The Economic Effects of Transportation Infrastructure on Output and Productivity

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Abstract

The overarching theme of this dissertation is the investigation of the relevance of transportation infrastructure for the development and performance of the private sector. I analyse this relationship for both firms located in developing and developed countries to highlight similarities and disparities of the importance of transportation networks for the performance of the firms. For the examination of this relationship, I have chosen two countries that differ substantially on various economic and social factors and their levels of transportation infrastructure: Colombia and Germany.

Research on developing countries is often limited by the absence of reliable panel data, this especially applies to data on firms. I propose the use of aggregated Colombian firm data to identify a pseudo-panel of manufacturing firms that can be used to simulate the analysis of firm-level effects. I provide further validity for this method by conducting a Monte Carlo simulation, which provides support for the appropriateness of pseudo-panels in the context of firm-level investigations and further highlights the particular suitability of different panel data estimation techniques for it. The identified pseudo-panel is employed for the subsequent analysis. The elasticity of highway infrastructure on the growth of a firm’s output is significant and positive, however the identified magnitude of this effect of approximately 0.13 to 0.15 is substantially larger than the average effect identified in similar studies for developed countries, hence implying the crucial importance of transportation infrastructure for economic growth in developing countries. The results further show a time lag of this effect of one year, suggesting that firms’ production processes require time to adjust to the transportation infrastructure changes. These results are robust to the inclusion of additional controls and alternative transportation variables used. An additional investigation reveals that
transportation benefits particularly accrue to firms of the heavy industries. A further analysis highlights the role of transportation infrastructure within the context of spatial heterogeneity of this effect across regions. The results indicate the benefits of transportation infrastructure predominantly only accrue to firms located in relatively stronger regions with reported output elasticities of around 0.15. Additional analyses provide no support for the importance of transportation for fostering economic convergence in Colombia.

This thesis contains furthermore an examination of the role of the German highway network in influencing firm-level productivity patterns. This work uses German firm-level data and relies on the use of the Levinsohn-Petrin methodology and historical transportation data to conduct a two-step productivity estimation. I further derive two different transportation measurements to investigate the importance of transportation spillover effects. In line with previous studies of the German economic geography, I find spatial differences in productivity levels where larger levels are predominantly found in the districts of the South and West of the country, and lower productivity levels are identified throughout the Eastern districts. The investigation of the whole country identifies positive and significant productivity elasticities of highways where estimates range from 0.03 to 0.07 and 0.061 to 0.23 depending on the choice of method, controls and highway variable. This represents an increase of the firm’s productivity of 0.03 to 0.0.7 per cent following a 1 per cent increase in highways, or alternatively an increase of 0.061 to 0.23 when highway spillover effects are accounted for. This indicates that firms derive benefits from local highways and those located in the surrounding regions and the remainder of the country which points towards large spillover effects. The results further show that while highways are important for a firm’s productivity growth, alternative productivity enhancing factor, predominantly the amount to skilled labour, present relatively more important productivity determinants. The
investigation of subsamples designed to capture districts with relatively high and low highway levels points towards diminishing returns of transportation infrastructure and satiation effects. While no consistent differences in the estimated effects could be identified across districts of the Eastern and Western states and for those districts which have recently received new highways under the “Transportation Projects German Unity”, further disaggregate results show that highways particularly benefited firms in rural districts in the West and those located in urban districts in the East. Overall, the robustness of the results of this chapter requires further analyses, however they tentatively point towards productivity enhancing benefits of transportation and additionally reveal a large degree of heterogeneity of this effect.
Declaration of Contribution

I hereby declare that this thesis is the entirely the result of my own original work and that I am the sole author of this thesis. The contribution of my supervisors was only supervisory and editorial. Any material used from the work of others is fully referenced with appropriate acknowledgement given.

I further declare that all sources cited or quoted are indicated and acknowledged in the list of references in this thesis. Parts of thesis have been presented in academic conferences and submitted for journal publication. These are indicated in a list of references included at the end of the thesis.

Samira Barzin

Prof. Daniel J. Graham
Disclaimer

This work contains statistical data obtained from the Colombian National Statistics Office (Departamento Administrativo Nacional de Estadística/DANE) and the Institute for Employment Research of the German Federal Employment Agency (Institut für Arbeitsmarkt- und Berufsforschung - Die Forschungseinrichtung der Bundesagentur für Arbeit). The analyses have been conducted and results have been produced with the permission of the above named entities. The copyright of the data remains with the Colombian National Statistics Office and the Institute for Employment Research of the German Federal Employment Agency for the respective analyses. The research work which were undertaken for this thesis do not imply the endorsement of the above named entities with regards to the statistical analyses or interpretations drawn from it. Any datasets used throughout the analyses of this dissertation may not exactly reproduce any aggregate National Statistics.

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For my Parents and my Sister
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Chapter 1

Introduction
I Background

Transport infrastructure represents a crucial factor ensuring the efficient organisation of economies. Transportation networks facilitate the transportation of goods and people across distances, and more efficiently designed and organised transportation networks generally allow for faster transportation at lower costs.

The role of transportation within an economy is manifold. For households, transportation infrastructure results in savings in time and costs, e.g. fuel and maintenance cost given that better infrastructure allows for a longer lifespans of vehicles. Additionally, efficiently organised transportation networks further allow for journeys to be split across multiple transport modes to optimise along travel time and cost criteria. Further benefits arise through reductions of generalised travel costs which additionally account for possible induced demand and congestion factors. Furthermore, transport networks allow for more flexibility in the location choice of households where efficient transport links can induce a residential shift from urban towards cheaper suburban locations while households continue to benefit from urban wage premiums (see for example Baum-Snow, 2007 and Venables, 2007). On the other hand, transportation infrastructure can also increase the accessibility of locations, hence making them more attractive residential location choices and increasing their land rents. Transportation infrastructure can therefore also influence the spatial dimension of the residential household distribution.

The literature is predominantly in unison regarding the beneficial effects of high density locations for firms, both with regards to economic activity and population. Firms in high density areas benefit from more efficient interactions between them and their suppliers, a larger local labour market, and from the generation of knowledge, innovation and skills which is generally substantially higher in high
density urban environments. All of these factors allow for a more effective organisational structure of firms and generally result in economies of scale allowing firms to increase their productivity level. Transportation infrastructure essentially increases the geographic reach of these benefits and allows firms to reap them over longer distances. Transport networks further increase the geographic size of the market the firm can reach. This expands the firm’s final consumer markets and thus allows for further increases of the productivity benefits arising from the firm’s economies of scale. The increase in the geographic extent of markets reduces any geographic boundaries allowing for regional (quasi) monopolies, and hence increasing overall efficiency, but it also exposes any firm to increased levels of competition and heightened pressure to survive. Overall, this results in an increased efficiency of the private sector and generally leads to higher average productivity levels. Transport further establishes improved inter-city connections which often lead to the development of specific sectoral advantages across cities; examples are the historic formation of the American Manufacturing Belt and the concentration of the financial sector across a small number of cities globally. In summary, efficient transportation infrastructure allows for a more effective organisation of the spatial economy for both households and firms.

Transportation infrastructure can additionally also influence the economic development of regions. It is often assumed that there exists a complimentary relationship between public and private capital. Transportation connections often increase the attractiveness to households and firms, and hence are often followed by private investment. This will generate additional employment which can further induce migration to these locations. However, it remains an open debate whether these private investments are predominantly reallocated funds from alternative investments in other regions or whether these funds are additional investments. While the former would merely be a redistribution of investment across regions,
which leaves the overall investment unchanged, the latter would represent an increase in the overall aggregate investment level. In cases where private investment is redistributed from one place to another following transportation improvements, transportation infrastructure can significantly influence the spatial distribution of economy activity across regions where it is possible that some regions benefit economically at the expense of others.

Overall, the economic effects of transportation are extensive. Transportation infrastructure allows for a more efficient organisation of the economy across space, it allows for travel time and cost reductions and increases in economic productivity. However, transportation infrastructure can also increase congestion and emission levels, it can considerably increase land prices and result in increased firm competition levels. Further, transportation infrastructure can also substantially shape the economic geography within and across countries.

II The Relevance of Economic Geography for Developed and Developing Countries

The discussion outlined in Section I.I provides a general overview of the economic benefits that arise from transportation networks. These benefits are generally also assumed to be valid for the developing countries, however an additional discussion of the role of transportation specifically for developing countries is required to provide a more thorough survey of the impact of transportation infrastructure on economies.

There exists a general consensus throughout the literature that transportation infrastructure is beneficial for the economic growth and the efficient organisation of an economy. Given that developing countries often have transportation networks that are substantially smaller, in terms of reach and capacity, and that the
assumption of diminishing returns of capital holds, it can be expected that the economic benefits derived from transportation infrastructure are substantially larger for developing countries. The arguments outlined in Section I.I. further show the crucial relevance of transportation networks for the development and efficient organisation of the private sector. The World Bank frequently conducts surveys of participants of the private sector to investigate the investment climates of countries. They generally identify insufficient infrastructure as a major impediment for doing business (The World Bank, 2015). This further highlights the importance of infrastructure for fostering economic growth. Research has further shown that infrastructure plays a crucial part in promoting welfare, equity and economic growth, and thus contributing to the reduction of poverty in developing countries (see for example Estache et al., 2000 and 2002).

Overall, issues relating to the transportation networks of developing countries can be summarised into three major points:

Firstly, the transportation infrastructure quantity, measured in terms of road density, is generally observed to be substantially lower and critically behind the road densities measured for developed countries. Secondly, research has generally shown a correlation between the quantity and quality of transportation infrastructure (Calderón and Servén, 2010). Hence, the issue of the existing physical transportation network is twofold: its quantity and quality are both significantly low. Further, the growth rate of vehicle ownership has shown to be on average in excess of the growth rate of transportation infrastructure (The World Bank, 2005). Therefore, while new transportation infrastructure expands the existing network, it will not necessarily result in a more efficient transportation network given further congestion arising from induced demand. High levels of congestion pose further environmental and health risks.

An additional problem arises from the financing of transportation projects.
Developing countries often suffer from increasing national debt. If this results in increased austerity, which often leads to cuts in infrastructure spending, then this can lead to reductions in economic growth which subsequently further depress the economy. Throughout the last decades, Public-Private Partnerships (PPP) have become a more commonly employed option for the government to (partly) outsource the operations of transportation infrastructure. The evidence of the suitability and success of these remains mixed (Calderón and Servén, 2010). While there exists some successful examples, often PPPs come with obligations to the public sector to either repurchase the outsourced transportation infrastructure segments and services or come with liabilities to guarantee minimum revenues to their private partners, which overall do not alleviate the uncertainty of transportation projects from the public sector.

In summary, it can be concluded that transportation infrastructure plays an important role for the development and growth of economies. Hence, the expansion and improvement of the existing transportation network alongside an efficient financing is of crucial importance to ensure the development of a functioning economy.

III Research Aims and Motivation for this Work

The overarching theme of the work presented in this thesis is the investigation of the economic impacts of transportation infrastructure, its role in fostering economic growth and its effect on the spatial distribution of economic activity. In more detail, the analyses were oriented along the following main research focuses:

*The quantification of output elasticities of transportation infrastructure for developing countries.*

The existing literature has provided numerous studies quantifying the effect
of transportation infrastructure, however these are almost exclusively relying on developed countries or in cases of developing countries, they use nationally aggregated data. However, given that developing and developed countries differ on various economic and social characteristics, it cannot be assumed that the transportation infrastructure elasticities identified for developed countries are valid for developing countries. Hence, the identification of output elasticities of transportation infrastructure for disaggregate data of developing countries presented one of the goals of this research.

The analysis of the impact of transportation infrastructure for the economic geography.

The existing literature has generally established that the effect of transportation infrastructure is positive. However, further investigations are required to examine the distributional effect of transportation infrastructure. It is of further interest to examine which characteristics allow firms or regions to derive relatively larger benefits from transportation infrastructure. In this context it was a further focus to analyse the impact of transportation across regions as a regional growth promoting investment. Therefore, an additional aim of the work of the thesis was to investigate the differing impact of transportation infrastructure across economically and socially different countries and regions.

The investigation of the validity of aggregate data for disaggregate investigations

Research on developing countries is often hindered by the non-existence of the specifically required data. Often however, there exists some alternative data. Therefore, a further goal of this work was to identify the usefulness, shortcoming and validity of aggregate data for disaggregate analyses.
IV Research Contributions

The work contained in this thesis adds several extensions to the existing literature, where the contributions of this work are predominantly empirical.

Foremost, the overall aim of this work was the detailed investigation and quantification of the economic effects of transportation infrastructure. The majority of the existing literature in this field has relied on aggregate data to examine the role of transportation infrastructure. While this provides average estimates for the aggregate or regional economy, it cannot reach conclusions of disaggregate effects and the impact of transportation infrastructure in shaping the spatial economic heterogeneity. Hence, in order to investigate the role of transportation infrastructure on a disaggregate level, I rely on firm-level information for the analyses outlined in this thesis. This complements the existing literature by extending the analysis to the level of the firm.

This work additionally contributes to the quantification of the effects of transportation infrastructure. The work of this thesis relies on different methods to control for statistical complications in order to quantify the effects of transportation infrastructure. Given that this work contains analyses of a developed and a developing country, it follows that this work also adds to the literature investigating the role of different factors aiding economic development. Overall, the investigation of two very different economies allows to examine the differences of the role of transportation for different countries. The use of disaggregate information further permits to analyse the influence of transportation infrastructure in shaping the spatial economy of developing and developed countries which would be ignored when aggregate data is used.

The use of an extensive German firm level data set additionally allows for a detailed investigation of the impacts of transportation for firms. This work
additionally investigates the relative impact of transportation on productivity in comparison to alternative productivity enhancing channels.

In addition to the empirical contributions outlined above, this work also makes a methodological contribution. Data availability is often a problem for developing countries, hence this work proposes the transformation of aggregate data to pseudo-panels to overcome the absence of disaggregate data. The investigations of this work contain support and an investigation of its validity.

V Outline of the Thesis

This dissertation provides an in-depth discussion of the economic role of transportation infrastructure. This discussion is organised in 7 chapters, including the introductory chapter under which this section falls. Chapter 2 provides a comprehensive overview of the context of this work. I outline both theoretical and empirical aspects of previous work highlighting the possible channels through which transportation infrastructure can affect firms and the overall economy. I summarise the relevant econometrical specifications and the methodological difficulties for methods employed throughout this work in Chapter 3. Chapters 4 to 7 represent the empirical contributions of this dissertation. In Chapter 4, I conduct an analysis of the role of transportation infrastructure within a developing country and in Chapter 5 I highlight the spatial heterogeneity of these effects. Chapter 6 focuses on the impacts of transportation infrastructure for the spatial distribution of firm-level productivity across Germany. Chapter 7 concludes.

Concise summaries of each chapter are provided below:

Chapter 2: An Overview of the Context and Related Literature
This chapter provides a discussion of the context and literature relating to the work presented in this thesis. The chapter encompasses theoretical approaches
modelling the role of transportation infrastructure for an economy overall (Section II.II) by outlining the structures of the Neoclassical and Endogenous Growth Theories of Solow (1956) and Swan (1956) and Romer (1986, 1990) respectively in Sections II.I and II.II. Further, this chapter presents an overview of the literature of the determinants of firm locations (Section II.III) and its connection to transportation infrastructure. This is followed by the discussion of some of the recent theoretical contributions relating to the impacts of transportation infrastructure for the spatial distribution of economic activity (Section III.III.III). In particular, this subsection outlines the models of the New Economic Geography by Krugman (1991) and Fujita et al. (1999) and an extension proposed by Helpman (1998), Redding and Sturm (2008), and Redding (2012). The presentation of theoretical models is followed with an overview of notable empirical contributions of this research field which are organised into four subsections where the effects of transportation infrastructure are (1) evaluated for population dynamics, (2) related to the economic development of regions and firms, (3) assessed for trade and (4) highlighted within the context of developing economies.

**Chapter 3: The Methodology of Production Function Estimations and Its Difficulties**

This chapter presents a thorough review of the most established econometric methods employed within the context of the estimation of production functions. Following an introduction to the chapter in Section I, this chapter initiates the discussion with an outline of four of the most prevalent complications often resulting in biased estimates in Section III.II: (1) the bias stemming from simultaneity and endogeneity of the data, (2) the selection bias, (3) the bias arising from price heterogeneity and (4) an additional bias that can affect estimations for multi-product firms. The discussion of each of the bias sources is followed by an evaluation of these within
the context of the research on economic geography. The remainder of the chapter presents the most commonly used estimation techniques within the context of this work in Section III.III, where the following methods are outlined: the pooled OLS (POLS), the within estimators of first differences and fixed effects (FD and FE), the generalised method of moments estimators of System and Difference GMM and the structural approaches proposed by Olley and Pakes (1996) and Levinsohn and Petrin (2003). This chapter additionally provides comparison of the one- and two-step productivity estimation in Subsection III.III.VI.

Chapter 4: A Pseudo-Panel Approach to Estimating Dynamic Effects of Road Infrastructure on Firm Performance in a Developing Country Context

This chapter is one of the empirical results chapters of this thesis. The investigation of this work focuses on the examination of the validity of pseudo-panels and the identification of quantifiable effects of transportation infrastructure of firms of the private sector. This work relies on Colombian manufacturing data, as outlined in Section IV.II, to identify the overall effects of transportation infrastructure on output growth. The System GMM methodology is employed to control for endogeneity of the locations of firms and highways. Further, this chapter proposes alternative transportation variables to test the robustness of the results. This chapter additionally provides evidence on the validity of pseudo-panels in the context of firm level information and the suitability of different estimation methods by conducting a Monte Carlo simulation in Section III.

Chapter 5: The Geographic Heterogeneity within the Relationship of Roads and Firms

The analyses of Chapter 4 are extended by the investigation of the spatial distribu-
tion of the output effects of transportation infrastructure in Colombia in Chapter 5. This chapter in particular focuses on the spatial distribution of the effects of transportation infrastructure to investigate its impact on the form of the Colombian economic geography. The examination is organised along the regions distinct in economic and geographic factors.

**Chapter 6: Roads and Productivity: An Investigation of the Effects of Transportation Infrastructure on Firm Productivity Patterns across East and West Germany**

This chapter consists of an examination of the influence of transportation on the spatial distribution of firm-level productivity. This work relies on German firm information as summarised in Subsection V.IV which is combined with an extensive set of NUTS3 level highway information over 15 years. This analysis is set in the context of Germany and investigates in detail the role of the German Autobahn in influencing regional patterns of productivity, in particular those patterns that have emerged across districts located in the former East and West of the country. The investigation of this chapter follows a two-step procedure where the methodology of Levinsohn and Petrin (1996) is employed to identify time-varying firm-level productivity estimates. Subsequently, the influence of different factors, incl. transportation infrastructure, on the development of the firm’s productivity level is examined. In order to control for any biases stemming from the endogenous locations of firms and highways, information extracted from historical railroad and highway networks is used. This chapter further analyses the heterogeneity of the productivity impacts of transportation across firms in districts of the East and West (Subsection V.VI.V), those that exhibit high and low highway densities (Subsection V.VI.IV) and across firms located in urban, suburban and rural districts (Subsection V.VI.VI.)
Chapter 7: Conclusion

This is the concluding chapter of this thesis. This chapter summarises the results of the empirical Chapters 4 to 7 and highlights their contributions to the existing literature (Subsection VII.II and VII.III). Further, the importance of the findings identified throughout the chapters of this thesis are translated into policy recommendations in Subsection VII.IV. This chapter concludes with a brief discussion of future research questions aiming at extending the work outlined in this thesis.
Chapter 2

An Overview of the Context and Related Literature
I Introduction

The aim of this chapter is to provide a comprehensive overview of both theoretical explanations and empirical insights into the important role of transportation infrastructure for an economy. Additionally, the intent of this chapter is to discuss the effects of transportation on shaping the national, regional, and urban economy with respect to, inter alia, output, productivity, and employment in more detail. Economic theories can provide insight into the channels through which transportation infrastructure affects economic growth, or other economic variables. They further allow to generate hypotheses regarding the impact of transportation on different economic variables that can subsequently be employed and tested within an empirical investigation. In this chapter, I further provide a discussion of the empirical literature of this field. The goal for this part of the chapter is to highlight the various effects transportation has on different economic variables within different contexts. Throughout this review, research that represents a notable contribution to the field or is particularly closely related to the empirical work of this thesis is discussed in more detail.

This chapter will provide an outline of the role of transportation within models of economic growth in Section 2, Section 3 provides an overview of models highlighting the determinants of firms and industrial location. The empirical literature is discussed in Section 4 of this chapter.

II Economic Growth and Transportation Infrastructure

The theoretical models of economic growth and the conclusions derived from them represent a fundamental aspect of economic theory. The early contributions
to the field, which were predominantly focused on trade and the division of labour (Smith, 1776), have been complemented and extended by more recent theoretical approaches that have highlighted various structural aspects of economic growth and have generally been based on more thorough micro-level foundations than the early works (Blanchard, 1985 and Weil, 1989 provide examples). The canon of the classic macro-level economic growth theories does generally not include transportation infrastructure explicitly, therefore within the context of these models, transportation is implicitly assumed to be either included in the productivity residual, technological growth or the capital stock. Irrespective of the absence of this explicit role of the transportation infrastructure, and given that discussions of the relationship between transportation and economic growth remain important, two economic growth theories, which offer different channels through which transportation can influence economic growth, are outlined in the subsequent Sections 2.1 and 2.2 of this chapter.

II.I The Neoclassical Growth Theory

One of the earliest theories of economic growth has been put forward by Solow (1956) and Swan (1956). While the Solow-Swan model, also referred to as the neoclassical growth theory, has since been extended and advanced by economic growth models with more comprehensive microeconomic foundations, given the significance which the model still holds, it is outlined here.

The neoclassical growth theory is set up within the context of a closed economy without a public sector or government, where the economic production of the economy is represented by the following two-factor production function

\[ Y_t = F(K_t, L_t) \]  

(2.1)

where \( Y_t \) represents the economy’s output, or equivalently the economy’s income
variable, and $K_t$ and $L_t$ are the country’s capital and labour stock. Additional to capital and labour inputs, technology is assumed to influence the production. Technology, or technological growth, is modelled following either a Hicks neutral with $A_t$ (2.2) or Harrods neutral with $E_t$ (2.3) form

$$Y_t = A_t F(K_t, L_t) \quad (2.2)$$

$$Y_t = F(K_t, E_t L_t) \quad (2.3)$$

The Hicks neutral specification of (2.2) assumes technology to function as an augmenting factor within the economy. In this case, technology does not affect the relative distribution of the input factors or the Marginal Rate of Substitution between the factors within the production, but rather increases the total output. Within the Harrods neutral version of (2.3), technology enters by increasing the efficiency of labour within the economy. Given the advantages of the steady state representation under the Harrods neutral specification, I follow the version of (2.3) for the remainder of this chapter. Including the Harrods neutral technology parameter, the production function generally follows a Cobb-Douglas form with constant returns to scale so that

$$Y_t = K_t^\alpha (E_t L_t)^\beta \quad \text{with } \alpha + \beta = 1 \quad (2.4)$$

Within this context of neoclassical growth, transportation infrastructure can enter the production via two separate channels: First, infrastructure can enter as part of the technology parameter $E_t$ or $A_t$ and hence increase the efficiency within the economy. This could be interpreted as technology which allows for the construction of more durable road and rail networks and the development of smarter materials aiding those transportation networks. Further, technology that
guarantees the continuous functioning of the transportation network and allows for more effective maintenance would affect the production through the channel of the technology term. Alternatively, transportation infrastructure can enter the economy through the capital stock, where it is assumed that the capital stock captures both the private and the public capital stock. Hence, if the transportation network is assumed to be included within the public capital stock then the economic effects of physical infrastructure of the transportation networks would be captured through the capital parameter.

