Assessment of trucking bans in urban areas as a strategy to reduce air pollution

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ABSTRACT

Introduction: With the aim to reduce/mitigate the externalities due to freight transportation, sometimes the circulation of trucks is banned in urban areas. Some of these restrictions and bans are applied without proper technical support, justifying human health affectation. Thus, it is necessary to analyse how convenient are these restrictions and how efficient they really are.
Methods: To assess the effectivity of restrictions policies, the authors used regression analyses to estimate truck emissions with and without restriction of trucks. The models developed by the authors allow to estimate truck emissions based on distance (Vehicles Milles Traveled) by the trucks. Moreover, the models allow to determinate changes in the amount of pollutant emissions by changes in the Vehicles Milles Traveled due to restrictions or policies in urban areas.
Results: To test the proposed model, numerical experiments were conducted in Medellin, Colombia, where there is a history of trucking bans due to emissions. The results for the Medellin Metropolitan Area show that the truck circulation restriction does not reduce the amount of emissions that affect human health. Instead, the emissions were more concentrated in the hours without restriction, having a counterintuitive effect, that could affect more human health.
Conclusions: In terms of environment, a political strategy that at first hand appears to be a good decision, could not be one in the long term. For this reason, it is necessary to have technical support and prevent undesired effects to the city. In the Medellin Metropolitan Area with the truck ban policy, not significant change was found in the amount of pollutant ($PM_{2.5}$). Nevertheless, with the restriction, the emissions are concentrated, and this is an undesired effect, especially for human health.

1. INTRODUCTION

The freight movements in an urban region are an expression of the economy of the area. For this reason, stopping the freight movements is equivalent to stop the economy, and nobody wants that. However, sometimes large trucks are banned from the city streets due to the externalities they produce, especially congestion, noise, and emissions. Then, what happens with the cargo that has to be delivered in the commercial establishments, restaurants, pharmacies, etc.? The flow of cargo in the city cannot be stopped,

otherwise the economy will collapse. Thus, when large trucks are prohibited in the cities, the only real option that the carriers have to continue in the market is to send the merchandize in smaller trucks, contributing to more congestion, accidents, and pollution. Nevertheless, it is important to note there are situations that do not contribute to the circulation of trucks in urban areas. For example, when capacity constraints exist for trucks, e.g., narrow streets, there is a need to study different freight initiatives that help to alleviate the problem produced by them. A comprehensive research work on freight initiatives is presented in Holguín-Veras et al. (2015a). Based on this report, an initiative selector for urban freight externalities was developed. "The initiative selector is an HTML webpage that, for a given set of inputs, return suggestions of potential initiatives that could be implemented for a given problem" Holguín-Veras et al. (2015b). The user can choose the nature of the problem, geographic scope and problem source. If we select for example externalities produced by trucks in a city, the initiative selectors gives 25 possible initiatives to be implemented. However, if we focus the problem specifically associated to a specific externality, there are 12 initiatives for congestion, for noise there are 2 initiatives, and for pollution there are 5 freight initiatives. This paper is focused mainly in the latter, i.e., in emissions produced by trucks in the city, especially for pollutants that affect human health.

The sets of air pollutants that cause human health detriment and environmental hazard are named Criteria Air Pollutants (CAPs). The CAPs are: sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), lead, and Particulate Matter (PM) (EPA, 2011). Road transportation is a significant source of air pollutants and the effects of CAPs emitted by vehicles are associated with asthma, high blood pressure, lung cancer, diabetes, Alzheimer's disease, dementia, and premature deaths. Kheirbek et al. (2016) show that for the New York City, mobile sources contribute to about 320 deaths annually due to $PM_{2:5}$ exposures. The World Bank (2016) has estimated that premature deaths due to air pollution in 2013 alone cost the global economy about US $225 billion. In the city of Medellin, Colombia, it is estimated that 4500 people die due to acute respiratory diseases. Nevertheless, it isn't possible to determine how many of these casualties are related to air pollutants.

In the city of Medellin at some year's periods, the air circulation becomes difficult, especially for the Particulate Matter. Because of $PM_{2.5}$ effects over human health, reducing the emissions of this pollutant is essential for the welfare of the city. According to 2015 emissions inventory, the 80% of $PM_{2.5}$ emissions come from mobile sources. Fig. 1 shows the distribution of $PM_{2.5}$ emissions by source in Medellin city.

