Modelling the Impact of Road Dust on Air Pollution: A Sustainable System Dynamics Approach

Sarah Khan [1*], *Quamrul* Hassan[1], *Kaushal* Kumar[2], *Saurav* Dixit[3,4], *Kshama* Sharma[5], *Vivek Kumar* C[6], *Navdeep* Dhaliwal[7] and *Bhukya* Madhu[8]

[1]Department of Civil Engineering, Jamia Millia Islamia, 110025 New Delhi,India
[2]Department of Mechanical Engineering, KR Mangalam University, Gurugram 122103,Haryana,India
[3] Division of Research & Innovation, Uttaranchal University, Dehradun, India,
[4]St. Peter the Great St. Petersburg Polytechnic University, St.Petersburg, 195251, Russia Federation
[5]SOMC,KR Mangalam University, Gurugram 122103, India
[6]Department of Civil Engineering, GRIET, Bachupally, Hyderabad, Telangana, India
[7]Lovely Professional University, Phagwara Punjab, 144001, India
[8]KG Reddy College of Engineering & Technology, Moinabad, Hyderabad, Telangana, India

Abstract. Road dust contributes significantly to air pollution by releasing fine particulate matter (PM) and other pollutants into the air, which can cause respiratory and cardiovascular problems and premature death. This dust is generated through the wear and tear of vehicle tires and road surfaces, as well as the accumulation of dirt and debris on the road, primarily from construction activities and cargo trucks carrying building materials. Wind, weather conditions, and vehicle movement play crucial roles in the distribution and concentration of these particles in the air. To address this issue, this paper focuses on identifying various variables that are connected to road dust operations and their interrelationships with air pollution variables, representing the dynamic pattern of the entire system. The paper proposes the establishment of a sustainable causal-loop model using system dynamics (SD) modeling in Vensim, connecting feedback mechanisms to effectively control the road dust concentration. Additionally, the paper suggests different policy interventions applied to the whole system to achieve optimized results. In the future, this research aims to convert and simulate the causal-loop model to a stock-flow model and compare the effectiveness of different policy interventions to further reduce road dust contributing to air pollution.

Keywords: Sustainable Approach, System Dynamics; Air Pollution; Road Dust; Modelling; Construction Activities

1 INTRODUCTION

* Corresponding author: sarah14khan@gmail.com; ghanghaskaushal@gmail.com

Road dust is a major cause of air pollution, releasing various types of particulate matter and pollutants into the air, which can result in respiratory and cardiovascular issues. The World Health Organization (WHO) estimates that outdoor air pollution is responsible for around 4.2 million premature deaths worldwide each year, and road dust is a significant contributor to this problem [1]. The composition of road dust varies depending on local factors, including climate, geography, and traffic patterns. However, common components of road dust include soil, mineral dust, brake and tire wear, and other debris. These particles can range in size from less than 2.5 micrometres (PM2.5) to less than 10 micrometres (PM10), which are small enough to penetrate deeply into the lungs and cause health problems.

In India, the percentage contribution of road dust to total PM pollution varies by location and season. Nevertheless, research has indicated that road dust is a significant source of PM pollution in numerous Indian cities. According to a report by the Central Pollution Control Board (CPCB), road dust accounts for the largest percentage of PM10 emissions in Indian cities, at 45% of total emissions. The report also indicates that road dust contributes to 10.9% of PM2.5 emissions in Indian cities [2-7]. These statistics demonstrate the considerable impact that road dust can have on air quality in India, particularly in urban areas with concentrated traffic and construction activities. The contribution of road dust to air pollution in an urban region is presented in figure 1 as a pie chart.

In order to comprehend the intricate behavior of air pollution caused by road dust, it is essential to examine the parameters of road dust operations and their associations with other parameters. These parameters are linked to one another through a feedback loop, and analyzing the response of these loops to modifications in one or more parameters is crucial to reduce road dust operations and control air pollution.

This paper aims to identify the inter-relationships between various parameters associated with road dust emissions and develop a Causal Loop Diagram (CLD) using the SD approach to comprehend the behavior of these relationships. The purpose of this paper is to establish a qualitative model that links road dust operations to air pollution [8-12].

