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Decomposing the decoupling of road-based traffic emissions and economic growth:

Regional disparities between the national and city-level in Germany during 1999-2013

by

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Abstract

The process of decoupling is often considered to fulfil the prediction by the Environmental Kuznets Curve hypothesis that negative environmental externalities diminish with increasing income. Recent research has found many instances of delinking between economic growth and environmental harm on the national level across the globe. This study examines the development of the relationship between economic growth and carbon dioxide emissions from road traffic for the case of Germany during 1999-2013. Additionally, it adds a geographical dimension by investigating decoupling in the three German cities Stuttgart, Frankfurt a. M. and Berlin. To explain the delinking that is uncovered by the decoupling analysis, a subsequent Shapley decomposition of the carbon emissions from road traffic on five underlying factors is conducted. The study shows that decoupling occurred in Germany and the cities throughout the entire period, except for recessive coupling in 2000 in Berlin. Nevertheless, periods of desirable decoupling, with increasing GDP and decreasing emissions, were only prevalent in Germany for nine years, in Berlin for seven, in Frankfurt for six and in Stuttgart for four years. The emission factor, representing the carbon intensity of traffic activities, was the most impactful factor in the total period, resulting in a significant decline in road traffic carbon emissions. Furthermore, the study revealed that the factors that are influencing on-road carbon emissions vary substantially between different regions and time periods. Consequently, the results suggest that the development of carbon emissions from road traffic changes over time and is subject to regional characteristics.

Keywords: Decoupling, Traffic, CO_2, Decomposition, Germany, City.

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1 Introduction

Transportation is a major source of greenhouse gas (GHG) emissions. According to the IPCC's fifth Assessment Report (AR5), the transport sector produced approximately 23% of the global energy-related CO_2 emissions in 2010 (Sims et al., 2014). Making matters worse, the report shows that the global direct GHG emissions of the transport sector increased 2.5-fold between 1970 and 2010. The substantial part of transport GHG emissions is a result of road transport, which amounts to almost 70% of all transport-related carbon emissions in 2010 (Sims et al. 2014). A similar development is visible in Germany. The German Environment Agency (2018a) states that carbon dioxide emissions from the traffic sector comprise 18% of Germany's total carbon emissions in 2017. The report further states that a staggering 96.2% of the total traffic emissions are a consequence of on-road traffic, with the remaining traffic modes only accounting for 3.8%. Additionally, carbon dioxide emissions from traffic increased again after 2010 and in 2017 the amount of CO_2 released exceeded that of 1990 (German Environment Agency, 2018a).

Nevertheless, policymakers ratified the Paris Agreement and committed to limit the release of GHG to keep global warming to less than 2ºC and avoid further environmental harm (UNFCCC, 2015). The German government incorporated the Paris Agreement's goals into their "Climate Action Plan 2050". In the Climate Action Plan 2050 an overall GHG reduction to 55% of the 1990 level has been set as the goal for 2030 (Bergk, F., Knörr, W. & Lambrecht, U., 2017). Furthermore, the plan sets the goal that emissions from the transport sector should not exceed 42% of the 1990 level by 2030. Given that the CO_2 emissions from traffic were more in 2017 than they were in 1990, Germany's transport and traffic sector in general must undergo a widespread intensive transformation to reduce its emission output in only a little more than ten years.

Decoupling studies are frequently used to analyse the development of environmental harm and economic growth. They allow scholars to identify and assess which changes occur when economic growth is realised with less negative environmental impact (Loo & Banister, 2016). While decoupling between carbon emissions and economic growth was rare in Europe before the 1990s, especially in the transport sector, it became more relevant in subsequent periods (Tapio, 2005; Jaunky, 2011). Rüstemoğlu (2019) identifies decoupling between economic growth and carbon dioxide emissions in Germany between 1990 and 2015. The presence of decoupling between economic activity and emissions then implies the question if a similar trend exists between the relationship of economic growth and emissions from road traffic in Germany. Lu, Lin and Lewis (2007) find signs for receding CO_2 emissions from highway transportation in Germany, which indicate that decoupling occurred in parts of the traffic sector.

However, there is an apparent need to study decoupling between economic growth and all road traffic in Germany. To fulfil the goals of the Climate Action Plan 2050, more detailed insights into the development of on-road traffic emissions are necessary. Since the development on country-level is the aggregate of the development in the country's sub-regions, it should be examined how regions differ in their road traffic emission output and what underlying characteristics are responsible. This study, consequently, conducts a decoupling analysis of the relationship between carbon emission from on-road traffic and economic growth in Germany. It uncovers differences between the country and regional level and examines the effect of local particularities like agglomeration and infrastructure on the emission output. Lastly, it analyses the effect of five socioeconomic factors on generating road traffic emissions and discusses them in a temporal and geographic context. Ultimately, by revealing mechanisms and considering the geographic role the study contributes to the existing literature and provides a foundation to extrapolate policy recommendation.

1.1 Aim and Objectives of the Study

This study's aim is to examine CO_2 emissions from traffic activities in Germany. More precisely, the study empirically analyses the relationship between CO_2 emissions from road traffic and economic growth. Additionally, the study intents to investigate the linkage between the national level and its sub-levels in generating emissions from road traffic. In the same manner, similarities and differences between the sub-levels, the urban (city) regions, are examined. The specific aspects outlined in this broader scope are analysed by the following detailed objectives: (i) How did the relationship between economic growth and carbon emissions from road traffic evolve in Germany, Stuttgart, Frankfurt am Main and Berlin during 1999-2013? (ii) To what extent did the five socioeconomic factors – economic growth, population growth, traffic volume, traffic intensity of economic activities, emission factor – contribute to the on-road carbon emissions in Germany, Stuttgart, Frankfurt a. M. and Berlin? (iii) How and to what extent did regional characteristics affect decoupling and the role of the main factors?

1.2 Outline of the Thesis

The introductory chapter is followed by an overview and discussion of the central concepts and theories regarding the study of carbon emissions in the decoupling context. Additionally, a review of the literature and an introduction to the methodologies that are applied in the empirical analysis are provided in chapter 2. Chapter 3 elaborates on the methodologies and discusses the basis for carbon emission estimation in the context of the study. Thereafter, the data that is used for the analysis is presented and discussed in chapter 4. Chapter 5 continues by displaying and elaborating on the results of the analysis. Subsequently, the results are discussed in chapter 6, with regards to noticeable deviations between the study objects, the regional dimension and factor development. Finally, chapter 7 contains a summary of the study, presents conclusions and suggestions for further research.

2 Theory

Realising economic growth whilst minimising environmental degradation is a high priority goal for most societies today. In particular, Europe has devoted itself to this objective, with the European Union pushing and striving to achieve a sustainable European economy. The notion of decoupling plays a vital role in assessing the development of the economy and environmental pressure. Decoupling of economic growth and environmental harm originated as a concept that could fulfil the prediction by the Environmental Kuznets Curve (EKC) hypothesis, which postulates that the environmental degradation inflicted by expanded economic activity would recess with higher income per capita (Grossman, 1995; Grossman & Krueger, 1995). The EKC hypothesis assumes an inverted U-curve will appear when economic output is depicted as the x-axis and environmental harm as the y-axis. While the relationship seems real for some pollution indicators, Arrow et al. (1995) argue that it does not hold for stocks of waste and pollutants like CO_2 with long-term and manifold effects. Moreover, Stern (2004) and Copeland and Taylor (2004) come to a similar conclusion that the existence of a simple relationship between environmental harm and per capita income as described by the EKC is unlikely. Many more studies have been conducted to verify or reject the EKC hypothesis for developed and developing countries, but an obvious general conclusion cannot be drawn. Some scholars moved to a theory of relinking that can be described by an N-shaped curve (de Bruyn, 2002), while others accept that environmental pressure declines with higher income but cannot be exclusively explained by income variations (Narayan & Narayan, 2010; Jaunky, 2011; Kais & Sami, 2016).

Nevertheless, decoupling studies have proven to be a popular tool in analysing the development and trends of economic growth and environmental degradation. Fundamentally, decoupling is represented by the income elasticity of negative externalities (Loo & Banister, 2016). This means that a unit of income or economic activity is put in relation to the amount of harm or degradation its creation caused. Consequently, the concept of decoupling allows for a historical view of the carbon intensity of economic development, if carbon emissions are used as the negative externality. The idea of using such an emission related indicator to measure the sustainability of economic activity became increasingly popular when the protection of the environment was made a goal of states and the international community. The OECD (2002) picked the concept up and introduced their decoupling indicator to measure the sustainability of economic activity. Two more indicators are common in decoupling studies. Firstly, Tapio (2005) introduced a decoupling model that he used to assess the decoupling process of transport volumes and transport emissions from economic growth. Secondly, Lu, Wang and Qiang (2011) developed decoupling indicators to assess the development of resource use, emissions from waste and economic growth. Of these three indicators, only the latter two acknowledge the existence of different decoupling states that describe desirable and less desirable trends.

2.1 Previous Research

Multiple decoupling studies have been performed in the original sense of the EKC hypothesis, examining the immediate relationship between economic growth in terms of income growth and emissions. Narayan and Narayan’s (2010) approach is based on the analysis of long and short-term income elasticity of CO_2 emissions. They tested 43 developing countries for the period from 1980 until 2004 and found that for approximately 35% of their sample decoupling has occurred in the long run. A related study conducted on 36 high-income countries by Jaunky (2011), with data for 1980 until 2005, concluded that carbon emissions are stabilising in developed countries. However, the study could only provide evidence for the EKC hypothesis for Greece, Malta, Oman, Portugal and the United Kingdom. The research performed by Kais and Sami (2016) contains a sample of 58 countries from all continents and uses panel data from 1990 until 2012. While they find that increased energy consumption tends to increase carbon emissions, their statistical analysis also shows that carbon emissions and per capita gross domestic product (GDP) delink with high levels of income.

The idea of delinking has also been tested in other fields. In transportation studies, it is widely accepted that transport volume correlates with economic growth. Initially, it was assumed that these variables are “coupled” and that they follow a linear relationship (Bennathan, Fraser & Tompson, 1992). However, subsequent inquiries questioned this assumption and stated that the relationship was more complex. Empirical studies of the transport development in the United Kingdom (McKinnon, 2007), the United States and Japan (OECD, 2003) showed decoupling of transport volumes and GDP. Another study by Tapio (2005) examined the trends in traffic volume, transport-related carbon emissions and GDP in the EU15 between 1970 and 2000. He found evidence for decoupling of both transport volume and GDP, and carbon dioxide emissions and GDP throughout the entire period. Nevertheless, the results varied between country and observed time, with periods of decoupling followed by anew coupling. In their study of road freight transport in Denmark, Kveiborg and Fosgerau (2007) provide significant evidence for the decoupling of on-road transport volume and economic growth. The increased use of larger trucks, better logistical activities leading to reduced empty running and larger average loads are stated as the main responsible changes. Lastly, Alises, Vasallo and Guzmán (2014), similarly to Tapio, reported a geographic difference in the decoupling of road-freight transport volume and economic growth between 1999 and 2007 in the United Kingdom and Spain. While their analysis showed an apparent delinking in the United Kingdom, their results showed coupling for Spain.

In a second step, researchers investigated the relationship between economic growth, traffic volume and traffic-related carbon emissions. Tapio (2005) showed that transport-related carbon dioxide emissions and GDP followed an ecologically friendly trend and slightly decoupled in Finland, the United Kingdom, Germany, Sweden, Denmark and the Netherlands in the 1990s. Additionally, Tapio studies the case of road traffic CO_2 emissions and economic growth in Finland. While decoupling between road traffic emissions and GDP is not present in Finland before 1995, he could show decoupling between 1995 and 2001. Similarly, mixed results were obtained by Lu, Lin and Lewis (2007) when analysing the trends in carbon emissions from highway transportation between 1990 and 2002. They saw decoupling in Germany and Taiwan where GDP grew while CO_2 emissions stabilised or declined. The same development did not occur in South Korea and Japan, which, while making improvements in their emission efficiency, saw rising GDP and emissions. Furthermore, in a more recent study, Loo and Banister (2016) contributed to this subject by employing an extended model based on Tapio (2005) in 15 countries, with samples from every continent and data from 1990 until 2012. They concluded that transport volume mostly follows the trend of economic growth. On the other hand, a slight reduction in the carbon intensity of transport could be observed with a significant decrease in Australia, Canada, France in Germany, indicating a positive trend in the decoupling of transport-related carbon dioxide and economic growth. All studies mentioned so far were conducted on a national level, capturing only nation-wide effects. Zhang, Kou, Zheng and Li (2018) contributed to extending the literature by studying emissions from the transportation sector and economic growth in six cities in the Hebei province in China. Their research showed an evident variation between regions in a nation-state as the cities experienced different developments. No clear trend could be established for the first period from 1996 until 2000 because both coupling and decoupling were equally present. Nevertheless, the development converged to a decoupling dominant stage between 2001 and 2008, which is followed by the opposite development and a stage of coupling between 2009 and 2013. In the last two years of their study (2014 and 2015) decoupling in different magnitudes was present in all cities.

To summarise, decoupling of economic growth and carbon emissions, just as the decoupling of economic growth and transport-related emissions were rare before the 1990s. While periods of coupling still occurred regularly after 1990, the literature showed a trend to decoupling in developed and high-income countries. In particular, European countries such as the United Kingdom, France, Germany, Denmark and Sweden experienced significant delinking in the relationship between their economic growth and environmental pressure. Moreover, the redefinition of this relationship appears to be a global phenomenon, since decoupling could be found in the United States, Taiwan, Japan and in recent years even in China. That being so, the reduction of environmental harm from economic and traffic activities is only this apparent in developed and high-income countries. The trend is less distinct in developing countries, where in most cases GDP and emissions grew in unison. However, a portion of Middle Eastern and South Asian countries present strong economic growth and stabilising or slowly growing emissions (Narayan & Narayan, 2010).

