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Simulation model for vehicle fleet growth to review public policies for transport demand management

Modelo de simulación del crecimiento del parque automotor para revisión de políticas públicas en gestión de demanda

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ABSTRACT: The rapid increase in vehicle numbers within densely populated urban areas with limited road networks has become a significant challenge to city inhabitants. Driven by demographic and economic growth in recent decades, this trend has led to a gradual intensification of traffic congestion and longer commuting times, directly impacting productivity and quality of life. To counteract these negative impacts, governments have implemented Transport Demand Management (TDM) to restrict the circulation of private vehicles, discourage their acquisition, reduce traffic, and promote the use of public transport. However, due to the coercive characteristics of TDM, its effectiveness in discouraging the acquisition of private vehicles and its long-term effect on controlling the growth of urban vehicle fleets have been harshly questioned. This research uses recent scientific methodologies to estimate variations in vehicle fleet growth and identifies estimation variables in Medellín, using the publicly available city databases and a method for selecting the proper evaluation model. The selected methodology allowed us to evaluate the relationship between the age of the vehicles circulating on the road network, the demographic growth, and the increase in new vehicles. To do that, we proposed a model for an alternative public policy aimed at controlling vehicle fleet growth and the problems addressing traffic congestion in the coming years.

RESUMEN: El aumento de vehículos en áreas urbanas densificadas con infraestructura vial limitada es un desafío global. El crecimiento demográfico y económico ha intensificado la congestión del tráfico y los tiempos de conmutación, afectando la productividad y calidad de vida de los habitantes. Para mitigar estos impactos, los gobiernos han implementado Medidas de Gestión de la Demanda (MGD) que restringen la circulación de vehículos privados y promueven el transporte público. Sin embargo, la efectividad a largo plazo de estas medidas coercitivas en el control del crecimiento de la flota vehicular ha sido cuestionada. Este estudio presenta metodologías científicas recientes para estimar variaciones en el crecimiento automotriz e identifica variables de estimación en Medellín usando bases de datos públicas, y establece escenarios para proyectar el parque vehicular basados en políticas MGD como restricciones por matrícula y desguace. Se evalúa la relación entre la edad permitida para la circulación de vehículos, el crecimiento demográfico y el aumento de vehículos nuevos en Medellín. El modelo propone una política pública alternativa para controlar el crecimiento del parque vehicular y los problemas de congestión en los próximos años, considerando factores demográficos y económicos específicos de la ciudad.

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1. Introduction

The expansion and densification of urban peripheries, coupled with population growth and increased purchasing power among city dwellers in recent decades, have led to widespread private vehicle ownership and its emergence

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as the preferred mode of transportation. Consequently, when the number of vehicles in an area increases, the operating capacity of the roads to meet transport demand decreases, leading to a gradual escalation of traffic congestion, which negatively affects the productivity and quality of life of citizens [1]. High vehicle congestion indicators mean that the use of the available road network is inefficient and that public resources need to be invested in creating strategies to control mobility indicators [2].

Furthermore, congestion levels have an impact on the quality of public transport service, making it more difficult for private vehicle owners to opt for modal change [3]. In this regard, the government of Medellin, as in many other cities around the world, has implemented various Transport Demand Management (TDM) measures as a strategy to restrict and manage the circulation of private vehicles in the city, discourage their acquisition, and promote the use of collective public transportation, especially in communities with greater purchasing power, in which a single family can access several vehicles [4]. However, national economic policies for the acquisition and scrapping of vehicles seem conflict with regional objectives aimed at improving mobility conditions [5]. That is why, in the last 10 years, research on the challenges derived from vehicle fleet growth, traffic congestion, and TDM has become increasingly relevant. Researchers and scholars in the field have proposed statistical methodologies and modeling solutions to a generalized problem in cities with a high population concentration [6].

Finally, in Colombia there is no public policy that forces owners of private vehicles to scrap them when their useful life has ended. Such lack of a scrapping policy has an increasing effect on the average age of circulation of this type of vehicles in the country. In the case of public transport vehicles, Laws 105 of 1993 and 2198 of 2022 establish an age limit of 20 years for companies to replace PTVs.

