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Analysing driving factors of India's transportation sector CO_2 emissions: Based on LMDI decomposition method

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ABSTRACT

India is the world's third-largest carbon dioxide (CO_2) emitter, with the transportation sector accounting for most of this emission. Using the logarithmic-mean Divisia index (LMDI) decomposition method and Tapio decoupling, this study examines the driving factors and their relationship with economic growth for the Indian transportation sector. Transportation-related energy consumption is decomposed into six factors. From 2001 to 2020, CO_2 emissions from the Indian transportation sector increased from 155.9 Mt to 368.2 Mt. Roadways produce 88% of all CO_2 emissions. Energy systems, economic advancement, and population scale increase CO_2 emissions, whereas energy performance and transportation form decrease. Transport advancement demonstrates both tendencies intermittently. CO_2 emissions from Indian transportation exhibit a weak decoupling. The increasing demand for vehicles, reliance on conventional fuel, and increase in energy consumption indicate a positive correlation with the increase in the nation's CO_2 emissions, while the transition from coal to electric locomotives and the increased use of electric vehicles offset the increase in emissions. In short, the government should update strategic sustainable transport policy measures and emphasize renewable energy. This study will assist policymakers in formulating robust sustainable transportation policies.

1. Introduction

The environmental problem, such as global warming, is becoming increasingly significant. The primary cause of global warming is the increasing concentration of GHGs (Greenhouse Gases) in the atmosphere. These increased global GHGs and their effects on the environment and human life have intensified concern about future natural threats, such as rising land and ocean temperatures, prolonged droughts, global warming, ozone depletion, agriculture crop destruction, and other natural hazards [1]. Many national and international societies have taken several steps to combat climate change to limit GHGs at the global level. Thus, the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement have globally ratified agreements to mitigate GHGs emissions [2].

Some of the most prevalent GHGs are Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluoride (HFCs), perfluorocarbon (PFCs), and Sulphur hexafluoride (SF_6) but among these scientists studying climate have determined that CO_2 emissions are the highest and account for approximately 75% of global GHG emissions [3]. The International Energy Agency (IEA) estimates that global energy-related CO_2 emissions will reach 31.5 billion metric tons in 2020, with the transportation sector contributing nearly 24% of total CO_2 emissions [4]. Increasing vehicle numbers and fossil fuel combustion make the transportation sector one of the most

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significant areas of concern. Generally, when studying research on CO_2 emissions, it can be helpful to divide it into two distinct parts. The first category focuses on the primary driving factors influencing the change in CO_2 emissions. In contrast, the second category investigates the relationship between CO_2 emissions and other driving factors, emphasizing future trends.

Various decomposition techniques, such as econometric regression, structural decomposition analysis (SDA), and index decomposition analysis (IDA), are used to assess the influence of various factors on the variation of energy consumption and CO_2 emissions. Even though SDA can provide a comprehensive breakdown of economic and technological effects, IDA offers a more precise time frame for country-based analyses. In IDA, the LMDI method has been recognized globally in decomposing energy consumption by transportation sectors [5,6]. Principally, LMDI decomposition is applied based on the most probable emission contributing sectors. In China [7], used LMDI to study transport sector's CO_2 emissions. The author decomposes transportation sector facilities, fuel consumption, population and Gross Domestic Product (GDP) into six factors and finds that per capita economic activity effect and modal transportation shifting are the leading causes of CO_2 growth, while transportation intensity effect and transportation services share effect reduce transportation CO_2. Similarly [8], examined transportation sector energy consumption and its factors. In Tunisia [9], decomposed energy consumption related to transportation, whereas [10] in Korea decomposes transportation sector emissions into energy, technology, urbanization, and R&D expenditure.

The decomposition factors can also vary depending on the area of concern and objective [11]. investigated the potential factors such as energy structure, energy efficiency, transport form, transportation development, economic development, and population size that influence the growth of CO_2 emissions in China's transportation system. Similarly [12], decomposed CO_2 emissions from the road transportation sector in six Asia-Pacific nations into five factors, mainly economic output, transportation intensity, energy intensity, carbon emissions coefficient of energy, and population size. Some studies examine CO_2 emissions from a particular mode of transportation. A study by Ref. [13] analyzes driving forces in China's freight transport, while [14] predict CO_2 emissions from energy consumption in Thailand's transportation sector, including the impact of vehicle size changes.

[15] was the first researcher to apply decoupling to environmental studies. The Tapio [16] theory was presented as a theoretical framework for the European transportation sector for the first time in 2005. later, it became a widely popular technique employed by modern researchers to determine the relationship between GDP and CO_2 emissions at both the global and regional levels [17,18]. Globally [19], examined the relationship between the growth of the transportation sector and CO_2 emissions in the Eurasian logistics corridor using the Tapio decoupling model. Similarly [20], used the decoupling analysis to examine the relationship between the CO_2 influencing factors and CO_2 emissions in the Organization for Economic Co-operation and Development (OECD). At regional [21], applied decoupling analysis to the Cameroon transportation system [22], to the Pakistani transport sector [23], to the Chinese transport sector, and [24] to the Pakistan, India, and China region.

India is the world's third-largest emitter of CO_2 after China and the United States. India is responsible for approximately 6–7% of the world's total CO2 emissions [25]. Transportation has become one of India's top three polluting sectors, accounting for about 10% of the country's GHGs [26]. Limited studies have examined the characteristics of CO_2 emissions from the transportation sector in recent years [27]. examined the role of various factors responsible for CO_2 emissions from Indian road passenger transport from 1971 to 2011 using LMDI analyses. The results show that economic growth, transportation activity, and population play a substantial positive role in increasing CO_2 emissions from road passenger transport, whereas energy intensity has a negative one. Other significant decomposition analysis studies are conducted for energy sources such as industry, households, power, and transportation [28,29]. Decoupling is performed for industrial economic growth, fuel consumption, and CO_2 emissions in Pakistan, India, and China for decomposition analysis [30] and India and China [31].

The literature lacks rigorous studies examining all major transport modes and their associated driving factors, such as energy consumption, transport facility, GDP, and population. It is essential to conduct exhaustive transportation sector studies to determine the role of each CO_2 contributing factor and to conduct a CO_2 – GDP growth analysis. This study utilizes the LMDI decomposition method and the Tapio decoupling technique to fill the gap or strengthen the literature in the Indian context. It evaluates the primary causes of CO_2 emissions from the Indian transportation sector from 2001 to 2020 based on an extended Kaya identity, decomposition, and decoupling. This study categorized each of the significant CO_2 decomposition factors into six groups: energy system, energy performance, transportation form, transportation advancement, economic advancement, and population scale. In addition, the analysis includes energy consumption and CO_2 emission analysis for all significant fuels, including motor gasoline, diesel oil, Jet Kerosene, aviation gasoline, CNG, and electricity, used in the various modes of the Indian transportation sector, such as roadways, railways, waterways, and airways. The findings of this study will be essential for policymakers to better comprehend the impact of these emissions on air quality and develop policies and regulations to reduce pollution levels, leading to more sustainable transportation and environmental conditions.

The structural organization of this paper is described below. Section 2 provides an overview of the energy consumption of the transportation sector in India. Section 3 describes the methods and database, followed by Section 4, which reports the analytical results. Section 5 concludes the study with a conclusion and discussion with a brief on policy recommendations.

2. Transport energy consumption in India

Energy consumption in India, which has a developing financial market and a rising GDP, has entered a rapid growth phase. In 2020, India was the fifth largest economy in the world, with a GDP of $2.87 trillion, and the second most populated country, with over 1.38 billion populations. It is anticipated to become the second-largest economy in the world by 2050, with approximately 1.64 billion people. Strong economic development and a fast-growing population are driving up energy consumption and transportation services demands. Further research and predictions estimate that India's total primary energy supply demand will increase from approximately

880 Mtoe in 2020 to about 1930 Mtoe in 2040/42. In 2020, coal met 44% of India's immediate energy demands, while oil and gas contributed 31%, primarily through imports. Energy consumption details show that transportation is India's third largest energy consumer, after industry and buildings, which has more than doubled since 2000.

