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Logarithmic Mean Divisia Index Decomposition of CO_2 Emissions from Urban Passenger Transport: An Empirical Study of Global Cities from 1960–2001

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Abstract: The urban transport sector has become one of the major contributors to global CO_2 emissions. This paper investigates the driving forces of changes in CO_2 emissions from the passenger transport sectors in different cities, which is helpful for formulating effective carbon-reduction policies and strategies. The logarithmic mean Divisia index (LMDI) method is used to decompose the CO_2 emissions changes into five driving determinants: Urbanization level, motorization level, mode structure, energy intensity, and energy mix. First, the urban transport CO_2 emissions between 1960 and 2001 from 46 global cities are calculated. Then, the multiplicative decomposition results for megacities (London, New York, Paris, and Tokyo) are compared with those of other cities. Moreover, additive decomposition analyses of the 4 megacities are conducted to explore the driving forces of changes in CO_2 emissions from the passenger transport sectors in these megacities between 1960 and 2001. Based on the decomposition results, some effective carbon-reduction strategies can be formulated for developing cities experiencing rapid urbanization and motorization. The main suggestions are as follows: (i) Rational land use, such as transit-oriented development, is a feasible way to control the trip distance per capita; (ii) fuel economy policies and standards formulated when there are oil crisis are effective ways to suppress the increase of CO_2 emissions, and these changes should not be abandoned when oil prices fall; and (iii) cities with high population densities should focus on the development of public and non-motorized transport.

Keywords: CO_2 emissions; urban transport; LMDI; megacity

1. Introduction

Climate change and CO_2 emissions mitigation have drawn extensive attention worldwide in recent years. Because of its continuously growing share in overall energy consumption, the transport sector has been acknowledged as one of the most important contributors to global emissions [1]. According to the International Energy Agency, world energy-related CO_2 emissions will increase from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and to 43.2 billion metric tons in 2040 [2]. Besides, 7.38 million tons of CO_2 was generated due to oil consumption in the global transport sector in 2013, accounting for 23% of the total fossil fuel-related CO_2 emissions [3]. In addition, with the continuous development of the urban economy and acceleration of the motorization process, cities account for 75% of global energy consumption and 80% of greenhouse gas emissions [4]. Therefore, the urban transport sector has become one of the major contributors to global CO_2 emissions. In addition, 1960–2001 was a key period during which the world urbanization level rose from 33% to 45% and global CO_2 emissions increased from approximately 190 billion tons to approximately 370 billion tons [5]. The contribution of this study is to investigate the driving forces of change in passenger transport CO_2 emissions in different cities. Further analysis is conducted for the megacities to provide experience for other cities, during this period. Furthermore, this paper classifies all kinds of policy rules based on the involved target factors to help formulate more effective carbon-reduction policies and strategies. This study can provide practical guidance to low-carbon urban planning in developing countries.

The remainder of this paper is organized as follows. Literature about this subject is reviewed in the next section. Section 3 introduces the research area, data sources, CO_2 emission calculations, and decomposition analysis. In Section 4, the study results and discussion are presented. Finally, we draw conclusions and presents the limitations for future research in Section 5.

2. Literature Review

Index decomposition analysis (IDA) method is one of the main approaches for investigating different driving factors and their environmental side effects in a harmonized way [6]. The basic concept of the IDA method is to decompose one target variable into a combination of many factors and then determine how much each factor affects the result, namely, the contribution. The main IDA method can be further categorized into the Divisia index method and the Laspeyres index method. For the Laspeyres index method, there are always residual items that cannot be merged and ignored in the process of decomposition, which has side effects on the result of decomposition. For the Divisia method, there are no residual terms, thus it has gradually become the mainstream method of empirical research in the academic field. Furthermore, logarithmic mean Divisia index (LMDI) is a typical Divisia index method that is convincing both in theory and application. Ang and Liu introduced a refined Divisia index method, the LMDI approach, which is characterized by perfect decomposition and consistency in aggregation [7]. Then, Ang compared various IDA methods and concluded that the LMDI method was the preferred method [8].

In the transport sector, several studies have been conducted to examine factors that have affected changes in energy consumption and emissions over the past few decades. From national and regional perspectives, Schipper et al. compared the CO_2 emissions growth from passenger transport and freight transport in some countries from the Organization for Economic Cooperation and Development between 1973 and 1992 [9,10]. Moutinho et al. identified the relevant factors that have influenced the changes in the level of CO_2 emissions among four groups of European countries, specifically eastern, western, northern, and southern Europe groups, based on the LMDI approach from 1999 to 2010 [11]. Yeo et al. used the LMDI decomposition method to identify and analyze the key driving forces behind changes in CO_2 emissions in two emerging countries: China and India [12]. Timilsina and Shrestha performed an LMDI analysis of CO_2 emissions in the overall transport sector in different Asian countries and identified different driving forces of CO_2 emissions in these countries [13]. Li et al. studied CO_2 emissions performance at both the national and regional levels; they traced the growth trend and spatial disparity of CO_2 emissions in China based on the LMDI method from 2000–2014 [14]. Using the LMDI method, Zhang et al. identified the relationships between transport sector energy consumption and changes of the transport mode, passenger-freight share, energy intensity, and transport activity in China between 1980 and 2006 [15]. Jiang et al. presented the CO_2 emissions trends from the transport sector at the Chinese provincial level and then quantified the related driving forces by adopting LMDI analysis [16].

From the city-scale perspective, Wang and Hayashi adopted the LMDI technique to decompose the total passenger transport CO_2 growth in Shanghai from 2000 to 2009 into five driving factors: Economic activity, population, modal share, passenger transport intensity, and passenger transport CO_2 emissions factor [17]. Then, this method was used to compare the CO_2 emissions from the urban passenger transport sectors in Shanghai and Tokyo. The driving factors of decomposition analysis were determined to be the population, trip generation rate, mode shift, travel distance, and load effect [18].