2. Literature review

Researchers have analyzed some models of systems and agents, as well as statistical analyses [7], to respond to the variations of the vehicle fleet and the implementation of TDM measures. Other authors published a theoretical model on factors that influence public acceptance of License Plate Restrictions (LPR) based on the formulation of local resident surveys in the city and a Partial Least Squares Structural equation model [8]. Their research found that the existing beliefs, perceived effectiveness, perceived value, and the social norms of the population in the area exert a significant direct and indirect impact on the acceptance of a demand management policy [7, 8]. Likewise, research on the characteristics of the long-term vehicle fleet in Turkey presented a multivariate statistics analysis model [5]. Its results evidenced that multiple factors must be considered in the formulation of transport policies. To obtain the analysis model of these policies, the vehicle fleet was projected until 2030 following government indicators of mobility and public health associated with congestion. Also, five scenarios were defined to conclude that the vehicle fleet increases rapidly, whereas the scrapping rate is minimal.

A study on the renewal of the car fleet in Finland provided a reference scenario projected up to 2040 using a model that combines sociodemographic data of the Finnish population and the age average of the fleet [9]. The study concluded that the areas in which growth models were conducted had an influence on the results, explicitly revealing the differences between rural and urban areas. Similarly, a published study aimed at developing scenarios for optimizing TDM for the cities of Hasselt, Belgium, and Bologna, in Italy, which was based on models of car fleet growth [10], revealed that the collective behavior of the citizens in their commutes is related to their quality of life, that the optimization of public transport generates a shift to the use of bicycles, and that it also brings undesirable results for sustainable mobility policies. The research used an Agent-Based Model (ABM) to simulate and analyze traffic variables influencing city mobility.

Other authors sought to identify a mathematical model to mitigate the adverse effects of greenhouse gases and pollutants derived from the current vehicle fleet by means of a vehicle renewal process towards cleaner vehicles [11]. This mathematical model presented growth projections over 30 years in Norway under a low-carbon fiscal policy scenario. The conclusions included that such policy makes a significant difference in terms of long-term fuel consumption and CO_2 emissions. Finally, it highlighted the importance of including key aspects like the scrapping rate, the traffic incidentally, and the travel choice in the new models of vehicle fleet growth.

Likewise, [12] studied the optimal fleet conversion policy from a life cycle perspective in the U.S., and explored an optimal fleet conversion policy based on medium-sized internal combustion engine vehicles. The conversion was defined as the minimization of the total lifecycle emissions of the whole new and used vehicle fleet. The study concluded that accelerated scrapping policies to reduce regulated emissions are recommended, although there is a risk of a greenhouse gas increase.

3. Model design

Based on the literature review, the method and variables used in different research were identified to analyze the vehicle fleet behavior and design the growth model in Medellin. The variables found allowed us to relate the behavior of the vehicle fleet to existing variables in the model, such as demography, traffic incidentally, and traffic control. To obtain that information, it was necessary to contact the different entities and municipalities this owned the data and verify their veracity through formal requests before using it in the study.

After defining the variables, an Agent-Based Model (ABM) [13–16] was selected to address the research objective, as this type of model focuses on individual behaviors. Thus, this model allows simulating scenarios using a graduated time scale and a defined geospatial interaction [17, 18]. The conceptual ABM model proposed was developed using the Overview, Design concepts and Details (ODD) protocol. This protocol is a standard format for describing ABMs, which facilitates the interpretation, reading, and writing of these models, thus enabling the replication of both simple and complex models across various topics [19].

Purpose: The proposed ABM is designed to predict variation in the number of cars, motorcycles, and public transport buses in Medellín's vehicle fleet over a period of 30 years, considering the implementation of TDM measures, such as License Plate based restriction (LPBR) and scrapping, using government data.

Entities, state variables and scales: Each vehicle is assigned an agent represented by a car, a motorcycle, or a bus within the model. These agents make decisions based on vehicle growth, scrapping, and License Plate based restriction policies defined on an annual scale for up to 30 years from the base year (Year zero). The following are some of the variables. Collective Public Transport (CPT), License and Plate Restrictions (LPR), Kilometers Traveled per Vehicle (KTV), Vehicle Fleet (PA, from the Spanish *Parque Automotor*), Average number of traffic incidents per year (AI), and the number of traffic agents (TA).