For neoclassical growth, one of the decisive factors of the model is saving. Private saving is assumed to be a constant fraction of income so that aggregate saving can be represented as

\[ Y_t - C_t = S_t = sF(K_t, E_t L_t) \]  \hspace{1cm} (2.5)

where \( C_t \) represents aggregate consumption and \( S_t \) and \( s \) represent the economy’s total savings and the savings rate respectively. The effects of interest rates, future productivity developments, any expectations regarding these, and any additional factors influencing the saving behaviour are ignored within this model. Given that this model operates within a closed economy, it follows that the sum of savings must be equal to the sum of investments, and hence capital accumulates according to

\[ K_{t+1} - K_t = sF(K_t, E_t L_t) - \delta K_t \]  \hspace{1cm} (2.6)

where \( \delta \) represents the exogenously determined depreciation rate of the capital stock. Additionally, the growth rates of the labour force and of the technology parameter affect the model and are characterised as
Similarly to the capital depreciation rate $\delta$, the growth rates $n$ and $g$ are determined exogenously. Combining the information of (2.7) and (2.8) with (2.6), capital accumulation, expressed as the ratio of capital to efficiency labour, becomes

$$\frac{K_{t+1}}{E_t L_t} = \frac{K_{t+1}}{E_{t+1} L_{t+1}} \cdot \frac{E_{t+1} L_{t+1}}{E_t L_t} = k^E_{t+1} (1 + z)$$

(2.9)

with

$$(1 + z) \equiv (1 + n)(1 + g)$$

(2.10)

so that

$$k^E_{t+1} - k^E_t = \frac{1}{(1 + z)} (sf(k^E_t) - (z + \delta)k^E_t)$$

(2.11)

where $k^E_t$ represents the capital to efficiency labour ratio. (2.11) is the driving equation of the model and determines the developments and resulting outcome for the economy. Given that production is concave in capital, in situations where gross savings per efficient labour $sf(k^E_t)$ outweigh the loss of capital stock represented as $(z + \delta)k^E_t$, the capital stock will increase and the economy will experience a period of growth. This will arise in situations where there exists a relatively low capital stock within the economy. Similarly, in situations where the reduction in capital outweighs investment, the aggregate capital stock will reduce. This is assumed to occur at relatively high levels of the capital stock. Consequently, the opposing
forces of investment and depreciation will push the economy towards a long run steady state. The steady state, which is determined by the economy’s rates of savings, population and technology growth, is characterised by a constant capital to efficiency labour unit ratio. The capital stock, total output and efficiency units of labour all grow at the same rate of \((1 + z)\). Hence, once the economy reaches its conditional steady state, growth is solely determined by exogenous factors and it is only in the short-run, while the economy is out of its steady state, where the economy experiences periods of growth.

If transportation infrastructure is assumed to be part of the capital stock, and hence affect the economy through this channel, then transportation can only aid economic growth in the short run, whilst the economy is out of the steady state. In the long run however, once the economy is in its steady state, transportation infrastructure will no longer have an influence on growth. On the other hand, if transportation infrastructure is assumed to enter the aggregate production through the technology parameter, then transportation can contribute to long run dynamics. An increase in transportation technology would thus raise the economy’s steady state and the long run growth of overall output, capital and efficiency labour units. However, given that the model assumes exogenously determined technology, the role of transportation within the model cannot be extended further.

Overall, the neoclassical growth theory presents a relatively simple framework which allows for a primary discussion on the channels through which transportation can affect an economy. However, the strict set of assumptions and restrictions limit the discussion of the role of transportation within this model.
II.II The Endogenous Growth Theory

Following the work of Judd (1985) and Lucas (1988), Romer (1986, 1990) acknowledged the importance of technology to modern economies and developed a theoretical framework which includes technology as a driving factor. Technological inventions aid an economy through multiple channels: they allow to increase the variety and quality of final goods supplied to markets, they benefit production processes by providing the knowledge of more efficient productions methods, and they aid the development of new intermediate input factors and materials which allow for enhanced final goods.

Romer’s (1986, 1990) model relies on four separate actors within the economy: the technology sector, the intermediate goods producers, the final goods producers, and the consumers. The final goods sector produces along the following production function

\[ Y_t = L_{Y,t}^{1-\alpha} \sum_{j=1}^{A_t} K_{j,t}^{\alpha} \]  

(2.12)

where \( Y_t \) is the final good’s output, \( L_Y \) represents labour used in the production of the final goods, \( K_j \) represents the different types of capital used with \( j \in \{1, 2, \ldots, A_t\} \) and \( A_t \) signifies technology. Within this model, it is assumed that new technology is manifested in new intermediate capital goods, for example machinery, so that \( A_t \) represents the various new capital goods developed up to time \( t \). The production function (2.12) is assumed to exhibit constant returns to scale in \( L_Y \) and all \( K_j \)’s jointly, the marginal product of new capital developed however is assumed to be infinite.

The technology sector produces new ideas and technologies where the growth rate of these is outlined as

\[ A_{t+1} - A_t = \theta A_t L_{A,t} \]  

(2.13)
where $\theta$ is a productivity shift term. $L_A$ represents the labour used in the production of new technologies, which is assumed to be constant. The total labour pool employed in the final goods and technology sector is $L = L_Y + L_A$. Technology and new ideas are non-rival, so that one’s consumption of it does not affect someone else’s consumption of it. This characteristic is also included in (2.13), where a technology increase leads to a smaller requirement of labour to generate the same amount of new ideas. Furthermore, new technology is determined by the previous amount of all technologies. Given that the development of new technology is costly and generally requires large a priori investments, this model assumes that firms of the technology sector can price their inventions and ensure their excludability. Subsequent to developing a new technology, firms of the technology sector sell their inventions to firms of the intermediate goods sector, where the new technology manifests itself in new materials which are subsequently sold to the final goods producer as capital inputs. Assuming a 100 per cent depreciation rate, so that the rental and sales rate of new capital align, the price of a new technological invention is determined by the discounted value of the expected profit from it

$$p_A = \sum_{s=t}^{\infty} \frac{\bar{\pi}}{(1 + r)^{s-t}} = \frac{(1 + r)\bar{\pi}}{r}$$ (2.14)

where $p_A$ represents the price of the new technology and the over-bar represents the values along the steady-state growth. Based on the ensured excludability of new technologies, intermediate goods producers purchasing these become monopolists of these technologies.

Combining the above, the steady state growth path of technology is characterised as

$$\bar{g} = \frac{A_{t+1} - A_t}{A_t} = \theta L_A$$ (2.15)
so that amount capital goods grows at $g$. The quantity of each capital good remains constant in the steady state. Solving for $g$ by including the complete labour pool with $L_Y = \frac{r}{\theta \alpha}$ produces

$$\tilde{g} = \theta L - \frac{r}{\alpha} \quad (2.16)$$

The consumers of the economy are assumed to be identical, infinitely-lived consumers which maximise an isoelastic utility function. Using the Euler condition, aggregate consumption can be characterised as

$$(1 + r) = \frac{1}{\beta} (1 + g)^{1/\sigma} \quad (2.17)$$

where $\beta$ represents the discount factor and $\sigma > 0$.

The steady state growth path is determined by (2.17) from the consumer side and by (2.16) from the supplier side. Along the steady state growth capital $K$, output $Y$, consumption $C$ and technologies $A$ all grow at the same rate which is determined by (2.16) and (2.17).

The modelling of technology within the model thus far introduces two sources of inefficiencies: (1) firms of the technology sector do not take externality and spill-over effects into account and (2) once the technology is sold, the intermediate goods producers act as monopolists. These factors generally result in an inefficient market outcome. The introduction of the government allows to partly address these issues. The government would operate along the maximum lifetime utility of the consumer given the production function of technology with

$$Y_t = L^{1-\alpha}_{Y,t} A_t K_t^\alpha \quad (2.18)$$

It is assumed that the government will produce equal quantities of new intermediate goods, and finance these through subsidies to the technology sector via
lump-sum taxes. The growth rate of output along the steady state path hence becomes

\[ \bar{g} = \frac{\beta \theta L - (1 - \beta)}{1 + \beta} \]  

(2.19)

This growth rate is higher than (2.16) since it internalises the positive spill-over effects of new technologies.

Transportation infrastructure, similarly to the role of technology within this model, allow firms to increase the efficiency of their production processes. In cases where firm’s production relies heavily on transportation equipment, new development in transportation machinery further allows firms more efficient production. This may additionally affect the marginal products of the capital used and hence also affects output via its effect on intermediate inputs. Furthermore, transportation infrastructure aids the distribution and diffusion of new technologies and hence benefits firms by increasing their productivity. Transportation further reduces effective distances, thus it increases the speed of technology diffusion, and hence allows firms to benefit from new technology at a faster rate.

### III The Determinants of Firm Locations

The firm’s choice of location can crucially influence the firm’s performance, its productivity and probability of survival. Conversely, the firm’s location also affects the regional economic performance and employment structure. First formally discussed by Weber (1909), the concept that a firm’s location over the geographical space is determined by the distances to input and output markets and the respective transportation costs has long been recognised in the literature. While Lösch (1940) already introduced the concept of the opposing forces which either push towards a concentration or a dispersion of economic activity in the first half of
the twentieth century, the discussion of these structural factors remains important and active today. The overall geographic distribution of economic activity is the result of the opposing forces that push firms either into locating away from urban centres and hence result in an overall dispersion or influence firms to locate within dense regions and hence lead to economically dense agglomeration centres. The underlying concepts of increasing returns at the firm level which motivate firms to locate in regions where these could be fostered and the issue of transportation costs that the firm incurs for both input factors and final goods are two of the most influential factors for the firm’s location choice. The body of literature is predominantly unanimous in the conclusion that locations in economically dense areas allow firms to benefit from increasing returns and proximity to larger consumer markets. However, locations in urban centres also heighten the pressure of competition and the increased urban costs on firms. Conversely, locations in less dense areas allow firms to circumvent the vigorous competition but also result in higher transport costs for inputs, employees and final goods.

While it is beyond the scope of this work to provide a complete in-depth review of all prevailing theoretical models, I provide an overview of mechanisms of agglomeration economies and central models of economic geography. For a thorough review, the reader is referred to the work by Duranton and Puga (2004), Ottaviano and Thisse (2004), and Redding and Turner (2015).

The following sections are structured as follows: Section 3.1 provides a discussion of natural advantages driving location choices, Section 3.2 discusses agglomeration economies and Section 3.3 outlines the models focusing on the spatial distribution of economic activity by Fujita et al. (1999), Helpman (1998) and Redding and Sturm (2008).
III.I Geography as a location factor

The drivers of location choices are manifold. While agglomeration economies have become one of the most established factors driving location choices, geographic locations close to natural resources have been proposed as another. Locations with favourable climate, soil conditions and those that offer direct access via land and water are attractive to firms if these aid their production. Investigating the firms’ location choices Kim (1995) analyses the geographic concentration of economic activity between 1860 and 1987 for the US. The US underwent a transition from a regionally focused to a nationally oriented economy during this period, which hence offers an interesting setting for a long-run investigation of location patterns. The author finds that regional specialisation reached its peak in the 1930s and has fallen since. He further finds that regions which are relatively more specialised exhibit more localised industries. He also identifies a positive effect of natural resources on firms’ locations, however as he does not identify a relatively stronger effect for high-tech industries, he concludes that the impact of natural resources relative to scale economies of dense locations is small. Ellison and Glaeser (1999) investigate the geographic distribution of US manufacturing firms to highlight the different effects of natural geographic advantages and industry spill-overs on firms. They identify that multiple highly concentrated industries investigated are majorly influenced by industry location effects. However, they also find strong evidence from natural advantages shaping the geographic concentration patterns. They conclude that around half of the observed concentration can be attributed to natural advantages. Healey (2015) adds to the discussion by analysing the role of transportation supply in shaping the geographic concentration of economic activity. He highlights the driving forces behind the American Manufacturing Belt’s emergence and finds strong evidence for the influence of external natural geographic factors. He argues that there existed a close relationship between the
exploitation of natural resources and the development of the railroad network. He argues that both, the companies relating to the railroad operations and those relating to natural resource exploitation, stimulated employment and industrial investment and hence lead to the emergence of manufacturing. He concludes that it was natural advantages rather than the direct benefit of economies of scale driving the development of the American Manufacturing Belt.

### III.II The Benefits of Agglomeration Economies

Aside from the geographic factors as, inter alia, soil and climate, the benefits of economically dense locations have been shown to influence firm’s location choices crucially. Marshall (1890) initially formalised some of the most prominent benefits accruing to firms in dense locations: (1) sharing of input suppliers, especially in those circumstances where intermediate input suppliers exhibit increasing returns to scale; (2) labour market pooling which allows for better matches across employers and employees and (3) knowledge spill-over resulting in increased learning and the faster dispersion and adoption of new technologies. Additional benefits of the home market effect, urban consumption opportunities and rent seeking behaviour have since been additionally proposed. The focus of this work is not to provide a complete insight into agglomeration economies, but rather provide an overview on their effect on firm’s locations; hence, for excellent overviews of the mechanisms of agglomeration economies I direct the reader to work by Duranton and Puga (2004), and Ottaviano and Thisse (2004). Thorough analyses of the empirical evidence of agglomeration economies are provided by Rosenthal and Strange (2004), Melo et al. (2009), and Combes and Gobillon (2015).

While it is outside of the scope of this literature overview to provide a detailed discussion of all agglomeration channels, I discuss the three most prominent agglomeration sources as termed by Puga (2010). Consecutively, I outline the
interlinkages between agglomeration economies, firm competition and transportation infrastructure.

**Input Sharing**

The possibility of benefiting from sharing facilities, suppliers and a common labour pool all reduce a firm’s overall costs through relative reduction of the cost share that each firm has to bear. An early formulation of this argument can be found in the 1977 paper by Dixit and Stiglitz which remains an influential paper within the present discussion. Dixit and Stiglitz (1977) draft a theoretical model with locally sold intermediate products and freely tradable final goods. They find increasing returns in the aggregate production at the city-sector level, and constant returns to scale at the firm-level in the final production, which is assumed to be perfectly competitive. They conclude that final production increases depend significantly on extended input sharing across an increased variety of suppliers. Analysing this issue empirically, Overman and Puga (2010) investigate the impacts of both a shared labour and intermediate supplier pool for UK establishments. They find that the degree of sectoral clustering is heavily influenced by the firm’s degree of dependence on intermediate inputs and the spatial clustering of the supplying firms. The authors furthermore employ the spatial concentration index proposed by Ellison and Glaeser (1997) across all supplying industries and weight them relatively to their input share with respect to the considered industry. Their results suggest that at the sectoral level, input sharing is a strong motive for agglomeration. The authors additionally investigate the role of a shared labour pool. They calculate employment fluctuations of individual firms relative to the average of their industrial sector, they average it by sector and find that industries with higher observed idiosyncratic volatility in employment exhibit a higher degree of spatial concentration. Rosenthal and Strange (2001) contribute one of the few
papers in this context that reaches the conclusion that sharing is a relatively weak agglomeration motive. They use US manufacturing data to regress geographic concentration across different sectors on various variables capturing the different agglomeration motives. They find that other agglomeration motives are relatively more important for the location decision of firms. Additional papers investigating the role of sharing as an agglomeration mechanism are provided by Holmes (1999) and Ellison et al. (2010).

Generally, the literature agrees that sharing is an important motive for agglomeration, scholars however reach different conclusions regarding its relative strength. The clear majority of research however agree with Puga (2010) who finds that compared to the mechanisms of matching and learning, sharing appears to be a relatively strong channel of agglomeration.

Matching

Matching between employers and employees, buyers and sellers, and between business partners is another agglomeration economies motive that has received attention. While there does not exist a literature body as extensive as there exists one for the sharing mechanism, various theories have been proposed to explain the underlying effects of matching on agglomeration economies and urban productivity. Relating to the concept of search with frictions within the context of the aggregate matching function, which relates the number of job vacancies and job seekers to the amount of matches, Coles (1994), and Coles and Smith (1998) develop a theoretical explanation of job matching within the context of searches with frictions across vacant jobs and job seekers. They argue that the total number of job matches depends positively on both the stocks and flows of unemployed workers and vacancies. As both of these can be expected to rise with city size, the number of matches can be assumed to also increase with it, i.e. the matching function
exhibits increasing returns to scale. Attempting to analyse the field of matching empirically, Gan and Li (2016) compare the job-worker matches of recently graduated PhD economics holders across differently sized academic specialisation fields. Their findings suggest that the matching probability of a particular specialisation field depends positively both on the number of job openings and the number of available candidates. They conclude hence that thick markets crucially affect the number of matches. Additional work investigating the role of matching can for example be found in Berliant et al. (2006), and Costa and Kahn (2000).

Overall, the body of literature concludes that the probability of positive matches increases with city size and is hence larger for urbanised areas. Therefore, it represents an important motive for firms to locate in economically dense areas.

**Learning and Knowledge Spill-over**

The importance of the acquisition of human capital for the economy has long been identified with initial mentions by Smith (1776) and Marshall (1890). Human capital and knowledge remain important drivers of economic growth and productivity. They have also been shown to be an enhancing factor for urban productivity. Cities facilitate the spread of knowledge, they foster the development of innovations, and they promote the acquisition of advanced skills.

In an important contribution to this field, Glaeser and Resseger (2010) research the complementarities of per-worker productivity and metropolitan area population. They show that 25 per cent of agglomeration effects can be attributed to skills. They infer that this is due to both increased learning between workers and a higher level of innovations in cities. They identify a wage-earning curve that is significantly steeper in urban than in rural settings. They base this finding on human capital growth, which is hence concluded to be higher in urban environments. They additionally analyse metropolitan areas that have particularly high
levels of human capital and find that in these 45 per cent of the per-worker productivity differences are explained by area population. They conclude that there exists a mutual influencing relationship; while more sophisticated skills result in agglomeration benefits, agglomeration in turn fosters skill acquisition. Researching human capital growth in detail, Glaeser and Maré (2001) find that there exists faster learning in cities. Their analysis strongly suggests that workers are therefore able to experience faster wage growth in cities. Highlighting the importance of the development of innovations on the other hand, Audretsch and Feldman (1996) find that innovations are majorly developed by firms that cluster in close proximity to each other. They measure innovations as the number of new products introduced to the market and show that for industries that rely heavily on new knowledge, the connection between close geographical proximity and innovation growth is particularly strong. No (2002) focusses on the spatial spread of innovation and finds that the adoption and diffusion of newly introduced technologies depends significantly on the number of firms that have already adopted new technologies within the same geographical region. He finds that this relationship is particularly strong for firms that rely on similar technologies but operate in different sectors and therefore do not compete. Analysing the life cycle of firms, Duranton and Puga (2001) show that the firm’s location decision depends on its development stage. Newly established firms locate in diverse and larger cities as it enables them to experiment with suppliers and the final product market without the need to relocate. Established firms often prefer to locate in more specialised cities to benefit from sector specific factors. They conclude that this explains both the existence of diverse as well as specialised cities. Additional work highlighting the role of learning and the spread of knowledge as an agglomeration factor is provided by Glaeser (1999), Faberman and Freedman (2016), and De la Roca and Puga (2017) among others.
III.II.1 Agglomeration Economies, Productivity and Firm Selection

Firms located in cities often exhibit higher productivity levels. It has been argued that this is mostly due to the afore mentioned productivity enhancing benefits of agglomeration economies. However, firms in economically dense areas also face heightened levels of competition which increase the overall pressure on the firm to be highly productive in order to remain operating in the market. Overall, this eventually results in market exits of less productive firms so that only firms with relatively high levels of productivity prevail.

In a recent research paper, Melitz and Ottaviano (2008) develop a theoretical model of the effects of firm competition which combines heterogeneous firms with endogenous price mark-ups. Their results show that firm competition toughens as the number of firms increases. Consequently, less productive firms exit the market. This can be interpreted as evidence for the existence of increased firm competition in cities. Baldwin and Okubo (2006) develop a model with heterogeneous firms within an economic geography context. They identify that sorting through relocations of the most productive firms to cities is an influential mechanism for overall productivity advances in cities. Contributing further to the discussion of firm selection, sorting and agglomeration economies, Combes et al. (2012) extend the Melitz and Ottaviano (2008) model and combine it with models of agglomeration economies. Their findings suggest that both agglomeration economies and firm competition increase the average log productivity of firms in cities. However, they show that with respect to city size both factors have differing effects on the distribution of log firm productivity. Agglomeration economies result in an increase of average productivity within cities, while stronger selection mechanisms result in market exits of the least productive firms. Testing both channels empirically, they find that firms in larger cities are on average 9 per cent more productive than those located in small cities which, they conclude, can primarily be attrib-
uted to agglomeration economies. Bougheas et al. (2000) further identify that heightened levels of competition in urban environments increase the pressure to develop a comparative advantage in cities so that specialisation becomes relatively more important in these highly competitive markets.

Overall, the body of literature gives support to sorting, selection and agglomeration economies as factors shaping the spatial productivity patterns of firms and hence remain an important topic of discussion.

III.II.II Agglomeration Economies and Transport Infrastructure

The productivity enhancing benefits of agglomeration economies and the increased competition levels in urban environment represent determining factors for firm’s location choices. The accessibility of the firm’s location through transportation infrastructure further influences the firm’s location decision. Transportation infrastructure allows for reductions in commuting times and costs for workers and hence increases the accessible pool of employees for firms. Better transport infrastructure further raises the firm’s accessibility to intermediate inputs, and final goods markets. Overall, transportation infrastructure therefore extends the geographical reach and spread of agglomeration economies.

Venables (2007) provides a thorough theoretical model combining agglomeration economies with increases in transportation infrastructure by interlinking transportation infrastructure, employment and wages. The underlying hypothesis of the model is that large urban centres generate higher levels of total factor productivity. He argues that the underlying reasoning influencing the location trade-off for workers between urban areas, with high rents and high wages, and peripheral regions, with low wages and low rents, lies in the cost of commuting. The extension of transportation connecting peripheral regions to the city centre reduces commuting times and costs so that more workers will subsequently com-
mute to the inner-city. This raises the total urban employment and consecutively the productivity of new and existing workers. This will result in wage increases for all workers and hence increase the real income. Graham (2007a) highlights the role of transportation infrastructure within the context of agglomeration economies by developing an empirical measure of the geographical scope of agglomeration economies which he terms “effective density”. Adding geographical elements to the discussion and measurement of agglomeration economies is crucial as this allows for the direct inclusion of transport in the discussion. Transport influences the proximity and scale of economic activity as better transport infrastructure enables firms to capture a larger geographical area at lower costs. This increases the amount of labour a firm has access to, the number of suppliers a firm can reach at the same costs, and also the final consumer markets the firm can reach. Graham (2007b) uses a translog equations system to estimate agglomeration elasticities for different industrial sectors. Subsequently, he applies his agglomeration elasticity estimates to appraisals of transportation projects. His results show positive elasticities of agglomeration economies for those industrial sectors predominantly located in urban areas, and for industrial sectors heavily dependent on natural resources he generally finds insignificant results. His subsequent analysis focuses on determining productivity elasticities that show how productivity varies with different levels of economic density. He finds a close relation between both variables. He argues that this is based on the effects of transport infrastructure investments which raise effective densities and subsequently raise agglomeration economies as well as increase total factor productivity (TFP). Transport investments influence agglomeration economies by reducing travel times and costs. Agglomeration economies in turn result in increased productivity levels through the channels identified by the standard agglomeration literature. Applying his agglomeration elasticity results to the reappraisal of the DfT CrossRail project, he shows that the
inclusion of agglomeration benefits raises the total calculated benefits of CrossRail by 25 per cent. Graham’s (2007a and 2007b) contribution to the research linking agglomeration economies and transport infrastructure provides a thorough analysis and disaggregate estimates of productivity elasticities. Overall, he shows that these wider economic benefits can be substantial and can alter cost-benefit appraisals of transport infrastructure projects significantly. Furthering this discussion of the connection of transport infrastructure and agglomeration economies by incorporating effective densities into their analysis, Graham et al. (2009) research the spatial effects of agglomeration economies. The authors examine a firm level panel data set, and estimate the effects that access to economic mass has on TFP across different industrial sectors. Graham et al. (2010) use a control function to treat a possible endogeneity bias due to unobserved firm heterogeneity in their regression of agglomeration economies and TFP. For the subsequent analysis of the spatial effect of agglomeration economies, they use a non-linear least squares approach. Their examination of agglomeration economies and TFP finds an elasticity value of 0.04 for the aggregate economy, an elasticity of 0.02 for the sectors of manufacturing and consumer services, and elasticities of 0.03 and 0.08 for the sectors of construction and business services respectively. These estimated elasticity values are in line with similar research in this field. The non-linear least squares estimation of the distance effects of agglomeration economies yields distance decay parameters of 1.0 for the manufacturing sector, 1.8 for the consumers and business service sector, and 1.6 for the construction sector. These results show that agglomeration economies’ benefits and their spatial effects can vary substantially across sectors. While business services derive the largest benefits from agglomeration economies, it is also the sector where the benefits of agglomeration economies diminish the fastest with distance. The use of effective density highlights the role of transportation infrastructure within the context of the firm’s location and the geo-
graphical reach of agglomeration economies. Focusing on the econometric issues of estimating agglomeration economies and TFP, Graham and Van Dender (2011) propose the use of semiparametric methods. They state that the standard estimation methods of econometric analyses of panel data sets in this context are not suitable to deal with the issues of reverse causality, confounding, and non-linearity that arise due to endogeneity issues, or unobservable time-invariant heterogeneity within the data. They state that there exists a high degree of sensitivity to the method chosen to treat unobservable heterogeneity, and also that measures of accessibility are highly persistent. These two issues lead the authors to conclude that standard panel data estimation methods are not suitable in this context and that estimated point estimates may be biased. They apply semiparametric estimation techniques to a sub-sample of their data, and find there exists a substantial amount of non-linearity within the accessibility and TFP relationship. Graham and Van Dender (2011) conclude that this non-linearity makes it difficult or impossible to distinguish between different productivity enhancing sources. Contributing to the discussion of agglomeration economies and TFP, Graham and Maré (2013) analyse a large firm-level panel data set based on data from New Zealand. They examine the effects of heterogeneous firm sorting, the convexity of agglomeration economies, and the identification of the impacts of persistent spatial differences in economic density on multi-factor productivity. Dense locations may attract firms with particularly high TFP levels, and also firms that derive particularly large benefits from high spatial density. This results in non-random heterogeneous firm sorting, which may result in an upward bias in any of the effects on productivity. If fixed effects are used in an estimation to control for firm heterogeneity in the presence of limited within-firm variation in the effective density, a downward bias in the estimation may also arise. Graham and Maré (2013) use alternative estimation methods to prevent any bias from firm heterogeneity, and firm sorting.
Their analysis shows an aggregate economy elasticity of 0.066, but also that there exists variation in agglomeration economies’ elasticities across regions, as well as across industries. The authors also find evidence for the convexity of the effects of agglomeration economies across regions and industries.