Most of these studies focused on national-level transportation systems, and only a few conducted city-scale transport sector decomposition analyses. However, to the best of our knowledge, the trends and driving forces of CO_2 emissions from the passenger transport sector in various cities, especially megacities with large populations and total emissions, have not been explicitly studied. However, as a result of imbalanced development worldwide, different cities are facing different challenges, leading to different CO_2 emissions trends. To fill this gap, this paper performs a comparative study of 46 cities to identify the driving forces of CO_2 emissions from the passenger transport sector between 1960 and 2001 by dividing these cities into megacities and other cities. Further analysis is conducted for the megacities, and the main driving forces of the CO_2 emissions from urban passenger transport in these megacities are identified to provide experience for other cities.

3. Methodology

3.1. Research Area

This paper studies CO_2 emissions from the passenger transport systems (excluding aviation and ferry transport) of 46 cities in 1960, 1970, 1980, 1990, 1996, and 2001. According to the research of the International Association of Public Transport [19], these cities can be categorized into four regions considering their geographic locations as shown in Figure 1, including North American cities, Oceanian cities, European cities, and Asian cities. The North American cities include Boston, Chicago, Denver, Detroit, Houston, Los Angeles, New York, Phoenix, Portland, Sacramento, San Diego, San Francisco, Washington, Toronto, Calgary, Winnipeg, Edmonton, Montreal, Ottawa, and Vancouver. The Oceanian cities include Adelaide, Brisbane, Canberra, Melbourne, Perth, and Sydney. The European cities include Amsterdam, Copenhagen, Frankfurt, Hamburg, London, Munich, Paris, Stockholm, Vienna, Zurich, and Brussels. The Asian cities include Hong Kong, Tokyo, Singapore, Bangkok, Djakarta, Kuala Lumpur, Manila, Seoul, and Surabaya. In this study, London, Paris, New York, and Tokyo are defined as megacities according to the population and metropolitan gross domestic product per capita.

Figure 1. Research area.

3.2. Data

The data include annual vehicle kilometers traveled, passenger kilometers traveled, fuel consumption data for all passenger transport modes, and population data for 46 cities in 1960, 1970, 1980, 1990, 1996, and 2001. Data used in this study come from *An International Sourcebook of Automobile Dependence in Cities, 1960–1990* [19] and the *Millennium Cities Database for Sustainable Transport* [20].

3.3. Passenger Transport CO_2 Emissions Calculation

The CO_2 emissions from each city's urban transport sector were calculated based on the accounting method described in *Guidelines for National Greenhouse Gas Inventories* [21], as shown in Equation (1):

$$\mathrm{CO}_2 = \sum_j EC_j \times EF_j \tag{1}$$

where CO_2 represents the total energy consumption-related CO_2 emissions from the passenger transport sector in a city, j denotes the type of energy source, EC_j denotes the energy consumption of fuel j, and EFj denotes the CO_2 emissions factor of fuel j. The CO_2 emissions factors of various kinds of fuels from the *Guidelines for National Greenhouse Gas Inventories* are used in this study. Because this study emphasizes the direct CO_2 emissions from the transport sector derived from end-use energy consumption, indirect CO_2 emissions from the transport sector, such as CO_2 emissions related to electricity consumption and fuel production, are not included.

3.4. Decomposition Methodology

The LMDI analysis of CO_2 emissions from the passenger transport sector in each city is conducted based on Equation (2).

$$C = \sum_{ij} C_{ij} = \sum_{ij} P \times \frac{L}{P} \times \frac{L_i}{L} \times \frac{E_i}{L_i} \times \frac{E_{ij}}{E_i} \times \frac{C_{ij}}{E_{ij}} \tag{2}$$

Equation (2) can be shortened to

$$C = \sum_{ij} P \times l \times m_i \times ei_i \times em_{ij} \times f_j \tag{3}$$

where C represents the total energy consumption-related CO_2 emissions from the passenger transport sector in one city, C_{ij} is the CO_2 emissions from passenger transport mode i with energy type j, P is the population of the city, L_i is the annual passenger kilometers traveled via mode i, L is the total annual passenger kilometers traveled by all transport modes, E_i is the energy consumption by passenger transport mode i, E_{ij} is the energy consumption from passenger transport mode i with energy type j, and l is the annual passenger kilometers traveled per capita. m_i refers to the share of travel of mode i in terms of passenger kilometers. em_{ij} is the energy share of type j in mode i. f_j is the CO_2 emissions factor of energy type j. $i = 1$ represents private transportation, and $i = 2$ represents public transportation. $j = 1$ represents gasoline, $j = 2$ represents natural gas, $j = 3$ represents diesel, and $j = 4$ represents electricity.

In additive decomposition, the effects of various driving factors from the baseline year 0 to the final year t can be expressed as follows.

$$\Delta Ctot = C_\mathrm{t} - C_0 = \Delta Cp + \Delta Cl + \Delta Cm + \Delta Cei + \Delta Cem + \Delta Cf \tag{4}$$

The various driving forces can be quantified according to the following equations.

$$\Delta Cp = \sum_{ij} u_{ij} \ln(\frac{P_t}{P_0}) \tag{5}$$

$$\Delta Cl = \sum_{ij} u_{ij} \ln(\frac{l_t}{l_0}) \tag{6}$$

$$\Delta Cm = \sum_{ij} u_{ij} \ln(\frac{m_{it}}{m_{i0}}) \tag{7}$$

$$\Delta Cei = \sum_{ij} u_{ij} \ln(\frac{ei_{ijt}}{ei_{ij0}}) \tag{8}$$

$$\Delta Cem = \sum_{ij} u_{ij} \ln(\frac{em_{ijt}}{em_{ij0}}) \tag{9}$$

$$\Delta Cf = \sum_{ij} u_{ij} \ln(\frac{f_{it}}{f_{i0}}) \tag{10}$$

$$u_{ij} = \frac{C_{ijt} - C_{ij0}}{\ln C_{ijt} - \ln C_{ij0}} \tag{11}$$

In multiplicative decomposition, the effects of various driving factors from the baseline year 0 to the final year t can be expressed as follows.

$$Dtot = \frac{C_t}{C_0} = Dp \times Dl \times Dm \times Dei \times Dem \times Df \tag{12}$$

The various driving forces can be quantified according to the following equations.