In the mobile sources the cargo vehicles generate the 65% of $PM_{2.5}$. The big contribution of trucks vehicles to $PM_{2.5}$ is one of the reasons that motive the policy of restrict the circulation of these vehicles in the city. Based on that, this research focuses on analysing the effectiveness of the truck restrictions due to emissions and its possible impact on human health.

This paper is divided in 5 sections. Section 2 presents a review of initiatives to improve freight systems focusing on emissions reduction. Section 3 describes the methodology to assess trucks ban policies. Section 4 presents a case study to test the model in Medellin, Colombia. The main findings and conclusions are presented in section 5.

2. Literature review

The literature review discussed in this section focuses on policies of transportation and strategies that seeks for a sustainable urban freight transportation, with emphasis on reduction of pollutant emissions. It also includes a review of emissions models and their application in the assessment of the emissions in these policies or strategies.

The need to improve the performance of freight transportation in urban areas has motivated research about strategies and policies to reduce or minimize the externalities associated with it. For example, Holguín-Veras et al. (2015a) after reviewing more than 150 references, identified 54 freight initiatives (projects, programs and policies to improve freight transportation system). Based on them, they created a guide that summarizes them and help the public sector and decision makers to address freight issues (negative externalities). In the same way, but focusing in environmental issues related to freight, VREF & RPA (2016) describe seven strategies that aim to reduce emissions of road freight transportation in metropolitan areas. These strategies are: 1) Adopt strict national (central government) emission and fuel efficiency standards; 2) Consider low emission zones (LEZs) in dense urban centers; 3) Separate noxious freight activity from conflicting land uses whenever possible; 4) Transition to alternatively fuel vehicles; 5) Evaluate non-road modes for delivers; 6) Implement anti-idling programs; and 7) Require comprehensive environmental impact mitigation
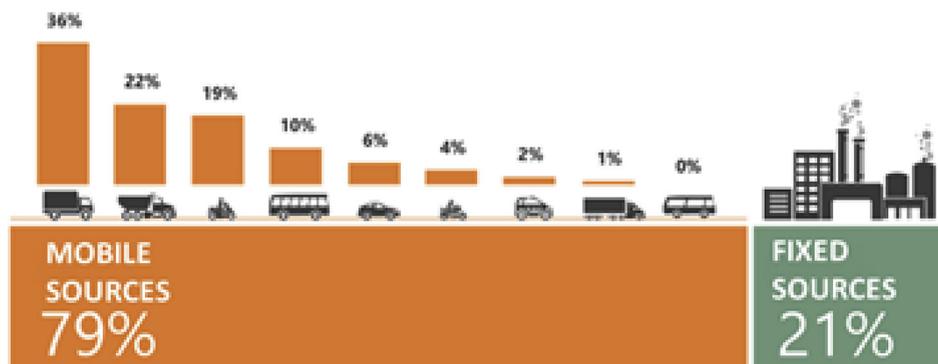

Fig. 1. $PM_{2.5}$ sources in Medellin city (AMVA, 2017).

programs at major freight hubs. Only one of the seven strategies mentioned above imply a kind of restriction or ban to the circulation of freight vehicles. For this reason, low emission zones are described further.

The LEZs are geographically limited zones where most polluting vehicles have restricted access. In Europe are about 200 LEZs distributed in different countries (mostly in Italy and Germany) (Cruz and Montenon, 2016). The LEZ frequently require freight vehicles to pay a toll, due to the high levels of pollution emitted by them (Dablanc and Montenon, 2015). Some studies have been developed to assess the reduction in pollutant concentrations after the start of LEZs in European cities (e.g., Boogaard et al. (2012); Ellison et al. (2013); Qadir et al. (2013)). These studies highlight significative benefit in reduction of emissions of pollutants due to freight transportation. Moreover, Dablanc et al. (2015) also evaluated socio-economics impacts of LEZs, founding a reduction in the number of transportation companies and logistic firms operating in cities with a LEZ.