2.1.1 Decomposition

Given that decoupling analysis provides insights in the joint development of various economic indicators and indicators of environmental harm, the analysis does not offer reasons or explanations for why the change in question played out as it did. Therefore, scholars frequently used regression or decomposition techniques to unveil and assess the underlying factors in the indicators' development. Regression techniques are commonly used where data coverage is extensive and underlying relationships are not fully uncovered. On the other hand, decomposition techniques are a popular tool to analyse changes in indicators and asses the influence and importance of underlying factors, where the causal connection between the indicator and the underlying factor is already established. Decomposition methods were first used to study changes in industrial energy demand in the late 1970s and quickly became popular in energy and environmental studies (Ang & Zhang, 2000). Ang and Zhang (2000) provide broad coverage of index decomposition studies before the year 2000. They find that the main interest lay on decomposing energy demand on a multitude of factors. Only in the last five years of their survey did they find an increasing number of studies analysing the development of energy-related greenhouse gas (GHG) and other environmentally harmful substances. Additionally, they could identify the logarithmic mean Divisia index (LMDI) and the refined Laspeyres index as the preferred methods among various different techniques.

In 2002 Albrecht, François and Schoors conducted a study using their Shapley decomposition approach to analyse the change in energy-related CO_2 emissions in Belgium, France, Germany and the United Kingdom between 1960 and 1996. The effects of energy intensity, carbon intensity, income per capita, population size and structural effects on energy-related carbon emissions were examined. Their results showed that energy and carbon intensity significantly hindered emission increase, while income per capita and population growth contributed to the rising pollution. The structural effect was minor for France, and it was minor and negative for Belgium. Germany saw an acceleration of emissions and the United Kingdom a deceleration as a consequence of structural effects. Similarly, the energy mix was identified as the main factor in emission growth at low levels of income per capita in Henriques and Borowiecki's (2017) study of long-run CO_2 emissions in Europe, North America and Japan. At high-income levels, they identified income per capita itself and population growth as the most significant drivers of CO_2 emissions. On the other hand, technological advancements and a more widespread use of renewable energy decreased carbon intensity and led to the most significant reduction of emissions.

Unsurprisingly, index decomposition was also applied to transport-related carbon emissions. An LMDI decomposition analysis of transport sector carbon dioxide emissions in 20 countries in Latin America and the Caribbean, conducted by Timilsina and Shrestha (2009), revealed economic growth and transportation energy intensity as the major factors influencing transport CO_2 during 1980 until 2005. They decomposed transport sector CO_2 on transportation energy intensity, economic growth, fuel mix, modal shift and emission coefficients. Another LMDI study by Wang, Zhang and Zhou (2011) examined how transport intensity, income per capita, population growth, modal shift, structural shift and technological advancements affect transport sector carbon emissions in China between 1985 and 2009. Their findings are in line with Timilshina and Shrestha (2009), showing transport intensity and economic growth in terms of income per capita as the major factors. While economic growth and the shift to less carbon efficient transport modes were the crucial driving forces of carbon emissions, transport intensity and structural change were responsible for the most significant reduction. Moreover, Eng-Larsson, Lundquist, Olander and Wandel's (2012) research used a Shapley decomposition approach to decompose freight transport carbon dioxide emissions in Sweden from 1990 until 2008 and yields similar results. For the studied period economic growth and transport intensity increased transport CO_2 intensively. The expanding emissions were dampened mostly by the inverse value density, which describes the efficiency of transport activities based on GDP, and secondly by decreasing traffic and carbon intensities. Moreover, they showed that the impact of the factors changed depending on the studied timeframe.

In a subsequent step, researchers analysed the change in road traffic-related emissions. Kwon (2005) used the IPAT identity to decompose carbon emissions from car travel in the United

Kingdom between 1970 and 2000. His research revealed that affluence, representing travel volumes, was the dominant factor in increasing emissions. On the other hand, technology, indicating advancements in fuel and carbon efficiency, hindered emission growth but could not offset the increasing effects. Then multiple countries were studied in an attempt to find regional disparities. Lu et al. (2007) conduct a Divisia index decomposition of highway traffic carbon dioxide emissions for Germany, Japan, South Korea and Taiwan during 1990-2003. They show that vehicle ownership, population intensity and economic growth have the same increasing or decreasing effect in every country, even though they may vary in magnitude. The carbon intensity of vehicles and the energy intensity, however, had vastly different effects in different countries. Overall, vehicle ownership and economic growth were most influential in expanding emissions, while population intensity led to a decline. Decomposing carbon dioxide emissions from passenger cars on vehicle ownership, traffic volume, fuel mix, engine capacity and technology, unveiled a vastly different composition of road emissions between Denmark and Greece in Papagiannaki and Diakoulaki's (2009) study. The LMDI I method was applied on data from 1990 until 2005 and showed that traffic volume increased CO_2 from passenger cars the most in 1990-1995, vehicle ownership was most significant in 1995-2005, and a less carbon efficient fuel mix had the most substantial impact on rising emissions in 2000-2005 in Denmark. At the same time, Greece's most influential factor in increasing passenger car CO_2 emissions for the whole period was the growing vehicle stock. Different results were also obtained for the most significant factors in CO_2 reduction. Denmark benefitted the most from technological advances during 1990 and 2005, while the reduction in traffic volume was the primary factor from 2000 until 2005. Traffic volume contributed to the emission reduction from passenger cars in Greece the most.

Decomposition methods have been a frequently used tool for 50 years. They were used in various fields and became vastly popular in energy and environmental studies. Additionally, they spread to transport studies and were used to decompose both transport growth (Kveiborg & Fosgerau, 2007; Alises et al., 2014) and transport or traffic-related emissions. However, decomposition studies were almost exclusively performed on a national or country-level. The same holds true for decoupling studies. This bears the question if the relationships and findings would be different on the sub-national level. Three recent studies following this inquiry are the work of Zhang et al. (2018), Fan and Lei (2016) and Zheng et al. (2019). All studies take place in China. The first examined the decoupling of carbon dioxide emissions from transportation on the city-level and was discussed in greater detail previously. The second decomposed energy-related carbon emissions from the transport sector in Beijing and the latter decomposes general CO_2 emissions for sub-national regions. While they find similarities between the national and sub-national level, they also find significant differences. Therefore, regional studies on the development of decoupling and its underlying factors might uncover trends and relationships that are not present or that are different in national studies.

2.2 Theoretical Approach

In this study, an initial decoupling analysis, of the relationship between economic growth and road traffic carbon emissions is conducted based on Tapio's (2005) decoupling model for transport emissions. Thereafter, a Shapley decomposition (Albrecht, François and Schoors, 2002) is performed to show the influence of economic growth, population growth, traffic volume, traffic intensity of economic activities and an emission factor in the change of road carbon emissions. Based on the literature review in the previous chapter, economic growth, population growth and traffic volume are expected to be positively correlated with road CO_2 emissions. That being so, an increase in one of these variables would lead to rising emissions. The traffic intensity of economic activities will provide information on the amount of traffic per unit of economic growth. In other words, it displays how dependent economic growth is on traffic activities. Lastly, the emission factor represents the environmental impact per unit of traffic activity. It captures advancements in reducing the carbon intensity of on-road traffic. Among others, these may be a result of better technologies, such as more efficient engines or electric vehicles, improvements in the carbon intensity of the fuel mix or improvements in the logistics of supply chains. Both analyses are applied to Germany and the German cities Stuttgart, Frankfurt a. M. and Berlin. The study relies on data for the period from 1999 until 2013.

Consequently, trends for the country and the regional level are examined and the influence of the five variables are assessed. Furthermore, this approach allows for the comparison of results between the cities and the national level. The comparison then yields information on how the development of on-road carbon emissions and its underlying factors varies from region to region. It allows an analysis of the emissions along a geographic dimension. Theories of agglomeration, regional externalities and economies of scale assign regions particular properties and comparative advantages that lead to the expectation of varying results in different regions (Henderson, 1997; Porter, 1998; Rosenthal & Strange, 2004). In the same manner, social studies imply a behavioural disparity between urban and rural residents (Yu, 2014). Then there are unique regional capabilities that comprise infrastructure differences, e.g. the state and extent of railways and streets, that influence road traffic and subsequent emissions (Maskell & Malmberg, 1999). Furthermore, conducting the decomposition on distinguished time frames, namely the total period and the periods of strong positive decoupling, enables the study to examine the impact of the factors along a temporal dimension. Lastly, investigating and discussing the change in the factors over time shows which events and trends affected on-road carbon emissions in a historical and geographical context. The results of this study then provide policymakers with valuable information to steer the change of on-road traffic and its emissions in a favourable direction. They additionally add to the existing literature by providing deeper, higher resolution insights into the geographic dimension in transport and environment studies.

3 Methodology

This thesis applies two widely established approaches in the fields of environment and transport studies. Firstly, decoupling analysis in the form of Tapio's (2005) decoupling model is used to analyse the joint development of economic growth and road carbon emissions. Secondly, a Shapley decomposition (Albrecht, François and Schoors, 2002), often also referred to as refined Laspereyes index method (Sun, 1998; Ang, Liu & Chew, 2003) is conducted to unveil the influence of five socioeconomic factors on the change of carbon emissions over time.

3.1 Tapio Decoupling Model

Tapio's (2005) elasticity decoupling model describes the relationship between economic growth and carbon emissions as the GDP elasticity of transport carbon emissions. This GDP elasticity of transport CO_2 then serves as the decoupling index *D*. Where D_{t-i}^{t} denotes the decoupling index from year *t* – *i* to year *t*. The decoupling index D_{t-i}^{t} is measured as follows:

$$D_{t-i}^{t} = \frac{\Delta CO2_{t-i}^{t}}{\Delta GDP_{t-i}^{t}} \tag{1}$$

Accordingly, $\Delta CO2_{t-i}^{t}$ and ΔGDP_{t-1}^{t} represent the change in on-road carbon emissions and GDP from year *t* – *i* to year *t*. They are derived by:

$$\Delta CO2_{t-i}^{t} = \frac{CO2^{t} - CO2^{t-i}}{CO2^{t-i}} \tag{2}$$

$$\Delta GDP_{t-i}^{t} = \frac{GDP^{t} - GDP^{t-i}}{GDP^{t-i}} \tag{3}$$

D_{t-i}^{t} shows the development of CO_2 and GDP relative to each other. Consequently, $D_{t-i}^{t} = 1$ represents that a change in one variable leads to the exact same change in the other and indicates perfect coupling. To capture weaker forms of coupling and to not overinterpret slight changes, Tapio classifies decoupling index values between 0.8 and 1.2 as coupling. Values outside this rage are considered to represent decoupling between the two variables. The decoupling index D_{t-i}^{t} together with the direction of $\Delta CO2_{t-i}^{t}$ and ΔGDP_{t-1}^{t} then gives one of eight decoupling or coupling states. As shown in Table 1.

We distinguish between coupling, decoupling and negative decoupling. *Coupling* can be *expansive,* or *recessive* depending on the growth or decline of the variables. Three states of decoupling and negative decoupling can occur. When the decoupling index lies between 0 and 0.8, and both variables increase, we have *weak decoupling*. If both variables decline and the decoupling index takes on values in the same rage, *weak negative decoupling* occurs. When the decoupling index is below zero, GDP increases, and CO_2 decreases we have *strong*

Table 1: Coupling and decoupling states, according to Tapio (2005).

	ΔGDP_{t-1}^{t}	$\Delta CO2_{t-i}^{t}$	D_{t-i}^{t}
expansive coupling	> 0	> 0	0.8 – 1.2
recessive coupling	< 0	< 0	0.8 – 1.2
weak decoupling	> 0	> 0	0 – 0.8
strong decoupling	> 0	< 0	< 0
recessive decoupling	< 0	< 0	> 1.2
expansive negative decoupling	> 0	> 0	> 1.2
strong negative decoupling	< 0	> 0	< 0
weak negative decoupling	< 0	< 0	0 – 0.8

decoupling. *Strong negative decoupling* describes the opposite case with D_{t-i}^{t} below zero, GDP declining and CO_2 increasing. For *expansive negative decoupling* GDP and CO_2 increase while the decoupling index takes on values above 1.2. Lastly, *recessive decoupling* is present when D_{t-i}^{t} is above 1.2 and both GDP and CO_2 decrease.

While all decoupling states are theoretically possible, their value in deriving useful results should be assessed in a broader context. Since many view economic growth as the underlying goal of economies, decoupling states that involve decreasing GDP are generally regarded as undesirable. A significant number of scholars, like Schneider, Kallis and Martinez-Alier (2010) or Demaria, Schneider, Sekulova and Martinez-Alier (2013), who study the concept of degrowth might argue that the focus on GDP is too narrow. While their concerns may carry a noticeable amount of validity, economic growth is to this day still the major goal in contemporary economic policy. Thus, this study regards decoupling states that display increasing GDP as more desirable than those that do not. Additionally, some decoupling states are more realistic and likely than others. Strong negative decoupling is, for example, a scenario that seems unlikely. Firstly, GDP decline is a rare phenomenon in modern industrialised states and is avoided whenever possible. Secondly, receding economic activity should, in most cases, lead to decreasing emissions.