The Indian transportation sector mainly consists of roadways, waterways, airways, and railways with passenger and freight modes. The passenger modes generally transport passengers from one place to another and consist of light-duty automobiles and trucks, buses, two- and three-wheeled vehicles, airplanes, waterways, and passenger trains. The freight modes transporting raw, intermediate, and finished commodities to consumers include heavy, medium, and light-duty vehicles, maritime vessels, freight airplanes, and railways. The demand for road passenger transport (measured in passenger kilometers traveled) increased by a Compound annual growth rate (CAGR) of 10% between 2001 and 2020, from 494 billion passenger kilometers to 2889.38 billion passenger kilometers. The demand for road freight transport increased by a CAGR of 14% between 2001 and 2020, from 2076 billion tonnes kilometers to 24192.8 billion tonnes kilometers. Similarly, the CAGR for rail passenger kilometers is 4%, from 457.02 billion passenger-kilometers in 2001 to 1050.7 billion passenger-kilometers in 2020.

In contrast, the CAGR for rail freight transport demand is 4%, beginning with 315.5 billion tonnes kilometers in 2001 and ending with 708.03 billion tonnes kilometers in 2020. Demand for airways passenger transport (as measured by the number of domestic travelers) increased at a CAGR of 13% between 2001 and 2020, from 28.01 million passengers to 274.4 million passengers. Between 2001 and 2020, the demand for airways freight transport grew at a CAGR of 8%, from 288.3 million tonnes kilometers to 1321.1 million tonnes kilometers. Correspondingly, the CAGR for waterways passenger transport is 3%, from 95.4 million passengers in 2001 to 162.2 million passengers in 2020, while the CAGR for waterways freight transport demand is 17%, from 26731 million tonnes kilometers in 2001–509671 million tonnes kilometers in 2020. This expansion of India's transportation fleet has produced and will continue to create significant energy demand and environmental challenges.

In the Indian road transportation system, petrol, diesel, CNG, and LPG are extensively utilized as fuels. Due to strict government regulations and safety concerns around LPG usage in certain Indian states, it is excluded from this study. The use of petrol, diesel, and compressed natural gas has increased dramatically. In 2001, petrol consumption was 6.6 million metric tonnes, projected to increase to 29.9 million metric tonnes by 2020, depicting a growth rate of 353% and 8% CAGR [32]. Similarly, diesel and CNG usage in 2001 were 36.8 million metric tonnes and 202 MMSCMD, respectively, and is projected to increase to 71.8 million metric tonnes and 3247 MMSCMD by 2020, with respective growth rates of 95% and 1510% and CAGRs of 4% and 16% [33]. Coal, diesel, and electricity are typically the three types of fuels utilized by railways. In the year 2001, four thousand tonnes of coal were consumed, which decreased to one thousand tonnes by the year 2020, with a growth rate and CAGR of −75% and −7%. Whereas in the year 2001, the consumption for diesel and electricity was 1.9 tonnes liters and 7933 million KWH, which increased to 2.3 tonnes liters and 18410 million KWH in 2020 with a growth rate of 19% and 132% and CAGR of 1% and 5%. In India, mainly just one type of ATF is utilized by airlines. Consumption of ATF increased from 1.4 million metric tonnes in 2001 to 6.1 million metric tonnes in 2020 at a growth rate of 310% and CAGR of 8%. For waterways, high-speed diesel is predominantly used. In 2001, waterway consumption was 0.24 million metric tonnes, projected to climb to 0.80 million metric tonnes (MMT) by 2020 at a growth rate of 227% and CAGR of 6% [34].

The Indian government implemented several regulatory measures, including the introduction of standards for energy-efficient vehicles, to achieve energy savings. Furthermore, the government took a number of measures to curb the expansion of energy demand, including increasing natural gas consumption and developing renewable energy sources. In addition, by 2025, the Indian government intends to blend 20% ethanol with gasoline (E20). Combining oxygenated alcohol and gasoline can significantly reduce emissions [35]. Other than this, the Indian government prohibited diesel and gasoline vehicles after 10 and 15 years, respectively, in certain states. At last, the Bharat Stage Emission Standards (BSES) engine vehicle norms were introduced and modified frequently to reduce pollution levels.

3. Methodology

3.1. Data sources

The levels of CO_2 emissions and energy consumption from India's transportation sectors will be analyzed in this study by accumulating annual data from 2001 to 2020 and using Logarithmic Mean Divisia Index (LMDI) decomposition analysis. For the LMDI decomposition method, transportation data such as energy consumption and service are collected from the airways, roadways, railways, and waterways. Data such as Gross Domestic Product (GDP) and country population are also utilized.

The GDP is expressed in 10^{11} US dollars, and the data is obtained from world development indicators [36]. The population is expressed in millions, and population data is calculated by interpolating the 2001 and 2011 Census of India survey population data [37] Data on civil aviation is received from the Airport Authority of India [38]. Data on energy consumption in the aviation sector is derived from the Ministry of Petroleum and Natural Gas [39] In this analysis, only domestic flights are evaluated, and they mostly use a single type of Air Turbine Fuel (ATF). Indian railways usually use three locomotives (stream, coal, and electricity) that run on three distinct fuel types (coal, diesel, and electricity). Railways operation and energy consumption data are obtained from the Indian railway's national yearbook [40]. This study considers solely offshore and coastal data for waterways. The waterway operation data was obtained from the Ministry of Ports, Shipping and Waterways (MOPSW) and the Indian National Shipowners Association under the Government of India. Waterways are powered mainly by a single type of high-speed diesel. Data for energy consumption of waterways is obtained from the Ministry of Petroleum and Natural Gas, which aggregates data from the petroleum planning and analysis cell. MORTH, MoPNG, and other offices of state transport commissioner's/UT administrations provide roadway data such as energy consumption and operation of passenger and freight vehicles. The majority of roadways are powered by one of four fuel types: diesel, gasoline (petrol), compressed natural gas (CNG), and electricity. For electric vehicles, back calculations were performed to determine the share of non-renewable sources in energy production. The electricity transmission loss of 15% is also considered during calculations. It is critical to mention that transportation facility is measured in tonne-kilometers traveled. Passenger trips for all modes of transportation have been translated from passenger-km to tonne-km in eq. (1). Total transportation facility of passenger-km and freight km equals passenger facility km divided by a conversion coefficient plus freight traffic km [41].

$$V_i^t = \frac{V_{ip}^t}{C} + V_{if'}^t \tag{1}$$

V_i^t - represents total transportation facility of ith transportation mode in year t.

V_{ip}^t - represents total passenger km traveled from ith transportation mode in year t.

$V_{if'}^t$ - represents total freight km from ith transportation mode in year t.

C - represents the conversion coefficient.

The conversion coefficient (C) is calculated by comparing revenue and expenditures per person-kilometer (moving one person 1 km) with those carrying one tonne of goods 1 km. This means that for transporting one tonne of cargo, 1 km is comparable to conveying one passenger 1 km [42]. Table 1 shows the conversion coefficients for different types of transportation.

3.2. Methodology to calculate CO_2 emissions

For the ith year, we used the method provided by the IPCC in eq. (2) to calculate CO_2 emissions from Indian transportation systems.

$$C^t = \sum_i C_i^t = \sum_{i,j} C_{ij}^t = \sum_{i,j} R_{ij}^t \times F_j \times N_j \tag{2}$$

In Eq. (2),

C_{ij}^t - represents the CO_2 emission from each transportation facility of the ith transportation mode based on fuel type j in year t.

R_{ij}^t - represents the energy consumed by each transportation facility of the ith transportation mode based on fuel type j in year t.

F_j – represents the carbon emission factor of the jth fuel

N_j – represents the net calorific value based on fuel type j

The R_{ij}^t are taken from various national and state yearly published databases in this case (explained in the data section). There haven't been many studies that look at F_j in the transportation sector. The values of F_j (t/TJ) used in this study were derived for Coking coal, Diesel/LDO, Petrol, CNG, and ATF (IPCC 2006). N_j values were obtained from IPCC 1996 and IPCC 2006. The value of F_j and N_j are mentioned in Table 2.