$$Dp = \exp(\sum_{ij} w_{ij} \ln(\frac{P_t}{P_0})) \tag{13}$$

$$Dl = \exp(\sum_{ij} w_{ij} \ln(\frac{l_t}{l_0})) \tag{14}$$

$$Dm = \exp(\sum_{ij} w_{ij} \ln(\frac{m_{it}}{m_{i0}})) \tag{15}$$

$$Dei = \exp(\sum_{ij} w_{ij} \ln(\frac{ei_{ijt}}{ei_{ij0}})) \tag{16}$$

$$Dem = \exp(\sum_{ij} w_{ij} \ln(\frac{em_{ijt}}{em_{ij0}})) \tag{17}$$

$$Df = \exp(\sum_{ij} w_{ij} \ln(\frac{f_{it}}{f_{i0}})) \tag{18}$$

$$w_{ij} = \frac{(C_{ijt} - C_{ij0})/(\ln C_{ijt} - \ln C_{ij0})}{(C_{it} - C_0)/(\ln C_t - \ln C_0)} \tag{19}$$

Some key factors play significantly important roles in the change of carbon emissions in urban transport. Lee Schipper established the ASIF framework model for carbon emissions from transport sector, which represents activity, structure, intensity, and fuels [22]. On this basis, this study further divided the ASIF framework model into five factors: Namely, "urbanization effect" (ΔCp, Dp), "motorization effect" (ΔCl, Dl), "mode structure effect" (ΔCm, Dm), "energy intensity effect" (ΔCei, Dei), and "energy mix effect" (ΔCem, Dem).

"Urbanization effect" (ΔCp, Dp) is generally measured by urban population size. "Motorization effect" (ΔCl, Dl) is measured by passenger kilometers per capita. "Mode structure effect" (ΔCm, Dm) has a great impact on the carbon emissions from urban transport. Different travel modes have different carbon emission intensities. They are ranked from high to low: Single-passenger cars, high-capacity cars, taxis, commerce vehicles, public transportation, bicycles, and walking [23]. "Energy intensity effect" (ΔCei, Dei) mainly refers to the energy consumption per unit kilometer. "Energy mix effect" (ΔCem, Dem) is a direct factor in determining the level of carbon emissions from urban transport. Different kinds of fuels have different carbon emission factors. It can be found that traditional fossil fuels such as gasoline and diesel have higher emission factors. Electric energy and hydrogen fuel produce no carbon emissions during the operating phase [24].

Large values of ΔC and D reflect large contributions of the driving factor. In this study, we use the emission factors from the *Guidelines for National Greenhouse Gas Inventories* [21] and assume that the emissions factors of various energy sources remained unchanged during the study period. Thus, $\frac{f_{it}}{f_{i0}} = 1$, and the emissions factor effect is 0.

4. Results and Discussion

4.1. CO_2 Emissions Calculation Results

CO_2 emissions from the urban passenger transport sector in 46 cities were calculated with the method presented above. The results are shown in Table 1.

Figure 2 shows the CO_2 emissions growth rate from 1960 to 2001. As shown in Figure 2, urban passenger transport CO_2 emissions from both megacities and other cities experienced decelerated growth over the study period. Additionally, CO_2 emissions from the urban passenger transport in both mega cities and other cities experienced a reduction from 1996 to 2001. Specifically, urban passenger transport CO_2 emissions peaked during the 1990s for most cities over the study period. High CO_2 emissions cities are mainly distributed in the United States, such as New York, Los Angeles. European cities such as Copenhagen and Zurich have relatively low emissions.

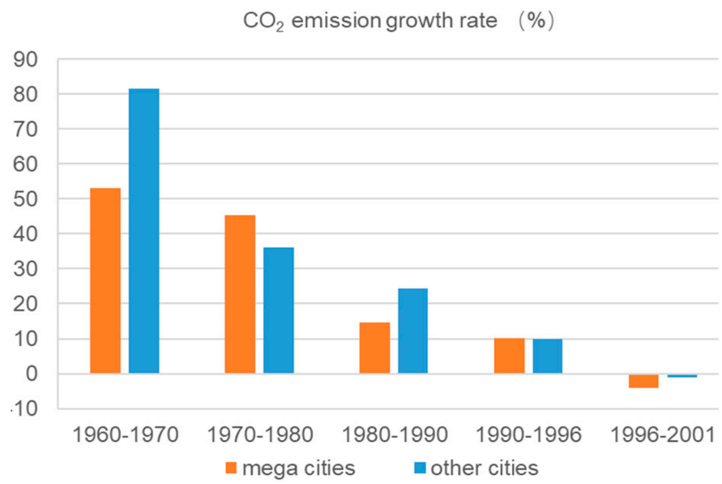

Figure 2. CO_2 emission growth rate from 1960 to 2001.

Table 1. Total CO_2 emissions from the urban passenger transport sector in 46 cities from 1960 to 2001.