Tapio (2005) points out, that there is an inherent inertia in changes in economic growth that lead to changes in consumption. Commute and daily travel patterns such as grocery shopping, doctor and gym visits seldom change, while we might hold off on travels for leisure and holiday because of economic pressure. Therefore, the change in GDP in one year will most likely hardly affect personal travel emissions in the same year but amount to a significant effect in subsequent years. To capture and account for this inertia, the decoupling analysis must contain multiple subsequent years. Similarly, real GDP data should be used to conduct the decoupling analysis. The nominal GDP over-represents economic growth in long periods because inflation tends to inflate GDP changes if market prices are used.

3.2 Road traffic emission decomposition model

3.2.1 Estimating aggregate on-road carbon emissions

The development of road traffic carbon emissions is analysed using decomposition. Decomposition techniques dissolve changes in an aggregated indicator in the effects of multiple factors that are causally linked to the aggregated indicator. Decomposition analysis is widely used in transport and energy studies, as has been established in Section 2.1.1. An extensive range of variables and factors can be used to decompose road traffic CO_2 emissions. The Kaya Identity serves as a first theoretical tool to model carbon emissions from underlying factors in energy-related studies (Kaya, 1990). It relates population P, economic activity Y and energy usage E with emissions C and provides factors to decompose road traffic CO_2 on. As Ang and Zhang (2000) showed in their survey of index decomposition analysis, scholars have relied on the Kaya identity in many early energy and environmental decomposition studies and have continuously added new factors to their models. A popular addition to the original Kaya identity is the inclusion of structural and sectoral effects, as seen in Albrecht, François and Schoors (2002). Another common approach found among others in Ang and Liu (2001) and the more recent study of Henriques and Borowiecki (2017) is to account for different carbon intensities of fuel types and fuel mixes, or of different energy mixes.

However, carbon emissions in the transport and traffic sector are, to some extent, differently compounded than emissions in general energy studies. REDEFINE (1999), a major study on the development of road freight transport, introduces an array of factors, such as the handling factor, the average length of haul, the load factor and the value density of transport, commonly used in transport studies. Kveiborg and Fosgerau (2007) use a model based on REDEFINE's findings and distinguish between commodity groups to decompose road freight transport growth in Denmark. They also established that carbon emissions follow the growth rates of road transport volume. In their literature survey of transportation studies, Fan and Lei (2016) presented the most influencing factors that determine transport carbon emissions. Most commonly referred to as significant are factors representing population effects, economic activity, energy intensity, modal structure and fuel or energy mix. Additionally, transport and carbon intensity were found to be relevant but are not as often included in studies.

Nevertheless, the decomposition in this study investigates underlying factors' impact on the development on all road traffic carbon emissions. Total emissions from road traffic that include commercial freight transport and private road traffic are analysed in this study. Therefore, it does not fit into the category of regular transport studies and does not use factors such as the average length of haul, the handling or load factor, and it does not distinguish between commodity groups. Furthermore, traffic can be viewed as a support process that plays a significant part in enabling economic growth in all sectors of the economy and is not limited to the economic growth of the transport sector. Consequently, this study analyses the influence of traffic on economic growth in general and does not differentiate between sectors of the economy. Based on these considerations and restrictions that arise because of limited data availability on the city-level, five factors were chosen to perform the decomposition. The change of road-based carbon emissions is decomposed in the effect of population P, economic growth *GDP/P*, traffic volume *V*, the traffic intensity of economic activities *V/GDP* and an emission factor *C/V*. The emission factor *C/V* represents the carbon intensity per unit of traffic activity and *V/GDP* indicates the efficiency of traffic activities in directly or indirectly generating economic value. Hence, the aggregated CO_2 emissions *AC* from road-based traffic are modelled as:

$$\begin{aligned} AC &= Population * economic\ activity * traffic\ volume \\ &\quad * \ traffic\ intensity\ of\ economic\ activity * emission\ factor \\ &= P * \frac{GDP}{P} * V * \frac{V}{GDP} * \frac{C}{V} \end{aligned} \tag{4}$$

An overview of the factors is given in Table 2.

Table 2: Overview of factors used in decomposition.

Notation	**Description**	**Unit**
AC	Aggregated carbon emissions	kiloton CO_2
P	Population	thousand persons
GDP/P	Economic growth represented as GDP per capita	2010€
V	Traffic volume	tonne-kilometre
V/GDP	Traffic intensity of economic activity	tonne-kilometre/ 2010€
C/V	Emission factor represented as carbon intensity of traffic activity	g CO_2/ tonne-kilometre

3.2.2 Shapley decomposition

Albrecht, François and Schoors’ (2002) Shapley decomposition technique is a perfect decomposition technique based on the Shapley value. It allocates the total change in the aggregate index entirely to the factors and leaves no residual. The Shapley value has its origin in game theory. It serves as an expression of importance for each player in a coalition voting game, in the way that it allocates a part of the output to each player based on each player’s importance and contribution in generating said output (Shapley, 1953). Shorrocks (1999) establishes that the Shapley value can be used to derive a decomposition method that allocates a specific part of the output or input to a given set of actors or factors, because of the similarity of both problems in game theory and decomposition. As an additive decomposition technique, the total change in the aggregated index *I* amounts to the sum of each factor x_i’s contribution C_i, without any residual (Ang, Liu, Chew, 2003):

$$\Delta I = \sum_{1}^{n} C_i = C_1 + \cdots + C_n \tag{5}$$

In the same fashion, as the Shapley value is derived in a coalition voting game, each factors' contribution in a set *S* of *n* factors is derived by two steps. Firstly, each factor x_i is successively eliminated for all *n!* possible sequences that the factor could have contributed to the output (Albrecht, François and Schoors, 2002). This gives the factor's contribution to every single sequence. Secondly, the sum of the factor's contributions is averaged by the *n!* possible scenarios that the factor could contribute to the output, yielding the factor's total contribution C_i (Albrecht, François and Schoors, 2002). Hence, each factor's total contribution to the output is discovered by:

$$C_i = \sum_{s=1}^{n} \frac{(s-1)!\,(n-s)!}{n!} * \sum_{S:\, x_i \in S} [\mathrm{V}(S: x_i = x_i^t) - \mathrm{V}(\mathrm{S}: x_i = x_i^0)] \quad (6)$$

Where $s = |S|$, x_i^t is the value of factor x_i in year t, while x_i^0 represents the value of the same factor at the observed period's beginning (year 0). V(S) is a function that denotes the value of the aggregate when all factors included in *S* take on values in year t, while factors not included in *S* take on values in year 0 (c.f. Albrecht, François and Schoors, 2002; Ang, Liu, Chew, 2003).

Applying this technique to the previously constructed aggregated on-road carbon emissions *AC* with the set of factors *S* = {*P*; *GDP/P*; *V*; *V/GDP*; *C/V*}, the total change in *AC* in the observed period can be expressed by:

$$\Delta AC = C_P + C_{\frac{GDP}{P}} + C_V + C_{\frac{V}{GDP}} + C_{\frac{C}{V}} \quad (7)$$

Each factor's contribution to Δ*AC* is accordingly found by Eq. (6). A detailed explanation of how a factor's contribution is calculated is presented in Appendix A.

The Shapley decomposition possesses various properties that make it preferable to use in the study at hand. Firstly, it is superior to all non-perfect decomposition techniques because it decomposes the aggregate's change fully on the underlying factors. This makes the results more robust and better interpretable (Ang, Liu, Chew, 2003). Secondly, the Shapley decomposition treats all factors equally and does not suffer from "path dependency" like many other methods (Albrecht, François and Schoors, 2002). Thirdly, the change in an absolute aggregate is presented as the sum of the underlying factors, making the results easier to understand than those of methods decomposing a ratio aggregate (Ang, Liu, Chew, 2003). Lastly, Albrecht, François and Schoors (2002) mention that the Shapley decomposition can handle many factors and allows for very complex decompositions, while it does not assume constant growth rates, as the LMDI approach does. On the other hand, its complexity makes the Shapley decomposition harder to compute and more challenging to apply than many other techniques (Albrecht, François and Schoors, 2002).

4 Data

The study is performed on two separate levels. Consequently, the data will be introduced and discussed on the corresponding level. Firstly, country-level data for Germany is presented and its application is explained. Then, city-level data is set out in the same manner.

4.1 Country-level data

Data on the country-level for Germany was obtained from various sources. The GENESIS-Online database from the German National Statistical Bureau (DESTATIS) provided data on the GDP and the population size *P* (DESTATIS, 2019). Additionally, GENESIS-Online supplied the price index with the base year of 2010 to compute the real annual GDP in 2010 Euros for Germany. This transformation eliminates the effect of inflation and makes the GDP data comparable over long periods. Subsequently, GDP per capita *GDP/P* is derived by dividing the real GDP by the population data for each year. Nationwide on-road carbon emissions *C*, freight (in tonne-kilometres) and public and private (in passenger-kilometres) road traffic volume are obtained from the German Environment Agency (German Environment Agency, 2018b).

To get general traffic data that allows for conclusions on traffic as a whole, public, private and freight road traffic volume must be combined. This means that passenger-kilometres must be converted into tonne-kilometres. Such a conversion follows the logic that the essential factor that determines how much carbon emissions are generated by traffic is the mass moved by traffic activities. Consequently, one tonne-kilometre can be converted into the equivalent of roughly 13 passenger-kilometre, given the average weight of a German person of 77kg (DESTATIS, 2018). The sum of freight traffic volume in tonne-kilometre, public and private traffic volume in converted tonne-kilometre gives the total traffic volume *V*. This transformation yields a consistent estimate for the total traffic volume on German roads. However, the total traffic volume generated by this method is not straightforwardly interpretable in the same manner as its original components. Since this new data combines multiple traffic modes, such as freight transport, public transport and individual traffic, and every mode possesses different carbon efficiency, one cannot assume the carbon intensity of one underlying mode for this indicator. In that case, the emission factor *C/V* can be built by dividing total on-road carbon emissions by total traffic volume, yielding an indicator for the carbon intensity per unit of total traffic activity. The same emission factor values are employed for the analysis on country and city-level. This is because of insufficient data to construct the emission factor for the cities. However, it can be assumed that the emission factor is similar, while not exactly the same, for the country and city-level, since it represents the carbon intensity of traffic activities on roads by cars and other vehicles. There is no difference in cars and trucks and their carbon intensity between the country and its cities. The same companies sell the same models everywhere in Germany. On the other hand, a differently compounded vehicle stock can, for example, leads to a divergent emission factor. Therefore, the emission factor on the country-level is approximative for that of the cities. Lastly, the factor representing the traffic intensity of economic activity *V/GDP* is obtained by dividing the total traffic volume by the real GDP. All data for the country-level is provided by official government bodies with high-quality standards to both data gathering and processing.

4.2 City-level data

The data on the city-level in Germany is not as extensive and well documented as on country-level. Therefore, this study relies on scattered resources on the city-level and cannot draw on a centralised source as on the country-level. However, the Regional Database Germany form the Federal and State Statistical Bureaus Germany contains much of the data used in the city-level analyses. Firstly, it supplies annual vehicle stock numbers, by vehicle type, for all vehicles licensed in the studied cities (Federal and State Statistical Bureaus Germany, 2019a). Secondly, it provides the cities' annual population size *P* (Federal and State Statistical Bureaus Germany, 2019b). Lastly, yearly nominal GDP data for the cities is found in the Regional Database Germany (Federal and State Statistical Bureaus Germany, 2019c). The nominal GDP is transformed into real GDP in 2010 Euros by applying the same price index from GENESIS-Online as on the country-level. Dividing real GDP by the population size yields the economic growth factor *GDP/P* for the cities.

The remaining data is gathered from other official bodies. Annual average kilometres driven by vehicle type, just as the number of persons transported by on-road public transport per year and the annual total kilometres driven by busses are extracted from the report "Traffic in numbers 2017/2018" published by the German Federal Ministry of Transport and Digital Infrastructure (Federal Ministry of Transport and Digital Infrastructure, 2018). Eurostat's database supplies data on freight road traffic volume in tonne-kilometres in Frankfurt, Berlin and Stuttgart (Eurostat, 2019a). Due to Eurostat's data collection method, the whole freight road traffic volume generated by one vehicle in one trip is allocated to the starting location of that trip. Consequently, all tonne-kilometres generated by that activity are assigned to the starting location, even if the majority of tonne-kilometres arose outside of it. That being so, a significant part of the traffic volume attributed to the cities might not have occurred within the city area. Nevertheless, the freight traffic coming from outside the city is not observed either, significantly reducing the overestimation by allocating all traffic volume to the location in which the corresponding traffic activity started. While this method leads to an approximate representation of general traffic activity amount and might not show accurate absolute traffic volume within a cities' limits, it reliably indicates the relative importance and the relative level of traffic activity and traffic volume, which allows for a logical analysis of trends and changes.