In terms of the assessment of the public policies on freight transportation in urban areas, Quak (2006) discusses that the research about the effects of public policies to reduce the impact of freight transportation is not enough. Nevertheless, the strategies mentioned above, the restriction on the circulation of trucks is a public policy applied to improve air quality and reduce traffic congestion. Campbell (1995) analyses the impacts on truck emissions and performance measures due to the switch from large to small trucks in the city of Los Angeles, California. The results show that the peak period large truck restriction have a small effect on emissions such as HC, CO and NO_x. Also, they highlight that a switch to small truck is an unwanted consequence of large truck restrictions. In the same way, Holguín-Veras et al. (2011) study the social cost of replacing heavy trucks with small trucks in Oakland, California. They show that the consequence is an increase in the cost in terms of traveled miles, and the reduction of social cost is fewer in that case. Other type of restriction is the time window policy. In the Netherlands case, Quak et al. (2007) (2009) found that time window policy increases the amount of the emissions (CO_2, CO, NO_x and PM_{10}) and also rise the retailers distribution cost. Castro et al. (2003) and Nakamura et al. (2008) used macroscopic simulation to assess truck ban in Manila and truck-forbidden corridor in Osaka, Japan, respectively. In the case of Manila, they found that not any truck ban scheme is favourable in terms of reducing total travel distances, travel times, and pollutant emissions. In the truck-forbidden corridors, the results show that total travel time and emissions decreased on the banned corridors, but increased on the total network. A methodology for ex-ante assessment of policies on freight transportation focused on emission is proposed by Filippi et al. (2010). In the methodology these was an application in the central urban area of Rome. They found that an urban distribution center can be more effective to reduce environmental externalities than fleet renewal policies.

In the Latin American context, research conducted in Mexico and Brazil asses truck ban policies. Lyons et al. (2017) (2012) evaluate the impacts of heavy trucks restrictions on corridors in the Metropolitan Zone of Mexico City. The results show an increase in total CO emissions, congestion and kilometers traveled. Also, the authors found a reduction in the CO and NO_x emissions produced by trucks. On the other hand, Pérez-Martínez et al. (2017) analyses heavy truck restrictions and air quality implications in Sao Paulo, Brazil. The authors found that pollutants (PM_{10} and NO_x) on the restricted corridor decreased as a direct consequence of heavy vehicles traffic restriction.

There are different models to estimate emissions due to transportation. According to Demir et al. (2014) they can be categorized in three groups: 1) Factor models. 2) Macroscopic models, and 3) Microscopic models. Factor models use an emission factor related to each type of vehicle. These are useful when the information about traffic flow and operation is deficient. Macroscopic models use average network parameters (i.e., average speed, distance traveled) to estimate the emissions along the network. Finally, microscopic models estimate instantaneous (time dependent) emissions rates (second by second). At the macroscopic level MOBILE and MOVES are two models widely used to estimate transportation's emissions. MOBILE 6.2 (the latest version of this model) reports emissions rates in gram of pollutant per vehicle-mile traveled. These estimations are based on vehicle-emissions data collected by the Environmental Protection Agency (EPA) (EPA, 2003) This model (MOBILE) was replaced by Motor Vehicle Emissions Simulator (MOVES) as EPA's official model. MOVES model provides emissions estimates of a great range of pollutant (e.g., CO, CO_2, PM, NO_x, SO_x) and from many types of vehicles including trucks, using vehicle's emissions data (EPA, 2014) The Comprehensive Modal Emission Model (CMEM) is a microscopic model that estimates second by second tailpipe emissions and fuel consumption, based in data collected from 343 light-duty vehicles under laboratory driving cycles (Borrego et al., 2016; Demir et al., 2014).

As seen, there are many models to assess transportation emissions. In this research the authors will use modelling tools to estimate pollutants to analyse if trucking bans are really efficient, as presented below.

3. Modelling approach

The methodology used in this research is based on the work of Holguín-Veras et al. (2016). They used GPS data and emissions factors (corresponding to truck type, model year, fuel type, and speed), from the EMFAC Web Database to assesses the impact of off-hour deliveries in the reduction of emissions due to urban freight transportation, in three major cities in the Americas (New York City, Sao Paulo and Bogota). The EMFAC Web Database provides daily emissions and emissions rates for different years, seasons and areas in the state of California. These data are generated from 2011 EMFAC model (EMFAC2011 Web Database) and 2014 EMFAC model (EMFAC2014 Web Database). In our research we used data from EMFAC2014 (the most recent approved version for the EPA) Web Database to develop emission models to estimate commercial vehicles pollutants in the city of Medellin (where traffic bans are common). To this effect, we had used emissions data corresponding to four types of diesel trucks, aggregated speed and aggregated model year, as it is explained below.