For the model, the following global variables were defined to evaluate the effects generated in the projected number of vehicles in the fleet:

- Number of cars: Number of cars registered in Medellín in year zero of the model.
- Number of motorcycles: Number of motorcycles registered in Medellín in year zero of the model.
- Number of CPT: Number of public transport vehicles registered in Medellín in year zero of the model.
- Number of traffic agents: Average number of traffic agents in Medellín in year zero, who were available to conduct traffic control in the different communes.
- Annual Car Growth: Average percentage of annual growth of cars in Medellin projected for the next 30 years.
- Annual motorcycles growth: Average percentage of annual growth of motorcycles in Medellín for the next 30 years.
- LPBR vehicle registry: Number of vehicles registered in Medellín which may circulate in accordance with the LPBR policy defined by the city. This number of vehicles is expressed as a percentage of the total vehicle fleet registered in the city for the same time.
- LPBR Vehicles circulating: Number of vehicles registered in the city of Medellín, which may be circulating in the city in accordance with the LPBR policy defined by the city.
- Vehicle's useful life: Number of operating years of a vehicle as defined by public policies. Once cars and motorcycles reach this limit of years, their scrapping must be conducted.
- Implementation period: An extended period, counted from year zero, for the implementation of public scrapping policies. It is defined as the necessary time for car and motorcycle owners to prepare logistically and economically for the implementation of the scrapping public policy.
- Percentage of annual growth of CPT to be evaluated: Average percentage of annual growth of CPT projected for the city in the next 30 years.
- CPT's useful life: Number of operating years of public transport vehicles defined by public policies before the scrapping of the CPT vehicles is conducted. Currently, the national government has defined it in 20 years.
- Annual Growth of TA: Average percentage annual growth in the number of transit agents available in the city.
- Year (n): year in which public policies are evaluated.
- Total vehicle fleet: number of vehicles (cars and motorcycles) projected in year n, in accordance with public policies defined for year zero.
- Total scrapped PA: number of vehicles (cars and motorcycles) to be scrapped in year n, in accordance with the public policies defined for year zero.
- Total CPT Vehicles: number of projected CPT vehicles in year n, in accordance with the public policies defined for year zero.
- Total scrapped CPT vehicles: number of CPT vehicles to be scrapped in year n, in accordance with the public policies defined for year zero.
- Incidents: number of incidents projected for year n, in accordance with the projections of the vehicle fleet associated with the public policies defined in year zero.
- AI Index: This indicator allows for the calculation the annual administrative burden of traffic agents on the municipality while attending their registered vehicle fleet.

Process overview and programming: The simulation is performed by two hierarchical processes that must be conducted to guarantee its success.

The first process is the initialization of the model or the initial configuration, in which the Geographic Information System (GIS) data is loaded. The information from the communes is loaded using NetLogo's GIS extension, which allows layers to be discriminated in accordance with the VCOMUNA information variable. Subsequently, the agents are created and classified into cars, motorcycles, public transport vehicles, and traffic agents, within the layers defined as communes, in accordance with the policies to be evaluated for the growth of the vehicle fleet, scrapping and LPBR. Agents associated with cars and motorcycles and public transport buses are assigned energy properties (service life) and, additionally, cars and motorcycles are assigned use properties (KTV) [20, 21].

The simulation process predicts changes in fleet size based on the public policies established in the initial process. With the simulation, the number of existing and scrapped vehicles for the evaluation period (year n) was calculated, as well as the number of CPT vehicles and the number of existing transit agents for the same evaluation period. The algorithm used in the simulation is shown in Table 1

3.1 Parameterization, Verification, and Model Validation

Once the ABM was designed, it was parameterized, verified, and validated to evaluate its behavior. Parameterization aimed to adjust the criteria of the model to ensure the behavior closely matched the observed conditions. The verification was used to authenticate that the model was free of programming errors that could affect the results. Finally, validation determined whether the outputs of the model correctly matched reality.

With the data range defined in Table 2, ABM produced 2,400 iterations, allowing us to observe the range of results obtained for the different interactions between variables. The vertical lines in Figure 1 show the dispersion range of the modeling results. The trend lines adjust to the universe of scenarios explored, helping to verify whether slight changes were generated in the initialization of the model and whether they produced significant variations in the results as seen in Figure 2. As a result of running each of the iterations, the graph representing the general behavior of different scenarios was validated. The validation made it possible to observe the trend lines without abrupt changes.