III.III The Spatial Distribution of Firms: The model of the New Economic Geography

The distribution of economic activity across space, the development of economically important urban centres and relatively less economically dense peripheral regions and their implications have been established as crucial factors for policy work (Ottaviano and Thisse, 2004, and Redding and Turner, 2015 provide thorough reviews). While cities have predominantly become one of the main drivers of economic output for many economies, the uneven distribution of economic activity across space does not come without problems: spatial inequality caused for example by excessive migration towards cities, differences in real incomes across regions and regional unemployment are significant factors determining the overall performance of an economy (see for example Combes and Gobillon, 2015; Desmet and Henderson, 2015; Lewis and Peri, 2015). In order to provide foundations for the explanation of the spatial economic distribution, a growing body of literature has provided insight into theoretical mechanisms and empirical findings. This section will outline two of the most acknowledged theories.

III.III.I Krugman’s core-periphery model of the New Economic Geography

Krugman (1991) and Fujita et al. (1999) draft a model of two regions and two economic sectors to explain the distribution of economic activity across those two and the importance of transportation infrastructure within this context.
There exist two types of labour within the model: workers with human capital $H$, who are employed by the manufacturing sector, and unskilled workers $L$, who work in the agricultural sector. The literature often refers to this as labour dualism. Workers can only work within the region where they reside, so that daily commuting behaviour does not exist within this context. However, workers with human capital can move from one region to the other, while workers of the agricultural sector are assumed to be immobile. The mobility of the skilled workers affects both the demand and the supply side. As workers earn and spend their income where they reside, they function as both consumers for goods and producers of the goods through their supply of labour. Given this, the determination of market size becomes endogenous through the relationship between firm location and the location of skilled labour (Stahl, 1995; Fujita and Thisse, 2002). The location choice of workers is motivated by their utility levels across the regions, so that regions offering higher utility will attract skilled labour. Labour market clearing remains intact given that the location of firms reacts to the movements of labour across the regions so that wages eventually adjust.

For any wage level, regions exhibiting a larger number of skilled workers, and hence a larger number of firms of the manufacturing sector, represent a larger market. The share of domestic products within a larger market is relatively larger to that of a smaller market. Hence, the amount of imported goods, whose price is higher due to incurred transportation costs, is relatively lower allowing for an overall lower price index, and a higher purchasing power and consumer surplus in larger markets. This is generally referred to as the cost of living effect.

For the remainder of the model, I follow the version put forward by Forslid and Ottaviano (2003) which provides an alternative interpretation of the effect of skilled and unskilled labour on variable and fixed costs (further details can be found in Forslid and Ottaviano, 2003, and Ottaviano and Thisse, 2004). Assuming a CES
utility form, the equilibrium wages in both regions $A$ and $B$ can be formalised as

\[
\frac{w^*_A(\lambda, \phi)}{w^*_B(\lambda, \phi)} = \frac{2\phi \lambda + [1 - \mu/\sigma + (1 + \mu/\sigma)\phi^2] (1 - \lambda)}{2\phi (1 - \lambda) + [1 - \mu/\sigma + (1 + \mu/\sigma)\phi^2] \lambda}
\] (2.20)

where $\lambda$ represents the distribution of firms across the regions with $\lambda \in [0, 1]$, $\phi$ signifies the freeness of trade, $\mu$ stands for the fraction of income spent on the manufacturing goods, $\sigma$ represents the elasticity of demand across all varieties and $w^*_i$ is the equilibrium wage with $i = A, B$. A differentiation of (2.20) with respect to the distribution of firms across the regions allows for the identification of

\[
\phi_r = \frac{1 - \mu/\sigma}{1 + \mu/\sigma}
\] (2.21)

where $\phi_r$ with $\phi_r \in [0, 1]$ represents a threshold level of $\phi$. Combining (2.20) and (2.21) allows for an interpretation of the effect of the trade openness on wages. In cases where $\phi$ is larger than the threshold $\phi_r$, the region with more workers offers a higher wage, conversely in cases where $\phi$ lies below the threshold level, it offers a lower wage. This pattern is explained by two opposing effects: the market crowding and the market size effect. For any given transport cost level, a larger number of skilled workers will result in a larger number of competing manufacturing firms within a region. This will decrease the local price index, which signifies a fall in demand for each firm which results in lower firm profits, and hence also in lower wages. This is the market crowding effect. Conversely also in markets with more firms, there exists more aggregate profit, which results in more skilled labour income, and hence results in an increase in demand for each firm. This is referred to as the market size effect. In cases where $\phi$ is relatively low and below $\phi_r$, the market crowding effect dominates the market size effect, and the opposite holds true in cases where $\phi$ is larger than $\phi_r$. Similarly, the market size effect is the
dominating effect in instances where transport costs are low, the relative amount of income spent on the manufacturing goods is high or the elasticity of substitution is low so that higher wages will prevail in the region with more skilled workers.

The equilibrium is determined by the indirect utility of consumers which is represented in its differential by

\[ \Delta v(\lambda, t) \equiv S_A(\lambda, t) - S_B(\lambda, t) + w_A(\lambda, t) - w_B(\lambda, t) = Dt(t^* - t)(\lambda - 1/2) \]  

where \( S_i \) with \( i = A, B \) is the consumer surplus in each region, and \( t \) represents transport costs with a threshold level of \( t^* \). \( D(> 0) \) represents parameters not affected by transport costs. Transportation costs further affect the distribution of workers, and subsequently firms, across the regions. In cases where \( t \) lies below its threshold level, the skilled workers will agglomerate in one region, conversely in cases where \( t \) is in excess of the threshold level, a symmetric distribution of economic activity across the regions will be established. Additionally, \( t^* \) is a positive function of \( f \), which represents the firm’s returns to scale, so that increasing returns to scale at the firm-level result in a higher transportation threshold, and hence increase the possibility of agglomeration. In cases with relatively low transportation costs, even small transitory shocks may have a long-term impact on the spatial economic distribution through the relocation of skilled work towards one agglomeration for which the market size effect dominates the market crowding effect. The opposite holds true for relatively large transportation costs.

The outline of the model discussed here represents an overview of the fundamental mechanisms of the theory, a fundamental thorough discussion is beyond the scope of this work but can be found in Krugman (1991), and Ottaviano and Thisse (2004). Similarly, extensions of the model incorporating vertical linkages

The New Economic Geography, as outlined by Krugman (1991) and Fujita et al. (1999), represents an in-depth model of the organisation of the spatial economy and its interlinkages to transportation infrastructure. However, it has been pointed out that the model lacks a full inclusion of agglomeration costs which are further hypothesised to affect the movements of workers across the regions. Further, the model does not discuss the treatment of transportation costs of the agricultural good (Picard and Zeng, 2005). Additionally, the model does not include an option of workers who are heterogeneous in their spatial preferences in which case their location behaviour is determined by factors different from regional wage levels. Hohenberg (2004) has further criticised that the spatial economy is often observed to not be as efficiently organised as the model predicts, where as Ottaviano and Thisse (2002), Baldwin et al. (2005) and Charlot et al. (2004) have criticised the absence of a full welfare analysis. Further, the absence of a discussion for which regions agglomeration can be expected to occur, the role of the public sector, regional unemployment and the limitations to two regions have been pointed out as criticism. In the subsequent subsection, I will present an extension of the model that allows for the incorporation of some of the points critiqued in the original model by Krugman (1991) and Fujita et al. (1999).

III.III.II The Multi-Region Model following Helpman, Redding and Sturm

In order to draft a thorough extension of the New Economic Geography model outlined in the previous subsection, Helpman (1998), Redding and Sturm (2008) and Redding (2012) develop similar theoretical models that allow for the extension
of the model to multiple locations and for a more thorough analysis of the effect of transportation costs of goods and people within and across locations. The aim of this section is to provide an insight into the model and the role of transportation within its context; for a more detailed explanation, the work by Redding and Turner (2015) is recommended in addition to the above-named papers.

Within the model there exists a set of locations where locations $n$ generally refer to consumer regions and locations $i$ to producer regions. The population of representative consumers, $\bar{L}$, is assumed to be mobile across all locations, and are endowed with a single unit of labour which is supplied inelastically. It is further assumed to for each unit $L_i$, only fraction $b_i$ is available as an effective labour unit as fraction $(1-b_i)$ is lost due to the worker’s commuting. The labour supply of any location $i$ is dependent on the level of the local population $L_i$ and the commuting costs $b_i$. The consumer’s utility follows a Cobb-Douglas form with

$$U_n = C_n^\mu H_n^{1-\mu} \quad \text{with} \quad 0 < \mu < 1$$

(2.23)

where $H_n$ is the nontradeable amenity, $\mu$ is the fraction of income spent on tradeable goods, $C_n$ represents the index of tradeable goods, which is assumed to follow a standard form with constant elasticity of substitution $\sigma$ across goods. Further, assuming that producers face the same demand elasticity, and hence charge the same prices across locations, the equilibrium demand for the tradeable goods in location $n$ can be presented by

$$x_{ni} = p_i^{-\sigma}(d_{ni})^{1-\sigma}(\mu v_n L_n)(P_n)^{\sigma-1}$$

(2.24)

where $p_i$ represents the equilibrium price of each variety produced, $P_n$ is the equilibrium price index, $v_n L_n$ is the total income and $d_{ni}$ represents the units of varieties traded. The model assumes trade costs to follow the iceberg trade cost
hypothesis, so that for each unit of the good arriving at location \( n \), \( d_{ni} > 1 \) units of the good have to be shipped. Hence, \( d_{ni} \) is the model’s parameter for measuring proportional trade costs.

Labour represents an input to the production of all goods \( x_i \) so that the total amount of labour needed to produce the tradeable goods in location \( i \) can be modelled as

\[
l_i = F + \frac{x_i}{A_i}
\]

(2.25)

where \( F \) is a fixed cost component affecting labour (with \( F > 0 \)) and \( A_i \) represents the available production technology in location \( i \). Combining the firm’s profit maximisation with the assumption of zero profits, the equilibrium output for tradeable goods \( x_i \) becomes a constant with the form of

\[
\bar{x} = x_i = \sum_{n} x_{ni} = A_i F (\sigma - 1)
\]

(2.26)

Assuming market clearing in the labour market allows to arrive at

\[
b_i L_i = M_i \bar{l}_i = M_i F \sigma
\]

(2.27)

where \( M_i \) is a measure of varieties produced in region \( i \) and \( \bar{l}_i \) symbolises the constant equilibrium demand for labour across all tradeable goods. (2.27) allows to establish the influence of the commuting costs on the amount of produced varieties across the locations, as increases in commuting costs would result in decreases of tradeable goods produced through reductions of available effective labour units. Further, it establishes the link between the production of goods and the population level.

Given the profit maximising behaviour of firms, (2.24) and (2.26) allow to establish a link between the wage levels and the production of tradeable varieties
\[
\left( \frac{\sigma}{\sigma - 1} \frac{w_i}{A_i} \right)^\sigma = \frac{1}{\bar{x}} \sum_{n \in N} (w_n b_n L_n) (P_n)^{\sigma - 1} (d_{ni})^{1-\sigma} \quad (2.28)
\]

Bilateral trade costs \(d_{ni}\) function as a weighting factor for the identification of the total demand for varieties produced in location \(i\), so that given the firm’s total demand, trade costs and productivity parameter, (2.28) represents the maximum wage level that firms in location \(i\) can pay their workers. Transportation enters (2.28) through both transport related factors, trade costs \(d_{ni}\) and commuting technology \(b_n\). Any transportation infrastructure improvements that lead to reductions in commuting costs increase the effective units of labour available directly.

Market access of firms within this context follows the definition\(^1\)

\[
fma_i \equiv \sum_{n \in N} (w_n b_n L_n) (P_n)^{\sigma - 1} (d_{ni})^{1-\sigma} \quad (2.29)
\]

Transportation infrastructure affects the firm’s market access twofold: transportation improvements result in reductions of trade costs of goods, \(d_{ni}\), and lead to increases in commuting technologies \(b_n\). Improvements in the transportation infrastructure directly affect trade costs through transportation cost reductions. Hence, transport improvements increase the firm’s access to markets, and further raise wages through (2.28). Additionally to affecting the wages, improvements in the commuting infrastructure that result in a reduction of commuting costs, allow for an increase of total income and thus raise both the firm’s market access and the wage level. The market access of consumers can be modelled as

\[
cma_i = \sum_{i \in N} M_i (p_i d_{mi})^{1-\sigma} \quad (2.30)
\]

The location of workers is determined by the differences in real income across regions. Hence, workers will move across locations until the point of real income

\(^1\)See Redding and Venables (2004)
equalisation across locations. In the equilibrium, the population of any region $n$ will therefore be

$$L_n = \chi b_n^\mu A_n^{\frac{\mu}{1-\mu}} H_n(f ma_n)^{\frac{\mu}{(1-\mu)(\sigma-1)}} \bar{H}_n(c ma_n)^{\frac{\mu}{(1-\mu)(\sigma-1)}}$$

(2.31)

where $\chi$ represents a function of the common level of real income. From (2.31) information regarding multiple interrelations can be identified: (1) the population in the equilibrium depends positively on the commuting technology, so that any improvements in the commuting infrastructure that reduce the commuting costs of workers through $b_n$ result in increases in the equilibrium population; (2) factors increasing the local productivity parameters $A_n$ further increase the equilibrium population through their impact on wage levels; and (3) growth in the supply of the non-tradeable good further result in a raise of the equilibrium population, e.g. through an increase in housing. Additionally, infrastructure improvements affect the equilibrium population further through reducing the transportation costs of goods. This raises both the firm’s market access and the consumer’s market access parameters, which in turn both raise the level of the equilibrium population. Given the above information, the price level of the non-tradeable amenity can now be summarised by

$$r_n = \frac{(1-\mu)w_n b_n L_n}{\mu b_n}$$

(2.32)

The price of the amenity will hence increase with increases in the level of the wage or the population. Further, both transportation related variables affect the price of the non-tradeable amenity. Changes in the commuting technology directly affect the price of the amenity through their effect on the effective units of labour available, which in turn will raise wages and thus the price of the non-tradeable. Improvements in the transportation infrastructure resulting in a decrease of the
transportation costs of goods lead to an increase of the price of the amenity through their impact on both consumer and firm market access.

Trade within and across regions within the model is assumed to follow the form of a standard gravity equation with

\[
\frac{X_{ni}}{X_{nn}} = \frac{\pi_{ni}}{\pi_{nn}} = \frac{b_i L_i (d_{ni} w_i)^{1-\sigma} (A_i)^{\sigma-1}}{b_n L_n (d_{nn} w_n)^{1-\sigma} (A_n)^{\sigma-1}} \tag{2.33}
\]

where \( X_{ni} \) and \( X_{nn} \) represent the value of trade between locations \( n \) and \( i \), and internal trade in location \( n \) respectively. Similarly \( \pi_i \) represents the trade shares between and within locations. The effect of transportation infrastructure on trade functions through the channel of both of the transportation related variables, commuting technology and trade costs. Any change in the transportation infrastructure that leads to a reduction of trade costs of goods, both within and between regions, will not alter the trade shares as it is assumed to affect the internal and external trade to the same extent. Similarly, any improvements of transportation that allow for a reduction in commuting costs across and within regions will leave the ratio of trade shares unaffected. However, if there exists heterogeneity in the effect of transportation infrastructure on goods across regions, through \( d_i \) or workers through \( b_i \), equivalently for \( d_n \) and \( b_n \), then changes in the transportation infrastructure will also affect the ratio of the distribution and the composition of trade. Further, this may also lead to changes in the distribution of employment and output across sectors.

The model extends its implication further to welfare, as measured in real income, across regions. The underlying rationale stems from regional real income equalisation and the mobility of workers, where workers are assumed to relocate given that the real income in another location is higher than the one previously earned. Hence, changes in population across regions are predominantly driven by
spatial changes in real income. If regions have low domestic trade shares, then they will exhibit a relatively higher level of interregional trade which should lower the index of consumer prices and hence allow for an increase in the real wage level. Workers will relocate to this region, which will in turn raise the regional population. Further, an increase in the local productivity parameter will raise the regional wage level and hence result in further growth of the regional population. Additionally, in cases where the supply of the non-tradeable amenity increases, its price will reduce and hence allow workers to experience a higher level of real income and attract them to relocate to the given region. Also, both commuting technology and trade costs will impact the spatial real wage differences and hence affect the population’s geographic distribution. Improvements in the commuting technology increase the region’s population through their effect on wages, changes in the transportation of goods resulting in the reduction of trade costs affect regional wages and the market access of firms and consumers, and hence affect the regional population level. This allows regions to benefit from the increased gains of trade and regional specialisation which will both result in growth in real incomes. The mobility of the consumers will determine the spatial distribution of the population and hence economic production. Workers will relocate to those regions that have gained relatively more from any changes affecting real income positively. This will increase the regional population and thus demand for the non-tradeable amenity, which will in turn raise its price which will then reduce real income and trigger any additional possible regional relocation. Transportation infrastructure is a crucial factor shaping the distribution of economic activity and population in this model through both channels of commuting and trade costs. In cases where some regions benefit relatively more from transportation infrastructure investments or have received higher levels of it, changes in population growth can be expected to result in a growth of the real income level if the improvements
in transportation have affected the regional real wage level.

This model allows for a more thorough investigation of the role of transportation infrastructure on the economic geography of production by highlighting its effect on both commuting and trade costs patterns and has thus become an important theoretical base within the context of spatial economics.

IV The Empirical Literature

Transportation infrastructure represents an important factor for an economy that crucially influences the general functioning of an economy, its firms and consumers. Firms rely on transportation infrastructure for the smooth logistics of the transportation of the input factors of raw materials, machinery and fuels as well as for the transportation of the goods to their final consumer markets. Transportation infrastructure further affects the economy through impacting commuting behaviour of workers and consumers.

Transportation infrastructure as part of technological growth is an important driver for economic development and growth. Railroads, for example, were a major driver of the economic advances of the industrial revolution and the following decades (see evidence for Prussia by Hornung, 2015; the US by Donaldson and Hornbeck, 2016; India by Donaldson, 2017). Further, the development of the internal combustion engine and the subsequent emergence of automobiles had a significant impact on the spatial economic structure of countries (Glaeser and Ponzetto, 2010). Advances in transportation remain important in current times, especially changes that have allowed for a more efficient use of transport modes have shaped the transportation of goods and people, e.g. the development of container shipping and the increased importance of air transport (Hummels, 1999 and 2007). Transportation infrastructure further is a factor influencing the regional economic structure through its effect on trade within and across regions (Keller

For the transportation of goods, it is often assumed that the incurred transportation costs follow the iceberg cost hypothesis of Samuelson (1954), where it is assumed that the cost of transportation is equal to a certain proportion of the value of the good transported which is then lost due to transportation. Researchers have pointed out that this method of measuring transportation costs is often not supported by the empirical data. Glaeser and Kohlhase (2004), for example, point out that for the fraction of GDP that represents trade in real goods, the observed share of GDP of the transportation sector would be an underestimate of transport costs. Additionally, transportation only enters the GDP under the transportation sector, that is if firms use external companies for the transportation of their goods. In cases where firms have their own fleet for their logistics, the economic value of transportation enters the GDP through the sector of the firm. Further, given that transportation relies on the usage of road and rail networks, which are predominantly publicly financed, the price of transportation incurred by firms underestimates the true costs as it does not include the costs associated with building and maintaining the transportation network (Redding and Turner, 2015).

Throughout the 20th century, the costs of transporting goods have exhibited declines of around 2 per cent p.a. (Redding and Turner, 2015). The costs of transporting goods via rail have reduced by approximately 16 per cent for the US during the last 100 years (Glaeser and Kohlhase, 2004). For road transportation in the US, the development of fuel prices and the heavy regulation of the sector have kept its transportation prices relatively constant over most of the second half of the 20th century. Technological improvements and sectoral deregulation however have allowed for decreases in road transportation costs since the 1980s.
Parallel to the reduction of transport costs over the course of the 20th century, the global trade has experienced a significantly large increase in volume; so that while transportation costs have reduced per unit, the absolute amount of transportation costs remain significant (Hummels, 1999; Limão and Venables, 2001; Clark et al., 2004). Changes in transportation modes and shifts in trade from low value to weight to high value to weight ratios have affected the organisation and structure of transportation, and the distribution of trade across modes. Transportation of high value goods relies predominantly on air transportation, while the transportation of low value to weight goods heavily employs ship and rail transportation. Globally, shipping is the predominant transportation mode for international trade while trucks remain the most used mode for internal trade (Eurostat, 2017; Redding and Turner, 2015).

The transportation of people and workers, and commuting represent a significant share of the expenditures of a household. Estimates of the time required to commute generally range from 40 to 75 minutes per round trips across countries (Schafer, 2000; Redding and Turner, 2015). Depending on whether the whole wage, or half of the wage rate as proposed by Small and Verhoef (2007), is used for the evaluation, this translates to approximately 8 per cent of the value of labour being lost to commuting. Redding and Turner (2015) identify that the relative share of commuting on a total household’s expenditures is around 15 per cent. Investigating this issue further, Schafer (2000) finds significant differences of expenditures between countries and reaches the conclusion that the differences in transportation infrastructure observed between countries can therefore also explain a large part of the spatial organisation of a country. He hypothesised that this is particularly the case for the differences in transportation and economic geography of developing and developed countries. Gimenez-Nadal and Molina (2014) provide further evidence by investigating the role of the commuting distance on hours worked.
using Spanish data. The authors find an increasing relationship between the two variables, where for an extra hour of commuting the daily amount of time worked increases by 35 minutes. The authors hypothesise that this is mostly driven by the influence of housing prices on the worker’s residential location. Gutiérrez-i-Puigarnau and van Ommeren (2010) find similar results from Germany.

In addition to the benefits transportation offers for the efficient functioning of an economy, both through its effects on firms and individuals, transportation does not come without issues. Bilbao-Ubillos (2008) for example investigates the external costs of urban roads and identifies various financial and environmental sources of welfare losses. A faster rate of the depreciation of vehicles, time costs, an increased level of accidents, and negative impacts on the economic value of certain areas within a city all arise from increased congestion levels of roads. He further identifies noise and air pollution as consequences of roads located in dense areas. Parry et al. (2007) investigate the issue of pollution in more detail and find that emissions of carbon monoxide, nitrogen oxides and hydrocarbons in the form of particulate matter have adverse effects on the health of a population. The most common consequences of exposure to these transportation emissions are breathing difficulties, cardiovascular issues, problems with the pulmonary functioning, and lung issues. All of these eventually increase the level of mortality within the population. Emissions further result in the formation of ozone.