Cities	Total CO_2 Emissions (Tons)					
	1960	1970	1980	1990	1996	2001
Adelaide	753,145	1,452,518	1,959,048	2,301,595	——	——
Amsterdam	139,354	410,849	409,081	547,084	477,197	424,334
Bangkok	——	——	——	7,992,878	7,248,321	——
Brisbane	942,360	1,335,469	2,446,702	2,952,208	3,226,841	——
Brussels	399,989	803,985	1,059,818	1,452,356	1,342,890	1,181,509
Calgary	463,652	648,290	1,387,636	1,798,388	2,155,923	——
Canberra	72,318	294,207	604,398	822,281	——	——
Chicago	11,984,967	20,672,796	24,364,656	23,944,161	23,807,436	24,572,262
Copenhagen	813,192	1,425,148	1,536,741	1,886,537	1,868,624	1,930,361
Denver	3,025,881	5,316,838	7,069,204	7,033,000	8,295,613	——
Detroit	14,665,897	16,682,938	18,615,653	14,976,034	——	——
Edmonton	——	——	——	1,401,608	——	——
Frankfurt	——	——	721,792	1,111,998	908,540	——
Hamburg	666,854	1,624,628	2,001,373	2,427,573	2,338,561	2,292,189
Hong Kong	——	597,704	968,492	1,399,872	2,742,408	2,173,105
Houston	4,589,931	8,720,103	14,126,373	15,431,244	23,315,558	——
Jakarta	——	——	——	——	2,696,824	——
Kuala Lumpur	——	——	——	3,761,963	3,121,615	——
London	3,809,240	5,036,130	6,089,349	6,294,083	6,764,779	6,795,893
Los Angeles	17,802,202	28,548,174	30,643,577	34,338,702	32,721,394	——
Manila	——	——	2,045,974	2,835,210	4,018,819	——
Melbourne	2,611,515	4,136,237	5,769,453	7,112,164	6,939,389	——
Montreal	——	——	4,150,770	6,216,421	6,466,730	——
Munich	354,273	899,101	1,143,412	1,293,750	1,490,535	1,600,833
New York	43,819,917	53,575,666	56,031,829	61,790,296	58,527,706	——
Ottawa	942,116	1,284,992	1,745,380	1,779,027	2,018,943	——
Paris	4,643,261	6,086,166	10,085,564	10,827,836	11,516,069	10,497,038
Perth	655,958	1,498,960	2,196,509	2,807,320	2,934,730	——
Phoenix	2,368,952	4,373,810	6,805,522	8,844,327	9,093,449	——
Portland	1,551,609	3,034,827	4,454,551	4,746,533	——	——
Sacramento	2,293,158	3,492,125	5,328,319	6,160,571	——	——
San Diego	3,570,849	5,315,035	9,091,069	10,648,447	9,749,195	——
San Francisco	6,705,341	11,629,440	12,680,274	15,188,924	15,902,239	——
Seoul	——	——	——	9,065,902	15,096,032	——
Singapore	——	——	1,268,533	2,412,346	2,449,976	3,174,598
Stockholm	——	1,192,078	1,562,252	2,411,189	2,411,770	2,183,012
Surabaya	——	——	——	500,354	——	——
Sydney	3,155,803	4,974,740	6,571,204	7,347,135	7,622,225	——
Tokyo	3,042,103	6,908,077	13,171,580	18,142,559	23,857,802	——
Toronto	——	——	6,320,739	9,272,646	11,399,222	——
Vancouver	——	2,137,340	3,258,998	3,482,666	4,164,010	——
Vienna	——	——	1,107,012	1,658,699	1,785,969	1,850,921
Washington	——	7,321,628	10,771,682	12,424,465	13,179,342	——
Winnipeg	963,225	1,249,858	1,480,888	1,469,463	——	——
Zurich	——	——	861,087	1,123,122	950,658	972,357

4.2. CO_2 Emissions Decomposition Results—A Comparison of Megacities and Other Cities

The LMDI method is used to decompose the CO_2 emissions trends from the urban passenger transport sector into five driving factors: The urbanization effect (*Dp*), motorization effect (*Dl*), mode structure effect (*Dm*), energy intensity effect (*Dei*), and energy mix effect (*Dem*). The average values of the multiplicative decomposition results for megacities (London, Paris, New York, and Tokyo) are calculated and compared with those of other cities (see Figure 3a–e).

Figure 3. (**a**) Multiplicative decomposition results for megacities and other cities between 1960 and 1970. (**b**) Multiplicative decomposition results for megacities and other cities between 1970 and 1980. (**c**) Multiplicative decomposition results for megacities and other cities between 1980 and 1990. (**d**) Multiplicative decomposition results for megacities and other cities between 1990 and 1996. (**e**) Multiplicative decomposition results for megacities and other cities between 1996 and 2001.

From 1960 to 1970, five driving forces had positive effects on passenger transport sector CO_2 emissions growth. For megacities, the urbanization effect (*Dp*) and motorization effect (*Dl*) were the most dominant driving factors that increased CO_2 emissions. The contributions of these two factors to passenger transport sector CO_2 emissions growth in other cities were larger than those in megacities because the urbanization and motorization processes in other cities were more rapid from 1960–1970. Modal shifting to private transport modes also substantially contributed to the passenger transport CO_2 emissions growth in megacities, but this impact was small in other cities (see Figure 3a).

From 1970 to 1980, urban transport CO_2 emissions in both types of cities increased by a factor of approximately 1.4 on average compared to the previous value as shown in Figure 2. The main contributor to the growth was the increase in trip distance per capita (motorization effect, *Dl*). The energy intensity effect (*Dei*) was a positive driving factor of the passenger transport CO_2 increase of megacities but a negative factor in other cities (see Figure 3b).

From 1980 to 1990, each driving factor played a similar role in megacities and other cities. Although an overall increasing trend was observed, the energy intensity effect (*Dei*) and energy mix effect (*Dem*) partially offset the increasing effects contributed by urbanization effect (*Dp*), motorization effect (*Dl*), and mode structure effect (*Dm*) (see Figure 3c).

From 1990 to 1996, the urban passenger transport CO_2 emissions in megacities displayed a modest rise, which was mainly caused by modal shifting to personal transport modes (mode structure effect, *Dm*). Additionally, the energy intensity effect (*Dei*) offset some increasing effects on CO_2 emissions in megacities and other cities (see Figure 3d).

From 1996 to 2001, urban passenger transport CO_2 emissions from both megacities and other cities significantly declined. Motorization effect (*Dl*) and mode structure effect (*Dm*) were the main driving forces of the reduction in passenger transport CO_2 emissions (see Figure 3e).

4.3. CO_2 Emissions Decomposition Results for the Four Megacities

To investigate the driving forces of changes in CO_2 emissions from the passenger transport sectors in megacities, a period-series LMDI additive decomposition analysis was conducted for the period of 1960 through 2001. Figures 4–7 depict the changes of CO_2 emissions from the urban passenger transport sector and contributions by different driving forces in 4 megacities (London, New York, Paris, and Tokyo). $\Delta Ctot$ represents the increment of CO_2 emissions in a given time period, such as 1960–1970.