To validate the congruence of the results of the ABM

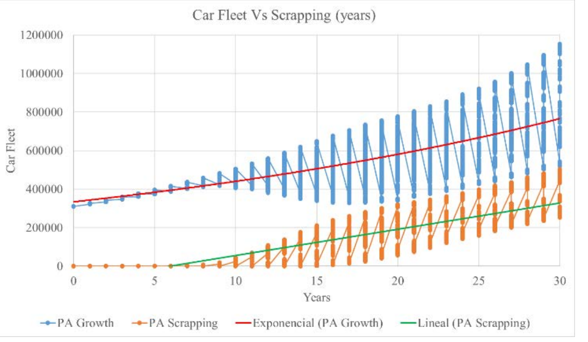

Figure 1 Graphic design of the model (Runs)

proposed for this study, experts from the Ministry of Mobility reviewed and provided feedback on the preliminary results of six scenarios.

The model developed through the NetLogo software 6.1.1. [22] evidenced a relationship between the fleet growth in each of the 16 communes and 5 corregimientos of the city. The model was based on the historical data of the fleet in the last 10 years, the road incidents of the last 2 years for each commune, and the database of traffic agents available for traffic control in the city in the last 10 years.

The graphical interface of the ABM allows the modeler to evaluate vehicle fleet growth projections and traffic control requirements over the next 30 years. The predictions include the definition of growth rates for cars, motorcycles, and CPT vehicles, policies for the scrapping period, and strategies to reduce the percentage of the vehicular volume circulating through the city, considering LPRs.

4. Results

In this section, six scenarios for projecting vehicle fleet variations in Medellín are proposed as seen in Table 3. They aim to evaluate the variation resulting from the implementation of TDM measures such as LPR and scrapping.

4.1 Base Scenario - BS

This scenario (Figure 3) presents the city's current motorization conditions projected for 30 years without implementing scrapping policies. To evaluate this scenario, a vehicle fleet lifespan of more than 30 years and its equivalent KTV were set up, along with a policy implementation period of no less than 30 years and complementary LPR measures of one digit during the same evaluation period. Its effectiveness in controlling the vehicle fleet growth over the next 30 years reflected an

Table 1 Algorithm from the model (Netlogo)

Main Loop: Each step
1. For each Auto in Autos:
1.1. Decrease energy by 1
1.2. Increase Kilometrage by a random value from a normal distribution with a mean of 15,000 and a standard deviation of 5,000
1.3. If energy $<= 0$ AND Kilometraje > (Vida_Útil_Vehícular * 15,000):
1.3.1. Set color to magenta
2. For each Moto in Motos:
2.1. Decrease energy by 1
2.2. Increase Kilometrage by a random value from a normal distribution with mean 15,000 and standard deviation 5,000
2.3. If energy $<= 0$ AND Kilometraje > (Vida_Útil_Vehícular * 15,000):
2.3.1. Set color to magenta
3. For each Bus in Buses:
3.1. Decrease energy by 1
3.2. If energy $<= 0$:
3.2.1. Set color to brown

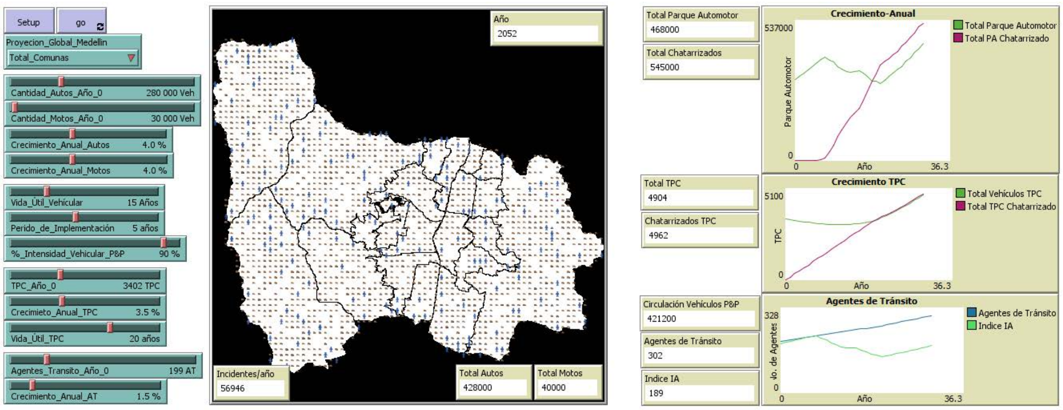

Figure 2 Graphic design of the model (NetLogo)

Table 2 Parameterization criteria

Criteria	Unit	Value
Car fleet	Cars	270,000
Motorcycle fleet	Motorcycles	29,000
Car fleet Growth	%	4 – 5
Motorcycle fleet Growth	%	4 – 7
Vehicle useful life	Years	–15 –20 - 25
Implementation period	Years	5 – 8 – 10
LPR Circulation	%	95 – 90
CPT	Buses	3,240
CPT growth	%	4 – 5
CPT useful life	Years	20