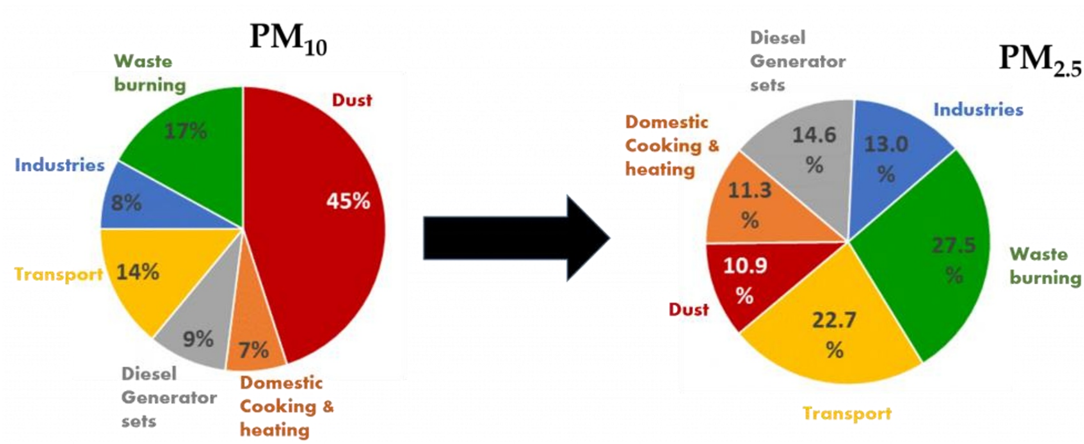

Fig. 1 Percentage contribution of Vehicular Sources (Line), Industrial Sources (Point) and Area Sources to PM10 and PM2.5 (Case Study of Delhi) Source: https://www.aqi.in/blog/analysis-of-air-pollution-and-indian-cities/

2 MATERIALS AND METHODOLOGY

The purpose of this study is to determine the relationship between road dust and air pollution. Rather than quantifying all parameters, the focus is on identifying specific parameters that need to be optimized in order to reduce pollution. The study follows the steps outlined below:

- Identification of parameters involved in road dust operations that are directly or indirectly linked to air pollution in general.
- Establishing a causal relationship between these parameters using feedback loops and creating a CLD diagram.
- Examining the nature of these loops to determine if they are positive or negative. Positive loops encourage the system to grow exponentially, while negative loops balance the system.
- Targeting the parameters in the loop system that are responsible for driving the pollution rate.

part of the experimental program, concrete cubes and beams were casted with and without coconut shells. The ingredients for concrete include Portland cement, sand, coarse aggregates, coconut shells, and water. Compressive strength was evaluated using the cubes, while flexural strength was evaluated using the beams.

3. CAUSAL LOOP MODEL

The process of System Dynamics Modelling involves two steps. The first step is a qualitative modelling approach that establishes the inter-relationship between different variables through a Causal Loop Diagram (CLD). The second step is a quantitative modelling approach that employs mathematical expressions to establish links between different variables [3, 4]. The CLD is developed by linking key variables in a system and expressing the causal relationship between them. It represents the qualitative aspects of the model, where variables are connected in a feedback loop, and their interdependencies can either have a positive or negative effect on each other. A positive effect means that an increase or decrease in one variable leads to a corresponding increase or decrease in another variable, respectively, while a negative effect opposes the growth and tries to maintain dynamic equilibrium in the system. These interdependencies can either create a self-reinforcing (positive) loop or a balancing (negative) loop. In this paper, a CLD of air pollution due to road dust operations is developed, and it is linked with population model [5, 13-14]. The parameters identified for the model and their function types are presented in Table 1.

Table 1: Parameters selected for CLD Model

Parameters	Function Type
Birth	A Function of Population
Construction Activities	A Function of Enclosure Construction, Exhaust Ventilation System, Urbanization, Wet Dust Suppression
Covered vehicles for transportation	Exogenous Variable

 https://doi.org/10.1051/e3sconf/202343001176

Death	A Function of Health Impact, Population
Dry/Arid Atmosphere	Exogenous Variable
Emigration	Exogenous Variable
Enclosure Construction	Exogenous Variable
Exhaust Ventilation System	Exogenous Variable
Health Impact	A Function of Pollution Load
Immigration	Exogenous Variable
Industries/Factories	A Function of Urbanization
Land Use Pattern	A Function of Population
Pollution Load	A Function of Road Dust
Population	A Function of Birth, Death, Emigration, Immigration,
Precipitation	Exogenous Variable
Prohibition of grinding and cutting of building material in open	A Function of Economic Growth
Road Dust	Construction Activities, Covered Vehicles for Transportation, Dry/Arid Atmosphere, Industries/Factories, Land Use Pattern, Precipitation, Prohibition of grinding and cutting of building material in open, Road Transport, Soil erosion, Unpaved Roads, Urbanization, Vegetation Cover, Water Sprinkling System, Wind
Road Transport	A Function of Urbanization
Soil Erosion	A Function of Vegetation Cover, Wind
Unpaved Roads	Exogenous Variable
Urbanization	Immigration, Population
Vegetation Cover	Land Use Pattern, Population
Water Sprinkling System	Exogenous Variable
Wet Dust Suppression	Exogenous Variable