Passenger-kilometre amount in cities is handled similarly. Firstly, the lack of sufficient data on city-level makes it necessary to construct the private and public traffic volume. Based on the information from the "Traffic in numbers 2017/18" report, the average number of persons transported by on-road public transport per kilometre and the average annual travel distance of a bus in Germany can be found. Multiplying this with the city's bus stock gives an estimation of public transport traffic volume in passenger-kilometre for each city. Additionally, the private traffic volume is approximated by multiplying the annual travel distance per vehicle type in Germany with the number of licenced vehicles to individuals in the city. These methods yield only rough estimates, and in the case of the private traffic volume it allocates all distance that the vehicle travels to the city, even if most of it occurs outside the city limits. However, the resulting overestimation of private traffic volume is considerably reduced, since traffic from vehicles that are not registered in the city but drive within its borders is disregarded. Even though the constructed data is inaccurate in absolute values, it still represents relative traffic activity and can serve as a logical proxy to analyse changes and trends. Transforming the private and public traffic volume into tonne-kilometres, in the same fashion as described for country-level data, and adding freight traffic volume, yields the total traffic volume *V* in tonne-kilometres. Frankfurt's total traffic volume consists only of the freight and private traffic volumes because data on public transport traffic volume was not available. Despite this, Frankfurt's results are comparable with that of Stuttgart and Berlin because the volume of on-road public transport is minor compared to the freight and private on-road traffic volumes. Even in Berlin, the share of on-road public traffic volume is only 2% of private on-road traffic volume in 2013. Dividing total traffic volume by real GDP gives the traffic intensity per unit of economic growth *V/GDP*.

Additionally, road traffic carbon emission data is not available on the micro level in Germany. Hence, road traffic carbon emissions must be estimated to conduct the decoupling analysis for Frankfurt, Stuttgart and Berlin. The study follows the "bottom up" approach by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories that recommend estimating greenhouse gas emissions by combining information on the extent of human activity with a factor that quantifies the emissions per unit of activity (IPCC, 2008). Here, the traffic volume *V* describes the activity and the emission factor *C/V* introduced in the previous chapter quantifies the carbon emissions per unit of traffic activity. Thus, annual estimated on-road carbon emissions *EC* are calculated with:

$$EC_t = V_t * \frac{C}{V_t} \tag{8}$$

All city-data is obtained on the respective level in the German region classification system, the so-called "Stadtkreis". This limits the study to the urban area of the city and excludes the more rural part of the metropolitan area. Frankfurt and Stuttgart are represented by their respective Stadtkreis, while Berlin is represented by the multiple Stadtkreise that comprise its urban area.

4.3 Differences in road carbon emissions

It is important to highlight that this study uses three indicators for the carbon dioxide emissions of road traffic. Firstly, the actual road traffic CO_2 emissions in Germany, as established by the German Environment Agency, are used for the decoupling analysis at the country-level. This indicator provides the most accurate view of emission development. Secondly, insufficient data made it necessary to estimate on-road carbon emissions for Stuttgart, Frankfurt and Berlin to conduct the same decoupling analysis on the city-level. The estimation is performed according to IPCC Guidelines, as elaborated in Section 4.2. Nevertheless, this approximation of the real emissions achieves not the same accurateness as the data used for the country-level. Lastly, index decomposition techniques assume that a causal relationship between the factors and the indicator that is composed exists and then expresses the indicator as a function of the factors. Consequently, this method does not decompose the real emissions but the constructed aggregated index. Therefore, significant differences in the development of the three indicators exist, as presented in Table 3.

Table 3: Different results for the total change in on-road carbon emissions by indicator. Author's own results.

Indicators for total change in on-road carbon emissions 1999-2013

	German Environmental Agency	Estimations according to IPCC Guidelines	Aggregated decomposition index
Germany [%]	- 13.69	-	12.62
Stuttgart [%]	-	- 31.47	- 28.99
Frankfurt a. M. [%]	-	- 30.16	- 26.26
Berlin [%]	-	- 54.95	- 55.86

The comparison of the indicators shows that the estimations for the city-level and the aggregated decomposition index yield similar results. On the other hand, the indicator that is based on the German Environmental Agency data and the aggregated decomposition index do not only vary in magnitude but show the exact opposite trends. The difference between the aggregated decomposition index and the indicator for the decoupling analysis shows that the real CO_2 emissions are compounded more complexly than what is assumed in the decomposition. This does not make the indicators unfit, but it emphasises that they must be interpreted in their specific context. The aggregated decomposition index for on-road emissions is used to unveil the impact and importance of the underlying factors relative to each other. This means that including other factors in the decomposition would also give different results. Thus, the aggregated decomposition index cannot be interpreted as representing real levels and development of emissions. The German Environmental Agency data or the estimations according to IPCC must be used in that case. Nevertheless, the aggregated decomposition index fulfils its function in assessing the importance and relative impact of the factors.

5 Empirical Analysis

5.1 Results of the decoupling analysis

5.1.1 Decoupling in Germany

Germany's constant economic growth in past years and its commitment to reducing all carbon emissions may lead to the assumption that the growth of GDP and on-road carbon emissions have decoupled or are decoupling. Looking at the change in both variables, this assumption seems to be valid. Figure 1 shows that Germany's real GDP has increased by 16% between 1999 and 2013, while on-road carbon emissions decreased by 13.7% in the same period.

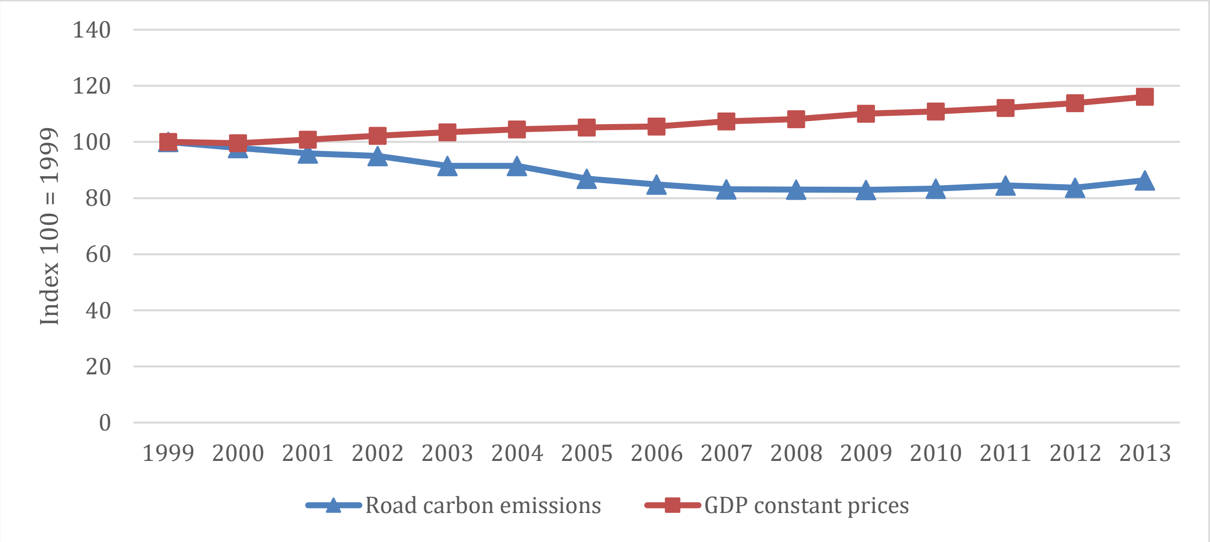

Figure 1: Growth differences between real GDP and on-road carbon emissions in Germany. 1999-2013.

Indeed, the decoupling analysis reveals decoupling between GDP and on-road carbon emission growth for the whole period. The results of the decoupling analysis are presented in Figure 2. Germany experienced a long period of strong decoupling from 2001 until 2009 and again in 2012, where GDP increased, while on-road carbon emissions shrunk. The analysis shows weak decoupling, with GDP and emissions growing but emissions grow at a slower rate, for the year

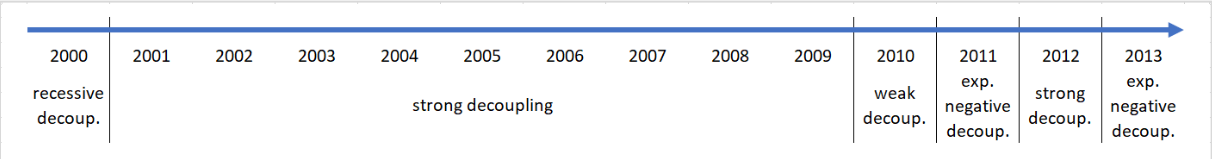

Figure 2: Decoupling results Germany 2000-2013.

2010. On the other hand, in 2011 and 2013 the on-road CO_2 emissions grew even faster than GDP, leading to expansive negative decoupling in Germany. Lastly, declining GDP and comparatively slower decreasing emissions led to recessive decoupling in 2000.

5.1.2 Decoupling in the cities

Similarly to real GDP and on-road carbon emission growth for Germany, Figure 3 indicates positive decoupling for Stuttgart between 2002 and 2013. By 2013 real GDP grew by 14.5% and on-road CO2 emissions declined by 31.5% compared to 1999. In 1999 until 2001 a period

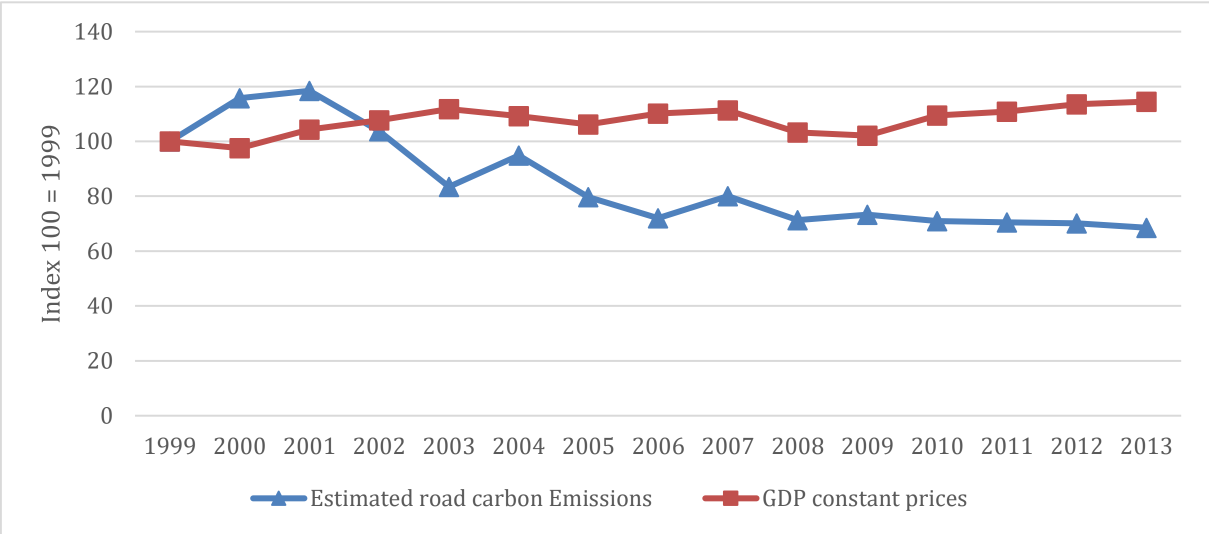

Figure 3: Growth differences between real GDP and on-road carbon emissions in Stuttgart. 1999-2013.

of negative decoupling, where emission growth outweighed GDP growth, occurred. The decoupling analysis presents strong negative decoupling in 2000, 2004 and 2009 (Figure 4). Moreover, expansive negative decoupling showed in 2007, where Stuttgart registered a significant increase in on-road emissions from the previous year. In 2001 Stuttgart experienced weak decoupling, followed by strong decoupling in 2002 and 2003 and recessive decoupling in 2005 and 2008. From 2010 until the end of the observed period GDP growth rates accelerated, while on-road carbon emissions slowly declined, leading to strong decoupling.

Frankfurt a. M. saw growth in on-road carbon emissions outperforming GDP growth from 1999 until 2004 and from 2006 until 2008 (Figure 5). Only after 2011 was Frankfurt experiencing GDP growth and rapidly declining road traffic emissions. Consequently, the decoupling analysis yielded no consistent trend for Frankfurt in the examined period. Decoupling results are found in Figure 6. Growing emissions and declining GDP led to strong negative decoupling

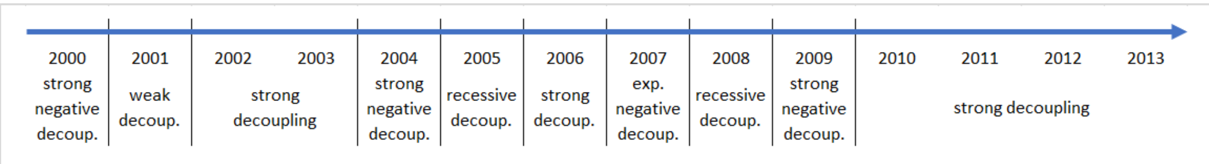

Figure 4: Decoupling results Stuttgart. 2000-2013.

