is the total emission of a particular chemical species *s* (in t day$^{-1}$), $\text{trips}_{ij}$ are the total trips per car from origin *i* to destination *j*, $\text{CO}_c$ is the car occupancy, $\text{distance}_{ij}$ is the distance travelled per vehicle, $F_s^{\text{vc}}$ is the base emission factor of emission type *s* for the vehicle category vc used in each trip (in g km$^{-1}$), $T_s^{\text{vc}}$ is the technology coefficient that accounts for technology improvements within a given vehicle category vc (e.g. three-way catalysts or other emission control device), $\text{fleet}^{\text{vc}}$ is the vehicle fleet composition for the vehicle category vc and $\text{Ag}^{\text{vc}}$ is the ageing coefficient that accounts for changes in vehicle emissions as they get older. The power coefficients are there for unit purposes. The calculation is executed for all trips done during the year.

On the other hand, to calculate the public transport emissions, Equation (2) was developed.

$${}^{m}E_s = (1 \times 10^{-6}) \times \sum_{ij} \frac{{}^{m}\text{trips}_{ij}}{{}^{m}\text{IPK}} \times^{m} F_s^{\text{vc}} \times^{m} \text{Ag}^{\text{vc}} \tag{2}$$

where IPK is the index of passengers per kilometre travelled by mode *m* (regular bus or BRT) and all other variables are as stated above. The power multiplication is there to standardize the units of the total emissions. For public transport no technology coefficient is included because new technologies were defined as separate vehicle categories with $F_s$ independent of previous models.

This shows how the outputs from the transport model are used to calculate emissions of different chemical species by applying an emission factor, based on average speed and other variables. The base emission factors ($F_s$) were aggregated up through the dynamic model to produce total emissions generated by specific transport modes within the system being modelled. However, according to the reports made by Behrentz et al. (2009b), not all pollutants were measured for every category. In accordance with the expected dominant trends, the authors measured gases ($CO_2$, CO, NO*x* and THC) for gasoline private vehicles but excluded the measurement of particles ($PM_{2.5}$). On the other hand, for diesel vehicles (buses), only particles were measured but no gas emissions where considered in their