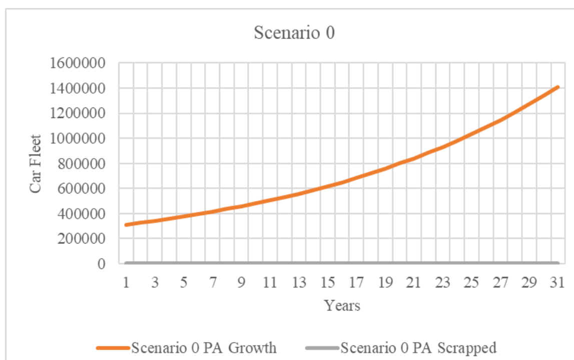

Figure 3 30-year projection of the base scenario for the vehicle fleet

increase of 373% compared to year zero. Additionally, the base scenario reflected an AI indicator equal to 200 for year zero and 721 for year 30, which represents an increase of 260%.

4.2 Scenario 1 - S1

This scenario (Figure 4), proposed by policymakers, is the most ambitious and provides the greatest control of the city's vehicle fleet in the next 30 years. It includes public policies that enable the city government to regulate the indicators of the vehicle fleet growth by 4%, based on several road safety and control strategies extracted from an interview with an expert from the Secretariat of Transportation of Medellín on July 26th, 2022.

The AMB defines this as the scenario with the most

Table 3 Scenarios (S) evaluated with the proposed ABM.

Criteria	Sb	S1	S2	S3	S4	S5
Car fleet year zero (Car)	280,000	280,000	280,000	280,000	280,000	280,000
Motorcycle fleet year zero (Motorcycles)	30,000	30,000	30,000	30,000	30,000	30,000
Car fleet Growth (%)	5	4	5	5	5	5
Motorcycle fleet Growth (%)	7	4	7	7	7	7
Vehicle useful life (years)	30	15	15	15	20	20
Implementation period (years)	30	5	5	8	5	8
LPBR registry (%)	95	90	95	95	95	95
Traffic agents (Agents)	199	199	199	199	199	199
TA Growth (%)	1.0	1.5	1.0	1.0	1.0	1.0
AI (Inc/TA*year)	200	190	200	200	200	200
Vehicle fleet year 30 (Vehicle)	1,467,000	471,000	824,000	830,000	973,000	978,000
Cars at year 30 (Car)	1,239,000	432,000	673,000	681,000	800,000	806,000
Motorcycles in year 30 (Motorcycles)	228,000	39,000	151,000	149,000	173,000	172,000
PA scrapped year 30 (Vehicle)	18,000	542,000	661,000	655,000	512,000	507,000
LPR Circulation	1,393,650	423,900	782,800	788,500	924,350	929,100

effective scrapping policy of private vehicles with a useful life of more than 15 years or their equivalent in KTV. This scenario proposes a policy implementation period that does not exceed five years and includes complementary LPR measures of two digits. Its effectiveness in controlling the vehicle fleet growth in the next 30 years results in a 50% increase a 50% increase compared to year zero and a 68% decrease compared to the base scenario. However, this scenario is based on vehicle fleet growth assumptions that the data do not align with the city's current mobility conditions. Additionally, in year 30, S1 presents an AIIA indicator equal to 197, representing a 1% decrease.

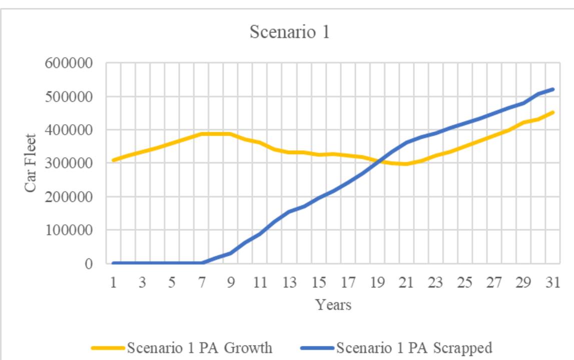

Figure 4 S1, vehicle fleet projection to 30 years

4.3 Scenario 2 - S2

Scenario 2 (Figure 5) includes the rigorous implementation of public policies to control the number of vehicles in the fleet over the next 30 years. It is based on the growth indicators found in the information sources. As in S1, the model is established by a scrapping policy for vehicles with a useful life greater than 15 years or their equivalent KTV, with a grace period for the implementation of the policy not exceeding five years and complementary LPR measures of one digit. Compared to year zero, the results indicate a 166% increase in the city's vehicle fleet in year 30 and, compared to the base scenario, they show a 47% decrease. Additionally, S2 presents an AI indicator equal to 408 for year 30, representing a 104% increase.