The key variables selected are Population and Pollution Load connected to Road Dust. There are 11 loops of population as the key variable in the model. Loop 1 has 2 parameters: only population and birth (Reinforcing Loop). Loop 2 also has only 2 parameters: population and death (Reinforcing Loop). Loop 3 has 5 parameters: Population, Vegetation Cover, Road Dust, Pollution Load, Health Impact and Death (Reinforcing Loop). Loop 4 has 5 parameters: Population, Urbanization, Road Dust, Pollution Load, Health Impact and Death (Balancing Loop). Loop 5 has 5 parameters: Population, Land Use Pattern, Road Dust, Pollution Load, Health Impact and Death (Balancing Loop). Loop 6 has 6 parameters: Population, Vegetation Cover, Soil erosion, Road Dust, Pollution Load, Health Impact and Death (Reinforcing Loop). Loop 7 has 6 parameters: Population, Urbanization, Road Transport, Road Dust, Pollution Load, Health Impact and Death (Balancing Loop). Loop 8 has 6 parameters: Population, Land Use Pattern, Vegetation Cover, Road Dust, Pollution Load, Health Impact and Death (Reinforcing Loop). Loop 9 has 6 parameters: Population, Urbanization, Construction Activities, Road Dust, Pollution Load, Health Impact and Death (Balancing Loop). Loop 10 has 6 parameters: Population, Urbanization, Industries/Factories, Road Dust, Pollution Load, Health Impact and Death (Balancing Loop). Loop 11 has 7 parameters:

 https://doi.org/10.1051/e3sconf/202343001176

Population, Land Use Pattern, Vegetation Cover, Soil erosion, Road Dust, Pollution Load, Health Impact and Death (Reinforcing Loop).

There are 9 loops of Road Dust as the key variable in the model. Loop 1 has 5 parameters: ad Dust, Pollution Load, Health Impact, Death, Population and Land Use Pattern (Balancing Loop). Loop 2 has 5 parameters: Road Dust, Pollution Load, Health Impact, Death, Population and Vegetation Cover (Reinforcing Loop). Loop 3 has 5 parameters: Road Dust, Pollution Load, Health Impact, Death, Population and Urbanization (Balancing Loop). Loop 4 has 6 parameters: Road Dust, Pollution Load, Health Impact, Death, Population, Urbanization and Road Transport (Balancing Loop). Loop 5 has 6 parameters: Road Dust, Pollution Load, Health Impact, Death, Population, Vegetation Cover and Soil erosion (Reinforcing Loop). Loop 6 has 6 parameters Road Dust, Pollution Load, Health Impact, Death, Population, Urbanization and Construction Activities (Balancing Loop). Loop 7 has 6 parameters: Road Dust, Pollution Load, Health Impact, Death, Population, Urbanization, Industries/Factories (Balancing Loop). Loop 8 has 6 parameters: Road Dust, Pollution Load, Health Impact, Death, Population, Land Use Pattern and Vegetation (Reinforcing Loop). Loop 9 has Road Dust, Pollution Load, Health Impact, Death, Population, Land Use Pattern, Vegetation Cover and Soil erosion (Reinforcing Loop).

Furthermore, the feedback loops in the CLD are supplemented by auxiliary variables and exogenous variables to represent a dynamic system (Fig 2). While the CLD provides a qualitative model that highlights the relationships between different variables, it can also be converted into a Stock and Flow model that demonstrates the quantitative behavior of the system. The Stock and Flow model establishes the mathematical relationships between the variables in the system.