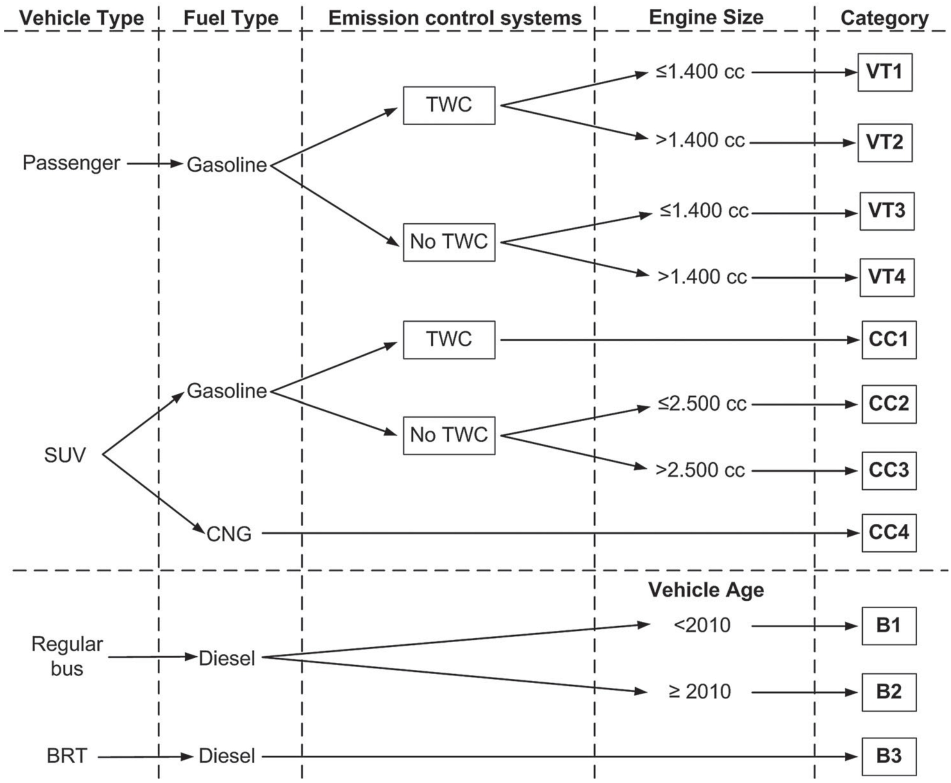


**Figure 3.** Vehicle categories. Source: adapted from Behrentz et al. (2009a).

analysis. In order to have an estimated emission factor for the missing pollutants and GHG, they used secondary data from other international studies.

Not all vehicle technologies where considered in their analysis either since no buses better than Euro II where available in Bogota at the time. Latter measurements in other Latin American cities have made available other sources of data (D'Angiola et al. 2010, 483–493; Weaver and Balam 2006) so when possible in this paper, these were used to replace the emission factors from secondary information. Measured emission factors were preferred over any other source for considering them closer to local conditions. The base $CO_2$ emission factors used for regular buses, natural gas buses and other smaller buses are those reported by Weaver and Balam (2006) considering the meteorological similarities between Mexico City and Bogota and technological similarities between fleets. Some categories reported in Bogota where merged using a weighted ratio in accordance with the number of vehicles reported in each category. The final vehicle categories used in the model are shown in Figure 3.

The ageing coefficients (Ag) were calculated assuming a lineal reduction in vehicle performance with time based on the results reported by Behrentz et al. (2009b). For private cars 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 car has a TWC with optimal performance that decreases annually and after 10 years the catalyst has no effect on the tailpipe emissions of the engine. This assumption implies, for example, that a new average gasoline vehicle in 2011 will have a $CO_2$ emission factor of close to 270 g km$^{-1}$ and that same vehicle year 10 years latter will be emitting something closer to 363 g km$^{-1}$. Considering poor maintenance practices in Bogota, this sounds like a reasonable estimate. Note that a functional TWC will reduce CO, NO*x* and THC emissions but oxidizing them, and thus $CO_2$ emissions would in theory increase. However, these increases are negligible for total $CO_2$ emissions that are associated with fuel consumption patterns.

Buses' ageing was assumed to have a similar trend and all buses older than 10 years where removed from operation according to the national public transport regulations. Technology coefficients for private cars ($T_s$) were calculated based on the assumption that Colombia's emission regulations for new vehicles will face a 10-year lag with respect to European emission standards. Considering historical trends of emission standards in Latin America, this seems to be a reasonable assumption and thus new public transport categories were defined under the same assumption of emission standards which follows an equivalent pattern.

In order to have an approximation of the growth rate of the different vehicle 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 using the city's gross domestic product (GDP). Having the motorization rate and the age distribution for 2010, an extrapolation was made considering that no private 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 regular buses and the BRT. In this way, the kilometres travelled by such systems will be proportional to the trips in each mode. There are no buses older than 10 years of age and any additional bus needed will be new. The base emission factors by emission type $s$, used for each vehicle category, are shown in Table 2.

Thus, this model is able to estimate the emissions levels because of travel patterns in Bogota over time, based on emission factors measured for local conditions, taking into account the travellers' behaviour (transport modes), distances and speeds travel, the composition of the vehicle fleet and its ageing.

## *Linking emissions and transport model*

The process by which travel demand mode and emissions models were merged was based on the use of a causal loop structure and user-friendly software (Vensim®) that helps to improve the transparency, and hence the usefulness, of the modelling tool.

The model consists of two main elements: a three classical steps transport model (trip generation, trip distribution and mode choice), a fourth step consists in the speed–flow relationship estimations influencing the travel costs private car (travel time public transport is also influenced by the speed–flow relationship and the share of public transport operated by regular buses) and an emission model based on activity transport factors, a dynamic technology correction process and a vehicle fleet model. The external vehicle fleet model updates the vehicle fleet according to fuel type and the projections, models the process of buying new vehicles and discards the ones that reach the end of their useful life in each time period.