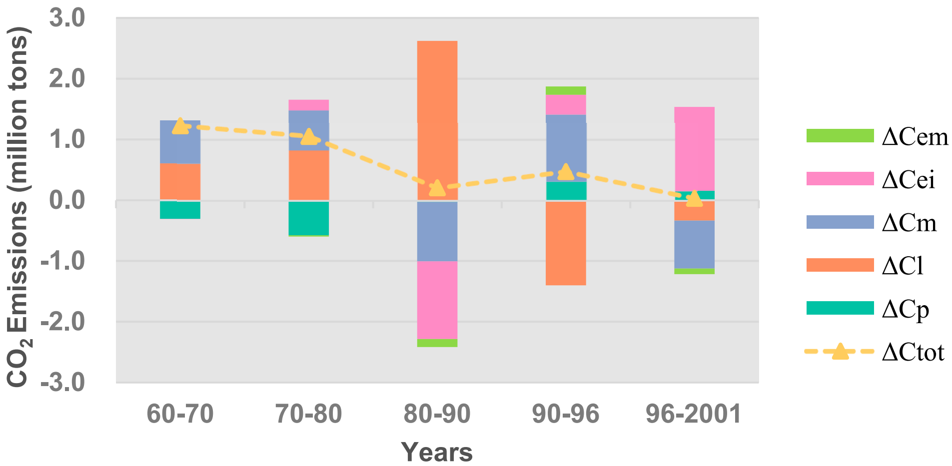

Figure 4. Decomposition results for London.

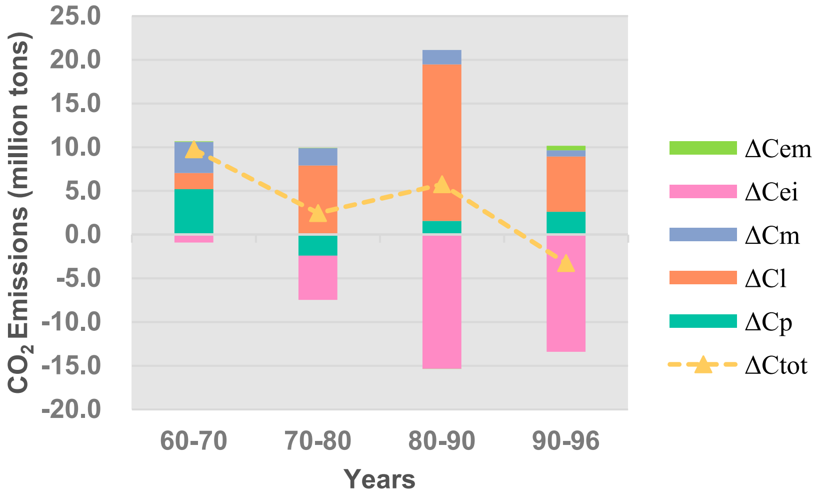

Figure 5. Decomposition results for New York.

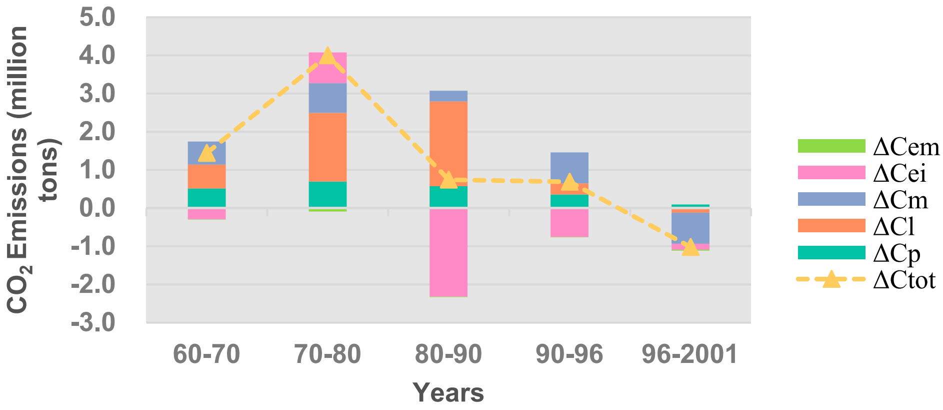

Figure 6. Decomposition results for Paris.

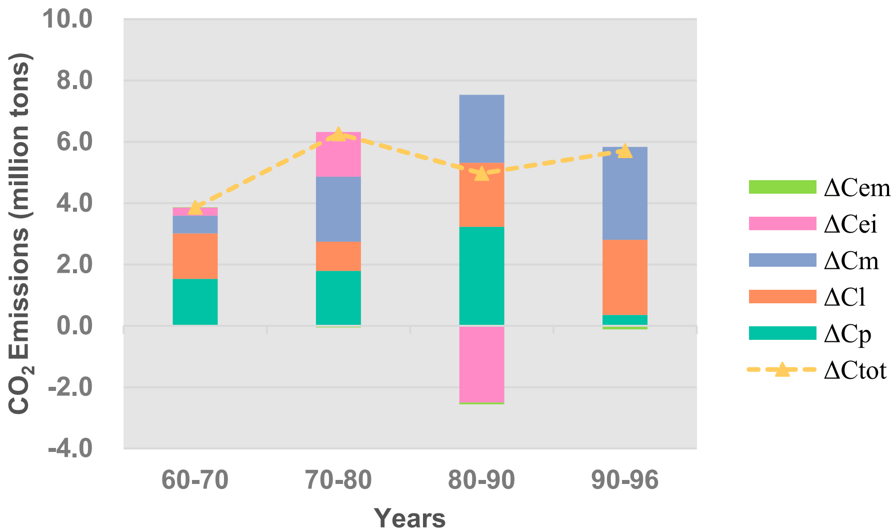

Figure 7. Decomposition results for Tokyo.