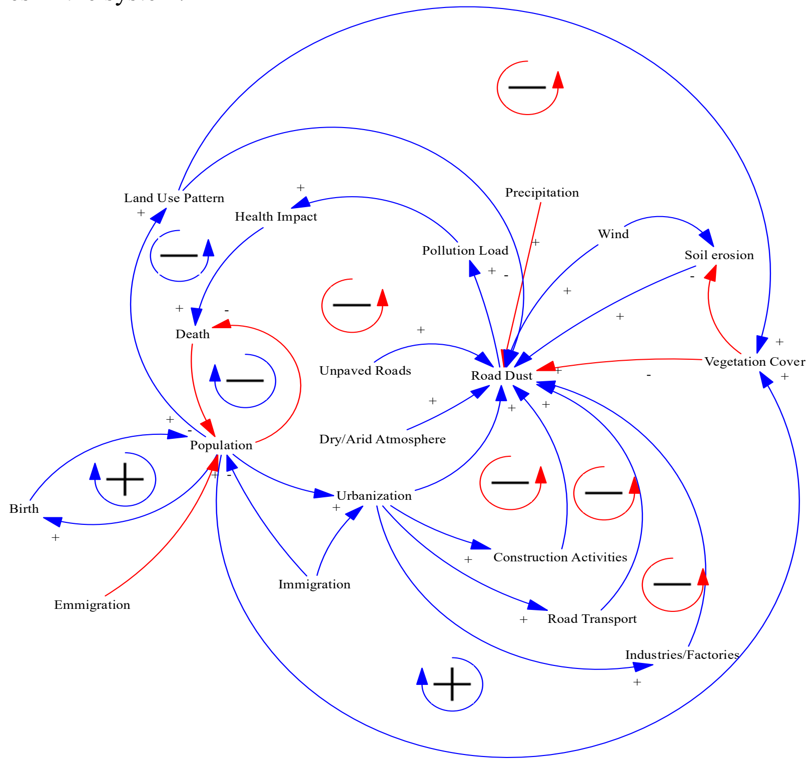

Fig. 2. CLD for Air Pollution System for Road Dust

 https://doi.org/10.1051/e3sconf/202343001176

4. POLICY IMPLICATIONS

The study selected two sub-systems connected to road dust via exogenous and endogenous variables, as shown in Fig 2. These sub-systems are linked together in mostly negative feedback loops, indicating a balancing system. Fig 3 displays various policies that have been directly linked to the variables and can impact one or more of them. Implementing these policies can help reduce road dust pollution and mitigate air pollution. Examples of existing policies include using a water sprinkling system to control road dust diffusion and transportation, using covered vehicles for transport, and prohibiting grinding and cutting of building material in the open. Exhaust ventilation systems, wet dust suppression, and enclosure construction can be used to control dust released from construction activities. Although this study did not consider some techniques due to the complexity of modelling them, such techniques include covering unpaved surfaces with gravel, increasing the moisture content of the road surface, binding particles together, and avoiding road-side storage of construction material [5].However, these type of techniques are more valuable for concrete or green technology as well [6-8].