Figure 4 shows the simplified CLD for the transport-emission model, where the underlined variables come from the transport model (Figure 2). This figure shows the interaction between the transport model, the vehicle fleet (fuel type and vehicle category) and the emission factors. The quantity of trips (car and public transport trips) tends to change over time, according to attractiveness of car/public transport usage, population location and accessibility levels and in turn this produces changes of the emission levels. The emission model was used to translate vehicle $\times$ km calculated in the transport model into local pollutant and GHG emissions. The model comprises estimations of the fleet composition developments for Bogota city.

The benefits of this linkage are twofold. On the one hand, it allows to extend the feedback effects between travel patterns and fleet considerations: on the other, it allows for interaction over time of variables such as fuel price, car usage and technological improvements. In this model, the most important interaction is this relationship between transport demand and the evolution of the total fleet. The resulting emissions are linked with travel time patterns of individuals simulated within model in order to estimate annual emissions for the Bogota region.

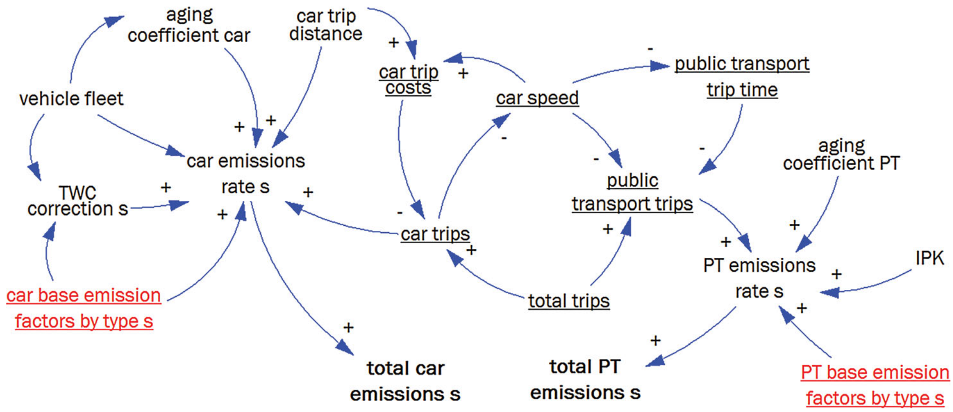


**Figure 4.** CLD for vehicles emissions modelling – basic relations.

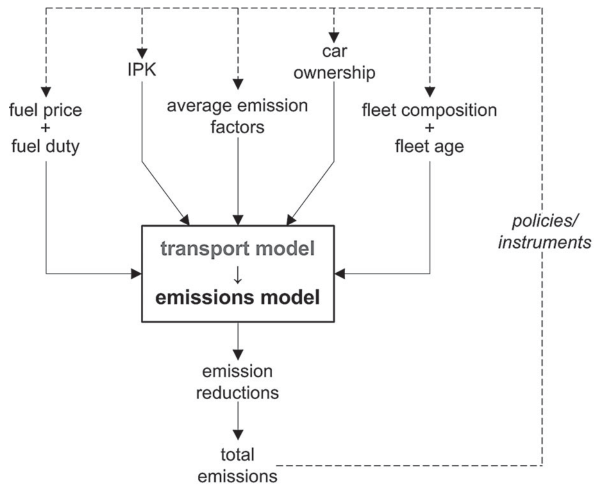


**Figure 5.** Summary of the framework proposed.

## *Model summary*

This methodology allows for the development of an emission model from mobile sources that takes into account the travel patterns, the vehicle fleet age and composition (by fuel type) and technology improvements, and its integration with a transport model.

The big benefit of the model presented is its great flexibility and sensibility for evaluations of policy interventions. As stated before, this model has been developed for Bogota but it is easily adaptable to other developing cities in the need of evaluation tools for transport and environmental policies. Inputs, outputs and data requirements are shown in Figure 5.