3.3. KAYA - LMDI approach

Index Decomposition analysis (IDA) has been extensively utilized to investigate better the trends of driving factors of CO_2 emissions and energy consumption [44,45]. The primary IDA technique can be subdivided into the Divisia index and Laspeyres index methods. There are always residual items that cannot be merged and are ignored throughout the Laspeyres index method's decomposition procedure, which has adverse effects on the result of decomposition. Since there are no residual variables in the Divisia index method, it has become the predominant empirical research method in the research field. Moreover, the logarithmic mean Divisia index (LMDI) is a typical way of calculating the Divisia index that is compelling in both practical and theoretical [46]. subsequently proposed the well-known LMDI decomposition analysis approach. The LMDI approach can be decomposed in both additive and multiplicative ways. The additive decomposition analysis determines absolute change, whereas the multiplicative decomposition analysis determines relative change [47].

In this paper, we use addition decomposition to decompose CO_2 emissions levels between a reference year and an end year into additive components called factors from India's transportation sector. Assume that the total energy consumption of the initial period is E_0 (2001) and that the total energy consumption of the end period is E_t (2020). Incorporate these values into Eq. (3), respectively, and calculate the logarithms for both sides of the formula. The CO_2 is decomposed into six factors in eq. (3) and eq. (4) through the use of an analysis of general index decomposition (IDA) and an explanation of Six decomposed factors are summarized as follows:

$$C^t = \sum_{i,j} C_{ij}^t = \sum_{i,j} \frac{C_{ij}^t}{EC_{ij}^t} \times \frac{EC_{ij}^t}{EC_i^t} \times \frac{EC_i^t}{V_i^t} \times \frac{V_i^t}{V^t} \times \frac{V^t}{GDP^t} \times \frac{GDP^t}{P^t} \times P^t \tag{3}$$

Where,

Table 1
Conversion coefficient for passenger and freight tonne (Unit: passenger/freight tonne).

	Railways	Waterways	Roadways	Airways
Conversion coefficient (C)	1	3.03	5	13.88

Table 2
Emission factor F_j and Net calorific value N_j for different fuels used in the transportation sector. Source: [43].

Fuel	F_j (t/TJ)	N_j
Coal	94.6	25.8
Petrol	69.3	44.3
Diesel/LDO	74.10	43
CNG	56.10	48
ATF	71.50	44.1

C^t- represents total CO_2 emissions
C_{ij}^t - represents CO_2 emission of the ith transportation mode based on fuel type j in year t.
EC_{ij}^t- represents the energy consumption by the ith transportation mode based on fuel type j in year t.
EC_i^t - represents the energy consumption by the ith transportation mode based on fuel type j in year t.
V_i^t - represents transport facility of the ith transportation mode in year t.
V^t - represents total transport facility in year t
GDP^t - represents the Gross domestic product of India in year t.
P^t - represents the population of India in year t.
Here, eq. (3) can be shortened and expressed in eq. (4)

$$C^t = \sum_{i,j} CI_{ij}^t \times ES_{ij}^t \times EP_i^t \times TF_i^t \times TA^t \times EA^t \times PS^t \tag{4}$$

The definition of CO_2 decomposition factors is as follows:

$CI_{ij}^t = \frac{C_{ij}^t}{EC_{ij}^t}$ the emission coefficient (CI): it represents the changes in the emission coefficient of the ith transportation mode based on fuel type j in year t.

$ES_{ij}^t = \frac{EC_{ij}^t}{EC_i^t}$- the energy system (ES) represents the proportion of energy source of the ith transportation mode based on fuel type j in year t.

$EP_i^t = \frac{EC_i^t}{V_i^t}$ - the energy performance (EP) represents energy consumption per unit of total transport turnover facility by ith transportation mode in year t.

$TF_i^t = \frac{V_i^t}{V^t}$- the transportation form (TF) represents the proportion of a specific transport form's comprehensive turnover facility to the total comprehensive turnover facility by ith transportation mode in year t.

$TA^t = \frac{V^t}{GDP^t}$transportation advancement (TA) represents the volume of total transportation turnover facility per unit of GDP in the year t.

$EA^t = \frac{GDP^t}{P^t}$ the economic advancement (EA): it represents the level of economic activity per capita in the year t

$PS^t = P^t$- the population scale (PS): it represents the population in year t

When comparing a base year 0 to a target year t, C_T represents the change in transportation-related CO_2 emissions. The change in total emission due to the underlying factors is broken down into six effects, as shown in Eq. (5):

$$\Delta C_{TOT} = \Delta C_{CI} + \Delta C_{ES} + \Delta C_{EP} + \Delta C_{TF} + \Delta C_{TA} + \Delta C_{EA} + \Delta C_{PS} \tag{5}$$

ΔC_{TOT}: represents the changes in total CO_2 emissions in the transport sector
ΔC_{CI}: represents the changes in the carbon emission coefficient
ΔC_{ES}: represents the changes in the energy system
ΔC_{EP}: represents the changes in the energy performance
ΔC_{TF}: represents the changes in the transportation form
ΔC_{TA}: represents the changes in the transportation advancement
ΔC_{EA}: represents the changes in the economic advancement
ΔC_{PS}: represents the changes in the population scale

To conduct this study, it is essential to determine the various driving factors that generate changes in transportation-related energy use. The major driving factors are divided into seven categories and are expressed in Eq. (6) to Eq. (12) [48].

$$\Delta C_{CI} = \sum_{i,j} \Delta C_{CI,ij} = \begin{cases} \Delta C_{CI,ij} = 0, if\ C_{ij}^t \times C_{ij}^0 = 0 \\ \Delta C_{CI,ij} = \sum_{i,j} L\left(C_{ij}^t, C_{ij}^0\right) ln\left(\frac{CI_{ij}^t}{CI_{ij}^0}\right), if\ C_{ij}^t \times C_{ij}^0 \neq 0 \end{cases} \tag{6}$$

$$\Delta C_{ES}=\sum_{i,j}\Delta C_{ES,ij}=\begin{cases}\Delta C_{ES,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{ES,ij}=\sum_{i,j}L\left(C^{t}_{ij},C^{0}_{ij}\right)\ ln\left(\frac{ES^{t}_{ij}}{ES^{0}_{ij}}\right),if\ C^{t}_{ij}\times C^{0}_{ij}\neq 0\end{cases} \tag{7}$$

$$\Delta C_{EP}=\sum_{i,j}\Delta C_{EP,ij}=\begin{cases}\Delta C_{EP,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{EP,ij}=\sum_{i,j}L\left(C^{t}_{ij},C^{0}_{ij}\right)\ ln\left(\frac{EP^{t}_{ij}}{EP^{0}_{ij}}\right),if\ C^{t}_{ij}\times C^{0}_{ij}\neq 0\end{cases} \tag{8}$$

$$\Delta C_{TF}=\sum_{i,j}\Delta C_{TF,ij}=\begin{cases}\Delta C_{TF,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{TF,ij}=\sum_{i,j}L\left(C^{t}_{ij},C^{0}_{ij}\right)\ ln\left(\frac{TF^{t}_{ij}}{TF^{0}_{ij}}\right),if\ C^{t}_{ij}\times C^{0}_{ij}\neq 0\end{cases} \tag{9}$$

$$\Delta C_{TA}=\sum_{i,j}\Delta C_{TA,ij}=\begin{cases}\Delta C_{TA,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{TA,ij}=\sum_{i,j}L\left(C^{t}_{ij},C^{0}_{ij}\right)\ ln\left(\frac{TA^{t}_{ij}}{TA^{0}_{ij}}\right),if\ C^{t}_{ij}\times C^{0}_{ij}\neq 0\end{cases} \tag{10}$$

$$\Delta C_{EA}=\sum_{i,j}\Delta C_{EA,ij}=\begin{cases}\Delta C_{EA,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{EA,ij}=\sum_{i,j}L\left(C^{t}_{ij},C^{0}_{ij}\right)\ ln\left(\frac{EA^{t}_{ij}}{EA^{0}_{ij}}\right),if\ C^{t}_{ij}\times C^{0}_{ij}\neq 0\end{cases} \tag{11}$$

$$\Delta C_{PS}=\sum_{i,j}\Delta C_{PS,ij}=\begin{cases}\Delta C_{PS,ij}=0,\ if\ C^{t}_{ij}\times C^{0}_{ij}=0\\ \Delta C_{PS,ij}=\sum_{i,j}L\left(\mathrm{C}^{t}_{ij},\mathrm{C}^{0}_{ij}\right)\ \mathrm{ln}\left(\frac{\mathrm{PS}^{t}_{ij}}{\mathrm{PS}^{0}_{ij}}\right),\mathrm{if}\ \mathrm{C}^{t}_{ij}\times \mathrm{C}^{0}_{ij}\neq 0\end{cases} \tag{12}$$