The remainder of the chapter is structured as follows: in Section 4.1 I discuss the contributions to the literature analysing the effects of transportation on the spatial distribution of the population, in Section 4.2 the role of transportation for regional output and firm-level economic outcomes will be analysed, Section 4.3 highlights the role of transport for trade and Section 4.4 concludes by presenting transportation literature focusing on developing countries.
IV.I Transportation Infrastructure and Population Dynamics

As the theoretical models of Section 3.3 of this chapter have shown, there exists an interrelationship between transportation infrastructure and the distribution of the population across space. Redding and Sturm (2008) employ the multi-region theoretical structure of the model discussed in Section 3.3.2 and apply it to the context of the distribution of the population across West German cities before and during the division of Germany, and after the reunification in 1989. The authors use the separation of Germany as a natural experiment for a sudden loss of market access. Redding and Sturm (2008) focus on West German cities and argue that the loss of market access from the West to the East of Germany affected real income levels, the cost of living and hence population dynamics through three channels: the loss of market access would (1) decrease the expenditures on tradeables and hence reduce real wages (home market effect), (2) reduce competition and hence increase real wages (market crowding effect) and (3) lessen the access to tradeable goods and hence increase the cost of living and subsequently reduce the real wage level (cost of living effect). Following the division of Germany, the volume of trade across East and West German cities reduced significantly so that the home market and cost of living effect were the dominating factors leading to a reduction of real wages for West German cities. The authors argue that this was particularly the case for cities located within close proximity to the East German border. Redding and Sturm (2008) use a Difference-in-Differences estimation for West German cities within a range of 75 kilometres from the border as the group of treated cities and declare cities further away from the inner-German border as their control group. They identify a relative population decline of 0.75 percentage points within the treated cities which amounts to a cumulative effect of a third compared to the control group cities. They further show that this effect is strongly localised within 75 kilometres of the border. Additionally, they find evidence that
this effect is particularly strong for smaller cities, which they hypothesise is due to a stronger dependence on external market access for these. They further show that the pre-division population patterns partly re-emerge following the German reunification. Another work investigating the role of transportation on spatial population patterns is provided by Bird and Straub (2015) who investigate this relationship for Brazil between the 1960s and 2000s. Bird and Straub (2015) rely on the economic and political development of Brasília as the new capital city as a quasi-experiment. They find very different effects for the Northern and Southern part of the country, where the latter represents the more developed part of the country. The expansion of roads lead to a population and economic concentration around smaller municipalities neighbouring metropolitan areas in the South, and it resulted in dispersion and the development of new smaller regional sub-centres in the North. Bird and Straub (2015) conclude that half of the GPD per capita growth experienced during the investigated period could be attributed to the effects of roads. The authors further find that the expansion of the road network also lead to a reduction of spatial inequality. A significant contribution of this paper lies in its focus on the regional heterogeneity of the effect of road networks and its analyses of the differing effect on peripheral and concentrated regions.

Another strand of literature focuses on the population shaping effect of transportation infrastructure within a historical context. Hornung (2015) investigates the role of the rapid expansion of the Prussian railway network in the 19th century on the population growth of cities. To control for the possible endogenous placement of the railway network, he relies on a straight-line instrument which drafts straight lines between railway nodes and uses these as instruments for the actual railway network. He uses propensity score matching of cities along the railway lines to those without direct access to the network and finds that cities with direct access experienced an additional population growth of 1 to 2 per cent per annum.
He further identifies that these changes were predominantly driven by firm size dynamics. Following the construction of the railway, firms with direct access to the network experienced a growth in firm size which was double in magnitude relative to firms in regions without direct access. He concludes that this resulted in an increased labour demand so that the effect of the railway on population growth was driven through firms and labour demand. Berger and Enflo (2017) investigate this relationship between railways and population growth during the second half of the 19th century for Sweden. The authors employ two instrumental variables to control for a possible endogeneity: a straight-line instrument equivalent to Hornung (2015) and instruments based on previous railway plans. They use a Difference-in-Differences estimation and find that towns along the railway network experienced significant growth in population. Similarly to Hornung (2015), they conclude that this may have been predominantly driven by a relocation and concentration of economic activity towards cities with direct access to the railway network. Additionally, they find little evidence of population convergence with the further extension of the network, and hence deduce that the initial railway network shaped the long-run location dependence of economic activity. Michaels et al. (2012) investigate the development of population patterns across urban and rural regions from 1880 to 2000 for the US. The authors investigate the effects of multiple factors and use a 1947 highway and the 1898 railroad plan as instrumental variables. The authors find evidence that spatial population growth was mostly driven by the differences in the initial share of employment in agriculture and the subsequent relative shifts towards industrial sectors across rural and urban regions.

Changing the focus to a more disaggregate scale, a growing body of literature has focused on the effects of transportation in shaping the dynamics of populations within cities. Baum-Snow (2007) provides one of the most influential papers within
this context. This work highlights the role of highways in shaping the population distribution across urban and suburban districts of US cities between 1950 and 1990. He argues that the highway network was predominantly built for military purposes and is hence independent of urban population dynamics. He additionally uses the 1947 highway plan as an instrumental variable for the actual highway rays built and finds a reduction of 9 per cent of central city population per inner-city highway ray. He further finds that while the population grew by 64 per cent overall and 72 per cent in cities, the central city population decreased by 17 per cent. He concludes that the construction of highways was a predominant factor for the explanation of inner-city population declines. He additionally observes that both firms and residents relocated to suburbs; while in 1950 approximately half of the jobs were located in the inner-city, in 1990 only approximately 30 per cent of jobs remained in cities, so that spatial reorganisation was a significant contribution for the observed patterns. Baum-Snow et al. (2017a) investigate the role of urban railways and highways in shaping the form of Chinese prefectures between 1990 and 2010. They rely on 1962 data on radial roads, railways and indicators for planned ring roads as a quasi-experimental variation for a city’s transportation infrastructure. They find that for each inner-city highway radial and ring road the central city population decreases by 4 and 20 per cent and the industrial GDP reduces by 20 and 50 per cent respectively. The authors conclude that radial highways are a major factor driving the decentralisation of the service sector, while railroads mostly influence the shift of industrial and manufacturing activities to peripheral areas. Baum-Snow et al. (2017a) research several other possible sources explaining the decentralisation of population and economic activities, but find that transportation infrastructure is the dominant factor. In a related work, García-López et al. (2015) investigate the role of the limited access highway network on the spatial distribution of the Spanish population across 123 Spanish metropolitan
regions throughout the years 1991 to 2011. For their identification, the authors rely on three historical instruments: the road network under the Roman rule, the 1760 postal roads of the Bourbons and the network of the main roads of the 19th century. Garcia-López et al. (2015) identify that each highway radial in a central city, leads to a reduction of approximately 9 per cent in the inner-city population and increases the suburban population by 20 per cent. This effect was particularly strong for suburban municipalities with a direct access to the highway. The authors find no effect of the number of highway kilometres on population developments, but identify that for each kilometre closer to a highway ramp, the density growth of a municipality increased by 8 per cent. Focusing solely on the metropolitan area of Barcelona, Garcia-López (2012) uses the distances to the historical instruments used in Garcia-López et al. (2015), and the distance to the 19th century railway network as instruments for the contemporaneous transportation infrastructure and finds that both highway and railroad improvements result in population growth in suburban areas. He further finds that within the central business district, locations close to railway stations were preferred residential locations. Shifting the analysis to the effects of public infrastructure on residential property prices, Gibbons and Machin (2005) use the opening of the Docklands light rail line in London during the 1990s as a treatment on real estate developments. They use a Difference-in-Differences approach where the treated group consists of postcode wards that experienced changes in their railway access, measured in terms of distance to the nearest station; those that were not affected by the Docklands light rail line constitute the control group. The authors find that properties located within 2 kilometres of the new station and that experienced a reduction of distance to a station of around 1 kilometre exhibited a 2 per cent increase in value. They conclude that subway stations were not chosen at random but were rather decided with the criteria of expected property value developments. They further find
evidence that households value public transportation access relatively more than other urban amenities.

Duranton and Turner (2011) highlight another aspect of transportation within cities by investigating the role of road kilometres and congestion across US cities. They use historical instruments of a 1947 highway plan, the 1898 railroad network and exploration routes between 1528 and 1850 for contemporaneous kilometres of roads. They find evidence that the amount of kilometres travelled by vehicles increases proportionally to the amount of road kilometres. Therefore, road or public transport extensions do not necessarily reduce congestion. They term their finding as the “fundamental law of congestion”. Hsu and Zhang (2014) conduct this analysis for Japan and find similar evidence.

IV.II The Economic Impact of Transportation Infrastructure on Regions and Firms

One of the first analyses investigating the effects of transportation on economic variables was provided by Aschauer (1989) who investigates the effects of the public transportation infrastructure on an aggregate production function for the US. His results reveal an elasticity of 0.35 of the aggregate production with respect to public infrastructure. He further shows that 55 per cent of this effect stem solely from energy and transportation infrastructure. Fernald (1999) extends Aschauer’s analysis and focuses on a production function where transportation explicitly enters as a separate input factor. His results confirm those of Aschauer (1989). While this literature opened the empirical discussion of the effects of transportation infrastructure, the identification strategies used have been heavily criticised for their simplicity in controlling for a possible endogeneity of transportation and economic variables. Chandra and Thompson (2000) investigate the role of US highways in shaping the county-level economy between 1969
and 1993 by using rural highways as an exogenous infrastructure supply variation. The authors argue that US highways are predominantly constructed to connect large metropolitan areas so that the exact placements of highways between two nodes is not determined by economic factors of rural counties placed between metropolitan areas and along the network. Chandra and Thompson (2000) focus on a sample of 185 rural counties and 391 adjacent counties, and find that while the economic activity of rural counties with direct highway access grew, economic activity in counties adjacent to those with direct access decreased. The authors attribute this mostly to a spatial reorganisation of economic activity. Focusing on the effects of railways, Ahlfeldt and Feddersen (2017) investigate the 2002 opening of a high-speed rail link between the German cities of Cologne and Frankfurt which allowed for a travel time reduction of 55 per cent between the end nodes. Similar to Chandra and Thompson (2000), the authors argue that the rail link was constructed to connect the end nodes and that the exact placement of the rail lines between the cities was exogenous to economic factors of counties along the rail connection. Hence, the variation in rail infrastructure in counties along the route can be used as an exogenous variation in infrastructure provision. Ahlfeldt and Feddersen (2017) use matching methods to match cities along the rail link to a synthetic cohort group of cities closely resembling the treatment group in economic growth variables. Their results reveal that the rail connection led to an 8.5 per cent GDP growth of cities of the treated group within the first six years of the rail line’s opening. Further, they find an elasticity of 12.5 per cent of local GDP with respect to their travel time based market access indicator. Ahlfeldt and Feddersen (2017) show that this effect is highly localised with a reduction of the effect by half for every additional 30 minutes of travel. They additionally identify an elasticity of 3.8 per cent of per worker output with respect of economic density along the rail line. Qin (2017) highlights the effect of high-speed rail in China
across the years 2004 to 2007. The author investigates the effect on non-targeted rural counties along the rail link and finds, differently from Ahlfeldt and Feddersen (2017), that following the opening of the high-speed rail links, a reduction of GDP per capita and GPD of around 3 to 5 per cent could be observed. The author concludes that this effect could largely be explained by a simultaneous drop of investments in fixed assets accompanying the rail link opening. Banerjee et al. (2012) provide an additional work on the effects of transportation access and regional development for China. The authors investigate the effect of distance to the highway network on regional GDP and GDP per capita developments. For their identification, Banerjee et al. (2012) construct a hypothetical transportation network of straight lines connecting trading centres to treaty ports and to each other and subsequently use the distance to the hypothetical network as an instrument for the distance to the actual highway network. Their results reveal an elasticity of -0.07 of per capita GDP with respect to distance to the transportation network; they find no effects on GDP growth. Banerjee et al. (2012) focus on the network of roads built during the early years of the 20th century and hence investigate the long-term effects, Faber (2014) on the other hand focuses on the more recent development of the Chinese National Trunk Highway System between 1992 and 2005. Faber (2014) follows the same identification strategy as Ahlfeldt and Feddersen (2017) and Chandra and Thompson (2000), and investigates the effects of the highway extension on non-targeted peripheral counties along the network. He drafts two instrumental variables, one following a least cost highway route plan and one of Euclidean distances between nodes, and argues that these would have been likely alternative routes for the highway network. Faber (2014) employs Difference-in-Differences and the instrumental variables and finds reductions of total GDP, industrial GDP and government revenues throughout the treated peripheral counties. He concludes that the decrease in trade costs following
the opening of the highway network shifted industrial output towards urban areas which subsequently reduced peripheral output. Baum-Snow et al. (2017b) conduct a similar analysis and compare regional access to domestic and international markets across Chinese regions. Similarly to Faber (2014), the authors find that increased highway access led to reductions in population and economic output for peripheral regions and equivalent gains of these for urban regions. They further find that better highway access resulted in a shift of specialisation across urban and hinterland regions; while regional centres specialised in manufacturing and service activities, hinterland regions shifted a part of the economic activity from manufacturing to agriculture. Highlighting international market access through a region’s connection to ports, Baum-Snow et al. (2017b) find that regions with increased international market access experienced increases in GDP, population and private sector wages, and that this effect was particularly strong for peripheral regions.

Bogart (2009) shifts the analysis to the context of pre-industrial England between 1692 and 1798. He investigates the effect of roads on per acre land rent by focusing on English turnpikes. He treats parishes closely located to turnpikes as the treatment group and uses the proximity of a parish to trade routes as the instrumental variable for turnpikes. The author finds that a closeness to turnpikes led to a 20 per cent or more increase of the average property income in the surrounding area. Overall, the author derives that 20 per cent of the total growth in land rents and at least 1.65 per cent of national income in the 19th century could be attributed to the turnpike trust. Donaldson and Hornbeck (2016) highlight the role of the US railway network on the agricultural sector at the end of the 19th century. The authors derive a counties’ market access by identifying the lowest cost routes for freight between counties via both waterways and the railway network. They find that increased market access led to an annual raise of 34 per cent
of the agricultural land value. The authors further identify that a hypothetical removal of the complete railway network in 1890 would have led to a reduction of 60 per cent in agricultural land value, which could only partly be offset by the waterway and road network. They further show that regional access was affected by both access to near and far counties. Ahlfeldt et al. (2015a) focus on the role of historic transportation within the urban environment of Berlin. They investigate the interrelationship between public transportation provision and land values during the early construction of the public transportation network of Berlin between 1890 and 1914. The authors rely on a structural panel VAR approach of multiple simultaneous equations to control for any endogeneity in the placement of the public transportation network and find evidence for a bi-directional relationship. They find elasticities of land value with respect to public transportation proximity of 2 and 8.5 per cent for the short and long-run respectively. They further identify a shift from residential to commercial use of land and property within close proximity of the transportation stations which in turn attracted more transportation connections. Ahlfeldt et al. (2015b) further investigate the spatial economy of Berlin by exploiting the division and reunification of Berlin as a natural experiment. They gather employment, land, population and location data on 16,000 statistical blocks for the years of 1936, 1986 and 2006 which represent years before and during division, and following reunification. They find significant heterogeneity in the effects of economic density on productivity patterns. Furthermore, they identify elasticities of 0.07 of productivity with respect to workplace density and 0.15 of amenities with respect to residential density. Investigating the effect of the division of Berlin on its spatial economy, the authors find that the central business district of Berlin, identified via employment and land price patterns, shifted from its historical position in the East to the West during division, but gradually re-emerged in the East following reunification. Further, they show that city blocks
located further away than 250 metres of a 1936 underground station experienced a 13 per cent smaller decrease in price following division than those located within a 250 metres radius.

Shifting the analysis to employment effects, Duranton and Turner (2012) add a crucial paper to the literature. The authors draft a model linking a city’s employment to its initial level of employment and its transportation supply. Applying their model to US highway and city data for the years 1983 to 2003, and using a 1947 highway plan, a 1898 railroad plan and major exploration routes used between the 16th and 19th century as instrumental variables for current transportation infrastructure, the authors find significant effects of highways on shaping urban employment. An increase of 10 per cent in a city’s highway stock results in an employment increase of 1.5 per cent throughout the following 20 years. They further show that an additional kilometre of road infrastructure allocated randomly has larger effects on employment than if it were allocated through the political process. Therefore, the authors derive that roads can partly offset negative population shocks. Jiwattanakulpaisarn et al. (2009) investigate the role of US highways for regional employment further. They use dynamic panel vector autoregressive models and find that annual highway growth leads to employment growth. This effect is driven by growth in highways within the county and its adjacent regions. The authors also find that there exist long-run negative spill-over effects of employment growth for neighbouring counties. Additionally, the results reveal a large degree of heterogeneity in estimated effects which is driven by the different road categories and econometric specifications. Applying the theoretical structure of Duranton and Turner (2012) to German data, Möller and Zierer (2018) use a 1937 Autobahn plan to test its effect on regional employment and wages across German counties. Möller and Zierer (2018) focus on lagged relative changes within the Autobahn network between 1937 and 1994 to identify relative changes in the
labour market between 1994 to 2008. The authors find that an increase of one standard deviation of the Autobahn network resulted in an increase of regional employment of 1.8 to 3 percentage points and an increase of 2.7 to 4.3 percentage points for the regional wage bill. They further find no effect of employment influencing subsequent Autobahn growth. D’Costa et al. (2013) investigate the effect of transportation infrastructure on wages through including urban access changes by using worker-level data for the UK. They show that travel time reductions can lead to increases in wages. However, the authors argue that this effect was predominantly driven by changes in the composition of the work force and sorting effects rather than through increases of wages for local workers. D’Costa et al. (2013) provide additional evidence that individual wages were shown to grow at faster rates in areas with better transportation accessibility. Investigating the role of a different mode of transportation, Sheard (2014) analyses how the existence of airport in US cities affects urban sectoral employment patterns. Employing a 1944 plan for airports as an instrumental variable for current airports, Sheard (2014) finds an elasticity of 0.22 of relative employment in tradable services with respect to the size of an airport. No effects were found on manufacturing, the majority of the non-tradeable sector and total employment, so that the author hypothesises that airports foster specialisation but do not increase overall employment.

Changing the focus to firm-level developments, Holl (2012) examines the role of highways on firm-level productivity through its effect on the firm’s market access in Spain. Holl (2012) derives the firm’s market access measure as a weighted index of travel times which in turn are influenced by the existing highway infrastructure. To control for endogeneity, she uses historical data on postal routes to identify historic market access variables which she subsequently employs as instrumental variables. She identifies three effects: (1) elasticities of firm-level productivity with respect to market access range from 0.03 to 0.07, (2) elasticities
of firm-level output with respect to market access were found to be between 0.05 and 0.10, and (3) elasticities of labour productivity with respect to market access are between 0.03 and 0.05. Furthering her investigation on Spanish firms, Holl (2016) shifts the focus to a firm’s access to highways as a productivity influencing factor. She employs historical instrumental variables based on Roman roads and 1760 postal routes for current highway infrastructure, and uses the distance of a firm’s location to the nearest highway ramp as the transportation measure. She identifies an elasticity of -0.01 to -0.02 of the firm’s productivity in regard to the distance variable. Her results are significantly heterogeneous across subsamples; while firms in urban and suburban regions benefit substantially from highway access, firms located in regions adjacent to these experience negative productivity effects. Additionally, she highlights that benefits mostly accrue to firms of the manufacturing sector and she further shows that firms tend to relocate to locations closer to the highway network. Gibbons et al. (2017) investigate the role of new road infrastructure on employment and labour productivity on firms for the UK. Different from Holl (2012, 2016), who focused on a time of large extensions to the Spanish highway network, Gibbons et al. (2017) analyse the effects of 31 discrete new road schemes between 1998 and 2008 across UK electoral wards. The authors use British firm-level data and measure changes in transportation through changes in the firm’s accessibility determined by minimum journey times along the road network. Gibbons et al. (2017) find growth in employment and the number of firms of approximately 0.3 to 0.4 per cent for locations which have experienced increases in the accessibility index of 1 per cent. Further, their results show reductions in employment, and increases in wages and output per worker at the firm-level. Gibbons et al. (2017) derive that growth in accessibility attracts new firms to these locations, in particular firms that depend crucially on transportation access. This growth in the number of firms subsequently induces growth in the
overall employment of a location. Incumbent firms on the other hand substitute labour with purchases of goods and services, resulting in a decrease of employment at the firm-level. Datta (2012) provides additional evidence on the relationship of highway networks and firms by emphasising the effect of transportation infrastructure on inventory behaviour. Datta (2012) employs the upgrade of the Indian Golden Quadrilateral highway network to conduct a Difference-in-Differences estimation for the years of 2002 and 2005 where the treated group consists of those firms located along the upgraded part of the highway network. He finds that firms of the treatment group reduce their average input stock by 6 to 12 days’ worth of production; he finds no significant effect for firms of the control group. He additionally finds heterogeneity in this effect depending on the distance to the highway network. Furthermore, treated firms were observed to reorganise their production by switching their primary input suppliers, which Datta (2012) interprets as evidence that the highway upgrade allowed for firm restructuring which may have been restrained before. Li and Li (2013) provide similar empirical evidence for China. Ghani et al. (2016) also investigate the upgrade of the Golden Quadrilateral highway network but change the focus to its effect on the Indian manufacturing sector. The authors use firm-level data and define the treatment group as those firms located within 0 to 10 kilometres and the control group as those firms located further than 10 kilometres away from the highway network. Additionally, they employ instrumental variables of hypothetical straight-line connections between nodes and a plan for a highway, that was eventually not constructed, as instrumental variables for the current highway network. The results of Ghani et al. (2016) show that for the treatment group, manufacturing grew disproportionately along the network where the growth can be attributed both to incumbent as well as entrant firms so that the authors deduce that the highway upgrade allowed for more efficient industrial sorting and allocations. Holl (2006) highlights that changes in trans-
portation costs affect firms’ input choices. Additionally, in cases where transport cost reductions result in changes in relative prices of intermediate inputs, it may be optimal for the firm to change its input factor mix. Furthermore, decreases in transport costs can result in an increased firm-level demand if these cost changes translate into reductions of the firm’s final good’s price (Lahr et al., 2005). Barnes and Langworthy (2003) show that firms additionally benefit from better transportation infrastructure through its effect on aiding the lifespan of the firm’s capital stock of vehicles as trucks often depreciate at a slower speed on better quality roads.

The literature outlined thus far in this sub-section only represents a fraction of the available literature on the productivity effects of transportation. I acknowledge the vast literature on this topic, and refer the avid reader to the reviews on the economic impacts of transportation infrastructure provided by Gillen (1996), Boarnet (1997) and Jiang (2001). Additionally, overviews of the literature on the relationship between the economy and public capital can be found in Munnell (1992), Gramlich (1994), Rietveld (1994), Button (1998), Banister and Berechman (1999), Bom and Ligthart (2008 and 2014) and De la Fuente (2000 and 2010). Notable recent thorough analyses of this field provided by Venables et al. (2014) and Melo et al. (2013).