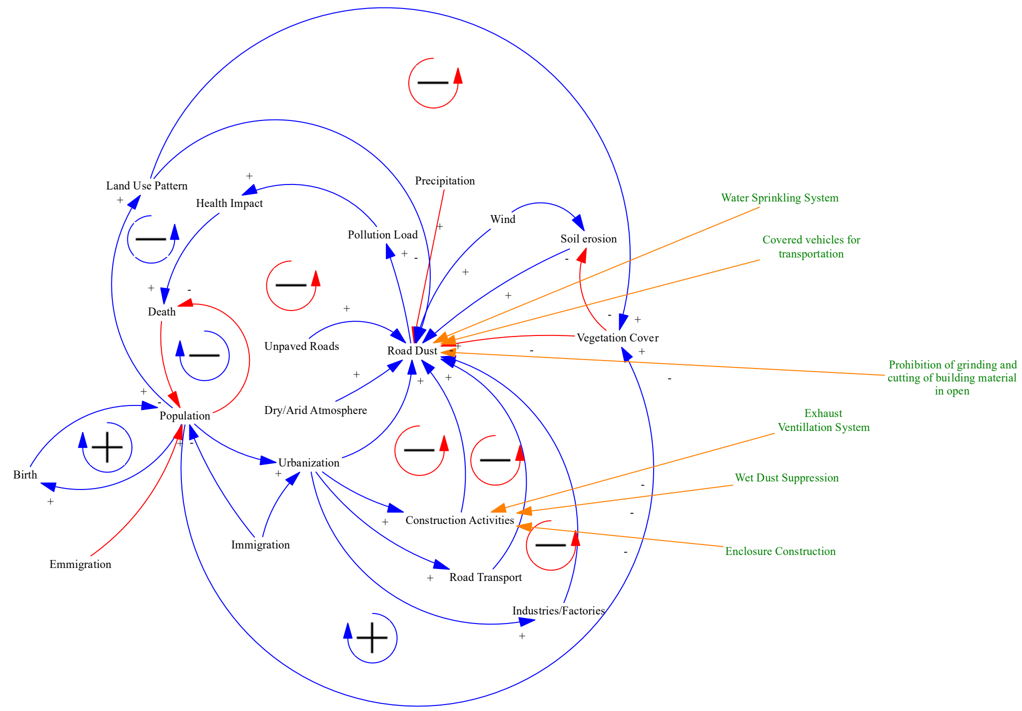

Fig. 3. Policy intervention applied to CLD of Air Pollution System

5. CONCLUSION

India consistently features on the list of the world's most polluted cities, with pollution originating from a variety of sources including the transportation sector, industry, road dust, power plants, and the domestic sector, among others [9]. Road dust is comprised of particles that collect on the surface of paved roads and can be released into the atmosphere due to turbulence generated by vehicles or wind [10]. These emissions from non-exhaust sources are a significant contributor to the concentration of atmospheric PM pollutants in urban and industrial settings, leading to violations of air quality standards. Road dust emissions are influenced by a range of factors, including traffic volume and composition, driving speed, road surface materials, as well as meteorological factors such as temperature, humidity, rainfall, and wind conditions. The measures required to reduce road dust emissions can vary from one region to another due to differences in traffic and climatic conditions. Preventative strategies, such as paving access to unpaved areas or restricting road traffic, aim to prevent the accumulation of particles on the road surface, while mitigating measures focus on the removal or binding of the already deposited particles [4].

The recognition of the dynamic behavior of variables and their interrelationships with each other in a system is essential. This study focuses on identifying the parameters associated with road dust and linking them to other subsystems in a real-world scenario. The population and pollution subsystems that are part of road dust operations are combined to understand their dependencies using a CLD model. This model illustrates how feedback loops work, either leading to system expansion resulting in catastrophe or reinforcing the system, leading to maintaining equilibrium. Additionally, the model highlights the need for policies to target specific variables instead of applying them to the entire system. The future scope of this research is to convert the qualitative model into a quantitative one by linking variables through mathematical expressions. To achieve this, secondary data is collected through literature and expert opinions. This will assist policy makers and other stakeholders in effective planning and management [9-12].

References

1. Ambient (outdoor) air pollution, World Health Organisation, 2022; retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health
2. Shocking Situation of Air Pollution in Indian Cities, Air quality index, 2019. Retrieved from: https://www.aqi.in/blog/analysis-of-air-pollution-and-indian-cities/
3. J.P.Walters, D.W. Archer, G.F. Sassenrath, J.R. Hendrickson,J.D Hanson,J.M. Halloran and V.J. Alarcon, *Ecol. Model.* **333**, 51-65 (2016). https://doi.org/10.1016/j.ecolmodel.2016.04.015
4. E.R. Hosseinabad and R.J. Moraga, J. Appl. Environ. Biol. Sci. **7,**164-174(2017). https://www.textroad.com/pdf/JAEBS/J.%20Appl.%20Environ.%20Biol.%20Sci.%207(12)164-174%202017.pdf
5. Workshop on Dust Control Measures at Construction Sites to Control Air Pollution, Dept. of Environment, GNCT Delhi, 2018,

   Retrieved from: http://fs.delhigovt.nic.in/wps/wcm/connect/fd888e004761d34d9e03ff47ba5b58d3/CRRI.pdf?MOD=AJPERES&lmod=2120739862&CACHEID=fd888e004761d34d9e03ff47ba5b58d3
6. K. Kumar, R. Arora, S. Khan, S. Dixit,. https://doi.org/10.1016/j.matpr.2021.11.160
7. K. Kumar, R. Arora, J. Singh, S. Khan, L. Mishra, P. Bhandari, S. Dixit , C. Prakash Lect. Notes Mech. Eng. **58**, (211–217) 2020: Springer, Singapore. https://doi.org/10.1007/978-981-19-4147-4_22
8. K. Kumar, R. Arora, S. Dixit, Asian J. Civ. Eng. **24**, 7 (2023) https://doi.org/10.1007/s42107-023-00858-0

9. AIRUSE, Report 28, 2016, http://airuse.eu/wp-content/uploads/2013/11/R28_AIRUSE-TechGuide-road-dust-emission-reduction.pdf
10. S. Khan and Q. Hassan. Mater. Today: Proc. **69**, 413-418(2022)
11. S. Dixit, K. Sharma, and S. Singh, *Identifying and Analysing Key Factors Associated with Risks in Construction Projects* (2020)
12. S. Dixit, A. Stefańska, and A. Musiuk, Ain Shams Engineering Journal **12**, 2321 (2021)
13. M. S. Malik, R. I. Alsantali, R. S. Jassas, A. A. Alsimaree, R. Syed, M. A. Alsharif, K. Kalpana, M. Morad, I. I. Althagafi, and S. A. Ahmed, RSC Adv **11**, 35806 (2021)
14. S. P. Arunkumar, C. Prabha, R. Saminathan, J. A. Khamaj, M. Viswanath, C. K. Paul Ivan, R. Subbiah, and P. M. Kumar, Mater Today Proc 1411 (2022)