Lastly, we keep the index number as described in Eq. (13) -

$$\frac{\Delta C_{CI}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{ES}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{EP}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{TF}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{TA}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{EA}}{\Delta C_{TOT}}\times 100\%+\frac{\Delta C_{PS}}{\Delta C_{TOT}}\times 100\%=100\% \tag{13}$$

Eq. (6) reflects variations in the carbon emission coefficient. ΔC_{CI} will monitor the change in emission intensity of transportation modes for a unit of energy consumption. This impact indicates any changes in overall emissions from the transportation sector due to changes in fuel quality or technical advancements in automobile construction (e.g., an increase in an electric vehicle or a decrease in CNG vehicles, reduced vehicle weight). Eq. (7) reflects the variation of changes in transportation energy consumption. ΔC_{ES} represents the change of fuel type in a transport mode, one of the most influential variables in reducing CO_2 emissions. The rise in environmentally friendly fuel types, rather than conventional fuels (for example, electric vehicle and CNG), lowers emissions and help to enhance air quality. Eq. (8) reflects the variation of changes in the transportation energy consumption per transportation facility available. ΔC_{EP} represents the change in energy consumption versus transportation facility per transportation type, it is essential to determine energy consumption change respective of transportation facility. Eq. (9) reflects the variation of changes in transportation mode shifts facility. ΔC_{TF} represents a measure of the ratio of a mode's transportation facility to the overall transportation facility between the reference year and the target year. It typically denotes the change in emission produced by a shift in transportation mode. Eq. (10) reflects the variation of increases in transportation intensity. ΔC_{TA} is used to assess transportation sector efficiency. Precisely it measures the difference in emissions between two years caused by changes in transportation services within the context of total economic activity. Eq. (11) reflects the variation in per capita economic activity changes. ΔC_{EA} demonstrates the impact of per capita economic activity on the change in emission levels. Eq. (12) reflects the effects of changes in the population. ΔC_{PS} demonstrates the impact of population change.

3.4. *Decoupling indicator*

Tapio initially developed the decoupling elasticity theory for processing causal links between variables. A decoupling analysis may be conducted in two ways: the OECD decoupling analysis and the Tapio decoupling analysis. In contrast to the decoupling analysis approach of the OECD, the results of Tapio decoupling analysis are often constant and unaffected by changes in the statistical dimension of the research. In addition, the Tapio decoupling study provides further information regarding the decoupling status [49]. Tapio's decoupling approach may determine if a variable increases when another increases or decreases. If both variables increase, this variable's growth rate is faster or slower than the other. This method's outcomes fall into three categories: decoupling, negative decoupling, and coupling, corresponding to three threshold values. When $D^t_{CO2} > 1$, strong decoupling is indicated. This indicates that the decrease in emissions following the implementation of current measures is more significant than the increase in emissions caused by base year expansion. The greater the D^t_{CO2}, the more pronounced the CO_2 reduction impact, the more optimized the energy structure. When $0 < D^t_{CO2} < 1$, it shows weak decoupling, which signifies that current emission reduction efforts have a role in CO_2 reduction, and the growth rate decreases to some extent. However, based on the absolute amount, the reduction in emissions following the implementation of current rules is more than the rise in emissions caused by the expansion of the base year, indicating that overall emissions are still growing. When $D^t_{CO2} < 0$, there is no decoupling. In other words, the measures for reducing emissions are ineffective and inefficient, and the reduction objective cannot be attained. This indicates that emission reduction measures cannot optimize the energy structure and reduce energy intensity. Decoupling Indicators split the decoupling states, negative decoupling, and coupling into eight subcategories based on their elastic qualities to analyze the decoupling of studied variables over time. Strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, recessive decoupling, recessive coupling, weak negative decoupling, and strong negative decoupling comprise the eight subcategories. Eq. (14) demonstrates the decoupling indicator where D^t presents decoupling index, ΔF^t represents CO_2 emission and ΔGDP^t represents the GDP of the area.

$$D^t = \frac{\Delta F^t}{\Delta GDP^t} = \frac{\frac{\Delta F}{F}}{\frac{\Delta GDP}{GDP}} \tag{14}$$

Further D^t is categorized into subgroups using scores and grades mentioned in Table 3.

4. Results and discussion

4.1. CO_2 emission from the indian transport system

Fig. 1 represents the trend of transport sector CO_2 emissions of the Indian region over the period 2001–2020. The aggregate transport sector's CO_2 emission has increased from 155.9 Mt in 2001 to 368.7 Mt in 2020, following a growth rate of 136% and a CAGR of 4.6%. CO_2 emissions increased slightly from 2001 to 2004 (Phase 1), whereas they increased sharply and moderately from 2005 to 2012 (Phase 2) and 2012–2019 (Phase 3). In 2020 a noticeable CO_2 emissions drip was noticed. During Phase 1, CO_2 rises from 155.97 Mt to 166.15 Mt with a CAGR of 2.12%. For Phase 2, CO_2 rises from 162.3 Mt to 298.47 Mt with a CAGR of 9.08%. Whereas for phase 3, CO_2 rises from 301.1 Mt to 402.4 Mt with a CAGR of 4.9%. From 2019 to 2020, CO_2 emissions dropped from 403.4 Mt to 368.7 Mt due to COVID restrictions and lockdown scenarios. Future CO_2 emission projections were also made using the business-*as*-usual (BAU) method. Emissions are anticipated to increase by 1.3 times to 482.46 Mt by 2030, 1.61 times to 596.20 Mt by 2040, and 1.92 times to 709.94 Mt by 2050. Similar results were shown in study conducted by Ref. [50], which predicted that India's GHG emissions would be 2.1–2.4 times higher in 2050 than in 2019.

Fig. 2 also illustrates the correlation between CO_2 emissions from transportation and economic growth. During the decades between 2001 and 2020, both CO_2 and the Indian economy grew consistently. The economy grew from 485.4 billion dollar in 2001–2660.2 billion dollars in 2020, with an average annual GDP growth rate of 4.48%.

Fig. 3 depicts the contribution of each mode of transportation to total transportation CO_2. From 2001 to 2020, CO_2 emissions from roadways increased from 137.86 Mt to 321.26 Mt, with an overall growth rate of 133% and a CAGR of 5%. Railway's CO_2 emissions increased from 12.60 Mt in 2001 to 25.53 Mt in 2020 at an overall growth rate of 103% and a CAGR of 4%. CO_2 emissions from aviation are projected to increase from 4.72 Mt in 2001 to 19.34 Mt in 2020 at a CAGR of 8% and a growth rate of 310%. The CO_2 emissions from waterways increased from 0.78 Mt in 2001 to 2.57 Mt in 2020 at a CAGR of 6% and an overall growth rate of 227%. During the study period, road transport is the primary factor in CO_2 emissions from Indian transportation. In 2020, the total CO_2 emissions from Indian transportation were 368.72 Mt, with road transport accounting for 87% of the total, followed by railways, airways, and waterways at 7%, 5%, and 1%, respectively [51]. reported a similar proportion of CO_2 emissions from the Indian transportation sector in 2003–04, with contributions from road transport, airways, railways, and waterways at 94.5%, 2.9%, 2%, and 0.6%, respectively. It can be interpreted that CO_2 emissions from roadways increased significantly in response to the growing demand for flexibility and convenience, closely tied to people's living standards and the industrial structure revolution. The primary rationale for the disparity in transportation CO_2 growth rates is modal shifting, which occurs when transportation modes transition from less convenient means, such as railways, to more time-saving modes, such as roadways and civil aviation. The gradual increase in railway

Table 3
The decoupling index, score, and grades.