IV.III Transportation and Trade

A different strand of literature focusing on the economic effects of transportation infrastructure investigates its trade fostering impact. Better transportation allows for a reduction in transportation costs and for faster shipping times, hence resulting in an overall decrease of trade costs. Michaels (2008) follows a similar identification strategy to Chandra and Thompson (2000) and focuses on highways in rural, non-targeted US counties. He uses historical instruments based on
historical plans for the highway network and finds that the increase in highway provision reduced trade barriers and therefore increased the trade volume of the counties. He further shows that this lead to a higher demand for skilled manufacturing workers and wage growth for high skill workers in counties where the amount of skilled workers was abundant. It also resulted in a lessening of demand for high skilled workers in the non-treated counties. He further shows that trucking activities grew by 7 to 10 percentage points following the highway extension. Duranton et al. (2014) provide an extensive investigation of the effect of the US interstate highway system on the composition and level of trade between US cities. They base their model on the theoretical outline by Anderson and van Wincoop (2003) and use historical instruments for the current highway stock equivalent to those employed in Duranton and Turner (2012). For improvements in the intercity highway stock, the authors find that a 1 per cent reduction in travel distance between trading counties leads to a growth of trade of 1.4 and 1.9 per cent in value and weight respectively. Investigating the intracity highway stock, the authors’ findings reveal a 5 per cent increase in the city’s exports following a 10 per cent increase of the intracity highway stock. No significant results could be identified for the effect of intracity highways on the city’s exports in value. The authors hence conclude that interstate highways fostered specialisation in heavy goods across cities with improved highway access. Following this paper, Duranton (2015) repeats the analysis for Colombia. He employs similar historical infrastructure variables relying on information of the road network in 1938 and during the time of colonisation and finds that his results indicate that intercity roads shifted the economic activity of Colombian cities towards lighter tradeable goods. These results are in contrast to the results identified by Duranton et al. (2014) for the US. He shows that increases in the travel distance between trading cities of 10 per cent result in trade reductions of 7 and 6 per cent of trade expressed in value and weight.
respectively. For the effect of intracity roads, he determines that urban exports grow by 3 and 5 per cent in weight and value respectively following a 10 per cent increase of intracity roads. Conversely to the Duranton et al.’s (2014) work on the US, no strong evidence for a specialisation fostering effect of road infrastructure can be found for Colombia. Providing further insight into the role of roads for trade in Colombia, Blyde (2013) examines the effect of a hypothetical upgrade of road quality for exports. He employs data on export flows, road quality and transport costs and finds that an upgrade of the road quality would only result in a small increase in the level of exports. His results also indicate heterogeneity across the results, where the benefits of improved road quality would disproportionately accrue more to hinterland regions that have relatively larger parts of bad quality roads within their road connection to the country’s ports. Volpe Martincus et al. (2017) study the effect of domestic roads on national exports for Peru. They employ historical information of Incan roads for the current Peruvian road stock and investigate the economic effects of a 10 per cent road network growth in the early 2000s. The authors determine that following the expansion of the highway network, national exports grew by 6.4 per cent annually and total employment grew by 5.1 per cent. They argue that the increase in roads lead to an increase in exports which subsequently fostered a higher demand for workers and therefore raised employment. Volpe Martincus and Blyde (2013) use a different identification strategy to explore the effect of transportation supply on national trade. The authors rely on Chilean firm-level data and investigate the influence of roads on trade by using the 2010 earthquake and the simultaneous destruction of parts of the road network as a natural experiment that results in an exogenous variation in the road stock. Using a Difference-in-Differences estimation, the authors find that the reduction in available roads resulted in a direct decrease of shipments and hence a decline of exports. Furthermore, they find that large firms with non-
differentiated products were particularly negatively affected. Coşar and Demir (2016) investigate a large road upgrade programme in Turkey and its effects on national trade levels. Employing the initial share of expressways across counties as an instrumental variable for the road stock following the upgrade, the authors find that counties that had the largest increases in infrastructure, and hence connectivity, also experienced the relatively largest growth in trade. Additionally, trade levels grew especially for time-sensitive goods.

The above outlined literature highlights the role of transportation in determining trade levels and patterns. Further details and insights for this topic are for example provided by Hummels (1999), Anderson and van Wincoop (2004), and Jacks et al. (2008).

IV.IV The Effects of Transportation Infrastructure on Economic Development

While the majority of the research to date has focused on developed countries, infrastructure has similarly been identified as an important driver for economic development in developing countries. Additionally, insufficient infrastructure has been proven as a crucial impediment for development. This notion is supported by findings of The World Bank (2005), which regularly surveys firms and entrepreneurs doing business in developing countries for their World Bank Investment Climate report. The report has identified that 20 per cent of the surveyed sample of East Asia and Pacific, and 55 per cent of the Middle East, North Africa and Latin America find insufficient electricity, telecommunications and transport infrastructure a severe obstacle to doing business. Calderón and Servén (2004b) estimate the effects of infrastructure on GDP using a large panel of 120 developed and developing countries from 1960 to 2000. Their infrastructure index includes both infrastructure quantity and quality, and their results indicate that GDP growth is
positively influenced by all included infrastructure factors.

Donaldson’s (2017) work on the historical effect of the colonial railroad system in India for the 19th and early 20th century provides an important contribution to the understanding of the role of infrastructure for economic development. He argues that the colonial railroad system was primarily built for military purposes and its development is hence orthogonal to any economic factors. Given that the agricultural sector was predominant for the economy, his identification strategy relies on the comparison of developments of an annual index of agricultural goods across districts with railroads, those without railroad access and those districts for which railroads lines had been planned but never constructed. His findings show that railroad access significantly reduced trade costs and increased interregional and international trade volumes. This lead to a reduction of interregional trade gaps. Additionally, he finds that access to railroads generated real income levels to grow by 16 per cent and raised real agricultural income per unit by 17 per cent in districts with railroad access relative to those without between 1870 and 1930. He determines that given the national increase of real agricultural income of 22 per cent during the period investigated, the relative increase of 17 per cent for treated districts allows to conclude that the effects of the railroad network represented the equivalent of 40 years of economic growth. Asher and Novosad (2016) contribute additionally to the investigation of infrastructure and the Indian economy. The authors investigate the role of a rural road construction programme that connected 100,000 villages to the paved road network. Using the fuzzy regression discontinuity framework, Asher and Novosad (2016) find a decline of 10 per cent in households and workers engaged in agriculture. They argue that this decline is accompanied by an equivalent 10 per cent rise in the labour market participation. This provides support for the notion that the increased road infrastructure supply allowed for a better access to external labour
markets which subsequently lead to a reallocation of the labour force from agriculture to wage labour. Additionally, they find that this effect is strongest for villages within relative close proximity to urban centres where workers tend to seek urban employment rather than employment within firms of their own village. Focusing on the regional level in India, Lall (2007) uses a pooled data set of Indian states and finds that transportation and communication infrastructure significantly and positively affects state-level output growth. Additionally, he identifies that the influence of transportation and communication on economic growth is larger in lagging states. Focusing on a different aspect of infrastructure, Duflo and Pande (2007) analyse the effects of dams on productivity and the agricultural sector in India. They use data on the river gradient as an instrumental variable for the existence of a damn within a district and compare economic factors in districts close to and downstream from the damn. For districts with dams, they find an increase in the level of poverty and vulnerability to rainfall shocks and no significant effect for productivity. Conversely, in districts located downstream from a damn, they find significant growth in agricultural production accompanied with reductions in the vulnerability to rains and poverty levels. Overall, they deduce that dams have significant distributional effect for the economy at the district-level. Gonzalez-Navarro and Quintana-Domeneque (2010) investigate the economic developments following a road paving programme across slums in Mexico. They find that households along paved roads experienced subsequent increases in their credit approval rate which in turn resulted in higher per capita expenditures and ownership of motor vehicles. They also find that the values of houses along paved roads grew by 15 to 17 per cent. In comparison for example to the work by Donaldson (2017), where changes in economic factors following the increase in transportation supply came predominantly through changes in transport costs, the work by Gonzalez-Navarro and Quintana-Domeneque (2010) highlights
the wealth effect of transportation infrastructure through its effects on land values. Jedwab and Moradi (2014) conduct a further analysis of the historical effects of rail infrastructure for the economy. Jedwab and Moradi (2014) gather data on the railroad network throughout Africa, and Ghana in particular, which was predominantly built under colonial rule and examine its effect on the subsequent economic developments. Controlling for possible endogenous placements, the authors use information on planned alternative rail lines that have previously been proposed but never been built as an instrumental variable, and find that railroads had a significant effect on agriculture and urbanisation across Africa. Following the declarations of independence of many African countries, the rail network collapsed due to mismanagement and inadequate maintenance. However, despite the breakdown of the rail network itself, cities along the rail network benefited further from the increased levels of coordination and organisation set up pre-independence by attracting investment post-independence. The authors conclude that the rail network substantially influenced the spatial economy of African countries in the long-run. Storeygard (2016) additionally adds to the research on the spatial economic geography of Africa. He focuses on urban income and intercity transport for 287 small cities between the years of 1992 and 2008. He uses night lights data\textsuperscript{2} to measure a city’s income level and interacts fuel prices with road distances between cities as his transportation variable. He argues that both intra-city distances, which vary across space but not across time, and fuel prices, which represent a significant part of a truck’s operating costs and vary across time but not space, influence the transportation costs of goods. Storeygard’s (2016) results show an elasticity of -0.28 of the city’s economic activity with regard to his transportation variable for cities located within 500 kilometres of ports. He further finds that doubling the distance from a city to the nearest port results in a 6 per cent de-

\textsuperscript{2}See Henderson \textit{et al.} (2012)
crease of the city’s GDP. His estimations also reveal heterogeneity across city types where large effects of transportation are identified for cities with paved road connections to ports and small effects are found for cities with unpaved connections to ports. He argues that for the latter category of cities, transport costs to secondary trading centres are relatively more important than those to ports. Bonfatti and Poelhekke’s (2017) work proposes a different option to solve the missing data issues experienced for many developing countries. The authors investigate the effects of transportation on trade across African countries by employing the number of mines within a district as the instrumental variable for road infrastructure. They argue that the majority of transportation infrastructure was constructed to connect mineral mines to ports, and therefore the number of mines represent a suitable instrumental variable for roads. The authors find that higher numbers of mines are on average associated with a larger international trade volume and reduced trade with the country’s neighbours. Conversely for landlocked countries, more mines are generally linked to a relatively higher amount of trade with neighbouring countries. The authors argue that this pattern is explained by the fact that roads connecting to mines were by definition constructed to establish connections to ports and hence to international markets rather than to neighbouring countries. For landlocked countries however, road connections from mines to ports have to run through neighbouring coastal countries and hence represent increased transportation supply to a landlocked country’s neighbours.

Further details on the role of transportation infrastructure for developing countries can for example be found in Straub (2008).
Chapter 3

The Methodology of Production

Function Estimations and Its Difficulties
I Introduction and Aim

The estimation of firm-level productivity parameters and elasticities has become a standard method to identify the underlying and structural factors of productivity, the heterogeneity of productivity levels across industries, regions and product types, and to evaluate the effects of various economic policies. The research on productivity parameters has for example been used to evaluate policies on trade liberalisation (De Loecker, 2011), firms’ export patterns (Amiti and Koning, 2007) and the degree of foreign ownership (Javorcik, 2004). In the context of the research focusing on the effects of the transportation network on firm-level performance, productivity has foremost been used to identify the effects of market access or transportation cost and times changes on firms (Holl, 2012). While productivity estimation has become a useful option to investigate firm-level patterns, the estimation remains empirically complex.

The majority of studies rely on the standard neoclassical Cobb-Douglas production function. The neoclassical production function can be drafted as static, when including only temporaneous variables, or dynamic, when including also lagged variables. Alternatively to the Cobb-Douglas form, production functions are also occasionally modelled along a trans-log form which is less restrictive than the Cobb-Douglas version and allows for more flexibility. Based on the ease of the implementation and the interpretation of the neoclassical form, this work uses the following general Cobb-Douglas production function structure

\[ Y_{it} = K_{it}^{\beta_K} L_{it}^{\beta_L} M_{it}^{\beta_M} \Omega_{it} e^{\gamma_t + \delta_s + \eta_i + \varepsilon_{it}} \]  

(3.1)

where \( K_{it}, L_{it}, M_{it} \) represent the firm \( i \)'s capital stock, labour and intermediate input levels, and \( Y_{it} \) is the firm’s output variable, e.g. value added or revenues, at time \( t \). The firm’s production is further influenced by time effects \( \gamma_t \), sectoral
and/or regional time-invariant effects $\delta_s$, and firm specific fixed effects $\eta_i$. $\Omega_{it}$ represents the Hicksian neutral total factor productivity parameter (TFP), which is assumed to affect all input factors’ marginal products simultaneously and hence does not affect the relative distribution of the input factors within the production. The firm’s TFP is generally unobservable to the researcher, however factors influencing it may be observed by the firm, e.g. managerial quality, soil quality or expected down-time due to machine maintenance. $\Omega_{it}$ may hence also influence the firm’s input factor choices. TFP is in some cases assumed to be constant over time or specified to be dynamic and contain productivity shocks. The error term is $\varepsilon_{it}$ is assumed to be non-predictable to the firm and hence does not affect input choices. The error term is further assumed to independent and identically distributed. In some cases, $\varepsilon_{it}$ is assumed to be serially correlated, e.g. in cases of serially correlated measurement errors in the left-hand side variable. Depending on the underlying dataset employed, studies may also incorporate further input factors into a production function, e.g. energy consumption or multiple labour inputs differing on the skill level. Within the context of Cobb-Douglas production functions, it should further be noted that the sum of the coefficients of the input factors allows for an interpretation of the firm’s returns to scale.

A log-linear transformation of the above (3.1) results in

$$y_{it} = \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \omega_{it} + \gamma_{it} + \eta_i + \delta_s + \varepsilon_{it}$$

(3.2)

where the lower-case letters represent the logarithmic version of the variables. Commonly used across the empirical literature, log-linear transformations of Cobb-Douglas production functions allow for a linear estimation.

The specification of the productivity parameter can be modelled along two different approaches. If it assumed that there exists no autocorrelation within the productivity parameter (Griliches and Mairesse, 1998), the productivity parameter
\( \omega_{it} \) follows the general form

\[
\omega_{it} = \alpha_{it} + \varepsilon_{it}
\] (3.3)

where if \( \alpha_{it} \) is known to the firm and it will influence the input choices, however it is not directly measurable or observable to the researcher, and \( \varepsilon_{it} \) is the error introduced through data measurement issues or computational factors.

If there is assumed to be serial correlation present within the productivity parameter (Blundell and Bond, 2000), then the productivity term generally follows

\[
\omega_{it} = \rho \omega_{it-1} + \varepsilon_{it}
\] (3.4)

where \( \omega_{it} \) represents the autoregressive productivity term and \( \varepsilon_{it} \) represents any shock or other deviations from it.

The remaining part of this chapter is based on the model of equations (3.2) and (3.3) if not otherwise specified, specification (3.4) is discussed in Sections 3.4 and 3.5 of this chapter. The following text is structured into two sections; while the former highlights the different sources of biases that will have to be controlled for empirically, the latter focuses on the different estimation strategies commonly used in the field of production function and productivity estimation.

## II Estimation Issues

### II.I Simultaneity and Endogeneity Bias in Input Choices

One of the most prominent sources of biases stem from the influence of unobserved productivity and productivity shocks on the firm’s choice of inputs. Given the unobservability of firm productivity, this influence results in a correlation between the error term, containing the productivity parameter, and the observed
inputs (De Loecker, 2011; Griliches and Mairesse, 1998). Furthermore, expectations of productivity shocks may additionally influence the firm’s input choices resulting in further correlation between the error term and the input factors (Olley and Pakes, 1996). Initially identified by Marshak and Andrews (1944), this bias resulting from these correlations is also referred to as the simultaneity bias.

If shocks to productivity are expected to be positive, the firm would adjust their production factors accordingly, i.e.

\[ E(x_{it} | \omega_{it}) > 0 \quad \text{where } x_{it} = (k_{it}, l_{it}, m_{it}) \quad (3.5) \]

Given that input factors differ in their flexibility of adjustment, the choice of input factors that are relatively more freely variable, i.e. labour and materials, can be adjusted faster to productivity developments than quasi-fixed or fixed production factors, i.e. capital (Van Beveren, 2012). Hence, productivity changes will particularly affect the firm’s choices for those input factors which can be easily adjusted. Further, in the presence of an autocorrelated productivity parameter, input choices will further be influenced by the serial correlation in the productivity term.

Granted that the input factors exhibit a positive correlation with the error term, the influence of unobserved productivity on the firm’s production factors will result in biases in opposite directions for variable and (quasi-) fixed input factors if not controlled for. A positive expected productivity development would result in an increased level of variable inputs employed by the firm and hence lead to an upwards bias in the estimated coefficients of these inputs. Conversely, the coefficient of fixed input factors would exhibit a downwards bias stemming from the lesser degree of influence of the productivity term on (quasi-) fixed inputs. Additionally, given the higher degree of sensitivity of variable inputs to changes in productivity, the correlation between variable inputs and productivity is expected
to be larger, and hence the resulting bias in the estimated coefficients can also be expected to be relatively larger than those biases expected for quasi-fixed and fixed inputs (Ackerberg et al., 2007).

Overall, if the influence of productivity on input choices is not controlled for in the estimation, an upwards bias of TFP for firms that are relatively more capital intensive in the production and a downwards bias of TFP for relatively less capital intensive firms can be expected.

II.II The Empiric Relevance of the Simultaneity Problem

In the context of research focusing on the relationship between transportation and firm-level productivity, transportation infrastructure can increase the attraction of a region and hence, similar to productivity growth, result in increases in input factors through increased levels of investments and labour demand (Crafts, 2009). Furthermore, if transportation investment is endogenous, i.e. regions with higher (expected) productivity growth receive a relatively larger investment or extension to their transportation infrastructure, and if this is not controlled for, then the TFP of firms in these regions would exhibit an upwards bias. Conversely, a bias in the estimated TFP would also occur if increased levels of transportation investment are placed to stimulate productivity growth in lagging regions (Holl, 2016). If the above-mentioned issues are not controlled for, e.g. under OLS, then the estimation results will be biased where the bias can be expected to be larger for those variables relatively more influenced by TFP and through this by regional factors.

II.II Selection Bias

Another essential source of biases to be addressed in the context of firm-level productivity estimation are the biases stemming from the endogeneity of the firm’s
market exit and entry decisions. While this issue was first formally identified by Wedervang (1965), the selection bias of surviving firms remains a potential problem for TFP estimations\(^3\). Firms base their decision of exiting the market, or remaining and subsequent input choices, on current and expected TFP developments, hence the sample of surviving firms is limited to those whose probability of survival is sufficiently high to remain in the market. Following the model that Olley and Pakes (1996) outline, the rationale for firms exiting the market lies in the comparison of its variable profits and its selloff or liquidation value. The firm would exit the market when the variable profits are lower than the selloff value of the firm or alternatively, the firm will not exit the market given its variable profits are at least as large as the firm’s selloff value. The firm’s productivity parameter and its capital stock will influence both the selloff value and its variable profits, hence resulting in endogeneity in the firm’s exit decisions. Further, given that firms with a higher capital stock may be able to survive with a lower degree of TFP, relative to those with a lower capital stock level, this endogeneity in the exit decisions additionally results in a negative correlation between productivity and capital in the surviving firms and a possible downward bias in the estimated capital coefficient. Even if the capital stock may be exogenous in a cross-sectional sample, it remains present in a within sample. This leads to a downwards bias in the estimated capital coefficient and an upwards bias in the estimated TFP. This issue remains particularly crucial for estimations based on balanced panel data sets as these are by definition restricted to only include surviving firms (Van Beveren, 2012). Within the context of balanced panel data, an additional upwards bias in the estimated TFP can be expected.

\(^3\)For empirical evidence see Fariñas and Ruano (2005) for Spain and Dunne et al. (1988) for the US
II.II.I Selection Bias within the context of Economic Geography literature

Across the research field of transportation infrastructure and productivity, this issue arises in particular if changes in transportation result in changes in the degree of firm’s competition. If changes in the transportation network result in lower transport costs, firms are able to reach larger and geographically more distant markets. This will increase the level of competition for firms, and will subsequently force less productive firms to exit the market. Additionally, this will result in an increased pressure of surviving firms to increase their productivity and subsequently raise the market’s overall TFP level (Baldwin and Okubo, 2006; Melitz, 2003). Furthermore, in this context transport changes may also increase the pressure of surviving firms to specialise given the heightened importance of comparative advantages to survive in markets with a higher degree of competition (Bougheas et al., 2000).

II.III Bias due to Heterogeneity in Prices

The standard firm-level data used for the estimation of production functions and TFP is supplied in monetary units, especially for the output variable and the input variables of capital and materials. It is a general procedure to deflate the monetary units of the production factors by industry-level price indices to obtain a proxy of the quantities of these variables. Given that firm’s input and output choices are influenced by their respective prices levels and that the underlying assumption of common input and output prices across the sector does not hold, i.e. in the presence of imperfect competition, the differences in prices within sectors will result in a further bias in the production function and productivity.
estimation. This issue can be formalised as

\[
y_{it} + (p_{it} - \bar{p}_{it}) = \beta_{0} + \beta_{k}(k_{it} + (p_{it}^{k} - \bar{p}_{it}^{k})) + \beta_{l}(l_{it} + (p_{it}^{l} - \bar{p}_{it}^{l})) + \beta_{m}(m_{it} + (p_{it}^{m} - \bar{p}_{it}^{m})) + (p_{it} - \bar{p}_{it}) + \omega_{it} + \epsilon_{it}
\]

where $\bar{p}_{it}, \bar{p}_{it}^{k}, \bar{p}_{it}^{l}, \bar{p}_{it}^{m}$ represent the industry-wide, and $p_{it}, p_{it}^{k}, p_{it}^{l}, p_{it}^{m}$ the firm-level prices of the given variables. In the presence of an influence of the unobserved firm-level prices on the firm’s input choices, the following will hold

\[
E(x_{it} | p_{it} - \bar{p}_{it}) \neq 0 \quad \text{where } x_{it} = (k_{it}, l_{it}, m_{it})
\]

Hence, in the absence of perfect competition and a difference between industry and firm prices a non-zero correlation between firm-level prices and input choices would result in a bias in the estimated coefficients of the input factors. If the firm’s input prices are lower than the industry-level prices then the input factor elasticities will be downwards biased and the firm’s productivity will exhibit an upwards bias (De Loecker, 2011; Katayama et al., 2009). In the case where the firm’s input prices are in excess of the industry wide prices, the input factor elasticities will be upwards biased and the firm’s productivity will be downwards biased.

Further, given that input and output are positively correlated, and output and output prices are negatively correlated, a negative correlation between input and firm-level prices is expected. This will result in a negative bias for the coefficients of the variable inputs. If data in quantities is directly available, then this source of bias can be prevented (Eslava et al., 2004; Foster et al., 2008). Alternatively, if data on market demand for the final goods is available, firm-level prices can be identified (Klette and Griliches, 1996; De Loecker, 2011). Klette and Griliches (1996) criticise that the use of common output deflators in the context of imperfectly competitive markets and differentiated products result in a downwards bias.
in scale economies under OLS. They argue that output prices of firms experiencing a cost reduction in inputs larger than the industry average will be lower than the sector’s average price level. However, given that the growth in sales is less than proportional to the growth in output, the use of sales deflated with industry price indices will introduce a bias in the standard estimation methods. They propose an estimation model augmented by industry output growth which allows to identify demand elasticities and scale economies. Applying their model to Norwegian plant level data, the authors find downward sloping demand curves with significant price elasticities which are moderate in magnitude. An alternative approach to correct for price heterogeneity is provided by De Loecker (2011) who uses trade liberalisation in the Belgian textile industry to identify observable shifts in demand. He combines these with a matched plant-product level data set and quota data to determine the separate price, sale and productivity effects. His results allow him to conclude that a correction for price heterogeneity leads to significantly lower productivity elasticities than in the absence of this correction.

If firms exhibit different levels of productivity, then this will translate into the price of the output assumed that the firm is a price setter in the output market. However, the notion of using industry wide price indices assumes homogeneity in output prices across the sector so that in the presence of heterogeneous output pricing a further source of bias is introduced. If the firm’s output price lies below the average industry price level, then the use of the industry wide price deflator would result in an underestimation of the output, and hence in a downward bias in the estimated level of productivity. Similarly, if the firm’s output pricing is above the observed industry price level, using industry prices would overestimate the firm’s output and subsequently overestimate the firm’s TFP⁴.

⁴See Foster et al. (2008) for an empirical comparison of the industry and firm-level price use
II.III.I The Price Heterogeneity bias in the Literature

In the area of the productivity enhancing benefits of transportation infrastructure, this bias is additionally introduced if transportation affects the input prices across firms to a different degree, i.e. transportation may exacerbate the price differences across firms. This issue arises if changes in the transportation network, transportation costs and times affect the relative prices of input factors, so that it would be optimal for the firm to adjust its input choices or input factor mix (Holl, 2006). An example of an explicit incorporation of different factor prices is provided by Graham and Kim (2008). The authors inspect the role of agglomeration economies on total and partial factor productivity, factor prices and factor demands for British firms. They employ a system of trans-log production functions for their investigation.

II.IV Bias in Multi-Product Firms

An additional problem arises in the context of firms that produce more than one product. The use of common output and input price deflators assumes homogeneity in prices not only across an industry but also within a firm. Additionally, the estimation of one firm-level production function is only valid on the basis that a common production function and productivity parameter can be assumed to hold for the entire firm. Additionally, the former named assumptions also incorporate the notion of a common final demand at the firm-level. In the case where firms produce more than one product however, the use of common price deflators, a common firm-level final demand and the estimation of one firm-level production function are no longer valid assumptions. This will result in a bias in the estimation of the firm-level productivity parameter, however across the literature the direction of this bias is not yet unanimously determined (Bernard et al., 2010).

5See Section 2.3 of this Chapter
The problem in this case stems not from an econometric issue rather it stems from the level of disaggregation within the firm. An improvement of the consistency of the productivity estimates here could be achieved through the use of data on the firm's product mix, specific product output and specific product prices. However, empirically these are generally not readily available. Alternatively, firms could also be categorised according to the production of single products. While this would allow for the estimation of product specific productivities, this does not include the notion of possible synergies across the production of different products within a firm. Hence, in a case with positive synergies across products within a given firm, the firm's productivity parameter would exhibit a negative bias (Bernard et al., 2010). In the case where information on the product types the firm produces is available, production functions that allow for different parameters across the products could be estimated (Bernard et al., 2009).