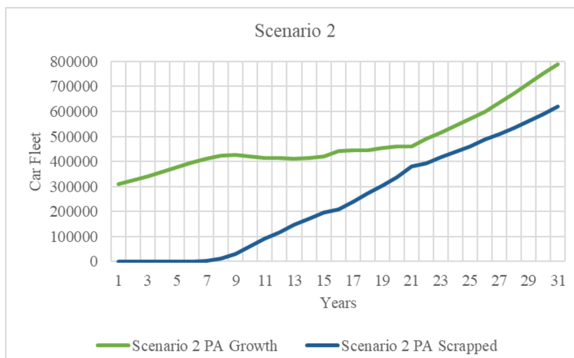

Figure 5 S2, vehicle fleet projection to 30 years

4.4 Scenario 3 - S3

This scenario (Figure 6) includes policies similar to those defined in S2, aimed at controlling the vehicle fleet over the next 30 years, but increasing the implementation period of these policies to eight years. Compared to year zero, S3 results indicate a 168% increase in the city's vehicle fleet in year 30 and a 44% decrease compared to the base scenario. S3 shows similar results to those of S2, suggesting that extending the implementation period of the scrapping policy does not considerably influence the projected vehicle fleet growth over 30 years if growth indicators remain constant. Additionally, in year 30, S3 presents an AI indicator of 406, representing a 103% increase.

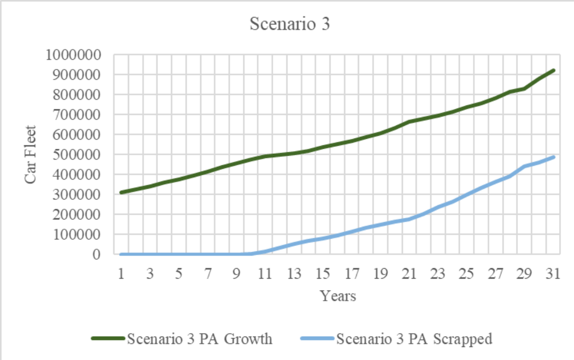

Figure 6 S3, vehicle fleet projection to 30 years

4.5 Scenario 4 - S4

This scenario (Figure 7) includes a conservative public policy to control the car fleet in the next 30 years, based on the growth indicators found in the information sources. The model consist of a scrapping policy for vehicles with a useful life greater than 20 years or their equivalent KTV, with a grace period for policy implementation not exceeding five years. Compared to year zero, the results show a 213% increase in the city's vehicle fleet by year 30 and a 34% decrease compared to the base scenario. Additionally, the S4 presents an AI indicator for year 30 equal to 484 for year 30, representing a 142% increase.

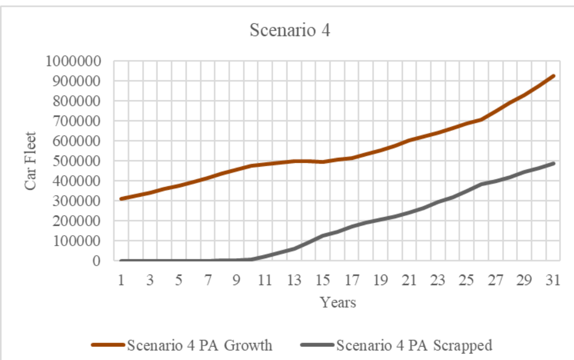

Figure 7 S4, vehicle fleet projection to 30 years

4.6 Scenario - E5

This scenario (Figure 8) includes the implementation of policies similar to those defined in S4, aimed at controlling the vehicle fleet over the next 30 years, but increasing the implementation period of these policies to eight years. Compared to year zero, the results show a 215% increase in the city's vehicle fleet in year 30 and a 33% decrease compared to the base scenario, showing results similar to S4. Therefore, S2 and S3 reinforce the hypothesis that increasing the implementation period of the scrapping policy does not considerably influence

Table 4 Scenarios (S) evaluated with the proposed ABM.