	ΔF^t	ΔGDP^t	D^t	Decoupling status
1	<0	>0	$D^t < 0$	SD (Strong decoupling)
2	>0	>0	$0.8 \geq D^t > 0$	WD (Weak decoupling)
3	<0	<0	$1.2 \geq D^t > 0.8$	RC (Recessive coupling)
4	>0	>0	$D^t > 1.2$	END (Expansive negative decoupling)
5	>0	<0	$D^t < 0$	SND (Strong negative decoupling)
6	<0	<0	$0.8 \geq D^t > 0$	WND (Weak negative decoupling)
7	>0	>0	$1.2 \geq D^t > 0.8$	EC (Expansive decoupling)
8	<0	<0	$D^t > 1.2$	RD (Recessive decoupling)

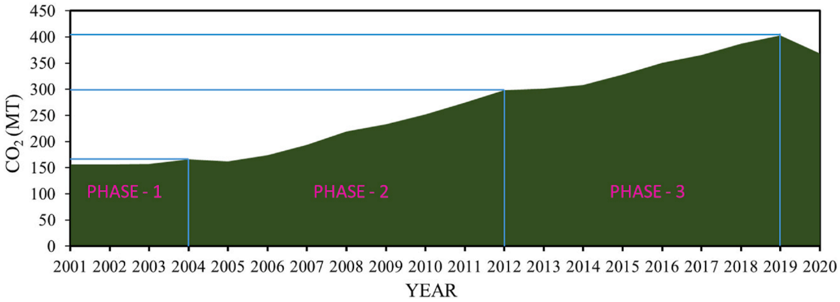

Fig. 1. Phase-wise CO_2 emission from the Indian transportation system from 2000 to 2020.

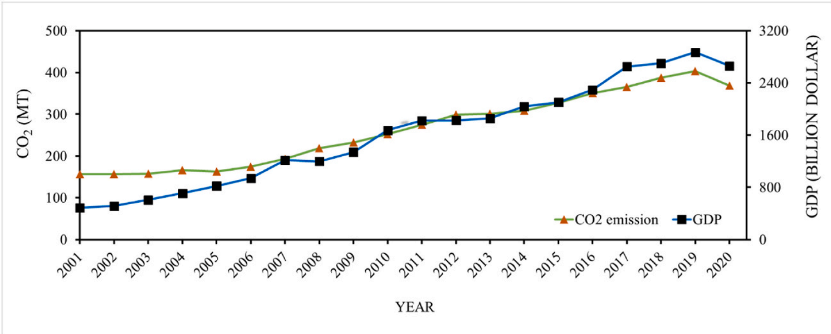

Fig. 2. GDP correlation with transportation CO_2 emissions.

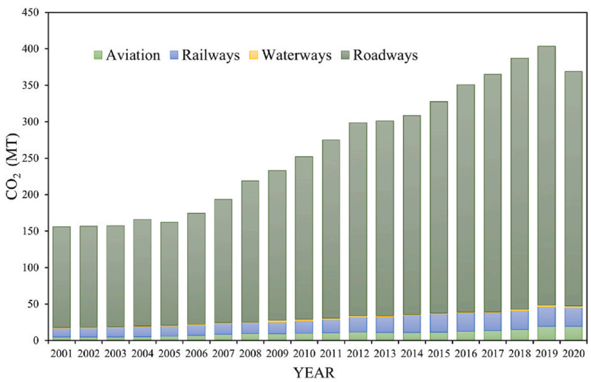

Fig. 3. Mode-wise transportation contribution towards CO_2 emissions.

CO_2 emissions is primarily due to the phase-out of steam locomotives and the addition of electric locomotives. CO_2 emissions from waterways are rising as a result of the expansion of more significant commercial routes and improved water sports tourists.

From 2000 to 2020, as shown in Fig. 4, overall CO_2 emissions from various transportation-related energy sources increased. CO_2 emissions from motor spirit (petrol), ATF, and kerosene have increased dramatically, while CO_2 growth rates for HSD, natural gas, and coal have been moderate. CO_2 emissions from motor spirit increased from 20.30 Mt in 2001 to 92.02 Mt in 2020, representing a 353% annual growth rate and an 8% CAGR. At the same time, CO_2 emissions from ATF increased from 4.72 Mt in 2001 to 19.35 Mt in 2020, with an average annual growth rate of 310% and a CAGR of 8%. Kerosene CO_2 emissions increased from 0.79 Mt in 2001 to 2.57 Mt in 2020, with a 227% average annual growth rate and 6% CAGR. However, there has been a decrease during this time period, from 2.37 Mt in 2009 to 0.94 Mt in 2017. The growth rates for HSD, natural gas, and coal have increased moderately due to reduced railways diesel and coal-powered locomotives and a limited increase in natural gas vehicles. CO_2 emissions from HSD increased from 123.11 Mt in 2001 to 235.59 Mt in 2020, representing a 91% annual growth rate and a 3% CAGR. CO_2 emissions from natural gas increased from 0.21 Mt in 2001 to 0.32 Mt in 2020, representing a 55% annual growth rate and a 2% CAGR. Further, Coal CO_2 emissions increased from 6.85 Mt in 2001 to 18.87 Mt in 2020, with a 176% average annual growth rate and 5% CAGR. Increasing fuel consumption and rising CO2 emission factors increase the emission burden of the nation. It is beneficial for a nation to modify convectional fuel under

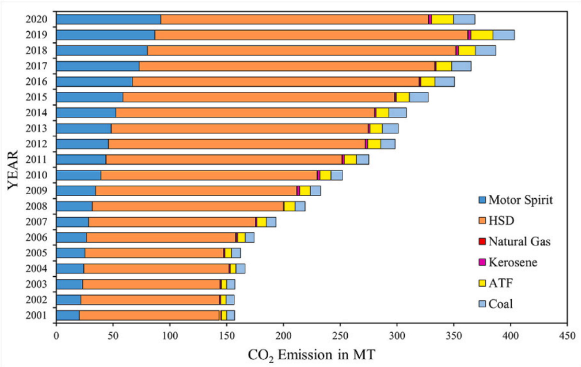

Fig. 4. Each transportation fuel's contribution to CO_2 emissions.

the influence of nanoparticles [52] or to increase the use of potential renewable energy, particularly solar energy [53].

4.2. *Uncertainty analysis*

This study determines uncertainty analysis for CO2 emissions. The method for determining uncertainty is based on [54] study. For CO_2 emissions uncertainty (%) is found to be 63.2% with standard error of the mean was approximately 38.32 with 95% confidence level. Energy consumption is an essential input that has a significant impact on CO_2 emissions. The transition from coal and diesel locomotives to electric locomotives in railways, as well as the increased use of gasoline and CNG fuel in roadways, contribute to the decrease in CO_2 emissions and the consequent reduction in uncertainty.*5*.3 KAYA - *LMDI Decomposition*.

We decompose the change in GHG emissions using the additive LMDI approach into six factors: an energy system (ES), energy performance (EP), transportation form (TF), transportation advancement (TA), economic advancement (EA), and population scale (PS). Based on LMDI, we will determine which factors have the most considerable impact on the change in India's GHG emissions between 2001 and 2020. Table 4 shows 2001 as year 0 (reference year), 2020 as year T (end year), and the decomposition results for Eq. (5).