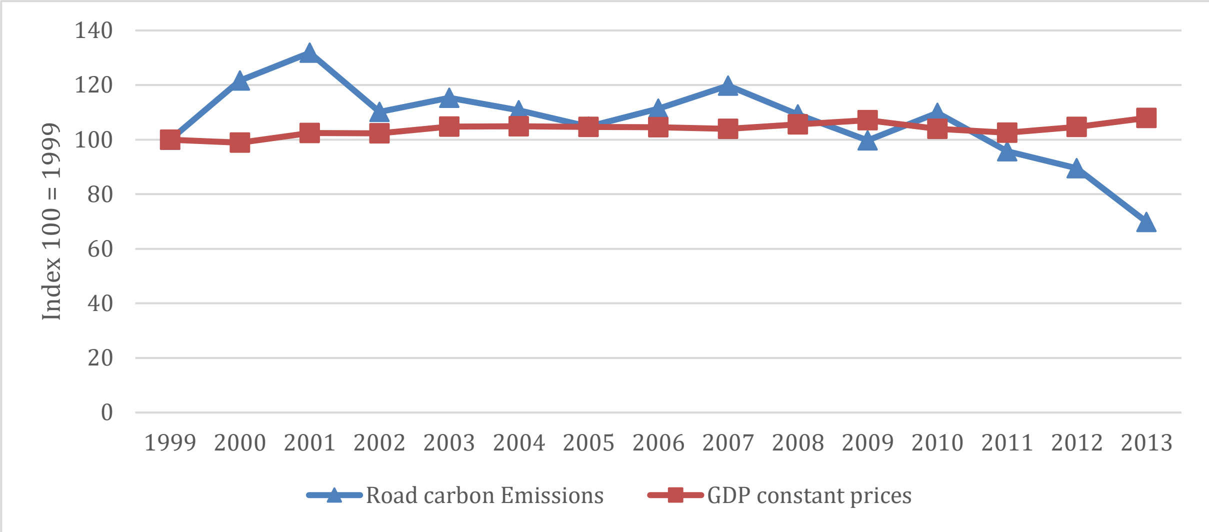

Figure 5: Growth differences between real GDP and on-road carbon emissions in Frankfurt a. M. 1999-2013.

in 2000, 2006, 2007 and 2010, while a sharp increase in on-road traffic emissions together with a gradual increase in GDP lead to expansive negative decoupling in 2001 and 2003. In 2002, 2005 and 2011 swiftly decreasing emissions combined with slightly decreasing GDP brought the opposite trend to Frankfurt. Only five years of strong decoupling, 2004, 2008, 2009, 2012

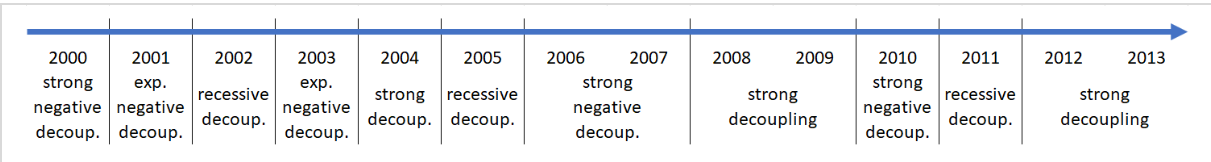

Figure 6: Decoupling results Frankfurt a. M. 2000-2013.

and 2013 were identified. Frankfurt reduced its emissions by 30.16% compared to the 1999 level.

Lastly, Berlin's steep reduction in on-road carbon emission of 55% between 1999 and 2013 and its GDP growth of 12.9% suggest apparent decoupling between GDP and emission change

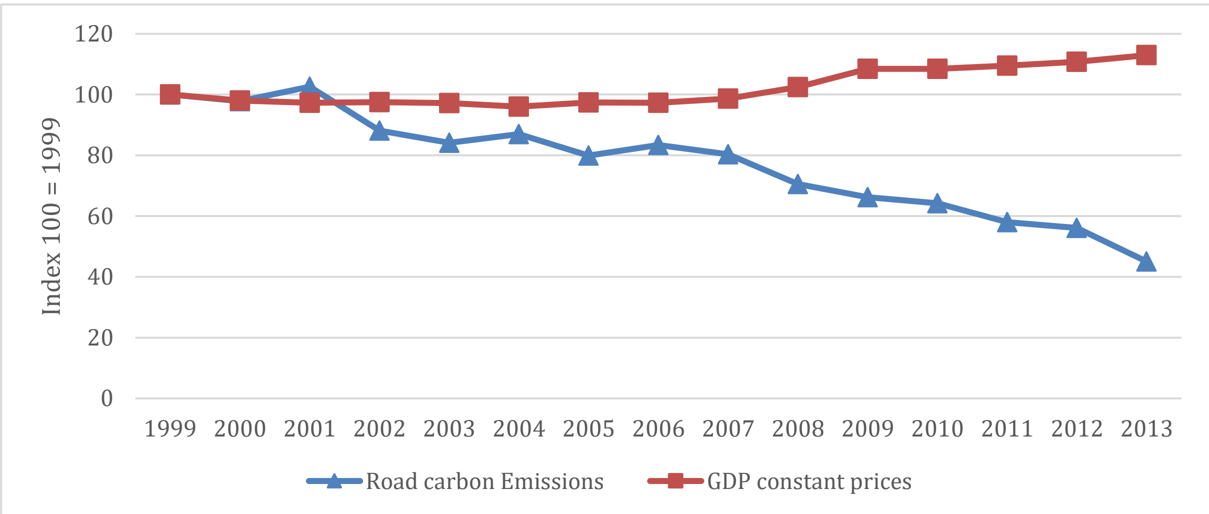

Figure 7: Growth differences between real GDP and on-road carbon emissions in Berlin. 1999-2013.

(Figure 7). However, in 2000 Berlin suffered from falling GDP and similarly declining on-road emissions, which makes it the only year to indicate recessive coupling in the entire study. Figure 8 shows the decoupling results for Berlin. Additionally, Berlin

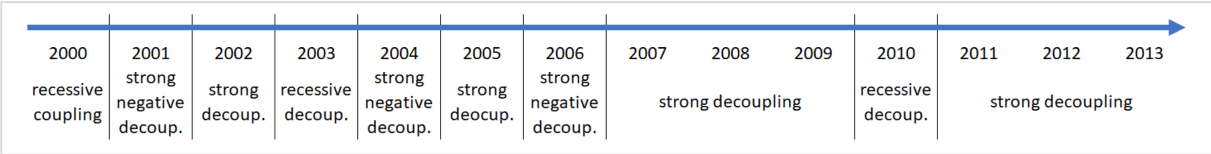

Figure 8: Decoupling results Berlin. 2000-2013.

experienced the most years of strong decoupling (2002, 2005, 2007, 2008, 2009, 2011, 2012, 2013) and two years of recessive decoupling (2003, 2010) resulting from slightly negative GDP change rates. Only 2001, 2004 and 2006 saw increasing emissions, while GDP slightly declined, resulting in strong negative decoupling.

Finally, Germany and all three cities, except Berlin in 2000, experience decoupling of GDP and on-road carbon emission growth between 1999 and 2013. Yet, the only desirable form of decoupling, where GDP increases while emissions decline, was rare in cities before 2010. Even so, it was prevalent for eight years, from 2001 until 2009, for Germany. Opposing to the development in the cities, Germany as a country diverged from strong decoupling in 2010.

5.2 Results of the decomposition analysis

The decomposition of the aggregated on-road carbon emissions *AC* in the contribution of the factors population *P*, economic growth represented by *GDP/P*, traffic volume *V*, traffic intensity of economic activity *V/GDP* and emission factor *C/V* unveiled significant differences in the impact of specific factors between the country and the city-level. The contribution C_i of each factor to the change of *AC* between 1999 and 2013 is displayed in Table 4. The analysis for the whole period shows that population development had a minor impact on the change in road traffic emissions. C_P led to an emission decrease of 1.86% for Germany and an increase of 3.17%, 7.51% and 0.73% for Stuttgart, Frankfurt and Berlin, respectively. This correlates directly with the change in population size. The expanding economic activity was responsible for 18.06% of the rising road carbon emissions in Germany. The effect was significantly lower for the cities with $C_{GDP/P}$ of 8.49% for Stuttgart and 7.87% for Berlin. Given the slight reduction in GDP in Frankfurt, a minor decrease of 0.81% in on-road emissions was attributable to the reduction in *GDP/P*. Similarly, a significant increase in traffic volume *V* caused road traffic emissions to expand by 28.85% for Germany. The smaller rise of traffic volume in Stuttgart and Frankfurt led to 3.06% and 4.77% increase in road traffic CO_2. A reduction of 14% of on-road emissions in Berlin is attributable to the similarly decreasing traffic volume. Growing traffic activity per unit of economic growth *V/GDP* was responsible for an on-road carbon emission increase of 12.69% in Germany. Surprisingly, *V/GDP* shrunk for all three cities, which translated to 8.56%, 1.92% and 22.24% fewer emissions in Stuttgart, Frankfurt and Berlin, respectively.

Table 4: Decomposition results for the period from 1999 until 2013. Contribution of each factor to the total change in aggregated on-road CO_2 emissions.

Decomposition results total period 1999 - 2013		Germany	Stuttgart	Frankfurt a. M.	Berlin
Population	C_P [%]	- 1.86	3.17	7.51	0.73
Economic growth	$C_{\frac{GDP}{P}}$[%]	18.06	8.49	- 0.81	7.87
Traffic volume	C_V [%]	28.85	3.06	4.77	- 14.00
Traffic intensity of economic activity	$C_{\frac{V}{GDP}}$ [%]	12.69	- 8.56	- 1.92	- 22.24
Emission factor	$C_{\frac{C}{V}}$[%]	- 45.12	- 35.15	- 35.80	- 28.21
	$\Delta AC = \Sigma$ C_i [%]	12.62	- 28.99	- 26.26	- 55.86

Finally, the emission factor *C/V* had the most significant impact in the period from 1999 until 2013. The reduction in emissions per unit of traffic activity yielded a reduction of 45.12% on-road CO_2 emissions in Germany. Likewise, emissions in Stuttgart decreased by 35.15%, emissions in Frankfurt decreased by 35.8% and emissions in Berlin decreased by 28.21% as a result of the change in the emission factor. Consequently, the change in aggregated on-road carbon emissions in Germany amounts to 12.62%, while Stuttgart, Frankfurt and Berlin registered a total decrease in aggregated on-road carbon emissions of 28.99%, 26.26% and 55.86%, respectively.

Interestingly, the impact of the factors varies significantly between the whole period and periods of strong decoupling for the cities. Considering that Germany experienced strong decoupling for nine out of 14 years, it is not surprising that the impact of the factors is similar for the whole period and the period of strong decoupling. Table 5 presents the contribution of the factors to the aggregate on-road carbon emissions for longer periods of strong decoupling. Berlin's period of strong decoupling started in 2007 and was interrupted by recessive decoupling in 2010, which is likely a consequence of the financial crisis. The year of recessive decoupling is included in the analysed period to deliver a cohesive examination of Berlin's steepest decline in on-road CO_2 emissions. In the same manner, 2010 and 2011 were included in the period for Frankfurt.

Table 5: Decomposition results for periods of strong decoupling. Contribution of each factor to the total change in aggregated on-road CO2 emissions.

Decomposition results for periods of strong decoupling					
		Germany	Stuttgart	Frankfurt a. M.	Berlin
Period of strong decoupling		2001 – 2009	2010 – 2013	2008 – 2013	2007 - 2013
Population	C_P [%]	- 0.78	- 0.37	5.09	0.14
Economic growth	$C_{\frac{GDP}{P}}$ [%]	9.66	4.75	- 2.99	11.59
Traffic volume	C_V [%]	14.26	- 2.10	- 6.02	- 14.24
Traffic intensity of economic activity	$C_{\frac{V}{GDP}}$ [%]	5.38	- 6.48	- 8.11	- 25.79
Emission factor	$C_{\frac{C}{V}}$ [%]	- 28.90	- 1.21	2.22	1.30
	$\Delta AC = \Sigma\ C_i$ [%]	- 0.37	- 5.40	- 9.81	- 27.01

The influence of population *P* and economic growth *GDP/P* on the change in emissions follows the development of both variables. That being so, a slightly shrinking population had a slightly decreasing effect of -0.78% for Germany and -0.37% for Stuttgart in their respective periods of strong decoupling. On the opposite, increasing population sizes led to a contribution to the change in on-road emissions of 5.09% in Frankfurt and a mere 0.14% in Berlin. The expanding economic growth in the periods of strong decoupling was responsible for a 9.66% increase in on-road CO_2 emissions for Germany, a 4.75% increase for Stuttgart and 11.59% increase for Berlin. Frankfurt, however, was struck badly by the financial crisis and drifted into recession after 2009. Together with a growing population, GDP per capita was responsible for a 2.99% decline and suppressed further rise in emission. The traffic volume's *V* influence on the change in emissions varies between the country and city-level. It led to a rise of 14.26% for Germany, while Stuttgart experienced a slight reduction of 2.10%. The dampening effect was even stronger for Frankfurt and Berlin, where the traffic volume factor was responsible for 6.02% and 14.24% fewer carbon emissions. Unsurprisingly, the traffic intensity of economic activities *V/GDP* affected on-road CO_2 in the same way. For Germany both traffic volume and economic growth increased in the period of strong decoupling, resulting in 5.38% growth in emissions by *V/GDP*. In the cities' period of strong decoupling, the opposite result was obtained. The decrease in traffic activity per unit of economic growth shrunk on-road carbon emissions of Stuttgart, Frankfurt and Berlin by 6.48%, 8.11% and 25.79%, respectively. Making the traffic intensity of economic activities the major influencing factor for cities in the periods of strong decoupling. Also, the importance of the emission factor *C/V* changed for the cities. It comprised only a slight decrease of 1.21% for Stuttgart. In Berlin and Frankfurt, the emission factor even contributed to 1.3% and 2.22% more on-road CO_2. However, the emission factor stayed the most crucial factor for Germany, decreasing CO_2 emissions from road traffic by 28.9%. Finally, the aggregated change in on-road carbon emission for the periods of strong decoupling amounts to -0.37% for Germany, -5.4% for Stuttgart, -9.81% for Frankfurt and -27.01% for Berlin.