Decomposition Results for London. As Figure 4 indicates, generally the motorization effect (ΔCl) and mode structure effect (ΔCm) are sensitive factors related to CO_2 emissions change. Specifically, the effect of motorization (ΔCl) is positive from 1960 to 1990 and negative from 1990 to 2001. The mode structure effect (ΔCm) appears to be positive for the periods of 1960–1980 and 1990–1996 and negative for the periods of 1980–1990 and 1996–2001. From 1960 to 1980, motorization effect (ΔCl) and mode structure effect (ΔCm) were the main contributors to the CO_2 emissions increase from the passenger transport sector in London. Motorization effect (ΔCl) contributed to 49.5% and 78.3% of the total change for the period of 1960–1970 and 1970–1980, respectively. Mode structure effect (ΔCm) contributed to 57.6% and 62.0% of the total change for the periods of 1960 to 1970 and 1970 to 1980, respectively. During the period of 1960–1990, the urbanized area in London expanded. Therefore, the motorization effect (ΔCl) reached a historical peak as a result of urban sprawl. Additionally, counter-urbanization led to a scattered population, a longer average trip distance and an increased private transport share, thereby promoting carbon emissions growth. From 1980 to 1990, the inhibitory effects of the mode structure (ΔCm) and energy intensity (ΔCei) weakened the growth trend of CO_2 emissions. The three oil crises that occurred between 1973 and 1990 made the British government focus more on the development of public transport than in the past, and technological progress further reduced the energy intensity.

Decomposition Results for New York. As Figure 5 indicates, the total CO_2 emission from the urban passenger transport sector in New York increased from 1960 to 1990 and then decreased from 1990–1996. Overall, the largest contributor was the motorization effect (ΔCl), followed by the mode structure effect (ΔCm). The energy intensity effect (ΔCei) constantly negatively contributed to CO_2 emissions, and the contributions in the periods of 1960–1970, 1970–1980, 1980–1990, and 1990–1996 were −9.4%, −205.8%, −266.5%, and −411.2%, respectively. The impact of this factor increased over time because the Corporate Average Fuel Economy (CAFE) standards were enacted in 1975 after the first oil crisis. The fuel economy of vehicles in 1985 was twice as high as that in 1975, and the energy intensity effect (ΔCei) has become the key negative factor to offset the increase of CO_2 emissions since the 1980s. During the same time period, the average trip distance per capita increased as a result of counter-urbanization; thus, the motorization effect (ΔCl) promoted CO_2 emissions growth.

Decomposition Results for Paris. As Figure 6 illustrates, CO_2 emissions from urban passenger transport in Paris increased from 1960 to 1996 and then decreased from 1996–2001. From 1960 to 1996, motorization effect (ΔCl) and mode structure effect (ΔCm) were the key contributors to the urban passenger transport CO_2 emissions increase in Paris. In 1965, Paris proposed the plan to construct new cities with low population densities in the surrounding area. Additionally, the travel distance and private transport share increased, which contributed to the increase in CO_2 emissions. However, the Paris government approved the "Seine Rive Gauche" zone development plan in 1991. The local government has changed this area from an industrial land into a livable area by integrating housing, offices, services, and general amenities [25]. The mix of everyday destinations, rather than individual isolated space, makes travel distances shorter and makes it easier to improve public transportation. The average travel distance became shorter and the public transport share began to rise due to the operation of metro line 14 in 1998. Therefore, the motorization effect (ΔCl) and mode structure effect (ΔCm) were the key contributors to the urban passenger transport CO_2 emissions decrease in Paris in the period of 1996–2001.

Decomposition Results for Tokyo. As Figure 7 shows, the CO_2 emissions from urban passenger transport in Tokyo steadily increased from 1960 to 1996. Due to rapid urbanization and the popularization of private cars in Tokyo, urbanization effect (Dp), motorization effect (Dl), and mode structure effect (Dm) promoted the growth of CO_2 emissions. The "Energy Conservation Act", which focused on improving the fuel economy, was implemented in 1979. Consequently, the energy intensity effect (ΔCei) became the most important negative factor related to the growth of CO_2 emissions. Specifically, the energy intensity effect (ΔCei) has reduced 250,350 tons of CO_2 emissions in the period of 1980–1990.

4.4. Policy Implications

After evaluating the contributions of five key driving forces of CO_2 emissions from urban transport, some policy implications involved with these five factors are recommended to develop low-carbon urban transport planning.

For the "urbanization effect", controlling the urban population size is a feasible way to decrease carbon emissions from urban transport. The global population will continue to grow over the next few decades. Even though the population of some developed countries has stabilized or even declined, the population of developing countries has exploded. It is estimated that by 2100, the total global population will exceed 10 billion [26]. The Chinese government clearly states the aim of "strictly controlling the population size of megacities" in the National New Urbanization Plan (2014–2020) [27].

For the "motorization effect", it has contributed more to the CO_2 emissions in the United States cities than in other mega cities according to the above decomposition result. Millard-Ball and Schipper also revealed that the average motorized travel distance per capita in the United States was twice that in Japan under the same level of the per capita GDP [28].

For the "mode structure effect", private cars have a higher energy intensity than public and non-motorized transport. Bristow A. L. et al. suggested that adjusting the mode structure was the most effective way to decrease the CO_2 emissions from urban transport [29]. Most North American cities are car-oriented. The number of global car ownership will rapidly increase to 2 billion in the next few decades, most of which are from developing countries [30]. Therefore, it is really important for the government to advocate and improve public or non-motorized transport services.

For the "energy intensity effect", many cities took measures to improve the fuel efficiency in the 1980s because of oil crisis. Consequently, the "energy intensity effect" was the key negative factor to offset the increase of CO_2 emissions from urban transport in the 1980s. The increased fuel economy also reduces the cost of using vehicles, thus leading to the increase of the motorization, which is called the "rebound effect" [31]. Mishina and Muromachi identified an increase in fuel prices by implementing a fuel tax increase, which would be one feasible method to improve the on-road fuel economy and reduce the rebound effects [32]. Therefore, fuel economy policies and standards formulated when oil prices are high should not be abandoned when oil prices fall. Furthermore, high-capacity cars can also decrease the fuel use per capita. The shared mobility service can be an effective way to decrease the CO_2 emissions from urban transport.

For the "energy mix effect", electric energy and hydrogen fuel have lower emission factors than traditional fossil fuels such as gasoline and diesel during the operating phase. The interest in electric-powered vehicles has rekindled worldwide in recent years because of global climate change. It is estimated that the number of electric cars would need to exceed 700 million by 2040 [2]. The transportation fuels will show a diversified trend in the future, including not only traditional fossil fuels, but also alternative energy such as electric energy, biofuels, and clean natural gas.