As shown in Fig. 5, using 2001 as the base year, the energy system continued to have a favorable impact on CO_2 emissions, whose overall trend was upward from 2001 to 2002 to 2019–2020, except for 2002–2003. In 2002–2003 the contribution impact decreased somewhat compared to the previous year, 2001–2002, falling to −12.17 ten thousand tonnes from 8.45 ten thousand tonnes with a growth rate of −244%, respectively. From the year 2012–2013 to 2014–2015, the contribution decreased compared to previous years with 634.26, 637.20, and 677.03 ten thousand tonnes with a growth rate of −16%, 1%, and 6% compared to last years. From 2015 to 2016 to 2019–2020, the average growth rate was 21%, a slight upward trend. Decomposing further the fuel consumed by various modes of transportation, initially, diesel consumption by the waterways shows a negative contribution towards the energy system with an average annual growth rate of 1376% from 12.10 ten thousand tonnes in 2001–2002 to 178.75 ten thousand tonnes in 2019–2020.

Table 4
Decomposition analysis outcomes of the transportation energy consumption in India's transportation sector (ten thousand tonnes).

	Ten thousand tonnes					
	ES	EP	TF	TA	EA	PS
2001						
2002	8.5	−2040.2	−3299.0	1039.1	666.8	255.3
2003	−12.2	−4165.0	−6421.8	413.6	3013.0	506.2
2004	34.6	−4783.3	−6142.0	−759.7	5330.8	771.8
2005	100.3	−6325.5	−9089.2	−2690.7	7345.1	1005.9
2006	234.1	−9073.7	−12011.0	−802.4	9621.4	1289.3
2007	377.3	−9412.1	−12644.5	−3674.4	14377.6	1613.2
2008	433.4	−10616.1	−16452.5	−891.0	14805.1	1986.6
2009	596.2	−11831.0	−26534.0	−989.6	17186.4	2319.6
2010	609.1	−13765.7	−20544.0	−2688.4	22106.7	2693.3
2011	668.9	−15757.1	−26036.8	−1666.0	24677.0	3104.1
2012	755.8	−17067.6	−31849.9	633.0	25577.4	3531.9
2013	634.3	−18869.3	−40946.9	2193.1	25771.2	3830.0
2014	637.2	−20895.3	−48012.3	2416.6	27931.4	4158.9
2015	677.0	−23061.7	−49694.1	4466.8	29330.4	4582.6
2016	794.4	−25605.9	−5196.2	6084.5	32282.6	5046.3
2017	882.8	−28316.3	−35599.4	5398.8	36307.6	5446.3
2018	1142.6	−30838.5	−35710.9	8189.5	37725.7	5915.4
2019	1657.1	−33215.5	−26979.1	9544.2	39936.7	6341.5
2020	1684.6	−34845.6	−27128.8	12517.2	35783.3	6282.9

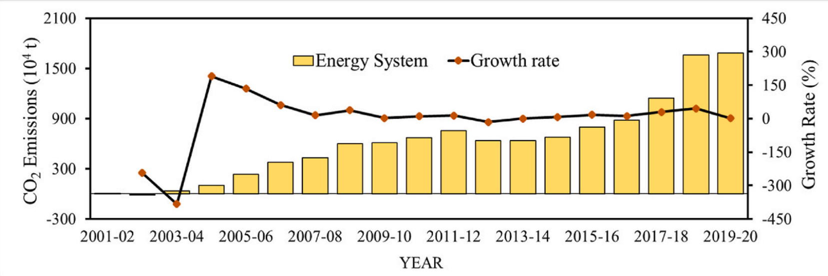

Fig. 5. Effect of the energy system on the growth of CO_2 emissions.

Besides this, ATF consumption by airlines exhibits the highest contribution growth rate with 54336%, from 2.68 ten thousand tonnes in 2001–2002 to 1462.53 ten thousand tonnes in 2019–2020. Similar trends in energy systems can be observed in a study by Ref. [55]. Still, the difference between energy consumption by different transportation systems and energy system change indicates the difference in CO_2 emissions.

Fig. 6 demonstrates that Energy performance has retrained the growth of CO_2 emissions from transportation. It reflects a growth increase from −2040.24 ten thousand tons in 2001-02 to −34845.6 ten thousand tons in 2019–20, representing an increase of −32805.3 ten thousand tons at a Compound Annual Growth Rate (CAGR) of 16%. For energy performance, the yearly growth rate shows dynamic changes occur in three phases – from 2001 to 02 to 2002-03, the growth rate is highest at 104.14%, whereas it drops to 14.84% in 2002-03 to 2003-04. Secondary from 2004 to 05 to 2005-06 and 2005-06 to 2006-07 growth rate increased from 32.24% to 43.44%, finally decreasing to 3.72%. Finally, from 2006 to 07 to 2019-20, the growth rate was almost constant, with an average of 10%. In this scenario, improving energy performance in the transportation sector has contributed significantly to slowing the growth of CO_2 emissions, providing opportunities for India to promote renewable energy resources [56]. reported energy performance as the most crucial contributor to declines in transport-related energy consumption, accounting for 14.31% of total Tunisian transportation energy consumption.

Fig. 7 demonstrates that the transportation form had a significant restrictive impact on CO_2 emissions. Specifically, the entire period of analysis can be divided into three phases: from 2001 to 02 to 2008-09, the contribution effect of transport form, whose average contribution value was −11574.25 ten thousand tons, was relatively weak and showed a decreasing trend; from the year 2009–10 to 2014-15, the factor of transport form maintained a substantial effect on inhibiting CO_2 emissions when the average contribution value reached −36180.67 ten thousand tons, especially, in 2014–15, the inhibitive effect reached its peak with the contribution value of −49694.1 ten thousand tons; during 2015–16 to 2019-20, The restrictive result of transport mode demonstrates the same negative trend as in previous cases, inhibiting CO_2 emissions by an average of −26122.9 ten thousand tons. From 2001 to 02 to 2015-16, the average growth rate was 18%, but 2016-17, the growth rate skyrocketed to a staggering 585%. From 2016 to 17 to 2019–20, the growth rate remained stagnant at −8% [57]. found a 20.24 tMt reduction in CO2 emissions from transportation in China from 2001 to 2005. The improvement of India's transportation system is evidenced by the development of railway locomotives, the introduction of more electric vehicles (EVs), and the constant improvement of vehicle performance. These factors have contributed to the slightly offset the transportation CO_2 emissions.

Fig. 8 demonstrates that the development in transportation had a mixed effect on CO_2 emissions. Specifically, the entire period of analysis can be divided into three phases: from 2001 to 02 to 2002-03, the contribution value was positive with an average of 726.38 ten thousand tons; from 2003 to 04 to 2010-11, the contribution value shifted from positive to negative and caused a transportation CO_2 constraining effect with an average of −1770.28 ten thousand tons; and from 2011 to 12 to 2019-20, the contribution effect shifted back to positive with a promoting effect of an average of 5715.95 ten thousand tons. Annual growth rates exhibited significant fluctuations, with four positive peaks in 2004–05, 2006-07, 2009-10, and 2012-13, with respective growth rates of 254%, 358%, 172%, and 246%. In addition, two negative growth rate peaks were observed in 2003-04 and 2011-12, with growth rates of −283% and −138%, respectively. From 2013 to 14 to 2019-20, the yearly growth rate shows less variation, with an average rate of 31%. The

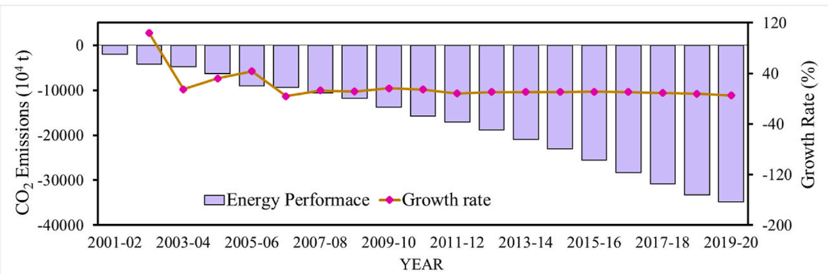

Fig. 6. Effect of energy performance on the growth of CO_2 emissions.