Thus, the decomposition analysis reveals apparent differences in the importance of the factors between the regional levels, the total period and periods of strong decoupling. Capturing the total period shows that the emission factor *C/V* has the most significant impact on the change of on-road carbon emissions for Germany and the cities. The second most significant impact results from the traffic volume *V* for Germany and varies between the cities. Traffic activity per unit of economic growth *V/GDP* was the second most influential factor in Stuttgart and Berlin, while population size *P* led to the second largest effect in Frankfurt. Additionally, the effect of the traffic volume factor *V* increased emission between 1999 and 2013 in Germany, Stuttgart and Frankfurt. Despite this, traffic volume led to a substantial decrease in emissions for Berlin.

Furthermore, the analysis of periods of strong decoupling led to the same hierarchy of factors in Germany but changed the importance of the factors when viewing the cities. Berlin’s change in road carbon emissions was influenced the most by the traffic intensity of economic activities *V/GDP*, while the emission factor C/V, the most significant factor in the total period, merely induced a 1.30% change. The emission factor also lost its importance for Stuttgart and Frankfurt in their periods of strong decoupling. Frankfurt’s change in emissions in that period was influenced the strongest by the traffic intensity of economic activities *V/GDP*, followed by total traffic volume, which here decreased emissions but increased them in the total period. Stuttgart also saw the same factor being the most impactful, while the economic growth factor *GDP/P* had the second largest impact.

6 Discussion

6.1 Discussion of the development on the country-level

The empirical results presented in section 5.1.1 show that Germany's carbon emissions of road traffic decreased and GDP increased during the total period. The decoupling analysis was conducted to answer the study's first objective. The relationship of economic growth and road carbon emissions was characterised by ten years of positive decoupling, where GDP grew while CO_2 emissions stabilised or declined, two years of negative decoupling, where the growth in emissions outweighed the rise in GDP and one year of recessive decoupling, where both values declined in a similar manner. Interestingly, real GDP for Germany grew or stabilised throughout the entire period, while road traffic carbon emissions declined between 1999 and 2007, stabilised during 2008 until 2010 and then increased again in the remaining years of the study. Subsequently, the decomposition analysis was performed to explain this development. As a result, it uncovered that changes in population size *P* and the emission factor *C/V* hindered emission expansion. That being so, economic growth *GDP/P* depicted by income per capita, traffic volume *V* and the economic efficiency of traffic activity *V/GDP* led to rising emissions from road traffic in Germany. Their influence relative to each other stayed almost the same for the period of strong decoupling between 2001 and 2009 and for the entire period. With -45.12% change in emissions in the total period, the emission factor *C/V* had the most significant impact of the five factors. The second most substantial impact had the traffic volume *V* with 28.85% in the total period. The findings of the decomposition analysis, laid out in greater detail in section 5.2, partly conclude the second objective of this study. Examining the development of

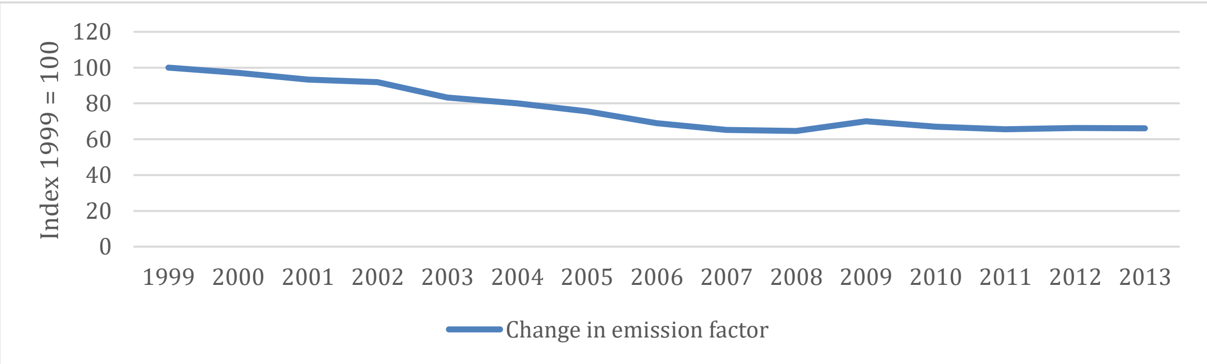

Figure 9: Development of the emission factor C/V 1999-2013.

these, it is noticeable that both the emission factor *C/V* and the traffic volume *V* reversed or stopped their positive trend after 2010. It is visible in figure 9 that the emission factor decreased until 2008, where it rose and stabilised afterwards.

This then leads to the question of why the emission factor *C/V* diverged from its previous trend. The emission factor is an abstract, high-level indicator of various properties that affect how much carbon emissions are generated by vehicles travelling on roads. For example, it encompasses technological advances, like improved fuel efficiency, but it also represents the fuel or energy mix, the share of new and old, petrol and electric/hydrogen vehicles, the share of trucks in relation to smaller vehicles, the size and the weight of vehicles. Hence, the source of change in the emission factor is difficult to detect and it could cover an entire study on its own to be adequately examined. Nevertheless, a few possible reasons shall be mentioned. Firstly, the average engine power of passenger cars increased considerably between 1999 and 2013 in the European Union (EEA, 2018). Since more engine power requires more fuel, this development dampened CO_2 reduction. Secondly, the EEA Report on CO_2 emissions from new passenger cars and vans (2018) shows that the mass of passenger cars increased slightly but steadily. Only after the studied period did the manufactures use more advanced, light-weight materials to reduce the weight of their cars. Finally, consumers demand larger and heavier cars. As reported by the EEA (2018), the market share of SUVs, vehicles with significantly worse fuel efficiency due to their weight, drag coefficient and usually powerful engines, increased from 8% in 2009 to 18% in 2013.

Moreover, the development to less environment-friendly cars is aided by political action, or the lack thereof. Car manufacturers and their supplier industry contribute 4.5% of Germany's total gross value added and employ more than 800,000 people, with 1.8 million jobs indirectly depending on this industry (DESTATIS, 2017; Seiwert & Reccius, 2017). As such the automotive industry assumes a pivotal role for economic growth in the country. Hence, their wellbeing is of high interest to German politicians, who regularly push for industry-friendly regulation like lax EU emission laws (Carrington, 2013) and even intent to increase thresholds of allowed air pollution to prevent traffic bans (Tagesschau.de, 2019). In combination with the industry's vital lobby work, many attempts to increase transformation pressure on the industry were blocked and the industry's economic wellbeing was preferred over environmental

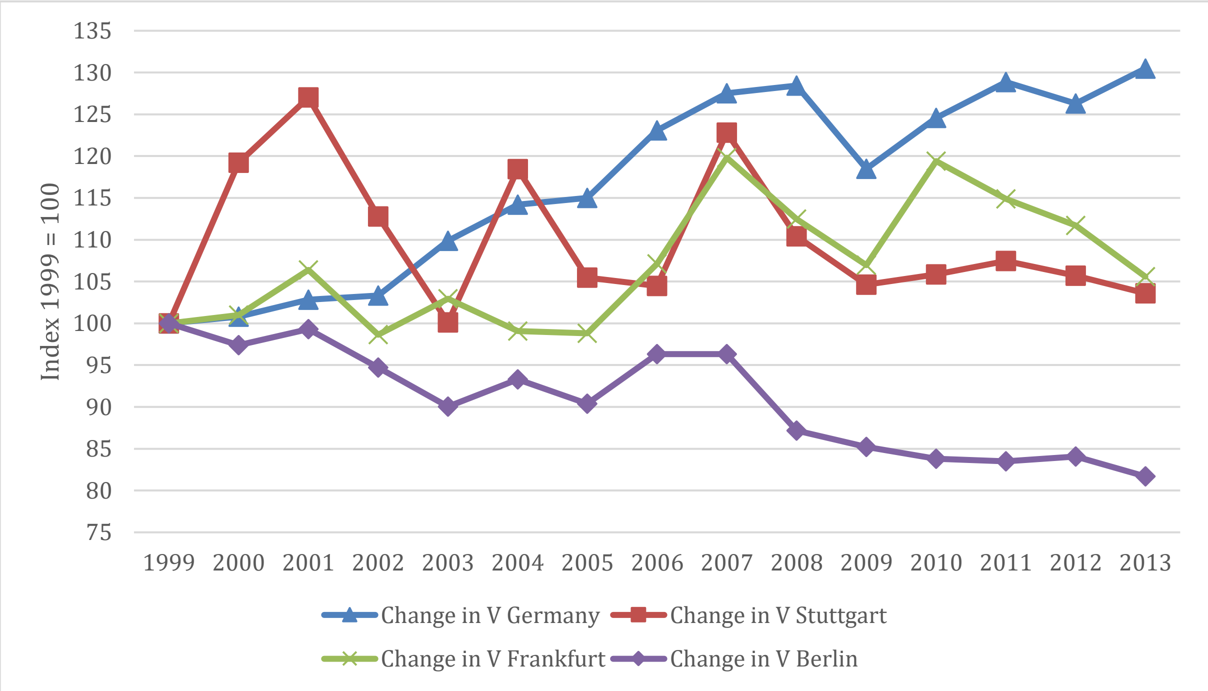

Figure 10: Development of traffic volume V in Germany, Berlin, Frankfurt and Stuttgart. 1999-2013.

protection. Considering that most road carbon dioxide emissions in the European Union are generated by passenger cars (EEA, 2018), these developments should carry some explanatory value in explaining the stabilisation of the emission factor. Additionally, traffic volume followed the development of economic growth and grew steadily but broke that trend after 2008, just to quickly increase again from 2010. The evolution of traffic volume in Germany and the three cities is shown in figure 10. It is fair to assume that the short and intense decline in traffic volume between 2008 and 2009 is a consequence of the financial crisis and the reduction in economic activity that followed it. Therefore, this event can be regarded as an exception in the general development and not as a trend change. This negative development in the most impactful variables gives some explanation for the rise in road carbon emissions in Germany after 2009 (Figure 1).

In summary, Germany has achieved significant success in decoupling its economic growth from road carbon emissions. However, improvements in reducing the environmental pressure from traffic activities are offset by a mix of separate developments. For example, the trend to an increased share of less carbon efficient cars. In addition, a consistent increase in transportation and travel demand led to stabilising and increasing emissions in recent years.

6.2 Discussion of the development on the regional level

This chapter elaborates on the second and third objectives of this study by first addressing the impact of regional characteristics on road traffic carbon emissions between the country and sub-regions, and in a next step between the cities. Then the impact and development of the factors is discussed for the three cities, while regional and temporal particularities are taken into account. The city-level results for objective one are laid out in Section 5.1.2.

6.2.1 Disparities between country, rural and urban regions

The most significant finding of this study is that there are major differences between the country and the regional level, even though they experience the same transformation pressure. They follow distinguished decoupling trends and have individual driving factors. Taking research on regional development into account, these findings are logical consequences of regional particularities. Porter’s (1998) theory on clusters, which are geographic accumulations of interlinked companies and institutions, describes how regions and cities accommodate and birth certain clusters as a consequence of their inherent capabilities. Furthermore, he states that the urban environment provides various productivity enhancing benefits to companies, which in turn incentivises more firms to locate in the cluster. Rosenthal and Strange (2004) review the empirical literature on agglomeration economies and show that multiple benefits arise from clustering and regional proximity. Additionally, they confirm that there is significant clustering of related industries and their consumers in agglomeration economies. The reduction in distance directly affects traffic as it reduces transport length and costs. Similarly, the high density of companies of a particular industry type makes logistics more profitable, since their products and production materials can be transported in larger volumes. Trucks are not optimal for the transportation of large volumes, which makes e.g. transport by train more desirable. Consequently, economies of scale in the transport of goods in, to and from agglomeration economies make transportation more profitable and lead to a switch from the road to other transport modes. This development contributes to the reduction in traffic volume *V* and traffic intensity of economic activity *V/GDP* in the cities.

Subsequently, transport infrastructure is further developed and more accessible in these agglomerated regions, as more agents rely on it and more transport activity occurs. This comprises infrastructure such as railway networks, goods stations, harbours, airports, public transport and streets. Whereas rural regions in Germany can in most cases only rely on streets and sparsely developed railways. The absence of a high-density infrastructure in rural regions forces companies and individuals to use cars or trucks. In the cities, however, the agents can choose which transport mode suits their needs and fits their preferences the best, leading to less road traffic *V*. Additionally, this disparity is amplified by policy. Policymakers privatised Germany's previously state-owned railway company in 1994. In their strive for profit the company closed unprofitable routes and 5,400 km of railway tracks in the succeeding years (Balser, 2018). Thus, boosting transport by car and truck in rural regions. On the other hand, transport operators in cities invested regularly and extensive in infrastructure. In 2007 Stuttgart invested 47.80 M€ in their public transport infrastructure (SSB, 2007). Frankfurt invested a similar amount of 47.66 M€ and Berlin spent 259.40 M€ in the same year (VGF, 2007; BVG, 2007). By 2012 investments sums increased to 51 M€ in Stuttgart, 134.58 M€ in Frankfurt and 511.80 M€ in Berlin (SSB, 2014; VGF, 2012; BVG, 2012). This enhances not only capacities but also the attractiveness of other transport modes, resulting in declining road traffic volume *V* in urban areas. Table 6 provides information on the share of journeys to an individuals' workplace made by car for Germany and the three cities. It confirms the suspicion that urban residentials substitute the car with other traffic modes more frequently.

Table 6: Share of journeys to work made by car. Source: Eurostat, 2019b.