Commune	S1	S2	S3	S4	S5
1	6,365	11,261	11,315	13,274	13,219
2	7,816	13,828	13,894	16,299	16,232
3	16,380	28,980	29,120	34,160	34,020
4	16,895	29,891	30,035	35,234	35,089
5	14,555	25,751	25,875	30,354	30,229
6	15,725	27,821	27,955	32,794	32,655
7	27,331	48,355	48,589	56,998	56,765
8	15,772	27,904	28,038	32,891	32,756
9	29,578	52,330	52,582	61,683	61,430
10	16,988	30,056	30,202	35,429	35,284
11	66,596	117,824	118,394	138,885	138,316
12	30,982	54,814	55,078	64,611	64,346
13	16,567	29,311	29,453	34,550	34,409
14	90,839	160,715	161,491	189,442	188,665
15	8,705	15,401	15,475	18,154	18,079
16	58,266	103,086	103,584	121,512	121,014
50	2,340	4,140	4,160	4,880	4,860
60	4,727	8,363	8,403	9,858	9,817
70	5,803	10,267	10,317	12,102	12,059
80	12,215	21,611	21,715	25,474	25,369
90	3,557	6,293	6,323	7,418	7,387

vehicle fleet growth over 30 years if growth indicators remain constant. Additionally, the S5 scenario presents an IA indicator equal to 485 for year 30, representing a 142% increase. According to the results of all the projected

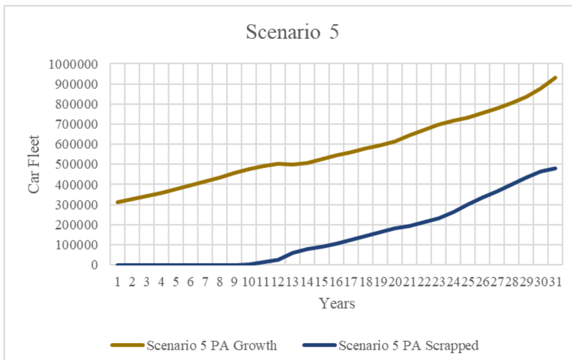

Figure 8 S5 vehicle fleet projection to 30 years

scenarios, S1, proposed by the policymakers, presents favorable indicators of the vehicle fleet projections for the next 30 years. However, due to the time needed to establish a public policy such as that proposed by S1, S5 stands out as the most conservative option considering the projection of motorization for the city in the coming years.

4.7 Growth Scenarios by Commune

Based on vehicle ownership records in the city and provided that these percentage ratios continue with minimal variations during the 30 years of the model evaluation, it is possible to obtain the projections of the vehicle fleet growth presented in Table 4 for each of the 21 communes of the city. The results show a significant increase in the vehicle fleet in the following communes:

14 (Poblado), 16 (Belén), and 11 (Laureles – Estadio). The increase is linked to the socioeconomic level of its inhabitants, their purchasing power, and the quality of the road infrastructure available for vehicular circulation in those communes. Conversely, communes located farther from these areas show the lowest vehicle fleet growth.

On the other hand, although the peripheral communes of the northeast and the northwest of the city present a lower differential growth compared to communes such as 14 (Poblado), a minimum vehicle fleet growth in these communes can have more significant negative impacts on congestion, commuting times and the quality of life of the inhabitants. This is because these areas are located on steep slopes and do not have adequate road infrastructure to serve larger vehicular volumes.

4.8 CPT vehicle scenarios

Regarding the growth policies of CPT, the information collected allowed us to evaluate the current conditions for the growth of the vehicle fleet in the city. In this sense, the existing CPT vehicle fleet operates under Law 105 of 1993, which outlines the basic provisions for transport, regulates planning in the transport sector, and establishes a useful life for the replacement of CPT vehicles of 20 years. However, with Law 2198 of 2022, the national government established some economic reactivation measures for public land transport, which included the extension of the useful life of CPT vehicles for 4 more years.

Based on these changes, the model was set to evaluate the effects derived from the extension of the useful life of CPT vehicles in the city's vehicle fleet. The results are shown in Table 5 and in Figure 9.

CPT S1 evidences a growth condition for CPT vehicles that has a relationship between the existing CPT vehicle fleet and scrapped for a projected useful life of 20 years, while scenarios CPT S2 and CPT S3 project a more ambitious growth to expand the coverage of this type of transport service. For its part, CPT S4 presents a growth of CPT vehicles with a useful life of 24 years, breaking the relationship between the existing CPT vehicle fleet and the number of scrapped units. Considering the above, CPT S1 has the most coherent policies regarding the growth needs of CPT vehicles in the city. S1 also considers the obligations imposed on transport companies, ensuring that vehicle scrapping occurs within the deadlines established by Colombian law. This approach not only promotes vehicle renewal but also supports the growth and modernization of CPT vehicles. Thus, the offer of public transport service is improved and the modal shift of private vehicle owners is encouraged.