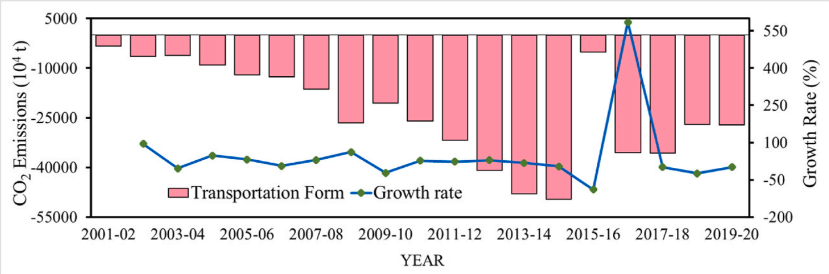

Fig. 7. Effect of transportation form on the growth of CO_2 emissions.

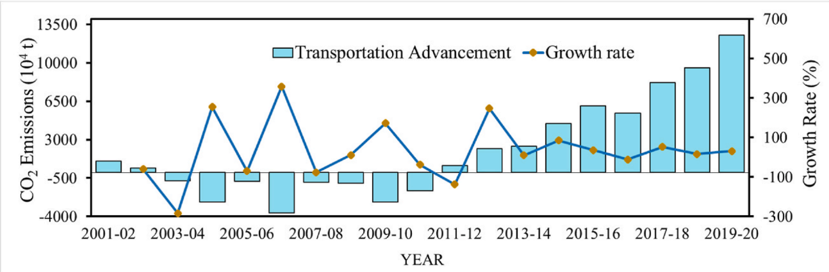

Fig. 8. Effect of transportation advancement on the growth of CO_2 emissions.

ratio of transportation turnover volume to GDP determines transportation advancement. A study by Ref. [58] indicates a decline in China's transport CO_2 emissions between 1985 and 2009 for the ratio of transport facilities to GDP [59]. found that turkey transportation CO_2 decreased in the initial years but was high in most years between 2003 and 2012. In the early years, a limited increase in transportation turnover volume, primarily on railways and waterways, relative to a continuously expanding GDP, constraining transportation CO_2 emissions. In contrast, recent years have witnessed a rapid increase in transportation turnover volume alongside a substantial rise in national GDP, which has positively affected transportation CO_2 emissions. Positive or promoting effects in later years also indicate increased fuel consumption for transportation.

GDP per capita is the primary indicator of a country's production capability per capita and services. As seen in Fig. 9, economic development was crucial in supporting CO_2 emission growth. During this research period, economic advancement exhibited an exponential growth pattern, with a contribution value that increased from 666.76 ten thousand tons in 2001-02 to 35783.32 ten thousand tons in 2019–20, representing an increase of 35116.56 ten thousand tons at a Compound Annual Growth Rate (CAGR) of 23%. As the economic level rises, people with a higher standard of living seek a higher quality of life, which increases the demand for vehicles. Even developing nations like China demonstrate similar economic growth trends [60]. The level of economic development exerts a substantial pulling influence on CO_2 emissions from the transportation sector due to the increased purchase of private vehicles and demand for public transport. The growth of the e-commerce sector, tourism, business parks, and demand for private cabs are also significant contributors to the rapid expansion of transportation CO_2 emissions.

Fig. 10 demonstrates that population growth significantly impacts the growth of CO_2 emissions from transportation. It demonstrates an exponential growth increase from 255.27 ten thousand tons in 2001-02 to 6282.93 ten thousand tons in 2019–20, representing an increase of 6027.65 ten thousand tons at a Compound Annual Growth Rate (CAGR) of 18%. It has been observed that both economic advancement and population scale show the same growth trend. Still, the contribution effect of population growth was relatively less significant than economic progress. Similar population growth trends and their impact on CO_2 emissions can be seen

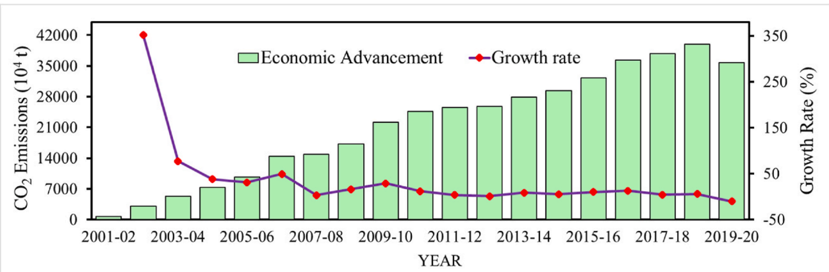

Fig. 9. Effect of economic advancement on the growth of CO_2 emissions.

globally in Turkey [61], in Saudi Arabia [62], and China [63]. The developing economic structures lead to an increase in urbanization and population, both of which have a negative impact on factors such as the amount of fuel consumed by transportation, CO_2 emissions, and urban sprawl.

According to the factor decomposition analysis, we determined the contribution of various factors to transportation-related CO_2 emissions from 2001 to 2020. The impact of the energy system, economic development, and population size on transportation system CO_2 emissions is positive, while the impact of energy performance and transportation form is negative. Transportation development has mixed effects, with adverse effects in the early years and positive implications in later years.

4.3. Decoupling indicators

The decoupling index also suggests that for the Indian transportation system from 2001 to 2020, CO_2 emissions increased with the transport sector's growth, although at a slower rate than transportation facility increases, indicating an improvement in the energy consumption of this sector. The observed result for the decoupling index is unique in that the Indian domain exhibits distinct transport characteristics and energy consumption.

Over the period 2001–2020, six decoupling states of CO_2 emissions from India's transportation sector appeared, as listed in Table 5. Progress in sub-period from 2001 to 04, 2005-07, 2008-10, 2012-14, 2015-17, and 2018–2019 shows weak decoupling. The incidence of weak decoupling is linked to the subsequent reduction estimates: First, the slow growth of the CO_2 emission coefficient compared to the robust economic expansion. Despite an increase in transport services and energy consumption, the growth rate has slowed due to technological and renewable energy advancements, as well as the presence of numerous measures taken by the Indian government to improve energy efficiencies, such as The Energy Conservation Act 2001, The Electricity Act 2003 and National Mission for Enhanced Energy Efficiency (NMEEE). In subdomains 2004–2005 and 2007-08, it shows strong decoupling and strong negative decoupling. It indicates an increase in ΔF^t value as a result of an increase in transport facilities and energy consumption. In the subperiod between 2011 and 12, 2014-15, and 2017-18, there is an expansive negative decoupling. During this time period, CO_2 levels are nearly constant, whereas ΔGDP^t Increases significantly. In sub-period of 2011–12, 2014-15, and 2017-18 show expansive negative decoupling. During the sub-period, the incidence of END was explained by the rising trend of transport facilities and energy consumption per GDP. In the 2019-20 sub-period, it exhibits recessive coupling. During this time period, both ΔF^t and ΔGDP^t are negative. As a result of early covid scenarios, energy consumption, transportation service, and carbon coefficient have decreased.

5. Conclusion and discussion

Using annual data from 2001 to 2020, this research combines the Tapio index decomposition model with the co-integration approach to assess CO_2 emission into its six influencing factors: energy system, energy performance, transportation form, transportation advancement, economic advancement, and population scale for India's transportation system. In addition, it also estimated the decoupling index to determine India's transportation CO_2 emission relation with the nation's economic development. Based on the aforementioned empirical findings, the primary conclusions of this study are as follows.

(1) Considering the growing demand for transportation, CO_2 emission has increased from 155.9 Mt in 2001 to 368.7 Mt in 2020, following a Compound Annual Growth Rate (CAGR) of 4.6%. Road transportation emits the most CO_2, followed by railways, airways, and waterways, which account for 88%, 7%, 4%, and 1% of total transportation CO_2 emissions, respectively. CO_2 emissions from diesel fuel have increased from 123.11 Mt in 2001 to 235.59 Mt in 2020, with motor spirit having the highest annual growth rate of 353% and an 8% CAGR. This is due to rising transportation demand and energy consumption in the Indian transportation system.