The proposed methodology is a useful tool where decision-makers can easily test and identify the impacts of different transport policies or even a combination of them. This is a flexible tool which can be used for different application types, such as policy optimization, scenario testing (like this case) or decision-maker training (Pfaffenbichler, Emberger, and Shepherd 2010, 262–282). The relationships between travel patterns, fleet issues and emissions are non-trivial problems that can be easily understood with tools such as these. Identifying synergies and contradictions while assessing best practices in transport and land-use systems is clearly a desirable characteristic (Guzman, de la Hoz, and Circella 2015, 99–110). The simulation of emissions and transport interaction over time in combination with a

GIS application could enable the user to evaluate spatial impacts and provide a better understanding of the processes and effects of emissions on the territory.

## Scenarios

In this section a simple example application of the Bogota model is presented in which a new policy is introduced. This paper first builds a business as usual (BAU) scenario, which is based on the situation observed in Bogota in 2010, for the travel behaviour factors and technology factors, which are then extrapolated to simulate 2026 conditions if no important interventions take place. Additionally, two interventions of the public transport have been proposed. These scenarios are not intended to suggest that these interventions as the best and should not be understood as recommendations. However, they are intended to show the evaluation of realistic interventions in the Colombian capital. The two proposed scenarios are described below.

### *Promotion of natural gas*

Compressed natural gas (CNG) has been shown to have lower emission levels of particulate matter and other pollution sources. Other cities in the region such as Lima (Peru) and Medellin (Colombia) have successfully implemented natural gas fleets. In the search for a greener city without major budget requirements, Bogota could potentially substitute part of the diesel fleet by natural gas. This would clearly imply infrastructure investment for the CNG distribution but the city already has a well-established network for taxis and a demand pulled by household usage. Current contracts with the private bus operators already establish a maximum operating age of 10 years so this represents a big opportunity to renew the fleet in the next decade. The scenario used in this paper suggests a change of 80% of the diesel fleet to until 2019 (20% per year starting in 2016).

### *Zero emission buses*

Electric buses have benefited from improvements in battery technology, but prices are still too high to expect all-electric fleets in the foreseeable future in Latin America. However, with clear intentions of reduce vehicular emissions; cities will have to start looking at more ambitious technology changes. As an illustration of the implications of a partial conversion to electric fleets, a scenario with a 20% substitution (between 2016 and 2019) of diesel vehicles by electric ones has been proposed.

It is worth noting that these scenarios are presented here as an illustration of the scenarios that can be modelled in the developed tool and are not to be interpreted as recommendations. However, they have been chosen based on the CAI and UdeA report of an Integrated Environmental Strategy for Bogota in 2011, one of the most recent and competing studies available of prices for CNG and electric buses in the city. This study suggests that introducing electric buses in the city could result in costs that are more than 50 times higher than those associated with the introduction of natural gas. The study also shows that the investment on CNG buses would require a financial aid from the local or national authorities that resulted in a 20% reduction of the vehicle price for the investment to be recovered over a 10-year period. For electric buses, this financial aid should be equivalent to 90% of the vehicle price. Based on this figures, the replacement figures for CNG and electric buses of 80% and 20% seem to be reasonable as a first modelling exercise.

## Results and discussion

One of the advantages of the model used is the option of including ageing of vehicles, more stringent emission standards for new vehicles and the adoption of new technologies in the analysis. These