Regression analyses were used to develop a relationship between emissions (dependent variable) and Vehicles Miles Traveled (VMT) (Independent variable). Obtaining the miles traveled by the trucks is not difficult. This allows to easily apply the model different situations. The type of vehicles used for the emissions models are: small trucks, medium trucks and heavy trucks. They are

Table 1
Vehicles description.

Vehicle	Description (GVWR = Gross Vehicle Weight Raiting)
LHD1	Light-Heavy-Duty Trucks (GVWR 8501–10000 lbs)
LHD2	Light-Heavy-Duty Trucks (GVWR 10001–14000 lbs)
T6	Medium-Heavy Duty Diesel instate Truck with GVWR > 26000 lbs
T7	Heavy-Heavy Duty Diesel Single Unit Truck

classified in the EMFAC model as LHD1, LHD2, T6 instate heavy and T7 single, respectively. These trucks were selected because they are similar to the trucks in Colombia that circulate in urban areas (e.g., Medellin). A brief description of the vehicles characteristics is given in the EMFAC2014 technical documentation and is showed in Table 1.

The air pollutants considered for this study were the ones that have more impact in human health. These pollutant are $PM_{2.5}$, Nitrogen oxides (NO_x) and Sulfur oxides (SO_x) (Kagawa, 2002; Kampa and Castanas, 2008).

The models developed by the authors allow to estimate truck emissions based on distance (VMT) traveled by the trucks (i.e., the more distance traveled the more pollutants emissions are produced). Moreover, the models allow to determinate changes in the amount of pollutant emissions (that affect human health) by changes in the VMT due to restrictions or policies in urban areas. To the best knowledge of the authors, this is one of the first research studies that analyses this topic.

3.1. Emissions models

From the EMFAC2014 web database, this paper used 64 data records to estimate the emission models. The information corresponds to fifteen years (2000–2015) of aggregated emissions data for the state of California. Fig. 2 shows the $PM_{2.5}$ Vs. VMT for four vehicles classes used.

Using the clean data, the authors used Ordinary Least Squares (OLS) regression analyses to estimate $PM_{2.5}$ emissions considering vehicle miles traveled (VMT). To this effect, two types of modes were estimated: 1) Linear-Linear and 2) Non-linear. For the latter, in order to get the best results, the authors analyzed different forms: Linear-Logarithmic, Logarithmic-Linear, and Logarithmic-Logarithmic.

Table 2 presents the best models to estimate emissions of $PM_{2.5}$ produced by trucks. The β parameter is a correction for the non-linear models bias resulting from the residuals coming from the non-linear transformation. The bias correction form is presented in Eq. (1):
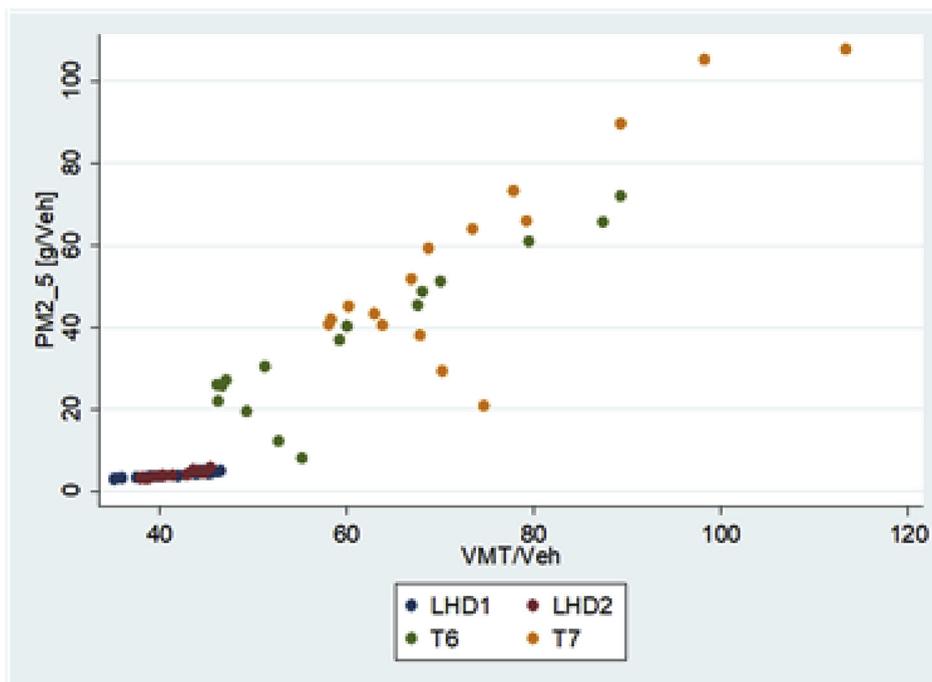
$$\beta = Exp^{s^2/2}$$