As shown in Table 2, this paper sorts out the typical urban low-carbon transport policy rules, which can be divided into five categories based on the involved target factors. Furthermore, these rules can be subdivided into 14 types of measures: Urbanization measures mainly include controlling the urban population; motorization measures include constructing facilities suitable for non-motorized transport, increasing land mix and promoting telecommuting; mode structure measures include constructing public transport facilities, controlling the number of license plates, tax collection, congestion charge, and parking management; energy intensity measures include fuel economy requirements and management of scrap cars; energy mix measures include constructing charging stations for electric vehicles, subsidizing vehicles with low-emission and advocating shared electric vehicles.

Table 2. Classification of urban low-carbon transport policies.

Policy Categories	Policy Measures	Typical Urban Cases
Urbanization Measures	Controlling the urban population	Chinese mega cities such as Beijing, Shanghai, and Shenzhen
Motorization Measures	Constructing facilities suitable for non-motorized transport	Bicycle transport network in Copenhagen; Broadway street project in New York
	Increasing land mix	"Seine Rive Gauche" zone project in Paris; Hamm Lake City in Stockholm
	Promoting telecommuting	Civil servant telecommuting in Korea
Mode Structure Measures	Constructing public transport facilities	Rail Transit Network in Tokyo
	Controlling the number of license plates	License plate lottery in Beijing; License plate auction in Shanghai
	Tax collection	Fuel tax in Britain; Carbon tax for cars in Europeans cities
	Congestion charges	Congestion charges in London, Singapore and Stockholm
	Parking management	Limiting parking spaces in Development Zone in London; Priority of vehicles with low-emissions in Los Angeles
Energy Intensity Measures	Fuel economy requirements	CAFÉ regulation in the United States; Top Runner Program in Japan; Fuel Consumption Limit of Passenger Vehicles in China
	Management of scrap cars	Scrapping standards for cars in Korea; Compulsory Scrapping Standards for Vehicles in China
Energy Mix Measures	Constructing charging stations for electric vehicles	Constructing charging facilities in Tokyo and Shanghai
	Subsidizing vehicles with low-emissions	Subsidizing to purchase electric vehicles in Los Angeles and China
	Advocating shared electric vehicles	Shared Electric Autolib service in Paris; Shared Evcard Project in Shanghai

5. Conclusions and Suggestions

This paper presented a holistic picture of CO_2 emissions from the urban passenger transport sectors in 46 cities. By conducting a period-wise LMDI analysis, this study quantified how the population, trip distance per capita, mode structure, modal share, energy intensity, and energy mix contributed to CO_2 emissions changes in the urban passenger transport sector during the period of 1960–2001 in different cities. The contributions of different driving factors in megacities and other cities were compared. Furthermore, detailed analyses of carbon emissions from urban passenger transport in the four megacities were conducted to identify the main driving factors. Finally, this paper classified all kinds of policy rules based on the involved target factors to provide practical guidance to low-carbon urban planning in developing countries. The main research outcomes are as follows:

(i) Urban passenger transport CO_2 emissions in both megacities and other cities experienced decelerated growth and a reduction from 1960–2001. It peaked during the 1990s for most cities over the study period. High CO_2 emissions cities are mainly distributed in the United States, such as New York, Los Angeles. European cities such as Copenhagen and Zurich have relatively low emissions.

(ii) From 1960 to 1970, the contributions of the urbanization effect (*Dp*) and motorization effect (*Dl*) to passenger transport sector CO_2 emissions growth in other cities were larger than those in megacities because urbanization and motorization processes in other cities were more rapid from 1960–1970. From 1960 to 1996, mode structure effect played a more important role in influencing CO_2 emissions from the urban passenger transport in megacities than in other cities. From 1996 to 2001, the main inhibitory effects of CO_2 emissions growth were mainly from the improvement of the public transport share and reduction in the trip distance per capita in both types of cities.
(iii) Energy intensity effect was the main inhibitory factor of urban passenger CO_2 emissions growth in megacities (London, Paris, New York, and Tokyo) from 1980–1990 because the government focused on improving the fuel economy of motor vehicles after the oil crisis. From 1970 to 1990, counter-urbanization led to longer trip distances and increased private transport shares, thereby promoting CO_2 emissions growth in megacities.

Based on this investigation of the driving forces of changes in CO_2 emissions from the passenger transport sectors in 46 cities, including 4 megacities, some effective carbon-reduction policies and strategies can be formulated for developing cities experiencing rapid urbanization and motorization. The main suggestions are as follows:

(i) Rational land use, such as transit-oriented development, is a feasible way to make average travel distances shorter and decrease the motorization level.
(ii) Fuel economy policies and standards formulated when oil prices are high are effective ways to suppress the increase of CO_2 emissions from urban transport. These policies should not be abandoned when oil prices fall. Oil crises provide important opportunities for improving the fuel economy.
(iii) Cities with high population densities should focus on the development of public and non-motorized transport. Some rules should be implemented to prevent the unlimited spread of cities and counter-urbanization.

This study can provide practical guidance to low-carbon urban planning in developing countries. However, there are some limitations to the current study. Some other important cities such as Beijing and Mexico City, are not mentioned in this study because of the limit of data. This paper only chooses 4 mega cities for further analyses. More cities can be chosen according to the region or the development stage in the future. The authors recommend that future studies focus on these issues.

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References

1. Nakamura, K.; Hayashi, Y. Strategies and instruments for low-carbon urban transport: An international review on trends and effects. *Transp. Policy* **2013**, *29*, 264–274. [CrossRef]
2. Conti, J.; Holtberg, P.; Diefenderfer, J.; LaRose, A.; Turnure, J.T.; Westfall, L. *International Energy Outlook 2016 with Projections to 2040 (No. DOE/EIA-0484 (2016))*; Office of Energy Analysis, USDOE Energy Information Administration (EIA): Washington, DC, USA, 2016.