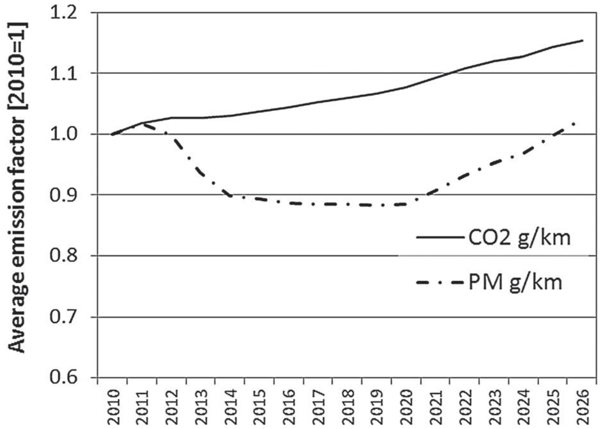


**Figure 6.** Average emission factors in the BAU scenario.

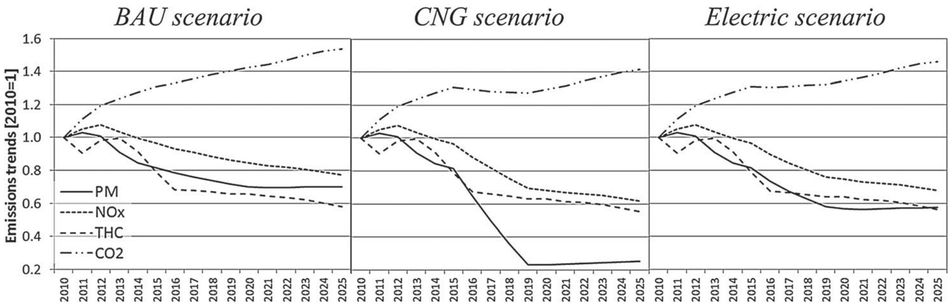


**Figure 7.** Emissions trends from road transport in the Bogota region.

parameters have different weights and trends that are then considered in the simulation with differentiated emission factors for different vehicle categories of different ages. Figure 6 shows the result of these interactions by calculating the annual average emission factors in the BAU scenario.

These results show how the renewal of buses in the first half of the 2010s did have an important effect on the average PM emission factors of the city but if these efforts are not continued as part of a sustainable policy, by the end of the decade they will start growing again. In the meantime, since no important efforts have been done in targeting $CO_2$ emissions in private vehicles, average emission factors have grown steadily as more vehicles age.

The results show that the BAU scenario or current policies will have little overall impact on the transport emissions, especially over emissions of $CO_2$. There is a clear decreasing trend over the years for ozone promoters (i.e. NO*x* and THC) as shown in Figure 7 driven mainly by the stringent bus fleet renewal policies currently in place. In the case of $CO_2$ there is an important increase in the annual emissions, which suggests that the growth in the distance travelled, the modal shift and growing car ownership have a greater influence on emissions than the foreseeable technological improvements.

According to the BAU scenario results, private cars are responsible for 86% of the $CO_2$ emissions considered in 2010. After 15 years, due to a population growth and car ownership combined with a more intensive use of the car, private cars are responsible for 94% of the passenger transport GHG emissions from all considered mobile sources. In order to reduce $CO_2$ emissions in the city policies should be directed towards the reduction in emissions from this transport mode.

An interesting result from the model presented here is the option of evaluating the sources of emissions by areas of origin or destination. Traditionally, spatial analysis has been left for concentrations in