(1)

Fig. 2. $PM_{2.5}$ Emissions vs Vehicle Miles Traveled for Different Truck Types.

Table 2
Preliminary models.

Model	Coefficient	R-squared	F-value	β
Linear-Linear	0.5649145 (13.37)	0.7394	178.72	
Linear-Log	6.914677 (8.47)	0.5326	71.79	
Log-Linear	0.0482555 (34.21)	0.9489	1170.42	1.09044691
Log-Log	0.6618694 (19.54)	0.8583	381.70	1.94662564

All the models that the authors estimated do not have an intersect, this is because any amount of emission when the VMT is equal to zero, will not bee coherent. The first important thing about the models is that, all the models estimated are statistically significant, as show by the F-value. On the other hand, the fourth models shows that VMT is valid as a emissions estimator, This is because the statistic t for the coefficient is grater than 2.8. Neverless, the log-linear and log-log models have a R-squared value close to 1, this means that the relation between the VMT and the emission by vehicle is better in these models. Thus, with the model it is possible to know the emission of $PM_{2.5}$ according to the VMT. These values (VMT) are easy to obtein as a result of a traffic assignment modelling, and this is the resson why the VMT is the independent varaible in the model. The results show that the best model is the Log-Linear, and for this reason it will be the model to use. The emission model estimated is showed in Eq. (2)

$$PM_{2.5} = 1.09054 \cdot e^{0.04825 \cdot VMT} \qquad\qquad (2)$$

Although the model was estimated with data of California State, it can be used to know the magnitude in the emissions change due to the restrictions, at different cities, i.e., the difference between emissions estimated with restriction and emissions estimated without restriction. What we are assessing is the magnitude's change in the emissions and not the exact value of the emission (it has to be measured with special equipment). Thus, the use of an emissions model based on California data (our case) will be valid for different urban areas where we want to measure the emissions' changes due to restrictions. However, the exact emission value could not be estimated, and it is out of the scope of the paper.

The next section presents the application of the proposed models to a case study in the city of Medellin, Colombia, where in the first semester of 2017 there was a trucking ban due to high concentrations of $PM_{2.5}$.

4. Case study: Medellin Colombia

4.1. Medellin's context

Medellin is the second-largest city in Colombia. This city is located in the Aburra Valley, a central region of the Andes Mountains in South America. The Medellin Metropolitan Area (MMA) is a significant urban agglomeration in Colombia in terms of population and economy, with more than 3.7 million people and GDP per capita of 8489 USD for 2014 year (DANE, 2016).

At the periods of transition between dry to wet season the meteorological conditions in the valley changed. In those periods the low-level temperature inversion is stronger, that combined with narrow valley topography, make the poor circulation of air. This particular situation of low-level temperature inversion, and their implications in the air quality in urban areas in mountain valleys, are well discussed for Rendón et al. (2014). Thus, the topography and the meteorology conditions are reasons why the emission produced in MMA cannot be dissipated and the concentration of pollutant is higher day after day, especially, in the transition between seasons. Fig. 3 illustrates the conditions described previously.

At the beginning of 2017, in the transition between dry to wet season, the air quality in Medellin became critical. After three consecutive days of high pollution in the city (orange prevention, that means concentration of $PM_{2.5}$ between 38 and 55 μg/m³), a worse situation in terms of contamination (red alert, that is concentration among 56–150 μg/m³ for $PM_{2.5}$) was declared by the Government. Table 3 shows the air quality levels (states and colours) for MMA according to concentration and exposure time of different pollutant. The values showed in Table 3 are defined by the MMA environmental authority and are according to different international standards of concentrations that affect human health. Due to the red alert state, the city authorities decided to implement a series of restrictions on the circulation of private and cargo vehicles. The restriction consisted in the prohibition of the

Fig. 3. Meteorology and topography conditions in Medellin (AMVA, 2017).