(2) The energy system considerably impacts CO_2 growth, whereas Energy performance has been found to have a restriction on CO_2 emissions. Regarding energy structure, the government should implement measures to promote renewable energy and expand clean energy usage. In contrast, energy efficiency significantly limited CO_2 emissions and was the primary element preventing CO_2 emission growth for energy performance. Therefore, it is evident that the government should increase energy-saving features and implement energy-efficiency technologies in vehicle engines to reduce CO_2 emissions from the transportation sector.

(3) Transport form positively impacts CO_2 emission reduction, whereas transport advancement has a negative effect in the beginning but a positive impact in later years. The reduction of diesel and coal railway locomotives, the decreased use of diesel fuel, and the widespread promotion of electric vehicles provide evidence of the reduction of CO_2 emissions from transportation. Initially, limiting the turnover volume of railways and waterways to a rising GDP stifled transport advancement, but later, increasing the overall turnover volume to GDP caused an increase in the CO_2 effect.

(4) Both Economic advancement and population scale contribute to the rise in CO_2 levels. India is a developing nation with an expanding economy and transit services. This influences the demand for personal vehicles, airline travel, and other modes. This also contributes to increased energy consumption and, consequently, CO_2 emissions.

(5) Weak decoupling is observed in the majority of subperiods, including 2001-04, 2005-07, 2008-10, 2012-14, 2015-17, and 2018–2019. This is observed because CO_2 emission growth rates have slowed relative to the nation's rising economic output. Increases in renewable energy and several other government policies likely cause lower CO_2 growth rates.

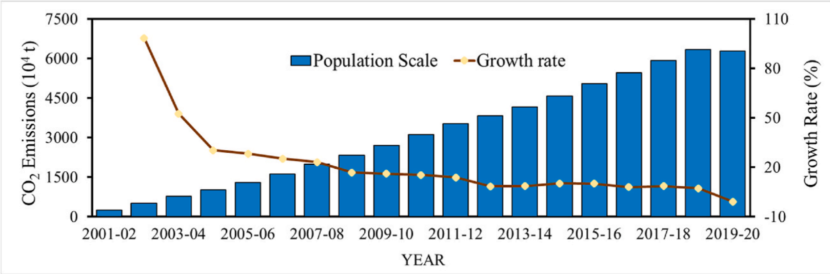

Fig. 10. Effect of population scale on the growth of CO_2 emissions.

Table 5
Decoupling index outcomes of CO_2 emissions from India's transportation sector from 2001 to 2020.

	Year	ΔF^t	ΔGDP^t	D^t	Decoupling index
1	2001–02	0.0042	0.0573	0.0733	WD
2	2002–03	0.0046	0.1526	0.0303	WD
3	2003–04	0.0529	0.1431	0.3699	WD
4	2004–05	−0.0233	0.1356	−0.1720	SD
5	2005–06	0.0692	0.1275	0.5428	WD
6	2006–07	0.0981	0.2272	0.4317	WD
7	2007–08	0.1170	−0.0149	−7.8612	SND
8	2008–09	0.0592	0.1066	0.5555	WD
9	2009–10	0.0762	0.1992	0.3828	WD
10	2010–11	0.0840	0.0809	1.0382	ED
11	2011–12	0.0782	0.0025	31.1445	END
12	2012–13	0.0088	0.0157	0.5643	WD
13	2013–14	0.0235	0.0895	0.2629	WD
14	2014–15	0.0587	0.0306	1.9148	END
15	2015–16	0.0657	0.0833	0.7885	WD
16	2016–17	0.0398	0.1345	0.2960	WD
17	2017–18	0.0566	0.0184	3.0790	END
18	2018–19	0.0405	0.0590	0.6868	WD
19	2019–20	−0.0941	−0.0790	1.1910	RC

Using the LMDI method, this research identifies the primary factors influencing CO_2 emissions from India's transportation sector. To further reduce CO_2 emissions from India's transportation industry, paying greater attention to the influential elements with minimal effect is necessary. Not only does the decoupling index based on influence factors illustrate the degree of decoupling, but it also vividly displays the causes of the decoupling state. During the study period, the current decoupling grade for India's transport sector is not very excellent. Therefore, the transportation sector's initiatives to reduce CO_2 emissions must be strengthened. In future, The government should update strategic measures of sustainable transport policy to enhance energy efficiency and emission standards for new vehicles. While other policies include increasing the insertion of electric vehicles, using natural gas fuels or biofuels, increasing electric locomotives in the railway sector, advancement of waterways and airways engines, and reducing GDP per unit of turnover, the listed policies are likely to limit transport emissions, a key contributor to emissions growth, thereby increasing India's likelihood of achieving the goals towards sustainable transportation system.

Author contribution statement

Siddharth Jain and Shalini Rankavat: Conceived and designed the study; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Siddharth jain reports administrative support was provided by Shiv Nadar University. Siddharth Jain reports a relationship with Shiv Nadar University that includes: employment and non-financial support.

Appendix

A1
Decomposition analysis of transportation energy consumption in India's transportation sector from 2001 to 2020 (ten thousand tonnes).

	Ten thousand tonnes					
	ES	EP	TF	TA	EA	PS
2001						
2002	8.5	−2040.2	−3299.0	1039.1	666.8	255.3
2003	−12.2	−4165.0	−6421.8	413.6	3013.0	506.2
2004	34.6	−4783.3	−6142.0	−759.7	5330.8	771.8
2005	100.3	−6325.5	−9089.2	−2690.7	7345.1	1005.9
2006	234.1	−9073.7	−12011.0	−802.4	9621.4	1289.3
2007	377.3	−9412.1	−12644.5	−3674.4	14377.6	1613.2
2008	433.4	−10616.1	−16452.5	−891.0	14805.1	1986.6
2009	596.2	−11831.0	−26534.0	−989.6	17186.4	2319.6
2010	609.1	−13765.7	−20544.0	−2688.4	22106.7	2693.3
2011	668.9	−15757.1	−26036.8	−1666.0	24677.0	3104.1
2012	755.8	−17067.6	−31849.9	633.0	25577.4	3531.9
2013	634.3	−18869.3	−40946.9	2193.1	25771.2	3830.0
2014	637.2	−20895.3	−48012.3	2416.6	27931.4	4158.9
2015	677.0	−23061.7	−49694.1	4466.8	29330.4	4582.6
2016	794.4	−25605.9	−5196.2	6084.5	32282.6	5046.3
2017	882.8	−28316.3	−35599.4	5398.8	36307.6	5446.3
2018	1142.6	−30838.5	−35710.9	8189.5	37725.7	5915.4
2019	1657.1	−33215.5	−26979.1	9544.2	39936.7	6341.5
2020	1684.6	−34845.6	−27128.8	12517.2	35783.3	6282.9

A2
The decoupling index produced CO_2 emissions from India's transportation sector from 2001 to 2020.

	Year	ΔF^t	ΔGDP^t	D^t	Decoupling index
1	2001–02	0.0042	0.0573	0.0733	WD
2	2002–03	0.0046	0.1526	0.0303	WD
3	2003–04	0.0529	0.1431	0.3699	WD
4	2004–05	−0.0233	0.1356	−0.1720	SD
5	2005–06	0.0692	0.1275	0.5428	WD
6	2006–07	0.0981	0.2272	0.4317	WD
7	2007–08	0.1170	−0.0149	−7.8612	SND
8	2008–09	0.0592	0.1066	0.5555	WD
9	2009–10	0.0762	0.1992	0.3828	WD
10	2010–11	0.0840	0.0809	1.0382	ED
11	2011–12	0.0782	0.0025	31.1445	END
12	2012–13	0.0088	0.0157	0.5643	WD
13	2013–14	0.0235	0.0895	0.2629	WD
14	2014–15	0.0587	0.0306	1.9148	END
15	2015–16	0.0657	0.0833	0.7885	WD
16	2016–17	0.0398	0.1345	0.2960	WD
17	2017–18	0.0566	0.0184	3.0790	END
18	2018–19	0.0405	0.0590	0.6868	WD
19	2019–20	−0.0941	−0.0790	1.1910	RC

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