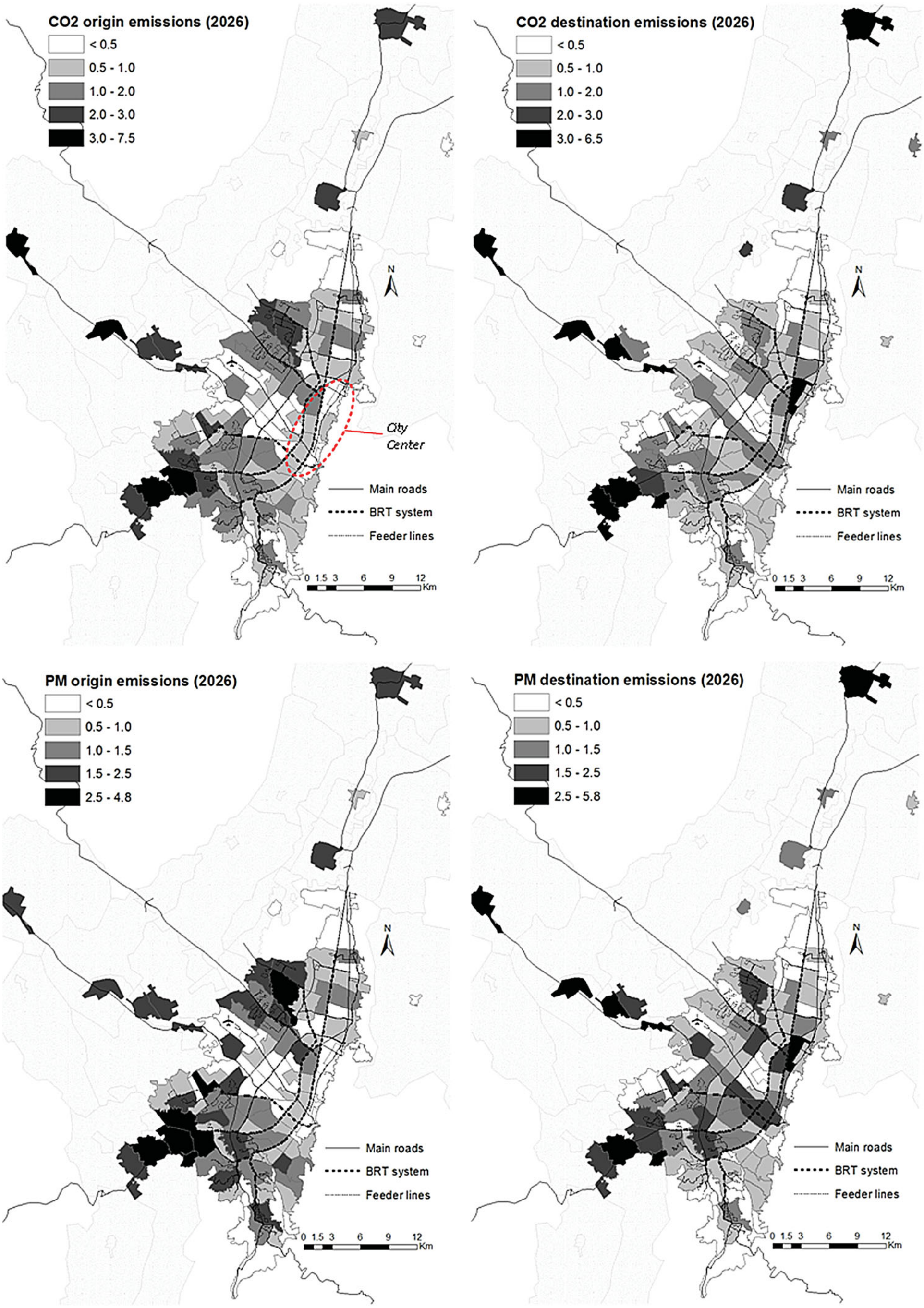


**Figure 8.** PM and $CO_2$ emissions according to origin and destination of trips in 2026 (normalized to the mean emissions of the city).

which areas of higher concentrations of local pollutants are prioritized. However, another equally interesting approach can be identifying the origin (or destination) of the most polluting trips and targeting those trips first.

Figure 8 shows in dark colours the areas of the city with emissions per trip that are higher than the city's average in 2026 for both origin and destinations. It is interesting to note that the south-west