3. The International Energy Agency, CO_2 Emissions from Fuel Combustion Highlights 2015. *Oecd. Observer.* **2015**, 1–152.
4. Liu, Y. Low carbon eco-city—The strategic choice of global city for sustainable development in the future under the influence of climate change. *Urban Stud.* **2010**, *5*, 35–41.
5. Guan, H.L.; Chen, J.C.; Cao, W. Empirical study on the relationship between carbon emission and urbanization. *China Popul. Resour. Environ.* **2013**.
6. Ang, B.W.; Goh, T. Index decomposition analysis for comparing emission scenarios: Applications and challenges. *Energy Econ.* **2019**, *83*, 74–87. [CrossRef]
7. Ang, B.W.; Liu, F.L. A new energy decomposition method: Perfect in decomposition and consistent in aggregation. *Energy* **2001**, *26*, 537–548. [CrossRef]
8. Ang, B.W. Decomposition analysis for policymaking in energy: Which is the preferred method? *Energy Policy* **2004**, *32*, 1131–1139. [CrossRef]
9. Schipper, L.; Scholl, L.; Price, L. Energy use and carbon emissions from freight in 10 industrialized countries: An analysis of trends from 1973 to 1992. *Transp. Res. Part D Transp. Environ.* **1997**, *2*, 57–76. [CrossRef]
10. Johansson, O.; Schipper, L. Measuring the long-run fuel demand of cars: Separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance. *J. Transp. Econ. Policy* **1997**, *31*, 277–292. Available online: https://www.jstor.org/stable/20053740 (accessed on 1 August 2018).
11. Moutinho, V.; Moreira, A.C.; Silva, P.M. The driving forces of change in energy-related CO_2 emissions in Eastern, Western, Northern and Southern Europe: The LMDI approach to decomposition analysis. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1485–1499. [CrossRef]
12. Yeo, Y.; Shim, D.; Lee, J.D.; Altmann, J. Driving Forces of CO_2 Emissions in Emerging Countries: LMDI Decomposition Analysis on China and India's Residential Sector. *Sustainability* **2015**, *7*, 16108–16129. [CrossRef]
13. Timilsina, G.R.; Shrestha, A. Why Have CO_2 Emissions Increased in the Transport Sector in Asia? *Underlying Factors Policy Options* **2009**. [CrossRef]
14. Li, H.; Zhao, Y.; Qiao, X.; Liu, Y.; Cao, Y.; Li, Y.; Weng, J. Identifying the driving forces of national and regional CO_2 emissions in China: Based on temporal and spatial decomposition analysis models. *Energy Econ.* **2017**, *68*, 522–538. [CrossRef]
15. Zhang, M.; Li, H.; Zhou, M.; Mu, H. Decomposition analysis of energy consumption in Chinese transportation sector. *Appl. Energy* **2011**, *88*, 2279–2285. [CrossRef]
16. Jiang, J.; Ye, B.; Xie, D.; Tang, J. Provincial-level carbon emission drivers and emission reduction strategies in China: Combining multi-layer LMDI decomposition with hierarchical clustering. *J. Clean. Prod.* **2017**, *169*, 178–190. [CrossRef]
17. Wang, Y.; Hayashi, Y.; Kato, H.; Liu, C. Decomposition analysis of CO_2 emissions increase from the passenger transport sector in Shanghai, China. *Int. J. Urban Sci.* **2011**, *15*, 121–136. [CrossRef]
18. Luo, X. *A Study on Factor Decomposition for CO2 Emission Generation and Its Causal Mechanisms in Urban Transport: A Comparison between Shanghai and Tokyo*; Nagoya University: Nagoya, Japan, 2013.
19. Kenworthy, J.; Laube, F. *An International Sourcebook of Automobile Dependence in Cities 1960–1990*; University Press of Colorado: Niwot, CO, USA, 2010.
20. Kenworthy, J.; Laube, F. *Millennium Cities Database for Sustainable Transport*; International Association of Public Transport (UITP): Brussels, Belgium, 2001.
21. Intergovernmental Panel on Climate Change. *Guidelines for National Greenhouse Gas Inventories*; IPCC: Kyoto, Japan, 2006.
22. Schipper, L.; Marie-Lilliu, C.; Gorham, R. *Flexing the Link between Transport and Greenhouse Gas Emissions-A Path for the World Bank*; Transportation Annual Meeting, Transportation Research Board (TRB): Washington, DC, USA, 2000.
23. Bradshaw, C. The Green Transportation Hierarchy: A Guide for Personal and Public Decisionmaking. Available online: http://vault.sierraclub.org/sprawl/articles/trips.asp (accessed on 1 August 2018).
24. Creutzig, F.; McGlynn, E.; Minx, J.; Edenhofer, O. Climate policies for road transport revisited (I): Evaluation of the current framework. *Energy Policy* **2011**, *39*, 2396–2406. [CrossRef]
25. Senly, D. Paris Rive Gauche. Images, réseaux et financement de l'aménagement. In *Les Annales de la Recherche Urbaine*; Centre de Recherche d'Urbanisme: Paris, France, 1999; Volume 82, pp. 25–35.

26. Desa, U. World urbanization prospects, the 2017 revision. In *Final Report with Annex Tables*; United Nations Department of Economic and Social Affairs: New York, NY, USA, 2017.
27. The editorial department of the journal. Interpretation of the National New Urbanization Plan (2014–2020). *China Econ. Trade Guide* **2014**, *29*, 19–20.
28. Millard-Ball, A.; Schipper, L. Are we reaching peak travel? Trends in passenger transport in eight industrialized countries. *Trans. Rev.* **2011**, *31*, 357–378. [CrossRef]
29. Bristow, A.L.; Tight, M.; Pridmore, A.; May, A.D. Developing pathways to low carbon land-based passenger transport in Great Britain by 2050. *Energy Policy* **2008**, *36*, 3427–3435. [CrossRef]
30. Sperling, D.; Gordon, D. *Two Billion Cars: Driving toward Sustainability 0199744017*; Oxford University Press: Oxford, UK, 2009.
31. Grant, D.; Jorgenson, A.K.; Longhofer, W. How organizational and global factors condition the effects of energy efficiency on CO_2 emission rebounds among the world's power plants. *Energy Policy* **2016**, *94*, 89–93. [CrossRef]
32. Mishina, Y.; Muromachi, Y. Are potential reductions in CO_2 emissions via hybrid electric vehicles actualized in real traffic? The case of Japan. *Transp. Res. Part D Transp. Environ.* **2017**, *50*, 372–384. [CrossRef]