II.IV.I The discussion of Multi-Product Firms within Empirical Research

While there does not yet exist a thorough body of empirical literature on this problem, it suggests itself that in the context of the productivity effects of transportation infrastructure this issue remains. Given that the effect of transportation on the firm's output and productivity parameter is generally estimated at the firm-level (Holl, 2016; Martin-Barroso et al., 2015), the issue of heterogeneity of this effect within the firm is ignored. However, if changes in transportation affect the production parameters, prices and final demand of the different products produced within the firm to a different degree, then this estimation of the effect of transportation on the firm's production parameters will be biased.
II.V Additional Sources of Biases

Further to the empirical identification problems discussed, issues in the measurement of data can be a contributing factor to biases. Output is often observed in monetary units rather than physical units, the firm’s capital stock is often listed as its book value rather than its economic value, and the labour variable is often not disaggregated by the workforce’s different skill levels. All of these factors introduce noise into the measured variables and hence may bias the estimation.

Additionally, possible multicollinearity across the different input factors can further introduce an econometric issue into the production function estimation and hence bias the identified production factors’ coefficients.

III Estimation Methods

III.I The Pooled Ordinary Least Squares Estimator (POLS)

The method of a pooled ordinary least squares estimator represents one of the most fundamental estimation methods used. However, the unbiasedness and consistency of the generated estimates rely crucially on the strict validity of the underlying assumptions. In addition to the assumptions of linearity of the model and independently distributed error terms, the following crucial assumption of exogeneity must be met. Exogeneity within the model is only met if all of the independent variables are exogenous and therefore uncorrelated with the error term and any unobservable effects included in it. Mathematically, this can be represented as

\[ E(x_{it} | e_{it}) = 0 \quad \text{where } x_{it} = (k_{it}, l_{it}, m_{it}) \]  

(3.8)
As long as the independent variables are exogenous, the estimated coefficients will be unbiased. However, the presence of multicollinearity, heteroscedasticity and serial correlation in the data can result in particularly large standard errors, wide confidence intervals and very small t-statistics, and hence reduce the efficiency of the OLS estimates.

In the context of productivity estimations, the fundamental issue lies in the unobservability of the productivity parameter so that the estimated regression relies on the observable production factors and becomes

\[ y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + e_{it} \]  

(3.9)

The productivity parameter becomes part of the error term which can hence be decomposed as

\[ e_{it} = \omega_{it} + \varepsilon_{it} \]  

(3.10)

This incorrect specification of the model results in numerous problems. Given that productivity is part of the error term, and hence not directly explicitly incorporated into the estimation, and additionally given the previously outlined relationship between the input factors and the productivity parameter\(^6\), the correlation between the input factors and the error term can no longer assumed to be zero.

However, if productivity enters as an effect that is random across time, then (3.8) remains true. In this case, the estimates will be unbiased in small samples and consistent in large samples, but not efficient. Hence, one should use a cluster-robust covariance estimator that uses each unit of observation as a cluster in order to obtain the correct standard errors.

\(^6\) See Section 2 of this Chapter
Conversely, if productivity enters as a time-invariant factor that is correlated with the independent variables, then the estimated coefficients will be biased and inconsistent. Mathematically, this yields

\[ E(x_{it} | e_{it}) \neq 0 \]  
where \( x_{it} = (k_{it}, l_{it}, m_{it}) \)  
(3.11)

Given the violation of this fundamental requirement, the estimated coefficients obtained through OLS can no longer be assumed to be valid. In case of endogeneity, the results will exhibit a bias and be inconsistent. The direction of this bias, often referred to as the heterogeneity bias, will be determined by the correlation of each input factor and the productivity parameter. If an increase in the productivity parameter results in an increased use of the input, the input’s coefficient would be overestimated, and hence exhibit an upwards bias. This can be expected for variables that are freely variable and can hence be adjusted to changes in productivity to a higher degree. The coefficient of (quasi-) fixed inputs are by definition not freely adjustable to contemporaneous productivity changes. The coefficients of this class of input factors would hence exhibit a downwards bias.

### III.I.I OLS Estimations within Empirical Production Functions

The majority of empirical work within the context of production function estimations includes OLS estimates. However, due to the large issues with the strict assumptions of the OLS estimator, OLS estimation results are generally limited to the use as benchmarks to results identified through alternative estimators or are used in conjunction with other estimation techniques. Drucker and Feser (2012) for example investigate the impact of large regionally dominating firms on the agglomeration economies and TFP effects of smaller firms located in the same region. They rely on OLS to estimate a neoclassical production function with the standard input factors, regional characteristics, and interaction terms of the
aforementioned for across three years. While OLS has been critiqued for not con-
trolling for endogeneity, and thus resulting in biased estimates, the authors argue
that for cross-sectional analyses, endogeneity biases may be exaggerated, and that
alternative methods used to control for these may introduce additional biases into
the estimation. De Loecker (2007) investigates the impact of a firm’s initial en-
trance into the export market on its TFP level. In this work, he employs OLS for
preliminary analyses testing for structural differences between exporting and non-
exporting firms. Additional examples incorporating OLS estimations are provided
by Ehrl (2013), who uses results obtained via OLS as a benchmark for semipara-
metric estimation results in an analysis of the effect of agglomeration economies
on firm-level TFP, and Holl (2012), who uses OLS in the second step of a two-step
productivity\(^7\) estimation investigating the impact of market potential on a firm’s
TFP.

III.II Two-Stage Least Squares Estimation and Instrumental
Variables (TSLS/IV)

In current empirical economic analyses, the IV approach has become one of
the most commonly used estimation methods in cases when an endogenous ex-
planatory variable, \(x_{it}\), is present. A variable \(z_{it}\) must fulfil two criteria to be a
valid instrument for the endogenous variable. The two conditions are:

\[
\text{Cov}(z_{it}, x_{it}) \neq 0 \tag{3.12}
\]

and

\[
\text{Cov}(z_{it}, e_{it}) = 0 \tag{3.13}
\]

\(^7\)See Section 3.6 of this Chapter
where $z_{it}$ is the instrumental variable, $x_{it}$ is the endogenous variable and $\varepsilon_{it}$ is the residual. The two conditions ensure that the IV is correlated with the endogenous variable (relevance condition), while it is uncorrelated with the error term (exogeneity condition). Both of these conditions jointly guarantee that the IV does not influence the dependent variable directly or through any other channel than through its relationship with the endogenous variable. The two-stage Least Squares (TSLS) estimation proceeds in two steps where in the first step the endogenous variable is regressed on the instrumental variable. In the second stage, the fitted values of the endogenous variables from the first stage are used in the regression of the target estimation.

In the context of productivity estimations, input prices of perfectly competitive markets have been proposed as possible instruments (Ackerberg et al., 2007). However, if firms are price makers, the firm’s prices will be influenced by the firm’s productivity and input factor developments. Hence, in this setting input prices, similar to input quantities, will be endogenously determined, and so are not suitable as instrumental variables. Given that the price of labour, i.e. wages, is often exogenous to the firm, this has been put forward as an alternative instrumental variable. However, wages are generally influenced by the skill level, or human capital, of the employee which in turn is hypothesised to affect the firm’s productivity. Consequently, wages can neither be concluded to be exogenous and are hence also not a suitable instrumental variable (Ackerberg et al., 2007). Additional to the above-mentioned criteria for an instrumental variable, in the context of productivity estimation, the instrumental variable approach requires productivity to evolve exogenously over time (Ackerberg et al., 2007). However, given the possibility of additional factors influencing the productivity development, this assumption is generally problematic if these additional factors are not explicitly included into the model. Exogenous shocks to the inputs, geographical variables or historical
variables have recently become prominent instrumental variables for production function estimations.

III.II.I The Use of TSLS and IVs for Production Function Estimations

For the research on the nexus of production functions and transportation infrastructure, historical transportation networks of roads and rail, or historical transportation network plans are a commonly incorporated feature in IV estimations to address the problem of endogenous placement and simultaneity biases. The rationale for the choice of this instrumental variable is based on the fact that current transportation networks are generally similarly placed as their historical predecessor, but do not affect current firm productivity developments.

A prominent example relying on this estimation strategy is provided by Holl (2012). Holl estimates the effect of a firm’s market potential on its TFP level across Spain. She employs a two-step productivity estimation, where the estimation combines a standard Cobb-Douglas production function in the first-step with an TSLS estimation in the second-step. She controls for the possible endogeneity within a firm’s market potential with historical instrumental variables based on medieval postal routes, and the firm’s location’s market potential at the beginning of the 20th century. Lu et al. (2017) employ the instrumental variable strategy to control for a possible measurement error within their estimation. The authors’ analysis focuses on the impact of the return on road investment through productivity growth rates across Chinese manufacturing firms. Their estimation uses firm productivity growth as a dependent variable, which is determined, among other controls, by an interaction term of the firm’s industry’s vehicle intensity and road growth. Lu et al. (2017) instrument their original vehicle intensity variable with

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8See Section 3.6 of this Chapter
data on industry vehicle share from an alternative source and combine this with a FE estimation. Further work employing a TSLS and IV estimation strategy can for example be found in Holl (2016).

III.III  The Within Estimator of Fixed Effects and First Differences Estimations (FE/FD)

In the existence of firm specific unobservable effects which remain constant over time, an estimator relying on the within information of the data can be used to estimate the firm’s production (Hoch, 1962; Mundlak, 1961; Mundlak and Hoch, 1965). In this context, the production function becomes

$$y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \omega_{it} + \epsilon_{it}$$

(3.14)

with

$$\omega_{it} = \gamma_t + \eta_i + \delta_s + \lambda_{it}$$

(3.15)

where $\lambda_{it}$ is an idiosyncratic transitory shock to the firm’s productivity which is realised after the firm’s decision of its production factors. All other factor influencing $\omega_{it}$ are observable to the firm prior to the firm’s input decision.

The above function is estimated in first (First Differences Estimation) following (3.16) or mean differences (Fixed Effects Estimation) as in (3.17). Alternatively, the model can be estimated with a least squares dummy variable estimator (LSDV) where each fixed effect is treated as a dummy variable. A pooled OLS regression is subsequently run on the independent variables and the dummy variables.
\[ y_{it} - y_{it-1} = \beta_k (k_{it} - k_{it-1}) + \beta_l (l_{it} - l_{it-1}) + \beta_m (m_{it} - m_{it-1}) + (\omega_{it} - \omega_{it-1}) + (\varepsilon_{it} - \varepsilon_{it-1}) \] 

\[ y_{it} - \bar{y}_i = \beta_k (k_{it} - \bar{k}_i) + \beta_l (l_{it} - \bar{l}_i) + \beta_m (m_{it} - \bar{m}_i) + (\omega_{it} - \bar{\omega}_i) + (\varepsilon_{it} - \bar{\varepsilon}_i) \] 

In (3.16) and (3.17) the intercept and any time-invariant factors will cancel out of the equation.

The first differencing or fixed effects estimations remove any time-invariant, observable or unobservable effects, from the estimation, so that as long as the assumption of time-invariance of firm specific effects remains intact, the estimated coefficients on the inputs can be expected to be consistent. Given that \( \lambda_{it} \) is only realised after the firm’s decision on its inputs, its existence does not introduce an endogeneity issue. In the presence of homoscedasticity and identically and independently distributed error terms, the FD and FE estimators are efficient and report the correct standard errors. In the case of heteroscedasticity across or within units or serial correlation within units, a covariance matrix clustered at the level of observation should be used to correct the standard errors.

These estimators only consider within firm changes, and hence solve the problem of endogeneity and, if market exit decisions are only determined by time-invariant firm productivity parameters, also the issue of selection bias (Ackerberg et al., 2007). However, given that these estimators only employ the information within units of observations across time and do not incorporate the cross-sectional information, estimates may often only be weakly identified. Further, it has been noted that this estimator adds the assumption of strict exogeneity of inputs, i.e. conditional on firm heterogeneity, so that input choices cannot be influenced by
productivity shocks (Wooldridge, 2009). Additionally, the demeaning process employed by the FE estimator creates a correlation between the regressor and the error by subtracting the individual’s mean of the dependent and independent variables from their respective variables so that the estimated coefficients and returns to scale are expected to be downwards biased (Nickell, 1981; Grilliches and Mairesse, 1998). It can be argued that the strict set of assumptions, in particular the assumption of $\lambda_{it}$ being only observed after the firm’s input choices and the absence of autocorrelation within the firm’s productivity, cannot be met empirically and hence affect the estimates. Another disadvantage of the use of within estimators stems from it differencing which removes any time-invariant effects from the estimation. Hence, in cases where it is of interest to estimate the effect of any of those time invariant factors on the firm’s production, within estimators cannot deliver any insight. Furthermore, the transformation to fixed effects or first differences may additionally inflate any issues of measurement error which will subsequently additionally affect the estimation results. Additionally, in the context of unbalanced data sets, the use of first differences magnifies missing data points. Further, if there exist time varying unobservable factors influencing the firm’s production, e.g. time-varying productivity, then the estimates identified with the use of within estimators can no longer assumed to be valid.

III.III.I The Application of Within Estimators to Production Function Estimations

Similar to the use of OLS, the application in the empirical literature of within estimators remains limited given its restrictive set of assumptions necessary for its validity. However, given its advantage of controlling for unobserved time-invariant heterogeneity, within estimators are employed to remove unobserved time-invariant factors from estimations or are used in conjunction with other es-
timators throughout the literature.

An analysis relying on a FE estimation is for example provided by Arimoto et al. (2014). The authors investigate the influence of agglomeration economies and firm sorting dynamics on firm-level productivity for Japanese pre-war silk-reeling plants. They estimate a standard Cobb-Douglas production with FE and, based on the assumption of time-invariant firm-level productivity, they interpret the estimation’s residuals as a firm’s annually varying productivity growth. Another work employing a within estimation is provided by Holl (2016), who researches the impact of a firm’s distance to the nearest highway access point on the firm’s productivity. She employs a two-step estimation⁹, where residuals from the first-step Cobb-Douglas production function estimation as used as the dependent variable in the second-step of the estimation. The second-step estimates the impact of highways on firm productivity relying on a combination of a FE estimation with historical instrumental variables, where the medieval postal route and Roman roads’ network are used as instruments for contemporaneous highways to control any endogeneity issues arising from the highways’ placement. A further example including a within estimation is the work of Lu et al. (2017) who investigate the return on road investment through firm productivity growth. They employ a FE estimation to control for endogenous firm market entry and exit which they argue is based on a time-invariant firm specific effect.

III.IV The Difference and System Generalised Methods of Moments Estimators (GMM)

In order to design an estimator that makes less assumptions on the structure of the underlying data, Arellano and Bond (1991) propose an alternative estimator. Following the initial work by Anderson and Hsiao (1981) and Holtz-Eakin

⁹See Section 3.6 of this Chapter
et al. (1988), the Arellano-Bond estimator allows the data to be dynamic, i.e. contemporaneous variables may be influenced by their past values, acknowledges the existence of endogenous regressors within the model and allows for arbitrarily distributed fixed effects that may vary over time or remain constant. Furthermore, apart from fixed effects, idiosyncratic disturbances may be present within the model. These may exhibit specific patterns of heteroscedasticity and serial correlation within units, but must be uncorrelated across individuals. Mathematically, the model can be represented as

\[ y_{it} = \pi y_{it-1} + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \omega_{it} + \gamma_t + \eta_i + \delta_s + \epsilon_{it} \]  

(3.18)

where

\[ \omega_{it} = \lambda_{it} \]  

(3.19)

or alternatively

\[ \omega_{it} = \rho \omega_{it-1} + \lambda_{it} \]  

(3.20)

and it is assumed that

\[ |\pi| < 1 \]  

(3.21)

The Arellano-Bond, or Difference GMM Estimator, first differences the original equation to be estimated and hence removes any unobserved time invariant factors that would otherwise result in a bias from an omitted variable. Subsequently, to control the issue of endogeneity, the estimator instruments the first differences with the lagged values of the endogenous regressors. Mathematically, this can be represented as
\[ y_{it} - y_{it-1} = \pi(y_{it-1} - y_{it-2}) + \beta_k(k_{it} - k_{it-1}) + \beta_l(l_{it} - l_{it-1}) \]
\[ + \beta_m(m_{it} - m_{it-1}) + (\omega_{it} - \omega_{it-1}) + (\varepsilon_{it} - \varepsilon_{it-1}) \]

(3.22)

The first differencing in (3.22) removes any time invariant factors from the estimation. In order to control for the issue of possible endogeneity, internal instruments are employed in the subsequent step. The lagged dependent variable is generally instrumented for with \( y_{it-2} \), strictly exogenous variables are instrumented for with \( (x_{it} - x_{it-1}) \), and endogenous or predetermined variables are instrumented with \( x_{it-1} \) where \( x_{it} = (k_{it}, l_{it}, m_{it}) \). The validity of the estimator depends crucially on the absence of serial correlation within the error so that zero correlation between the internal instruments and \( (\varepsilon_{it} - \varepsilon_{it-1}) \) can be assumed.

However, analyses of firm panel data have identified that input variables are often persistent over time in firms’ productions so that lagged levels are only weak instruments for the first differences in the regressions, e.g. when \( \pi \) is close to 1. Additionally, Difference GMM estimation results often exhibit large standard errors (Blundell and Bond, 2000).

Blundell and Bond (2000) develop an extension to the Difference GMM estimator which adds the additional assumption of zero correlation between the fixed effects and the differences of the explanatory variables, so that

\[ E(y_{it-1} - y_{it-2} | (\gamma_t + \eta_i + \delta_s + \varepsilon_{it})) = 0 \]

(3.23)

This method employs lagged values of the explanatory variables to instrument for current differences and it uses lagged differences as instruments for current levels. The Blundell-Bond estimator, referred to as the System GMM estimator, offers the additional advantage that it performs better for data with a large number
of observations over a finite time horizon. However, this method does not offer a solution to control for the selection bias that may arise from the firm’s market exit decision and the influence of the firm’s productivity on this.

III.IV.I Empirical Applications of GMM Estimators to Production Functions

For the work of transportation infrastructure and production functions, the use of the GMM estimators is particularly useful if the input variables exhibit a large degree of persistence over time and if it is possible that lagged levels of transportation infrastructure affect current firm performance, and hence require a dynamic modelling of the production function. Additionally, if productivity is expected to be influenced by the transportation network, then a two-step procedure where the GMM methodology is employed in the second step to identify the elasticity of productivity with respect to transportation changes is a possible solution to control for the endogeneity in the regression.

One recent work relying on a GMM estimation procedure is put forth by Martin et al. (2011). The authors investigate the effects of agglomeration economies on plant-level TFP across French firms. They employ a two-step estimation, where a Cobb-Douglas production function is estimated with the Levinsohn-Petrin method in the first-step, and a combination of FE and GMM is used in the second step estimation where firm TFP enters as the dependent variable. The authors argue that FE controls for any unobserved time-invariant heterogeneity, whereas GMM controls for any simultaneity issues between firm TFP and agglomeration economies. Another paper relying on a GMM estimation is provided by Jiwattana-

\[\text{98}\]

\[\text{An in depth review of the Difference and System GMM estimators can be found in Roodman (2009)}\]
\[\text{See Section 3.5 of this Chapter for details}\]
\[\text{See Section 3.6 of this Chapter}\]
\[\text{See Section 3.6 of this Chapter}\]
\[\text{See Section 3.5 of this Chapter}\]
kulpaisarn et al. (2012) who analyse the impact of highway capacity expansions on the regional economy of US states. The authors draft a Cobb-Douglas function that follows an autoregressive distributed lag structure of the 1st order where highways and urbanisation variables enter as separate input factors, and estimate this with the System GMM methodology. Another noteworthy work in this context is a recent work by Holl (2012) who uses both a two-step estimation procedure\(^{15}\) combining the Olley-Pakes methodology\(^{16}\) with an IV estimation, and a one-step GMM estimation incorporating internal and external instruments to estimate the effect of market potential on firm TFP. Her results show noticeable similarity across both estimation strategies once external instruments are included.

### III.V The Structural Approaches of Olley-Pakes and Levinsohn-Petrin

The control function approaches of Olley-Pakes (Ericson and Pakes, 1995; Olley and Pakes, 1996) and Levinsohn-Petrin (Levinsohn and Petrin, 2003) incorporate both idiosyncratic productivity shocks and the endogenous market exit decisions of firms to circumvent the biases stemming from selection decisions and simultaneity in input factors. The Olley-Pakes method exploits the influence of productivity on capital through investment to identify firms’ productivity and production function parameters. Levinsohn and Petrin (2003) question the assumption of a strict monotonic relationship between investment and productivity, and propose the influence of productivity on the firm’s intermediate inputs as an alternative identification channel. Both methods draft a framework which does not require additional structures to be assumed in order to identify the firm’s production processes.

\(^{15}\)See footnote 13

\(^{16}\)See footnote 14
III.V.I The Olley-Pakes Estimation Method

Olley and Pakes (1996) draw from the previous models of Hopenhayn and Rogerson (1993) and Ericson and Pakes (1995) to formulate their methodology. The underlying assumption of the Olley-Pakes method stems from the firm’s decision at the beginning of each period $t$ to remain operating or exit the market. This decision is based on the firm’s expected discounted value of net cash flows and its sell-off value. If the firm remains operating then it will subsequently choose its optimal level of variable input factors and investments. The firm’s survival is directly influenced by its productivity level $\omega_{it}$, so that the firm will continue operating if its productivity level is in excess of some lower bound productivity $\underline{\omega}_{it}$. Hence, the firm’s market exit indicator function can be formulated as

$$
\chi_{it} = \begin{cases} 
1 & \text{if } \omega_{it} \geq \underline{\omega}_{it} \\
0 & \text{otherwise}
\end{cases}
$$

(3.24)

where $\chi_{it}$ represents the firm’s survival indicator, so that $\chi_{it+1} = 1$ indicates that the firm will remain operating and $\chi_{it+1} = 0$ that it will exit the market in $t + 1$. $\underline{\omega}_{it}$ is determined as part of a Markov perfect Nash equilibrium which is in turn determined by all factors influencing the firm’s optimisation process.

Assumption I

It is assumed that firms incorporate information on past and present productivity developments into their decision process. Firms have no information on future productivity shocks, or in cases where firms expect future productivity developments, it does not affect the firm’s contemporaneous capital stock $E[\varepsilon_{it} | I_{it}] = 0$.

Assumption II

Firm’s productivity $\omega_{i}$ is expected to follow a first-order Markov process, i.e. this
allows for an autocorrelation in the firm’s productivity parameter, so that

\[ p(\omega_{it+1} \mid I_{it}) = p(\omega_{it+1} \mid \omega_{it}) \]  \hspace{1cm} (3.25)

and

\[ \omega_{it+1} = E[\omega_{it+1} \mid \omega_{it}] + \xi_{it+1} \]  \hspace{1cm} (3.26)

where \( \xi_{it} \) is an innovation parameter with \( E[\xi_{it+1} \mid I_{it}] = 0 \) by definition. Firms have information on the distribution of (3.25), which is stochastically increasing in the productivity parameter, however the firm only identifies accurate information on the productivity term \( \omega_{it} \) once it is realised at time \( t \). Muendler (2007) allows for an alternative specification of the development of the productivity parameter by incorporating both stochastic factors and the firm’s productivity increasing behaviour through growth in investments and improvements in managerial quality.

**Assumption III**
The firm’s capital is accumulated through the process of investments following

\[ k_{it} = \kappa(k_{it-1}, i_{it-1}) \]  \hspace{1cm} (3.27)

so that contemporaneous capital is determined by its past value and the level of investment chosen at time \( t - 1 \), conversely to the variable inputs which are determined at time \( t \). This further excludes a correlation between capital at time \( t \) and the error term at time \( t \).

**Assumption IV**
The firm’s investment process is modelled as
\[ i_{it} = f_t(k_{it}, \omega_{it}) \]  

(3.28)

The above function \( f_t(.) \) allows for heterogeneity in the influence of capital and productivity on investment across time within firms. However, it does not allow for unobserved heterogeneity across firms as it strictly excludes any additional unobservable factors influencing the model (Griliches and Mairesse, 1998; McElroy, 1987); exceptions are those factors which evolve independently over time. The firm’s dynamic inputs, i.e. labour, materials, etc., do not affect the firm’s investment, and hence capital accumulation process.