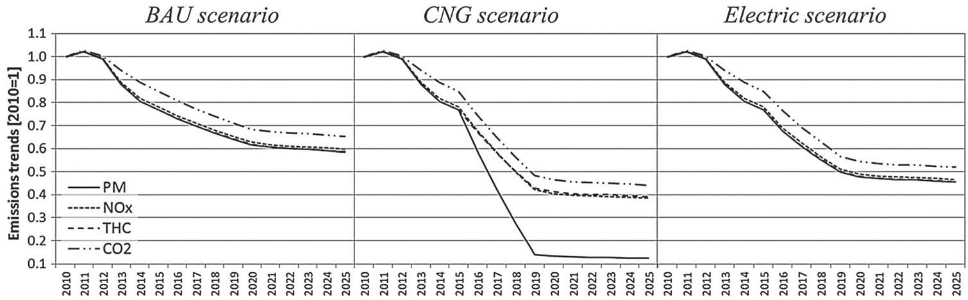


**Figure 9.** Emissions trends from public transport in the Bogota region.

of the city appear as high emissions related area for both origin and destination. This is an area of the city with low-quality transport infrastructure, and high population density, which would partly explain this trend. Having in mind that these are areas of the city of lower income citizens, there is probably an even higher difference associated with poor maintenance practices of vehicles and use of traditional buses. Also, note that the city's business centre (highlighted in the map) is not one of the destinations with higher emissions of neither pollutant presented. With this evidence, the definition of this area for congestion charges with environmental arguments should be reviewed carefully.

The behaviour of particulate matter is different to that of $CO_2$ stressing the importance of evaluating measures from an integral perspective. Public transport accounts for 92% of the $PM_{2.5}$ emissions in 2009. Colombia's current legislation makes mandatory for new buses to be Euro IV compliant and thus, these $PM_{2.5}$ emissions will be lower than traditional buses. However, these emission levels are still far from the goals set by the cities Air Quality Management Plan.

It is important to mention that these decreasing trends are based on the original renewal plan for the transport system in the city. However, in June 2015, the transport authorities took the decision to incorporate the city's old fleet of about 8300 traditional buses, meaning the scrappage objectives are now less stringent and emission reductions may be overestimated.

The results clearly show the expected benefit in terms of $PM_{2.5}$ emission when introducing CNG buses with some minor benefits in terms of the other pollutants considered. The drastic reduction in PM would have an immediate impact on concentrations and thus would constitute a health benefit for the city. The results for electric buses show a milder effect since only 20% of the fleet is replaced but the benefit is seen in all pollutants as expected. The benefits of introducing the different technologies can be clearly seen when emission trends are analysed for public transport only as shown in Figure 9.

The introduction of 20% of electric buses has almost the same effect than the substitution of 80% of the fleet with CNG buses in terms of $CO_2$, NO*x* and THC emissions. Having electric technologies mean a great advantage since it is a great step towards a continual reduction of vehicular total emissions.

## Conclusions

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

The paper has demonstrated how two models, that traditionally have been used separately, can be linked successfully with LUTI models in developing cities to enable a fuller set of assumptions concerning the travel patterns, the preferred transport mode and the development of fleet technologies (and changes) to be taken into account when considering transport policies in Latin America and possibly other developing regions. Further research related with the spatial effects of emissions using the LUTI model is the second step in this research line.

The use of an LUTI model in order to generate travel patterns inputs has enabled the achievement of more comprehensive emission results over time, that have taken into account the transport mode, vehicle and fuel types, and geographical zone. This modelling approach is very effective at capturing complex dynamics at a larger temporal and geographical scale than the other models, which incorporate different variables into the calculation of passenger road transport emissions. Another advantage of this approach is that it is possible to test different policies to reduce emissions, such as pricing instruments or promoting alternative transport modes, topics that are left for further research. In order to translate these effects into health implications, an effort to build a Land-Use regression (LUR) model based on this structure is recommended but it has been left for future study.

Its main purpose is not to precisely forecast the amount of emissions in the future. However, important policy guidance can be extracted from the scenario results. Although the expected technology improvements in the public transport vehicles will probably mean a considerable decrease in emissions from mobile sources, the high level of $PM_{2.5}$ emissions will continue to be a problem in the next 15 years if no additional actions are 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 ageing of buses seems to have a considerable effect and faster renovation schemes or new technologies should be considered in order to avoid excessive emission factors on the operating fleet.

The modal shift from public to private transport will probably mean an increase in travel times and congestion. The model shows how it is flexible and easy to use for other technology evaluations and it is a quick way of estimating expected benefits to aid policy-makers in the region. The results suggest CNG and electric buses as reasonable technologies to incorporate and thus a more detailed financial analysis is recommended.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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