Table 3
Air quality levels concentrations.

Pollutant	Exposure time	Concentrations ($\mu g/m^3$)				
		Level I		Level II	Level III	Level IV
		Good	Acceptable	Prevention	Alert	Emergency
		Green	**Yellow**	**Orange**	**Red**	**Purple**
PM_{10}	24 hours	0-54	55-154	155-254	255-354	≥ 355
$PM_{2.5}$	24 hours	0-12	13-37	38-55	56-150	≥ 151
O_3	8 hours	0-106	107-138	139-167	168-207	≥ 208
SO_2	1 hour	0-93	94-197	198-486	487-797	≥ 798
NO_2	1 hour	0-100	101-188	190-677	678-1221	≥ 1222
CO	8 hours	0-5094	5095-10819	10820-14524	14255-17688	≥ 17688

circulation of 60% of the vehicles (450,000 vehicles per day, based on the last number of the license plate) between 7a.m. and 7p.m. during three consecutive days. Besides this, trucks could only circulate between 10a.m. and 5p.m. However, the restrictions were a political decision where no technical studies were conducted to support these decisions (e.g., hours of restriction per day). Based on these facts, the authors decided to assess the effectiveness of the truck restriction. To this effect, we considered the amount of emissions (especially $PM_{2.5}$ because they are directly related with human health impacts) produced with and without restriction to analyse the efficiency of the trucking ban in the city. In doing so, the authors used regression analyses to develop an emission model relating pollutants with Vehicles Miles Traveled for both cases. This allows the evaluation of the restrictions (providing a comparison point to support/oppose it) and proposing new alternatives that could help in the reduction of emissions produced by trucks in the city.

After the episode of environmental contingency, the city authorities implemented different strategies to avoid that situation would occur again. One of these strategies is the prevention state. In the prevention state the usual restriction based in the last number license plate increases from 4 to 6 numbers. At the beginning of 2019 the prevention state was declared. As a result of this strategy, the pollution peaks, which are emissions generated during the morning and afternoon rush hours, were moved to other day times.

4.2. Model's application

The VMT of trucks vehicles in the study area are estimated as a result of traffic assignment modelling using the software TransCAD®. To this effect, an origin destination matrix of the MAM with 473 transportation analysis zones (TAZs) is used. (See Fig. 4(a)). Also, the transportation network, composed by 2605 links and 1963 nodes, was used (See Fig. 4(b)).

The trucks ban applied in MMA enforces to do 100% of daily trucks trips between 10a.m. and 5p.m (7 h). This implies that 15% of the daily trips make between 7a.m. and 10a.m. (3 h) cannot be made and have to switch to other schedule (the cargo has to be delivered). Table 4 shows both the VMT in a typical day without restriction and the VMT for a day with restriction. In the same way, the $PM_{2.5}$ estimated using the model proposed above (Eq. (2)) based on VMT, are showed for the two scenarios.

The results show that there are not differences between days with and without restrictions. Furthermore, in days without trucks restriction, a time of 10 h is useful to dissipate the emissions in the atmosphere. On the other hand, with the restriction, the emissions due to cargo vehicles are concentred and the time to dissipate the pollutants is lower. Fig. 5 shows the emissions estimated with and
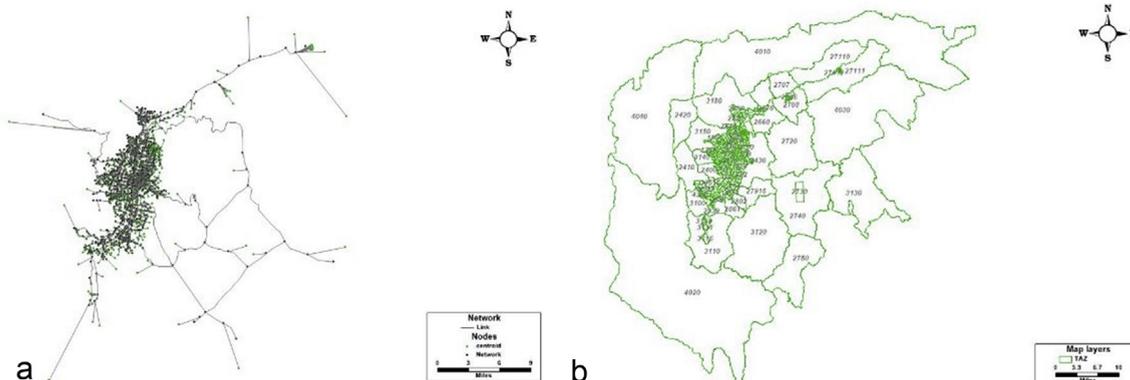

Fig. 4. (a) TAZs, (b) Transportation network.