**Assumption V**

The model critically assumes a strict monotonic relationship between investment and productivity, i.e \( f_t(.) \) is strictly increasing in \( \omega_{it} \)\(^{17}\), so that the investment function (3.28) can be inverted and hence expressed as

\[ \omega_{it} = f_t^{-1}(k_{it}, i_{it}) \]  

(3.29)

Given that assumption II holds and that the productivity parameter affects the marginal production of capital positively, it follows that firms with higher levels of productivity will also exhibit a higher expected future marginal product of capital at time \( t + 1 \) and hence a higher level of investment at time \( t \). The estimation relies critically on this assumption, hence only firms with non-negative investment values can be included in the analysis, consequential all observations with missing information on investment cannot be included in any estimation following the Olley-Pakes methodology. Furthermore, if the standard industry level price deflators are used to deflate input and output variables in monetary units, then

\(^{17}\)see Pakes (1994)
common prices for inputs and output are assumed within an industrial sector, i.e. firms are assumed to operate in identical input and output markets.

Following from the outlined assumption, productivity, which is unobservable to the researcher, can be expressed as a function of the observable variables of capital and investment.

\[ y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + f^{-1}_t(k_{it}, i_{it}) + \epsilon_{it} \quad (3.30) \]

where the exact identification of \( f^{-1}_t(.) \) is non-parametric. Resulting from this, \( \beta_0 \) and \( \beta_k \) cannot directly be identified in equation (30) so these are included in the composite term \( \phi_t(.) \) in equation (3.32) which is subsequently treated non-parametrically.

\[ y_{it} = \beta_l l_{it} + \beta_m m_{it} + \phi_t(k_{it}, l_{it}) + \epsilon_{it} \quad (3.31) \]

with

\[ \phi_t(i_{it}, k_{it}) = \beta_0 + \beta_k k_{it} + f^{-1}_t(i_{it}, k_{it}) \quad (3.32) \]

where (3.31) is estimated semi-parametrically. The Olley-Pakes model follows Newey (1994) to estimate (3.31) with a higher-order polynomial and a full set of interactions in \( i_{it} \) and \( k_{it} \). Equation (3.32) can be approximated by polynomials of the 3rd or 4th order.

The estimation proceeds in two stages.

**First Stage Moment**

The first stage relies on the moment

\[ ^{18}\text{In the original research paper by Olley and Pakes (1996), the firm’s age is added as an additional factor in the production function, for simplicity this is omitted here} \]
which allows for the consistent identification of the coefficients of the variable inputs, i.e. $\hat{\beta}_l$, $\hat{\beta}_m$ and $\hat{\phi}_t(k_{it}, i_{it})$, where the latter can be interpreted as estimated capital and investment coefficients of all orders. Investment functions as a proxy to control for the correlation of the productivity and the firm’s variable inputs.

Second Stage Moment

The second stage of the estimation relies on the firm’s information on survival $\chi_{it+1}$ and on the validity of assumptions I and II which imply that the productivity term can be decomposed further as

$$\omega_{it} = E[\omega_{it} | I_{it-1}] + \xi_{it} = E[\omega_{it} | \omega_{it-1}, \chi_{it} = 1] + \xi_{it} = g(\omega_{it-1}) + \xi_{it}$$

(3.34)

where $g(\omega_{it-1})$ represents the expectation of productivity at time $t-1$ conditional on the firm’s survival probability and hence includes information of the lagged values of $\hat{\phi}_t(k_{it}, i_{it})$ and capital. Substituting equation (3.34) into the production function and relying on the definition of $\phi_t(.)$ yields

$$y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + g(\omega_{it-1}) + \xi_{it} + \varepsilon_{it}$$

$$= \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + g(\phi_{t-1}(k_{it-1}, i_{it-1}) - \beta_0 - \beta_k k_{it-1}) + \xi_{it} + \varepsilon_{it}$$

(3.35)

(3.35) can be estimated by polynomials of higher-order expressions of $\hat{\phi}_{t-1}(k_{it-1}, i_{it-1})$ and $k_{it-1}$. Generally, the estimation of (3.35) is comparable to that of (3.32), however the existence of capital both in its contemporaneous value and in lagged values in the approximation of $g(\omega_{it-1})$ makes the estimation of (3.34) more complex so
that (3.34) is generally identified with a non-linear least squares estimation. By definition $E[\xi_{it} | I_{it-1}] = 0$ and $E[e_{it} | I_{it-1}] = 0$ following from $E[e_{it} | I_{it}] = 0$, so that the second stage moment of the estimation is

$$E[\xi_{it} + e_{it} | I_{it-1}]$$

$$= E[y_{it} - (\beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + g(\phi_{t-1}(k_{it-1}, i_{it-1}) - \beta_0 - \beta_k k_{it-1})) | I_{it-1}]$$

$$= 0$$

(3.36)

where the first stage estimates of $\hat{\beta}_l$, $\hat{\beta}_m$ and $\hat{\phi}_{t-1}$ are inserted into the second stage moment to identify the remaining production function parameter of $\hat{\beta}_k$.

TFP parameters can subsequently be identified by using the identified parameters of $\hat{\beta}_l$, $\hat{\beta}_m$ and $\hat{\beta}_k$ within a standard Cobb-Douglas production framework to obtain the estimated residuals.

The Olley-Pakes method uses the functions $\phi_t(.)$ and $g(.)$ in the first and second stage moments of equations (3.33) and (3.36) to estimate the production function, where $\phi_t(.)$ and $g(.)$ can be also generally be interpreted as IV estimators (Wooldridge, 2009) or as semi-parametric moment restrictions (Ai and Chen, 2003).

Empirical comparisons reveal that estimates obtained via the Olley-Pakes method tend to generally be higher for the firm’s capital and lower for the firm’s labour compared to those obtained via OLS and FE estimators. This lends further support to the existence of selection and simultaneity issues biasing estimations if not controlled for. Additionally, Olley and Pakes (1996) further compare the performance of OLS, FE, and the Olley-Pakes estimator across balanced and unbalanced panels. The identify a nearly 100 per cent increase in the capital coefficients and a reduction of the coefficient of labour by 20 per cent in unbalanced panels compared to balanced panels under FE and OLS. Under the Olley-Pakes method,
an estimation on an unbalanced panel resulted in a labour coefficient estimate 15 per cent lower and capital coefficient 12.5 per cent higher than the results obtained via OLS.

III.V.II The Levinsohn-Petrin Estimation Method

The Olley-Pakes approach is critically based on the assumption of monotonicity in investment, so that only observations with non-negative and non-missing investment data can be included in the analysis. However, as firms do not necessarily invest in each period, this restriction of the sample to only these observations will result in a significant reduction of the sample, and hence generates a loss in efficiency. Given that firms’ production processes continually require intermediate inputs, i.e. materials, fuel, electricity, Levinsohn and Petrin (2003) propose these as an alternative observable proxy variable for the firm’s unobservable productivity parameter.

The Levinsohn-Petrin approach employs assumptions I through III of the Olley-Pakes method and similarly also assumes identical input and output markets for the operation of firms, but it formulates alternative versions of assumptions IV and V.

Assumption IV - LP

While assumption IV under Olley-Pakes focuses on the firm’s investment decision, Levinsohn-Petrin focus on the role of the firm’s intermediate input demand function with

\[ m_{it} = f_t(k_{it}, \omega_{it}) \]  \hspace{1cm} (3.37)

where the choice of firm’s intermediate inputs is determined by the stock of the firm’s fixed input, i.e. capital, and the productivity term (Assumption IV). The
firm’s level of labour $l_{it}$ and materials $m_{it}$ are chosen once the level of productivity $\omega_{it}$ can be observed by the firm at time $t$ so that all factors influencing the firm’s intermediate input demand function, except the unobservable productivity parameter, are observable to the researcher.

**Assumption V - LP**

Similarly to Olley-Pakes, Levinsohn-Petrin require that the variable used as a proxy to determine productivity exhibits strict monotonicity in the productivity parameter, so that $f_t = (k_{it}, \omega_{it})$ is strictly increasing in $\omega_{it}$. The firm’s material $m_{it}$ and labour $l_{it}$ inputs are chosen at time $t$, following the realisation of the firm’s productivity $\omega_{it}$ at time $t$. It follows that the intermediate input demand function can be inverted to express unobservable productivity in terms of the firm’s observable input factors

$$
\omega_{it} = f_t^{-1}(k_{it}, m_{it})
$$

(3.38)

The Levinsohn-Petrin method is also designed along a two-step estimation process.

**First Stage Moment – LP**

The first stage consists of

$$
y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + f_t^{-1}(k_{it}, m_{it}) + \varepsilon_{it} = \beta_l l_{it} + \phi_t(k_{it}, m_{it}) + \varepsilon_{it}
$$

(3.39)

with the first stage moment

$$
E[\varepsilon_{it} | I_{it}] = E[y_{it} - \beta_l l_{it} - \phi_t(k_{it}, m_{it}) | I_{it}] = 0
$$

(3.40)
Equations (3.39) and (3.40) allow for the identification of $\hat{\beta}_l$ and $\hat{\phi}_t(k_{it}, m_{it})$.

**Second Stage Moment - LP**

Comparable to the estimation of the capital coefficient in the Olley-Pakes framework, the first stage estimates are used in the second stage to identify the coefficient for intermediate inputs through the second moment condition

$$
E[\xi_{it} + \varepsilon_{it} | I_{it-1}] = E[y_{it} - \beta_0 - \beta_kk_{it} - \beta_lm_{it} - g(\phi_{t-1}(k_{it-1}, m_{it-1}) - \beta_0 - \beta_kk_{it-1} - \beta_m m_{it-1}) | I_{it-1}] = 0
$$

(3.41)

One of the advantages of Levinsohn-Petrin over Olley-Pakes stems from the fact that it does not depend on investment, so that while Olley-Pakes is restricted to only those firms with non-negative, non-missing investment, this restriction does not apply to Levinsohn-Petrin. This can significantly increase the sample size under Levinsohn-Petrin. While both Levinsohn-Petrin and Olley-Pakes do not allow for serial correlation in unobserved heterogeneity in wages and the material prices across firms, Olley-Pakes further requires there to be no serial correlation in unobserved heterogeneity in investment prices and capital adjustment costs. Additionally, both methods differ in their approach to a possible selection bias. The Olley-Pakes method incorporates an explicit calculation of the survival probability, the Levinsohn-Petrin method does not include this given that only little efficiency gains were observed with this once an unbalanced panel was employed (Levinsohn and Petrin, 2003).
The Ackerberg-Caves-Frazer Correction

Ackerberg et al. (2015) criticise the identification issues and a possible bias introduced by multi-collinearity in the labour variable under both the Olley-Pakes and Levinsohn-Petrin methodologies, and hence draft an extension to the before mentioned that corrects for these biases. Ackerberg, Caves and Frazer’s (2015) main point of critique is the full dependence of the labour variable $l_{it}$ on the choice of capital $k_{it}$ and materials $m_{it}$ at time $t$ which implies that there is no variation in the labour variable, conditional on the choice of capital and materials, which could be employed to identify the coefficient of labour. Ackerberg et al. (2015) further criticise the strict assumption of no serial correlation in the unobserved heterogeneity of materials prices and wages across firms.

The Ackerberg et al. (2015) correction assumes the validity of the assumptions I and II of both Olley-Pakes and Levinsohn-Petrin but replace assumption III with an assumption that allows for dynamic flexibility regarding the timing of firm’s choice of labour. The dynamic flexibility of the choice of labour allows for further firm heterogeneity in the model as any firm-specific exogenous and serially correlated unobservable shocks to variable input prices do not violate the validity of the estimation. Their estimation relies on the invertibility of the input demand function that is drafted so that the choice of labour is conditional on the choice of materials. This is valid if the choice of labour is made subsequent to the choice of materials or when these inputs are chosen simultaneously.

Similarly to Olley-Pakes and Levinsohn-Petrin, the Ackerberg-Caves-Frazer model proceeds in two steps augmented for their alternative version of the inverted input demand function. Based on their critique of the full functional dependence of the labour variable, they do not identify the coefficient of labour in the first step.

\footnote{This also allows for flexibility in the influence of investment at time and on the labour variable under the Olley-Pakes framework}
but rather employ the first step to net out the production function’s error term. The coefficient of labour and all other production function factors is identified in the second stage, however the timing of the firm’s choice of labour determines the exact estimation technique employed for its identification. If the firm’s choice of labour precedes the realisation of productivity at time $t$, then a Non-Linear Least Squares estimation (NLLS) can be used for the identification of the labour variable. If the firm however chooses labour subsequent to observing productivity at time $t$, so that the choice of labour is influenced by the productivity observed, then a Generalised Method of Moments estimation (GMM) should be employed to correct for the non-zero correlation of productivity and labour through the use of its internal instruments\(^{20}\).

This correction proposed by Ackerberg \textit{et al.} (2015) has several advantages. It is generally less restrictive in its requirements of the data generation process. It further allows for unobserved heterogeneity in wages, and for the possibility that labour is chosen independently of materials, at a different time and with a different information set.

\textbf{The Wooldridge Correction}

Wooldridge (2009) criticises that estimations that proceed in two steps are inherently less efficient than one-step estimations. The main issues arising from two-step estimations results from their treatment of the error terms. In a two-step process, there exists a possibility for contemporaneous correlation of the error terms across the estimation steps, which, if not controlled for, will critically affect the estimation results. Further, another source of inefficiency stems from a potential serial correlation or heteroscedasticity in the error terms, which violates

\(^{20}\)for an empirical application of the estimator see Konings and Vanormelingen (2015)
the underlying assumptions of the previously outlined models and hence reduces
the efficiency of the estimated production parameters. Wooldridge (2009) drafts
a model of two equations which have the output variable as the identical left-
hand side variable and the input variables on the right-hand side. The difference
of the equations stems from the set of instruments employed. Under this GMM
framework the moments condition underlying Olley-Pakes, Levinsohn-Petrin and
Ackerberg-Caves-Frazer remain valid so that these estimators can alternatively be
estimated through a one-step GMM approach.

The advantages of this approach stem from its treatment of the error terms.
While a possible cross-correlation results in inefficiency within two-step estim-
ators, this GMM framework employs this cross-correlation to improve efficiency.
Further, the potential issue of serial correlation and heteroscedasticity does not
arise within this GMM system as the optimal weighting matrix used controls for
both of these issues. Both of the aforementioned arguments result in a higher level
of efficiency in the one-step GMM estimator relative to the previously discussed
two-step estimation procedures. Additionally, this one-step GMM approach allows
for the identification of the common robust standard errors, whereas the two-step
estimations require the use of bootstrapping to identify standard errors. This ap-
proach further does not suffer from the problem of the first-stage identification that
Ackerberg-Caves-Frazer criticise in the Olley-Pakes and Levinsohn-Petrin meth-
ods. It additionally allows for the identification of the underlying identification
assumptions.

III.V.III The Use of Semiparametric Estimation Techniques in
Production Functions

For the empirical research focusing on the relationship of transportation in-
frastructure and productivity, the production function and resulting productiv-
ity parameter can be estimated with either the Olley-Pakes or Levinsohn-Petrin method. The infrastructure or infrastructure related variable, e.g. market access, is generally introduced subsequently in the second stage to identify the elasticity of productivity with respect to transportation using the OLS, IV or GMM methods (Holl, 2016). This can also be observed for productivity estimations in the context of agglomeration economies (Martin et al., 2011).

One paper relying on the semiparametric approaches discussed in the preceding subsection is the work by Ehrl (2013). Ehrl investigates the effect of agglomeration economies on firm productivity across German establishments. His estimation employs a production function that combines the Cobb-Douglas form with a CES demand function which is modelled along the concept of Dixit and Stiglitz (1977). He relies on the Olley-Pakes method to estimate the production function but further combines it with an adjustment for heterogeneous firm output pricing along the idea of Klette and Grilliches (1996). Another work employing a semiparametric estimation approach is provided by Bellone et al. (2016) who research firm markups in the context of international trade and heterogeneous firms. The authors draft a two-step estimation\(^{21}\) which includes a Cobb-Douglas production function adjusted to allow for an explicit incorporation of the firm’ exporting behaviour into the intermediate input function as put forward by De Loecker and Warzynski (2012). Their estimation relies on the Levinsohn-Petrin method. Graham and Maré (2013) focus on the investigation of heterogeneous firm sorting, convexity of agglomeration economies, and persistent spatial factors within the context of agglomeration economies and firm multi-factor productivity. They rely on a translog production function with alternative error structures, employ the method put forward by Wooldridge (2009) and rely on the intermediate input function as the proxy for firm productivity. Other noteworthy work employing

\(^{21}\)See Section 3.6 of this Chapter
the structural approaches presented is for example put forth by Pacvnik (2002), who employs the Olley-Pakes method to research the effects of trade liberalisation on plant-level productivity, or Fernandes (2007) who uses a combination of the Levinsohn-Petrin and GMM methods to analyse on the impact of trade policies and exposure to foreign competition on firm TFP.

III.VI One-step vs. Two-Step Total Factor Productivity Estimation

The estimation of productivity parameters can be modelled as a one or two-step procedure. If the focus of the estimation is the calculation of explicit productivity parameters, then productivity can be identified through

$$\hat{\omega}_{it} = y_{it} - (\hat{\beta}_k k_{it} + \hat{\beta}_l l_{it} + \hat{\beta}_m m_{it})$$

(3.42)

where $\hat{\beta}_k$, $\hat{\beta}_l$, $\hat{\beta}_m$ are the coefficients identified through the estimation of the production function. The productivity parameter in levels can subsequently be identified via

$$\hat{\Omega}_{it} = exp(\hat{\omega}_{it})$$

(3.43)

This method is generally referred to as a one-step estimation of productivity.

If the focus of the analysis is however to determine how different policies or additional factors influence the productivity parameter, then a two-step estimation is required. The first step of the procedure is equivalent to that of a one-step estimation. This second step employs the productivity parameter estimated from the first step and subsequently follows the general form of

$$\hat{\omega}_{it} = \rho \nu_{it} + \epsilon_{it}$$

(3.44)
where the estimation of the parameter $\rho$ is of interest to determine how a policy or factor $\nu_{it}$ affects the firm's productivity parameter.

III.VI.I One-step vs. two-step Productivity Estimations in Empirical Analyses

In the empirical literature investigating the effect of infrastructure variables on firm-level or regional production and productivity both one-step or two-step approaches are used.

In cases where the direct effect of transportation on the firms’ or regions’ production is highlighted, the transportation variable can be modelled as an additional input factor entering the production function directly. Examples of this approach can be found in Jiwattanakulpaisarn et al. (2012) who investigate the role of highways on regional economic development in the US and Holl (2012) who researches the role of market access on firm-level output in Spain.

Alternatively, if it is of interest to investigate the effect of transportation infrastructure variables on firm-level or regional productivity, then it has become a commonly used approach to run a production function, capture the residuals as a productivity measure and regress them on the infrastructure variable. Examples of this approach can be found in Martin et al. (2011) who examine the effect of spatial agglomeration economies on firm-level productivity for French firms and Graham et al. (2009) who explore the importance of distance within the context of agglomeration economies and its effect on sector-level productivity.
Chapter 4

A Pseudo - Panel Approach to Estimating Dynamic Effects of Road Infrastructure on Firm Performance in a Developing Country Context
I Introduction

Transportation infrastructure is a crucial component to economic growth (Tripathi and Gautam, 2010 and Crafts, 2009). However, while the majority of developed countries possess relatively dense transport networks, developing countries often suffer from a low road stock and underinvestment in infrastructure. This notion is supported by findings of The World Bank (2015) which regularly surveys firms and entrepreneurs doing business in developing countries for their World Bank Investment Climate report. The report has identified that 20 per cent of the surveyed sample in East Asia and Pacific, and 55 per cent in the Middle East, North Africa and Latin America state insufficient electricity, telecommunications and transport infrastructure as a severe obstacle to doing business. In an empirical analysis, Calderón and Servén (2004a) estimate the effects of infrastructure on GDP using a large panel of 120 developed and developing countries from 1960 to 2000. Their infrastructure index includes both infrastructure quantity and quality and their results indicate that GDP growth is positively influenced by all included infrastructure factors. Focusing the analysis solely on Latin America, Calderón and Servén (2004b) identify positive and significant contributions of telecommunications, electricity and transportation infrastructure to per worker GDP growth. Additionally, they show that the marginal products of all three infrastructure measures included significantly exceed those of non-infrastructure capital. They also find that the output gap between Latin American and East Asian countries throughout the 1980s and 1990s is largely due to different stocks of infrastructure. Infrastructure remains a particular problem for Latin American countries where infrastructure stocks have noticeably fallen behind the rich Western and East Asian countries since the 1970s. Additionally, with an average infrastructure spending of 1 per cent of GDP across Latin America, infrastructure
investments have barely grown in the 2000s (Calderón and Servén, 2010).

While there exists some research on the effects of transportation infrastructure capital on economic growth for developing countries\textsuperscript{22}, to date this literature remains limited and is predominantly relying on Chinese or Indian data. Additionally, given the absence of reliable firm level (panel) data for most developing countries, this is particularly the case for research using firm-level data. As economies at different stages of development differ largely in their economic structure, it cannot be assumed that conclusions drawn from research on developed countries also hold for developing countries\textsuperscript{23}. Furthermore, the road stock and density are also notably different in developed and developing countries, where the former often have well-developed and dense road networks, and the latter often exhibit limited transportation infrastructure and low road densities.

Colombia has recently launched an immense road transportation programme consisting of 40 public-private partnerships to build 8,000 kilometres of highway road infrastructure until the year 2020. The main goal of this project, which is estimated to cost around 25 billion US Dollars, is to connect the main economic centres of the country with each other and to the ports of the Atlantic and Pacific oceans through interconnected four lane highways. This vast programme also includes the “Highway to Prosperity” project in the northwest of the country. Deemed currently as the most extensive transportation project globally with an expected cost of 7.2 billion US Dollars, it aims at establishing North to South and East to West transportation links. Additionally, with a recently signed free trade agreement between Colombia and the US, the road investment project is expected to increase trade volumes and furthermore aid economic development\textsuperscript{24}.

\textsuperscript{22}See Chapter 2.4.4
\textsuperscript{23}See for example Hansen (1965)
\textsuperscript{24}See reports by Agencia Nacional de Infraestructura de Colombia, 2013, Departamento Nacional de Planeacion de Colombia, 2010, and Infrastructure Journal Investment Guide: Colombia, 2012
While one can only forecast the economic benefits accruing to the Colombian economy from this extensive project, I provide an insight into the relationship between road infrastructure and the Colombian economy for the years 2000 to 2009 by conducting an ex-post evaluation. I use a pseudo–panel of Colombian manufacturing firms for the analysis which relies on data from the Annual Manufacturing Survey conducted by the Colombian statistical authority DANE. Estimating the effects of road infrastructure on the production of manufacturing firms, I find that while current highway infrastructure appears insignificant across all specifications, lagged highway stock affects output growth positively and significantly. The results indicate that a growth in transportation infrastructure of 10 per cent, results in manufacturing output growth of 1.31 to 1.53 per cent in the subsequent year for the whole sample. Results are significantly larger for heavy industries and are heterogeneous across the regions. These results suggest that firms’ production processes require time to adjust to highway expansions. The identified elasticities furthermore indicate that the returns from highway expansions on firms of the private sector are notably larger for developing countries relatively to firms in developed countries with extensive transportation networks.

This paper contributes to the literature by taking a microeconomic approach in a developing country context. I use aggregated Colombian firm data and combine it with transportation data to estimate the effects of the road network on firm-level output. This paper relates to recent work by Duranton (2015) and Blyde (2013) who focus on the effects of roads on trade patterns in Colombia. While Duranton (2015) focuses on the effects of within and intercity highway stock on exports, Blyde (2013) focuses on the effects of road quality improvements on export patterns. Both of the above papers investigate the relationship between the Colombian economy and transportation infrastructure, however as they exclus-

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25 See Chapter 2.4 for further details
ively focus on trade, I extend this research by using aggregated firm data to focus on the role of roads on output growth. Additionally, this paper contributes to the literature focusing on investigating the impacts of transportation infrastructure in the absence of reliable panel data. While Storeygard’s (2016) work on road infrastructure and city growth for 15 African countries proposes the use of satellite lights data as a proxy for income as an option when reported economic data is not available, I highlight the construction of pseudo-panels based on aggregate firm data to research firm patterns as an alternative approach.

This chapter is structured as follows: I discuss the data sources in Section 2, I outline the econometric model for the analysis, including a discussion of the pseudo-panel methodology and the associated Monte Carlo simulations in Section 3 and in Section 4, I analyse the results. Section 5 concludes.