	Share of journeys to work made by car [%]			
Year	Germany	Stuttgart	Frankfurt	Berlin
2001	67.00	51.20	45.30	46.70
2007	65.00	46.30	39.70	37.60
2012	67.00	47.40	39.70	38.20

Another reason for the difference between rural and urban regions might be the particularity that the urban population tends to possess a more pro-environment mindset. Berenguer, Corraliza and Martin (2005) investigate differences in environmental attitudes and behaviour between urban and rural regions. They find that the population in an urban area is more likely to be aware of their environmental impact and to assume a pro-environment attitude than people in rural regions. Similarly, Yu (2014) studies the environmental attitudes of a sample of rural and urban population in China. His study concludes that the urban population in China has a more environment friendly attitude and values environment protection higher than the rural population. The study also finds that a higher level of education and easy access to information regarding the environment in urban areas are the major responsible factors for this difference.

Taking into account that the urban population has access to developed infrastructure and public transportation, their pro-environment attitude might lead them to avoid carbon intensive on-road travel, which then results in less traffic volume *V.* In Germany the more pro-environment attitude in cities is visible in the voting behaviour. Whereas the green party secured 8.9% of total votes in the last national election in 2017, they got 29.7% of the votes in Stuttgart, 12.6% in Berlin and 15.5% in Frankfurt (Federal Returning Officer, 2017).

Nevertheless, the development of the country-level is, in essence, an aggregate of the developments on the regional level. Since the cities analysed in this study perform significantly better in decreasing on-road carbon emissions *C*, traffic volume *V* and traffic intensity of economic activity *V/GDP* than the country as a whole, one can conclude that the rural regions cannot compensate for the lack of agglomeration, infrastructure and pro-environmental behaviour. Hence, road traffic and related carbon dioxide emissions exceed that of urban regions, leading to the comparatively worse performance of Germany.

6.2.2 Disparities between the cities

On the city-level, all three cities converge to or follow a decoupling trend, but each city develops unique and different. As detailed in Section 5.1.2 Berlin experienced minor GDP growth before 2006 but reduced its road traffic-related emissions enormously since 2001. Stuttgart also followed an overall decoupling trend since 2001, however, it achieved this development by a substantial drop in emissions between 2001 and 2006. After that, emissions stayed at the same level, but GDP kept rising, with the exception of the financial crisis affecting economic growth in 2008 and 2009. Finally, Frankfurt managed to keep a stable GDP growth rate throughout the study. Nevertheless, it only experienced five years of positive decoupling and its emissions from road traffic grew faster than GDP between 1999 and 2008. This regional diverse development is in line with the findings of Zhang et al. (2018), who studied the decoupling of cities in China.

Similarly unique results are obtained by the decomposition analysis. The emission factor C/V is the most influential factor in the total period for all cities, but the magnitude is different for Berlin. Stuttgart sees its second most significant impact by the traffic intensity of economic activity *V/GDP* and the impact of economic growth *GDP/P* is almost as tremendous. Population increase *P* trumps the impact of traffic volume *V*, yet both are little. In spite of this, Frankfurt's second most influential factor is population growth, followed by traffic volume. Here economic growth and traffic intensity of economic activity have a minor impact. Lastly, Berlin's second largest decrease in emissions comes from a reduction in traffic intensity of economic activity and is almost as large as the impact of the emission factor. The decline in emissions is slowed by economic growth, but its impact amounts only to half of the effect of decreasing traffic volume. Section 5.2 presents the contribution of the factors in periods of strong decoupling and unveils the same uniqueness amongst the cities. Here, it is noticeable that the contribution of the emission factor, which was the most significant in the total period is now little. It even led to a slight increase in emissions in Berlin and Frankfurt. Additionally, while the order of most impactful factors may change with the periods, the most substantial emission increasing factors stay the same. For Stuttgart and Berlin this is economic growth, and for Frankfurt it is population growth.

To summarize, the study finds that the cities undergo unique developments and unveils regional disparities even between urban regions. Firstly, their emissions and economic growth unfolded differently. Secondly, the studied underlying factors varied in magnitude depending on the region. Thirdly, decomposition on distinguished periods shows that the factors' impact also changes over time. By investigating how the most impactful factors in each city, developed and what caused their development, one can reveal which underlying mechanisms and events led to the unique development.

Firstly, the emission factor *C/V*, which overall is the most influential variable, has the same values for Germany and the three cities in this study. However, its impact varies between the regions and between different periods. In Section 6.1. it is discussed how changes in the emission factor itself can occur. Even though the discussion explains how the emission factor can be manipulated over time, it does not explain the variation in its impact depending on the region. A possible explanation for Frankfurt and Stuttgart experiencing a larger impact from the emission factor than Berlin. would be that the vehicle stock present in Frankfurt and Stuttgart increased its share of less carbon intensive vehicles more than that in Berlin in the observed time period.

Secondly, the traffic intensity of economic activity *V/GDP* had the second most noticeable contribution in reducing road traffic emissions in Stuttgart and Berlin. Similarly, to the emission factor, its impact depends on the region. The traffic intensity of economic activity in the studied period is displayed in figure 11. This factor serves as a measurement of how much traffic is created in order to generate economic growth. Hence, a decrease in this factor represents that the economy in the studied region achieves its output with less traffic. Reasons for such a decline are diverse. On the one hand, a change in road traffic's share to a larger percentage of, for example, trains, cycling and walking may cause a decline in this factor. As Table 7 shows,

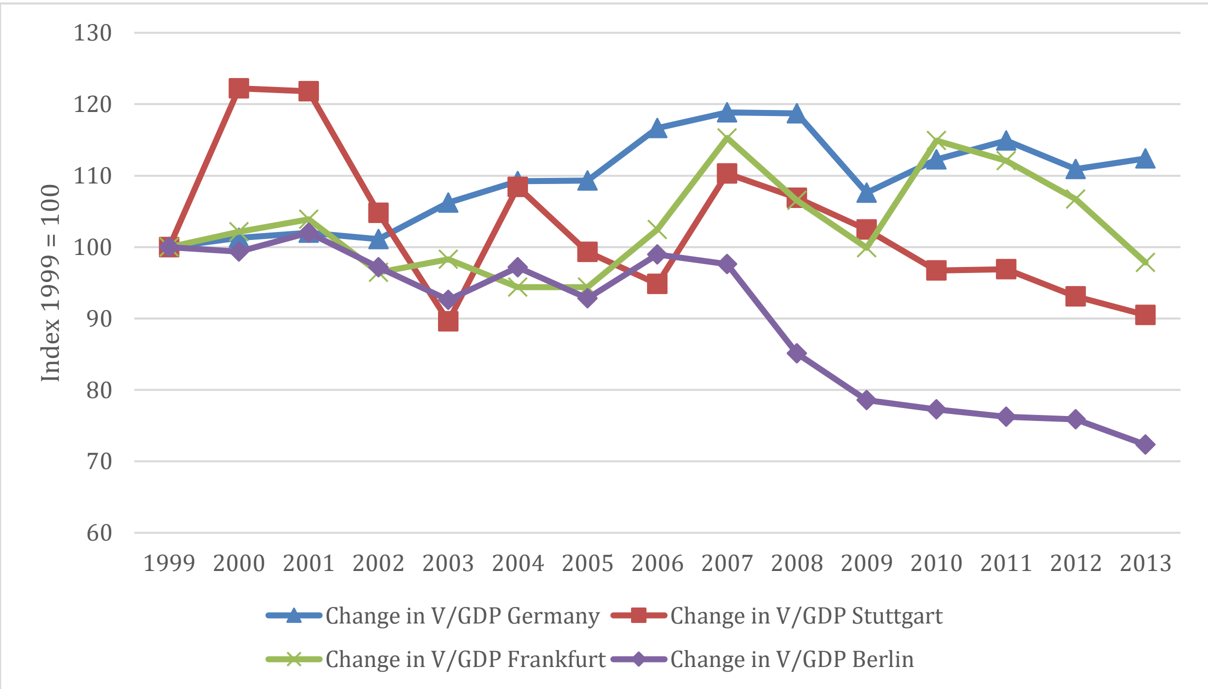

Figure 11:Development of traffic intensity of economic activity V/GDP in Germany, Berlin, Frankfurt and Stuttgart. 1999-2013.

Berlin's population uses cars for their mobility less than Frankfurt's, Stuttgart's and the country's population and uses more public transport.

Table 7: Share of journeys to work made by mode. Source: Eurostat, 2019b.

Share of journeys to work made by traffic mode [%]			
	2001	2007	2012
Share of journeys by car [%]			
Germany	67.00	65.00	67.00
Stuttgart	51.20	46.30	47.40
Frankfurt	45.30	39.70	39.70
Berlin	46.70	37.60	38.20
Share of journeys by public transport (rail, metro, bus, tram) [%]			
Germany	13.00	14.10	14.20
Stuttgart	32.50	36.80	36.70
Frankfurt	36.20	38.20	38.90
Berlin	38.30	41.00	44.00
Share of journeys by bicycle [%]			
Germany	7.90	8.90	8.80
Stuttgart	4.00	4.70	4.70
Frankfurt	6.10	9.60	10.00
Berlin	6.70	9.90	10.80
Share of journeys by foot [%]			
Germany	10.80	9.90	9.00
Stuttgart	11.20	11.10	10.50
Frankfurt	11.20	10.90	10.70
Berlin	7.20	7.20	6.50

Table 8: Annual expenses on public transport in Berlin, Stuttgart and Frankfurt a. M. in 2007 and 2012. Based on own calculations. Data from SSB, 2007, 2014; BVG, 2007, 2012; VGF, 2007, 2012; DESTATIS, 2019.

Annual expenses on public transport		
	2007	2012
Expenses on public transport [M€]		
Stuttgart	248.85	338.00
Frankfurt	253.30	281.10
Berlin	831.26	875.91
Expenses on public transport as share of real GDP [%]		
Stuttgart	0.58	0.74
Frankfurt	0.44	0.47
Berlin	0.88	0.80

This gives an explanation for the substantial difference in traffic volume's *V* development (Figure 10) and contribution to emissions between the cities. Furthermore, the investments in public transport infrastructure that were discussed in the previous section and the annual expenses for public transport (Table 8) indicate that Berlin sustains a more extensive and capable public transport system compared to Stuttgart and Frankfurt. Thus, incentivising its population to switch away from car travel and contributing to declining on road traffic volume. A total reduction in traffic volume without a decrease in GDP consequently reduces *V/GDP*, explaining the regional disparities in this factor and its magnitude to some extent.

Besides people switching to other traffic modes, the transition to a service economy can reduce emissions while maintaining economic growth (Dinda, 2004). Services involve less or no travel when compared to industrial activities. Additionally, new products, made possible by the ICT revolution and the Internet, do not require any traffic or transport at all. The shift to the service economy also reduces individual traffic, because remote working eliminates the need to be in a particular place. Since Berlin is Germany's ICT hub, one can assume that the steep reduction in traffic volume in Berlin is to some degree a consequence of the increasing share of the service sector.

Furthermore, the regional industrial sector can contribute to a reduction in the traffic intensity of economic activities by increasing the efficiency of its supply chain and logistical activities. Gunasekaran, Patel and Tirtiroglu (2001) identified that the effectiveness of transport-related actions in supply chain management is represented by the total distribution cost. The total distribution cost represents all costs involved with fulfilling distribution activities. These include amongst others transport activities, activities in distribution centres, planning and optimising activities. Accordingly, the industrial sector can reduce their traffic intensity, for instance, by minimising empty running, haul length, travel distance and delivery lead time. If these variables follow different trends in the cities then the traffic intensity of economic activity develops differently. Thirdly, Frankfurt experienced the second largest impact on emissions from population growth *P*. Figure 12 shows that its population increased by 9%, the equivalent of 57,529 people, between 1999 and 2013. As more population equals more traffic demand and

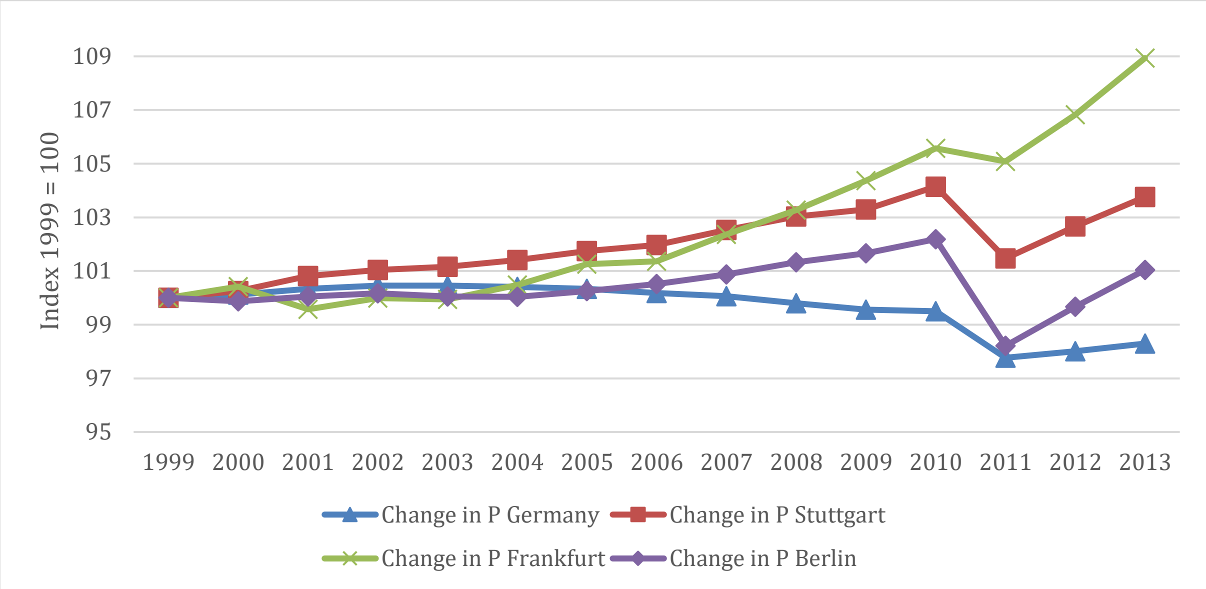

Figure 12: Population development P in Germany, Berlin, Frankfurt and Stuttgart. 1999-2013

more demand for goods, which in turn increases economic growth and this subsequently increases transport demand, road carbon emissions substantially grew as a consequence of population growth. This did not occur to the same magnitude in Berlin and Stuttgart, since their population did not grow as fast, explaining the smaller impact of population in the decomposition. For Germany, the population decrease even reduced carbon dioxide emission output.