5. Conclusions

The literature review shows that ABMs are an opportunity for public and academic institutions to formulate and evaluate public mobility and transport policies in their territories. ABMs enable the generation of different projected scenarios with multiple variables, making them useful for identifying problems and proposing effective solution strategies.

The ABM proposed in this study evidences the importance of accompanying TDM measures such as LPR, with public policies implemented by the National Government aimed at controlling the average age of the vehicle fleet, through strategies such as the scrapping of private vehicles that have completed their useful life. The aim of the measures and the ABM is to balance the relationship between population growth, the existing vehicle fleet, and the future vehicle fleet. Additionally, they intend to discourage the use and acquisition of private vehicles by strengthening the infrastructure and operation of the public transport system. Likewise, the strategy of including the KTV indicator within the vehicle scrapping factors might discourage the use of private vehicles as the main travel choice, as owners could be motivated to expand the KTV factor within their vehicles defined useful life period.

The projected growth of the vehicle fleet in the city's peripheral communes, characterized by a high slope topography and a limited road and traffic control infrastructure, represents a significant challenge for future governments. They will be responsible for implementing public policies that effectively encourage modal change and offer high quality public transportation, as future scrapping policies and TDM measures alone will be insufficient for the inevitable demographic growth of the peripheral communes, which are unlikely to develop an adequate road infrastructure to operate CPT vehicles.

A renewal of existing CPT policies, which currently operate under Law 105 of 1993, is necessary to facilitate the use of cleaner technologies for these vehicles. Additionally, the annual increase of CPT vehicles must reach at least 3.5% in the coming years to improve the offer, quality, and coverage of the service to motivate the owners of private vehicles to shift. This will involve the participation of the national government through subsidy strategies that help transport companies maintain a balanced operational cash flow.

Policies that allow transport companies to support technological tools aimed at controlling traffic in real time must be promoted, especially in peripheric and difficult access areas. The implementation of such technology

Table 5 CPT Scenarios

Criteria	Unit	CPT S1	CPT S2	CPT S3	CPT S4
CPT year zero	Buses	3,402	3,402	3,402	3,402
CPT Growth	%	3.5	4.0	3.5	4.0
CPT Useful Life	Years	20	20	24	24
CPT year 30	Buses	4,904	6,229	5,540	6,988
Scrapped year 30	Buses	4,962	5,234	4,326	4,475

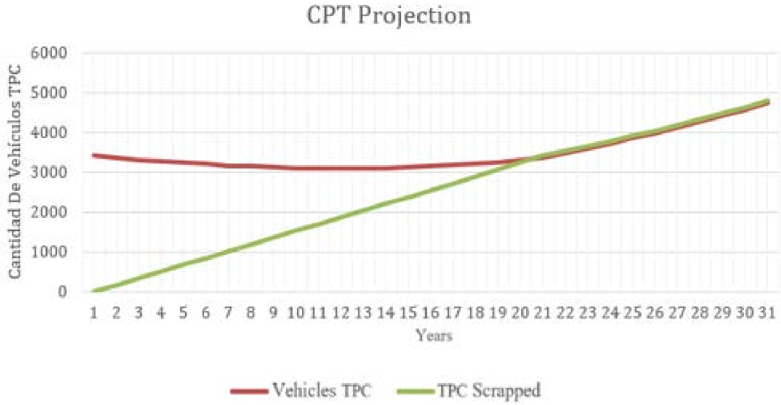

Figure 9 CPT S1 vehicle projection

might help mitigate the deficit of traffic agents expressed by the experts during the interviews and reflected in the model's estimations, which projected that within the next 30 years, the demand for traffic agents will be greater than 30%, leading to administrative and financial burdens for the district.

Declaration of competing interest

We declare that we have no significant conflicts of interest including financial or non-financial, professional or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

J. A. Zapata-Celis: Authored and designed the model as part of his master's thesis. Y. F. Ceballos and J. A. Castillo-Grisales: Contributed to the methodological support of the model with J. Zapata-Celis.

Data available statement

The authors confirm that the data supporting the findings of this study are available online at medata.gov.co

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