Table 4
Restriction assessment.

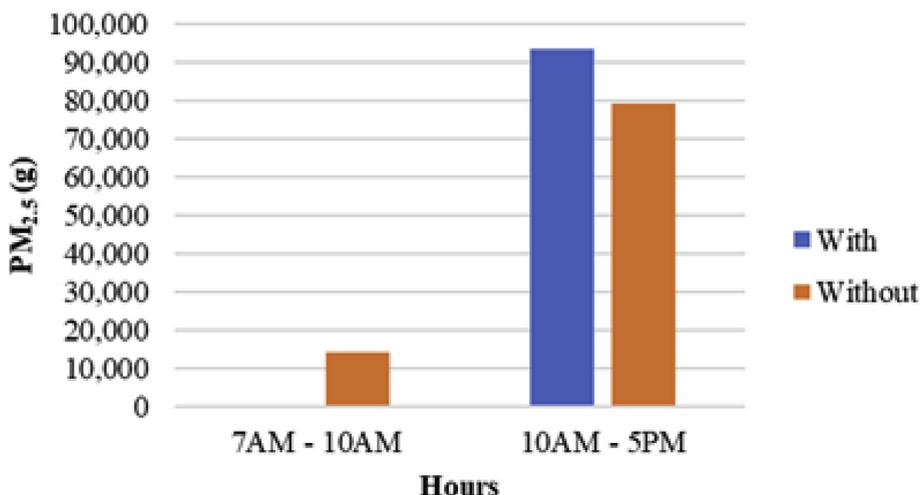| Restriction	Hours	VMT	PM$_{2.5}$ (g)
Without	7a.m.–10a.m.	55,490	14,000
	10a.m. to 5p.m	313,893	79,297
	Total	369,382	93,297
With	10a.m. to 5p.m	369,003	93,271

Fig. 5. Emissions with and without truck restriction.

without the trucks ban policy.

The results also show that the increment of the PM$_{2.5}$ between 10a.m. and 5p.m with the trucks' restriction could increase the risk over the human health during those hours. This is due to the concentration of pollutant and the time of exposure is greater, with more risk factors over human health.

5. CONCLUSIONS

This research analyses truck bans in cities due to emissions. To this effect, the authors used regression analyses to estimate truck emissions with and without restriction of trucks. To test the proposed model, numerical experiments were conducted in Medellin, Colombia, where there is a history of trucking bans due to emissions. The results for the Medellin Metropolitan Area show that the truck circulation restriction does not reduce the amount of emissions that affect human health. Instead, the emissions were more concentrated in the hours without restriction, having a counter intuitive effect, that could affect more human health.

In terms of environment, a political strategy that at first hand appears to be a good decision, could not be one in the long term. For this reason, it is necessary to have technical support and prevent undesired effects to the city. In the Medellin Metropolitan Area with the truck ban policy, not significant change was found in the amount of pollutant (PM$_{2.5}$). Nevertheless, with the restriction, the emissions are concentrated, and this is an undesired effect, especially for human health.

In relation with the air pollutants effects over human health two factors are important to consider: the time of exposure and the pollutant concentration. The trucks ban policy applied in MMA increased the concentration of PM$_{2.5}$ and in this way, it increased the risk over human health. This is due to that all trucks trips are concentrated during less time in the day.

Due to most of the truck trips are usually mandatory, the trucks ban policies not necessary implies a reduction in the number of trips, because the cargo has to be delivered, otherwise the economy would stop. For this reason, to reduce the emissions associated with the freight transportation is more effective to incentive changes in technology than forbade the trucks trips.

In this research an economy analyses of the effects of the restriction is not developed. However, it can be a good complement in the assessment of the effectiveness of the truck's ban based on emissions. However, the tool developed by the authors allows to assess the effectiveness of freight transportation policies in terms of the environmental impacts reduction/mitigation.

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