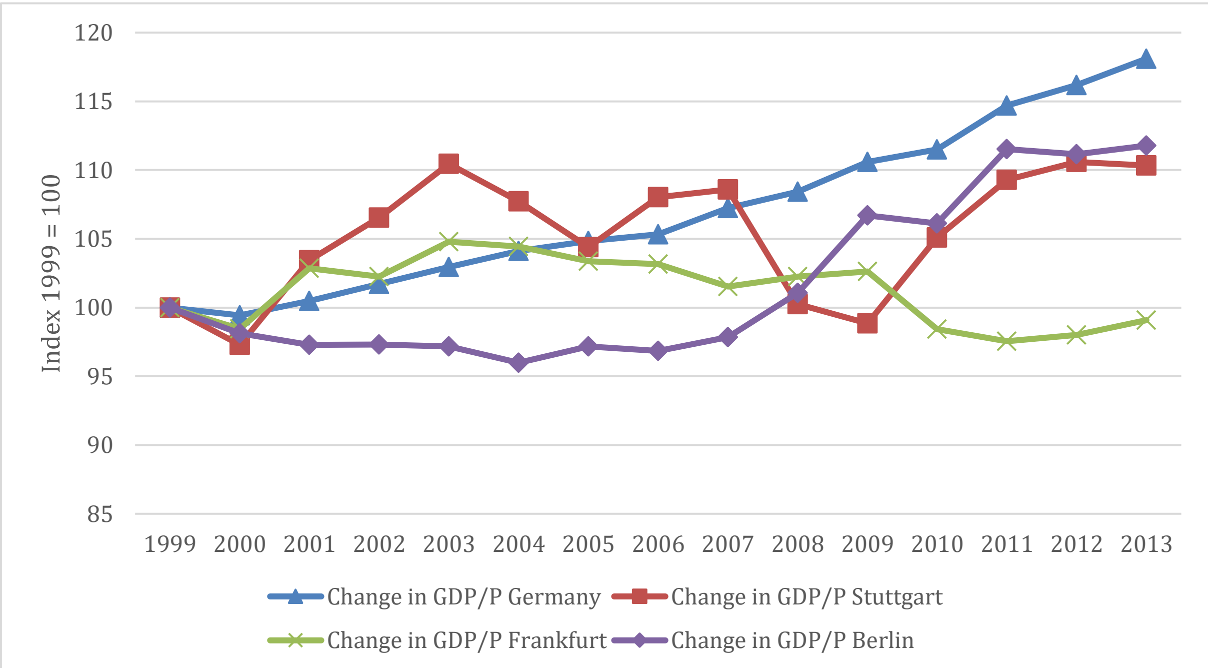

Figure 13: Development of economic growth, represented by GDP per capita GDP/P, in Germany, Berlin, Frankfurt and Stuttgart. 1999-2013

Lastly, as in Germany, the strong economic growth in Stuttgart and Berlin hindered emission reduction (Figure 13). Because of the expanding economic activity, traffic activity increased subsequently and contributed to a rise in road carbon emissions. Interestingly, Frankfurt’s GDP per capita developed differently and entered into a recessive trend from 2003 until 2010. This is likely a consequence of Frankfurt’s strong population growth. Real GDP stayed relatively stable for Frankfurt in the observed period and increasing population accordingly results in declining GDP per capita *GDP/P*.

7 Conclusion

This study examined the relationship between economic growth and carbon dioxide emissions from road traffic in Germany, Stuttgart, Frankfurt a. M. and Berlin during 1999-2013. Furthermore, it unveiled the influence of specific factors in the generation of on-road carbon emissions through decomposition and it discussed the results in a regional context. The literature on the subject of decoupling and decomposition was laid out, contemporary studies were discussed, the theoretical approach was introduced, and opportunities for additions to the literature were presented. Additionally, the methodological approach was elaborated by explaining and assessing the decoupling and decomposition techniques. Lastly, the data used in this study was presented, transformations to it, its limitations and its fit were discussed. Consequently, this study adds to the literature in environmental and transport studies by analysing regional disparities on sub-nation level.

The decoupling analysis showed that economic growth and on-road CO_2 emissions decoupled throughout the entire period in all four regions, except for Berlin in 2000. However, the desirable form of decoupling, strong positive decoupling, was rarer and its existence varied between both the temporal and the geographic dimension. Germany as a country experienced the longest period of strong positive decoupling during 2001-2009 and overall reduced its emissions by 13.7%. The second most extended period and the most significant reduction of 55% in on-road carbon emissions was yielded for Berlin between 2007 and 2013. Frankfurt reduced its road traffic-related emissions by 30.16% but only displayed an emission reducing trend from 2007. Strong decoupling in Frankfurt occurred for five years. Similarly, Stuttgart's on-road CO_2 emissions decreased by 31.5% in total. However, after an initial drop in emissions, a period of strong positive decoupling was only identified from 2010 until 2013.

The vital role of regional characteristics is evident in the decomposition results. Decomposition for the entire period unveils the emission factor as the most influential factor in all regions, even though its magnitude is different for the regions. In Germany and Frankfurt it was almost exclusively responsible for the reduction in emissions. On the other hand, the traffic intensity of economic activity contributed significantly to declining emissions in Berlin and Stuttgart, while it substantially increased road traffic emissions for Germany. The expanding economic activities led to a substantial rise in carbon dioxide emissions from road traffic for all regions with economic growth. Interestingly, Traffic volume changes were responsible for 28.85% emission increase in Germany but hindered CO_2 expansion in Berlin and had only a minor effect in Frankfurt and Stuttgart. Repeating the decomposition for the periods of strong decoupling yields the same hierarchy of influence for Germany but displays different impacts for the cities. Most noticeable is that the emission factor's influence is minor in these periods and regions, while traffic intensity of economic activity is the most impactful factor.

Furthermore, the discussion on the importance of regional characteristics shows that local infrastructure and particularly the condition and availability of public transport plays a crucial role in avoiding road traffic and the entailed emissions. Moreover, efficiency gains and clustering of industries, suppliers, customers and institutions through agglomerations gives urban regions a significant benefit compared to rural regions. Additionally, discussing behavioural disparities in rural and urban regions suggest that urban residents tend to act more commonly in a pro-environmental manner. Finally, it is shown that transformation capacity through policy exists.

To summarise, the study identified that decoupling of road traffic emissions economic growth was present throughout the entire study but unfolded uniquely for every region. It unveiled the emission factor to be most impactful in declining emissions and proved the significant impact of economic growth, traffic volume and traffic intensity of economic activity. Nevertheless, the study also highlights that geographic disparities exist and that regional characteristics have a major influence on how road traffic and the related carbon dioxide emissions develop.

Consequently, further research on the composition and progress of the underlying factors is recommended to unveil mechanisms that allow influencing the factors, particularly in a geographic context. Similarly, a further study on geographical differences in the emission factor, granted sufficient data can be acquired, would promise insights in how to manipulate the most impactful factor in road traffic emissions. Furthermore, distinguishing between on-road freight, public and private traffic in a subsequent study would yield more detailed information on how to steer the specific traffic modes in a sustainable direction. Lastly, an in-depth analysis of road-traffic specific policies with a regional dimension promises to improve the understanding of the regional characteristics' effect on policies in reducing carbon dioxide emissions from road traffic.

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Appendix A

The contribution of a factor C_i in the Shapley decomposition

This example elaborates on chapter 3.2.2 and illustrates how the contribution for one factor is calculated when conducting a Shapley decomposition. In this study emissions are decomposed on five factors (n=5). To keep this example as clear as possible it will use the factors $S = \{x1, x2, x3, x4, x5\}$, instead of the five socioeconomic factors introduced in the study. The Shapley index decomposition is an additive and perfect decomposition technique. Hence, the total change in the aggregated index I is found by the sum of each factor's contribution C_i:

$$\Delta I = \sum_{1}^{5} C_i = C_1 + C_2 + C_3 + C_4 + C_5$$

The contribution of factor x_1 to the aggregated index I is then found by:

$$C_1 = \sum_{s=1}^{5} \frac{(s-1)!\,(5-s)!}{5!} * \sum_{S:\, x_1 \in S} [\mathrm{V}(S{:}\, x_1 = x_1^t) - \mathrm{V}(\mathrm{S}{:}\, x_1 = x_1^0)]$$

$$= \frac{0! * 4!}{5!} * [x_1^t x_2^0 x_3^0 x_4^0 x_5^0 - x_1^0 x_2^0 x_3^0 x_4^0 x_5^0] + \frac{1! * 3!}{5!} * [x_1^t x_2^t x_3^0 x_4^0 x_5^0 - x_1^0 x_2^t x_3^0 x_4^0 x_5^0]$$

$$+ \frac{1! * 3!}{5!} * [x_1^t x_2^0 x_3^t x_4^0 x_5^0 - x_1^0 x_2^0 x_3^t x_4^0 x_5^0] + \frac{1! * 3!}{5!} * [x_1^t x_2^0 x_3^0 x_4^t x_5^0 - x_1^0 x_2^0 x_3^0 x_4^t x_5^0]$$

$$+ \frac{1! * 3!}{5!} * [x_1^t x_2^0 x_3^0 x_4^0 x_5^t - x_1^0 x_2^0 x_3^0 x_4^0 x_5^t] + \frac{2! * 2!}{5!} * [x_1^t x_2^t x_3^t x_4^0 x_5^0 - x_1^0 x_2^t x_3^t x_4^0 x_5^0]$$

$$+ \frac{2! * 2!}{5!} * [x_1^t x_2^t x_3^0 x_4^t x_5^0 - x_1^0 x_2^t x_3^0 x_4^t x_5^0] + \frac{2! * 2!}{5!} * [x_1^t x_2^t x_3^0 x_4^0 x_5^t - x_1^0 x_2^t x_3^0 x_4^0 x_5^t]$$

$$+ \frac{2! * 2!}{5!} * [x_1^t x_2^0 x_3^t x_4^t x_5^0 - x_1^0 x_2^0 x_3^t x_4^t x_5^0] + \frac{2! * 2!}{5!} * [x_1^t x_2^0 x_3^t x_4^0 x_5^t - x_1^0 x_2^0 x_3^t x_4^0 x_5^t]$$

$$+ \frac{2! * 2!}{5!} * [x_1^t x_2^0 x_3^0 x_4^t x_5^t - x_1^0 x_2^0 x_3^0 x_4^t x_5^t] + \frac{3! * 1!}{5!} * [x_1^t x_2^t x_3^t x_4^t x_5^0 - x_1^0 x_2^t x_3^t x_4^t x_5^0]$$

$$+ \frac{3! * 1!}{5!} * [x_1^t x_2^t x_3^t x_4^0 x_5^t - x_1^0 x_2^t x_3^t x_4^0 x_5^t] + \frac{3! * 1!}{5!} * [x_1^t x_2^t x_3^0 x_4^t x_5^t - x_1^0 x_2^t x_3^0 x_4^t x_5^t]$$

$$+\frac{3!*1!}{5!}*[x_1^t x_2^0 x_3^t x_4^t x_5^t - x_1^0 x_2^0 x_3^t x_4^t x_5^t] + \frac{4!*0!}{5!}*[x_1^t x_2^t x_3^t x_4^t x_5^t - x_1^0 x_2^t x_3^t x_4^t x_5^t]$$

The contributions for the remaining factors are found in the same manner. Calculating the difference when the analysed factor takes on the value in year t, while all others stay constant ($\mathrm{V}(S: x_i = x_i^t) - \mathrm{V}(\mathrm{S}: x_i = x_i^0)$) for all possible combinations that the factor in question can contribute to the index and weighing them according to how often the factor can contribute in that way ($\frac{(s-1)!(n-s)!}{n!}$).

Appendix B

Abbreviations

Carbon emissions – Another expression for carbon dioxide and other greenhouse gases

CO_2 – Carbon dioxide. Carbon dioxide is the most prevalent greenhouse gas. It is emitted from the burning of fossil fuels

EEA – European Environment Agency

EKC – Environmental Kuznets Curve

GDP – Gross Domestic Product

GHG – Greenhouse gas

ICT – Information and Communication Technologies. ICT is a broad term for information technology and refers to technologies that provide access to information through telecommunications.

IPAT – IPAT Equation I (environmental impact) = P (population) * A (affluence) * T (technology). The equation describes the environmental impact as the result of the multiplicative contribution of population, affluence and technology.

IPCC – Intergovernmental Panel on Climate Change

LMDI – Logarithmic mean Divisia index

M€ - Million Euro

OECD – Organisation for Economic Co-operation and Development