II Data

II.I A Brief Overview of the Colombian Transportation Sector

Following the 1991 constitutional reform of Colombia and its subsequent changes to the political system, the years of 2000 to 2009 represent a time of relative political stability for the country. During the majority of the first decade of the 2000s, Colombia was governed by the same president and Minister of Transport, which allowed for a consistent policy design during this decade. At the beginning of the 2000s, globally and regionally Colombia exhibited one of the largest transportation infrastructure gaps measured relative to its GDP per capita income levels (Calderón and Servén, 2004b). The increased focus on Free Trade Agreements during the decade also shifted the policy attention to improving the Colombian transportation network. The policy focus of the transport policy makers during the first decade of the 2000s were targeted on travel cost reductions, sustainable
regional economic growth, improvements in regional integration and increases in regional competitiveness (National Development Plans for 2002 – 2006 and 2006 – 2010). Further, a focus was set on improving urban transportation projects with the aim of reducing poverty, and reaching employment and equality goals. During the decade investigated, investments in roads represented 32.6 per cent of total public investment, equating to 0.5 per cent of GDP. While 26 per cent of the overall road infrastructure budget were spent on roads construction, the majority of 68 per cent were made available for road maintenance projects. Further, within the road infrastructure budget, primary roads received the largest budget of 75 per cent, while projects on secondary and tertiary roads were allocated 7 and 18 per cent of the total budget respectively (Nieto-Parra et al., 2013).

The overall budget on roads remained relatively constant throughout the years of this analysis, however the distribution of the funds across the regions exhibited relative disparity. During the first part of the decade, the focus was set on regions located in the centre and in the East which were allocated the largest absolute amounts of the budget. Further, regions on the Atlantic coast experienced the largest relative increase in road investments. An additional budget for road infrastructure was allocated to the regions according to their relative economic importance where the regions of Antioquia (located on the Atlantic coast), Valle del Cauca (located on the Pacific coast) and the capital region of Bogotá, D.C. received relatively higher shares of the overall budget. In the second part of the decade, the focus shifted predominantly to regions located on the Atlantic coast, and in the Central and Eastern part of the country. A relative increase in allocated funds could also be observed for the Western regions (Nieto-Parra et al., 2013).

The analysis of this paper focuses on the regional changes in the primary highway network during the years of 2000 to 2009. The main source of data used to

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26The analysis of urban transportation projects is beyond the scope of this chapter.
measure the road stock is yearly data on the Colombian highway stock (km) per Colombian region provided by the National Roads Institute of Colombia INVÍAS. The advantage of this data set lies in the fact that highways are measured in physical units rather than monetary units which allows for a reduction in measurement errors and further ignores possible inefficiencies in the policy implementation process. Figure 4.1 provides a graphical representation of regional road transportation growth across the years included in this analysis.

The majority of the regions of Arauca, Amazonas, Guainía, Guaviare, Putu-
mayo are not covered by the national highway network and are hence excluded. No consistent highway data could be obtained for the region of Vichada, thus this region was additionally dropped from the sample. Annual data covering the years 2000 to 2009 were used for the analysis. Given that the highway network of the capital region of Bogotá is consolidated with the highway network of the surrounding region of Cundinamarca, Bogotá is treated as part of Cundinamarca in the context of its highway network.

II.II Manufacturing Data

The information on aggregated firm data was taken from the annually conducted Colombian Manufacturing census (Encuesta Anual Manufacturera) and is used to obtain information on the output and input factors of the manufacturing sector. This data set covers all manufacturing firms with a minimum of 10 employees and provides information on output, capital stock, employment, inventories, raw materials usage, electricity usage, and investments. The data were provided aggregated by the 3-digit ISIC, Rev. 3 industry for each Colombian region. I employed the information on the number of firms included in each three-digit industrial sector–departamento pair to generate a pseudo-panel encompassing 4023 observations, where each observation represents an average firm for a given industry in each region in a given year. The compiled data set includes data from the capital district of Bogotá and 24 out of the 32 Colombian regions (departamentos). The regions of Casanare, Vaupes and the island state of San Andrés y Providencia were excluded due to insufficient economic data. In order to exclude that the effect of highway expansions on output growth is driven by selection and competition mechanisms across firms, I conduct preliminary tests on the data. The results do not reveal any evidence for strong effects of highway growth on

\(^{27}\)Further details on the pseudo-panel methodology can be found in Section 3 of this chapter

\(^{28}\)Additional descriptive statistics on the regional level can be found in Appendix A

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the average firm size and the number of firms within regions, hence allowing to conclude that the effect of highways on output growth is not determined through firm selection\textsuperscript{29}.

Information on the labour market was taken from the Encuesta Nacional de Hogares and the Gran Encuesta de Hogares for the years 1996 to 2000 and 2001 to 2010 respectively. Both these labour market surveys provide information on the working age population, unemployment rates, and the amount of employed among others for each region. Data on urban and municipal population was taken from the 2005 General Census. The Encuesta Anual Manufacturera, the Gran Encuesta de Hogares, the Encuesta Nacional de Hogares and results from the 2005 General Census have been obtained through the Departamento Administrativo Nacional de Estadística DANE.

Output, capital and raw materials were provided as measured in thousands of Colombian pesos. In order to compute quantities of these variables, output is deflated using the producer price indices at the two-digit ISIC level, capital is deflated with the producer price index for manufacturing of machinery and equipment, and raw materials are deflated by the annual average manufacturing producer price index. Adjusting these variables to both inflation and price differences across industries allows for the approximate identification of deflated physical units from the variables that were measured in monetary units. These are listed in Table 4.1. Energy, labour and the highway infrastructure stock are measured in physical units. Energy is measured in KWH, labour measures total permanent employment and highway infrastructure is measured by kilometres of highway per Colombian region.

\textsuperscript{29}Correlation coefficients of highway growth and the number of firms and highway growth and the average size of firms are 0.27 and 0.30 respectively across the sample.
Table 4.1: Descriptive Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>14,466,326</td>
<td>51,730,405</td>
</tr>
<tr>
<td>Capital</td>
<td>10,682,254</td>
<td>38,679,786</td>
</tr>
<tr>
<td>Employment</td>
<td>49.44</td>
<td>60.34</td>
</tr>
<tr>
<td>Energy</td>
<td>2,922,896</td>
<td>11,451,002</td>
</tr>
<tr>
<td>Materials</td>
<td>8,593,099</td>
<td>43,082,174</td>
</tr>
<tr>
<td>Highways</td>
<td>793.52</td>
<td>401.39</td>
</tr>
</tbody>
</table>

III Econometric Methodology

III.I Unobserved Endogeneity Bias in Inputs and the GMM Methodology

In the context of estimating production functions of firms, endogeneity issues may arise and bias the estimation results if they are not controlled for. In the context of this study endogeneity issues can arise if (1) highways are extended particularly in regions where high output growth is expected, if (2) there are omitted variables that simultaneously influence both the independent input variables and the value-added output variable, and additionally if (3) any expected temporary shocks to the firm’s productivity translate into changes in input choices. All of these possible sources of biases have been recognised in the literature researching firm performance and public investments. The most established methods to address these issues have been the use of instrumental variables that rely on historical data\(^\text{30}\) or econometric methods that use the advantages of dynamic panel data that allow to follow firms over time to design a set of internal instrumental variables\(^\text{31}\).  

\(^{30}\)See for example Duranton (2015) and Holl (2012)  
\(^{31}\)See Arellano and Bond (1991)
In the context of dynamic panel data, the pooled OLS estimator delivers biased results as it does not control for unobserved heterogeneity, endogenous variables and the dynamic autocorrelation of the error, and hence it is unsuitable for the analysis of the data used here. Compared to the pooled OLS model, the fixed effects (FE) model allows to control for any unobserved heterogeneity across the observations by differencing out any unobserved time invariant factors. Similar to the pooled OLS estimator, the FE model does also not control for endogenous variables, a possible autocorrelation of the errors or the high level of persistence of the independent variables so that the application of the FE estimator to dynamic panel data remains problematic, especially in the context of a large number of observations across a relatively small amount of time periods. The demeaning process employed by the FE estimator creates a correlation between the regressor and the error by subtracting the individual’s mean of the dependent and independent variables from their respective variables so that the estimated coefficients are expected to be downwards biased. This is generally referred to as the Nickell bias (1981).

The Difference GMM estimator first differences the original equation to be estimated and hence removes any unobserved time invariant factors that would otherwise result in a bias from an omitted variable. Subsequently the estimator instruments the first differences with the lagged values of the endogenous regressors, however analyses of firm panel data have identified that input variables are often persistent over time in firm production\textsuperscript{32} so lagged levels are only weak instruments for the first differences in the regressions. The System GMM\textsuperscript{33} specification adds the additional assumption of zero correlation between the fixed effects and the differences of the explanatory variables. This method employs lagged values of the explanatory variables to instrument for current differences and it uses lagged

\textsuperscript{32}See Blundell and Bond (2000) for further details
\textsuperscript{33}See Arellano and Bover (1995) and Blundell and Bond (2000)
differences as instruments for current levels. The System GMM method offers
the additional advantage that it performs better for data with a large number of
observations and a finite time horizon; hence it is the preferable GMM estimator
for this data consisting of 4023 observations over 10 years.

Further advantages are, given that there exists no correlation across the indi-
vidual units, it allows to control for heteroscedasticity and autocorrelation within
units and their errors. Furthermore, in the absence of historical instrument vari-
ables, the construction of internal instruments of the GMM methodology allows
to control endogeneity issues in the right-hand side variables and hence prevents
a bias stemming from this source. In the context of this analysis this allows to
control for any unobserved shocks that influence the input choices of the firms.

### III.II Estimation Strategy

I assume that firm output is a function of the standard input factors, capital
and labour, and the additional input factors of energy, raw materials and road
transportation infrastructure. The underlying hypothesis is that improvements in
transportation infrastructure directly reduce input factor costs for firms and hence
result in output growth and increased firm level TFP. Furthermore, reductions in
transport costs lower the distribution costs for final products and hence increase
the amount of economic mass the firm can access (“effective density”). Additional
effects arise through increases in industry level competition resulting in further
industry wide TFP improvements.

The estimation strategy of the firm’s output is an extension to the standard
neoclassical Cobb-Douglas production function and is represented by

\[
Y_{it}(K, L, E, M, , H) = K_{it}^{\beta_{K}} L_{it}^{\beta_{L}} E_{it}^{\beta_{E}} M_{it}^{\beta_{M}} H_{it}^{\beta_{H}} \varepsilon_{it} \tag{4.1}
\]

with
\( \varepsilon_{it} = \rho \varepsilon_{i,t-1} + \mu_i + \tau_t + \epsilon_{it} \) (4.2)

where \( Y \) is the deflated gross value of the output of a firm, \( K \) is the capital stock, \( L \) is the number of permanently employed staff, \( E \) and \( M \) are energy and raw materials used respectively, and \( H \) represents the highway stock for firm \( i \) at time \( t \) in region \( r \). \( \mu_i \) represents a firm-specific unobservable time-invariant productivity term and \( \tau_t \) captures any unobservable shocks affecting all firms in a given year. The composite error term is further composed of an autocorrelated term \( \rho \varepsilon_{it-1} \) and the true error \( \epsilon_{it} \).

A log-linear transformation of (4.1) yields

\[
\ln Y_{it} (K, L, E, M, H) = \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_E \ln E_{it} + \beta_M \ln M_{it} + \beta_H \ln H_{rt} + \varepsilon_{it} (4.3)
\]

Iterating (4.3) back by a period and solving for \( \varepsilon_{i,t-1} \) results in

\[
\varepsilon_{i,t-1} = \ln Y_{i,t-1} - (\beta_K \ln K_{i,t-1} + \beta_L \ln L_{i,t-1} + \beta_E \ln E_{i,t-1} + \beta_M \ln M_{i,t-1})
+ \beta_H \ln H_{r,t-1}) \] (4.4)

Substituting (4.4) into (4.2) and explicitly including all components of the error term transforms (4.3) into an ARDL model of the first order:

\[
\ln Y_{it} (K, L, , E, M, H) = \rho \ln Y_{i,t-1} + \beta_K \ln K_{it} + \alpha_K \ln K_{i,t-1} + \beta_L \ln L_{it}
+ \alpha_L \ln L_{i,t-1} + \beta_E \ln E_{it} + \alpha_E \ln E_{i,t-1} + \beta_M \ln M_{it}
+ \alpha_M \ln M_{i,t-1} + \beta_H \ln H_{rt} + \alpha_H \ln H_{r,t-1} + \mu_i + \tau_t + \epsilon_{it} (4.5)
\]
where $\alpha_{I_{t-1}} = -\beta_{I_{t-1}}\rho$ \quad with $I = K, L, E, M, H$ and $t = 1, \ldots, T$

This first-order autoregressive distributed lag ARDL(1) model specification allows for dynamic effects that arise when adjustments of the firms’ output and input choices to changes in the highway infrastructure are not contemporaneous.

The aggregated firm data for this paper stems from an annually repeated cross-sectional survey. It was provided aggregated at the three-digit ISIC code within each region, so that the data consisted of one annual observation for each industry within each region. As the underlying data stems from a repeated cross-section, it cannot be assumed that the participating firms remain identical and their numbers constant over time. In order to estimate firm-level effects, I follow the pseudo-panel methodology first developed by Deaton (1985) and introduce it as a possible solution for the estimation of firm production functions in the absence of true firm level data. This method allows to restructure the data so that it allows to follow cohorts consistently over time. Deaton initially developed this method for individual level data to estimate models of consumer demand. The cross-sectional data is required to include information on one or more observable and time-invariant variables by which the observations are grouped into cohorts. Subsequently cohort means for any variable are constructed, and tracked over time so that the matrix of cohort means forms a panel. This panel of cohort means is referred to as the pseudo-panel. While undoubtedly the major advantage of true panel data is that it enables the identification of precise individual information it can crucially be affected by attrition, whereas pseudo-panel data which is constructed from the renewed samples of each year does not suffer from this issue.

I use the three-digit ISIC code, the region identifier, the year and the information on the number of firms to identify the cohorts and to generate mean variables.

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For an additional discussion of the use of ARDL models in the context of roads see Jiwattanakulpaisarn et al. (2012)
Equation (4.5) becomes:

\[
\ln Y_{ct}(K, L, E, M, H) = \rho \ln Y_{c,t-1} + \beta K_t \ln K_{ct} + \alpha K_{t-1} \ln K_{c,t-1} + \beta L_t \ln L_{ct} \\
+ \alpha L_{t-1} \ln L_{c,t-1} + \beta E_t \ln E_{ct} + \alpha E_{t-1} \ln E_{c,t-1} + \beta M_t \ln M_{ct} \\
+ \alpha M_{t-1} \ln M_{c,t-1} + \beta H_t \ln H_{rt} + \alpha H_{t-1} \ln H_{r,t-1} + \mu_c + \tau_t + \epsilon_{ct}
\]  

(4.6)

with

\[
I_{ct}^{\alpha I_t} = I_{ct}^{\alpha I_t} \quad \text{with} \quad I = Y, K, L, E, M \quad \text{and} \quad t = 1, \ldots, T
\]  

(4.7)

where \( c \) represents an industry-region cohort, \( t \) represents the year and \( r \) denotes the region. Assuming that the size of the cohorts is sufficiently large and the composition relatively stable across the years, the yearly cohort average of the firm-specific time-invariant effects can be transformed into an industry-region specific unobserved time-invariant effect \( \mu_c \) that allows to control for unobserved heterogeneity between the cohorts.

If the data exhibit a relatively large degree of within-cohort variation compared to the across-cohort variation, the resulting pseudo-panel estimates may be less efficient than those of the underlying true panel. If the degree of within-cohort variation is relatively small however the loss of efficiency is small. I include cohort-specific effects into this analysis to control for any unobserved between-group heterogeneity across observations. The remaining unobserved between-group heterogeneity is not assumed to be substantial.

Each observation in the subsequent analysis is hence the mean firm of an industry-region cohort at time \( t \) and hence allows us to estimate the average effect of road infrastructure on firm output.
III.III  A Monte Carlo Experiment

In order to assess the validity of estimates based on pseudo-panel data in the context of firm data, I conduct a Monte Carlo experiment to compare the differences in the performance of estimators based on a true panel compared to those based on a pseudo-panel that has been constructed from the underlying true panel. While there exists a small body of literature assessing the validity of pseudo-panel estimations in the context of individual or household data\(^\text{35}\), the performance of pseudo-panel estimations has not been investigated for firm data and production function estimations. For the estimation of production functions, the literature has highlighted unobserved heterogeneity across firms as one of the main sources of endogeneity affecting the estimation results. This issue is further exacerbated if the unobserved heterogeneity affects the choice or level of input variables. Additionally, a possible autocorrelation in the error may introduce a further bias into the estimation of production functions. The established standard panel data methods have shown to control for these factors with different degrees of success, the motivation for this Monte Carlo simulation is hence to assess the performance of these methods in the context of pseudo-panel data to investigate whether these methods are also suitable to control for the above mentioned issues if the data is not true panel data. An additional motivation for this simulation is the assessment of the performance of logarithmic variables generated from averaged variables as employed by the pseudo-panel used for the empirical estimations of this paper.

The model set up follows a Cobb-Douglas ARDL(1) two input production function structure:

\[
Y_{it}(X_1, X_2) = X_{1it}^{\beta_1} X_{2it}^{\beta_2} e^{\nu_i + \omega_{it}} \quad t = 1, \ldots, T \quad (4.8)
\]

\(^{35}\)See for example Devereux (2007)
which can equivalently be expressed in its logarithmic form

$$lnY_{it}(X_1, X_2) = \beta_{X_{1it}}lnX_{1it} + \beta_{X_{2it}}lnX_{2it} + \nu_i + \omega_{it}$$  \hfill (4.9)

The variables $X_1$ and $X_2$ present the input factors for firm $i$ at time $t$. I introduce three possible bias sources into the model: a relationship between the lagged dependent variables and the current independent variable, a term capturing unobserved but time invariant heterogeneity which affects the dependent variable directly as well as indirectly through its influence on the independent variable, and serial correlation in the error. I model the development of both the independent variables in their logarithmic form according to (4.10). Serial correlation in the composite error term is introduced by including an autocorrelated shock $\omega_{it}$ which is independent but exhibits the same variance across the sample; this is expressed in the variables' logarithmic form as described in (4.11). The parameter $\nu_i$ represents the unobserved time-invariant effect which is positively correlated with both regressors. $\nu_i$ corresponds to a constant productivity term that acts as a shifter within the production function. This parameter influences both the development of the dependent variables in (4.8) and (4.9), and that of the independent variables through (4.10).

$$lnX_{dit} = \alpha lnX_{dit, t-1} + \gamma lnY_{i,t-1} + \delta \nu_i + \epsilon_{it} \quad d = 1, 2$$  \hfill (4.10)

$$\omega_{it} = \rho \omega_{it, t-1} + \epsilon_{it}$$  \hfill (4.11)

with

$$\epsilon_{it} \sim N(0, 1) \quad \epsilon_{it} \sim N(0, 1) \quad \nu_i \sim N(0, 1) \quad \omega_{it} \sim N(0, 1)$$
Endogeneity frequently occurs in empirical data in the context of production functions, and often results in biases and inconsistencies of the estimates generated across different estimators. I investigate the magnitude of this issue by generating endogenous explanatory variables with $\alpha > 0$ and $\gamma > 0$ according to (4.10).

The model follows the classical ARDL(1) structure where the coefficient of the lagged dependent variable is determined by the level of autocorrelation within the composite error $\omega_{it}$, and the coefficients of the lagged independent variables are determined by both the coefficient of the independent variable at time $t - 1$ and the level of autocorrelation in the error. The two explanatory variables are generated with relative differences in the parameters $\alpha, \gamma$ and $\delta$.

I generate 810 firms across 10 time periods over 1000 Monte Carlo trials. The size of 108 constructed pseudo-panel cohorts is uniformly distributed across a range of 5 to 10 observations. The model’s parameters are chosen to present the level of autocorrelation observed in true firm data with autocorrelation levels of 0.8 and 0.9 for the exogenous variables 1 and 2 respectively. The parameters $\beta_{X_1}$ and $\beta_{X_2}$ are set at 0.9 and 0.6 respectively. I further set the autocorrelation within the error term $\rho$ at 0.6. I generate a panel with a length of 20 observations for each unit, and subsequently ignore the first 10 observations for the calculation.

The coefficients are estimated with four standard panel methods: Pooled OLS, the Fixed Effects estimator, and the Difference and System GMM estimators. Results are listed in Table 4.2. The results of the Pooled OLS estimator exhibit an upwards bias at the second decimal point in the estimated coefficients of the contemporaneous variables, but only show a negligible bias in the lagged variables’ coefficients for both true and pseudo-panel estimates. For the estimates of the pseudo-panel, I further observe a relatively slightly lower bias in contemporaneous variables, and slightly larger bias in the estimates of the lagged coefficients. Standard deviations, and thus the root mean squared errors, are reported to be
Table 4.2: Monte Carlo Simulation for True and Pseudo-Panel Data

<table>
<thead>
<tr>
<th></th>
<th>Pooled OLS</th>
<th>Within</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient:</td>
<td>β&lt;sub&gt;true&lt;/sub&gt;</td>
<td>β</td>
<td>σ</td>
<td>RMSE</td>
</tr>
<tr>
<td>β&lt;sub&gt;Y_{t-1}&lt;/sub&gt;</td>
<td>0.6</td>
<td>0.620</td>
<td>0.013</td>
<td>0.024</td>
</tr>
<tr>
<td>β&lt;sub&gt;X_{1t}&lt;/sub&gt;</td>
<td>0.9</td>
<td>0.923</td>
<td>0.016</td>
<td>0.028</td>
</tr>
<tr>
<td>β&lt;sub&gt;X_{1,t-1}&lt;/sub&gt;</td>
<td>-0.54</td>
<td>-0.544</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>β&lt;sub&gt;X_{2t}&lt;/sub&gt;</td>
<td>0.6</td>
<td>0.628</td>
<td>0.016</td>
<td>0.032</td>
</tr>
<tr>
<td>β&lt;sub&gt;X_{2,t-1}&lt;/sub&gt;</td>
<td>-0.36</td>
<td>-0.372</td>
<td>0.017</td>
<td>0.021</td>
</tr>
</tbody>
</table>

larger for pseudo-panel estimates. The Fixed Effects estimator significantly underestimates the coefficient of the lagged dependent variable. This subsequently results in a bias of the coefficients of the lagged independent variables. These biases have already been documented for true panel methods (Nickell, 1981) and the above listed results do not indicate that these biases systematically differ for pseudo-panel estimations.

However, the results of the Difference and System GMM estimations require a more detailed discussion. For the true panel estimates, both Difference and System GMM only indicate biases for true panel data at the second decimal point, Difference GMM results generally indicate relatively small biases for the estimates of contemporaneous variables, but reveal downwards biases for the coefficients of the lagged dependent and independent variables. The shortcomings of the Difference GMM estimation method, discussed in the preceding Section 4.1 of this chapter, are exacerbated when pseudo-panel data is used. If the underlying data is highly persistent over time, then the lagged levels as used for the first differences in the regression are only weak instruments. A pseudo-panel employs cohort averages as observations, resulting in a data structure which is evidently
more persistent over time than the observations of the underlying true panel. This therefore weakens the link between the lagged levels and first differences even further for pseudo-panel data. For pseudo-panels, which have been generated from a true panel data that already exhibits large persistence in the independent variables, this will be particularly noticeable. This increased persistence hence worsens the performance of the Difference GMM estimator for pseudo-panel data.

For true panel estimates, System GMM results, similar to the POLS estimates, exhibit an upwards and downwards bias at the second decimal for the estimates of the contemporaneous variables and lagged coefficients respectively. Furthermore, the System GMM estimate of the coefficient of the lagged dependent variable exhibits the lowest bias across all estimators. While this coefficient reveals an upwards bias for true panel data, it exhibits a downwards bias under pseudo-panel data, however the magnitude of these biases remains very small, and thus negligible.

Across the different estimators, the results reveal a particular degree of heterogeneity across the estimates for the coefficient of the lagged dependent variable, where the System GMM estimates reveal the lowest bias for both true and pseudo-panel estimations. Furthermore, while estimates of the contemporaneous variables generally reveal only negligible biases across all estimators, there exists a relatively larger degree of heterogeneity for the estimates of the lagged dependent variables. An overall comparison of the results of the true and pseudo-panel estimations indicate some, but not significant differences, however there are some deviations at the second and third decimal point; I deem these to be within an acceptable range. The exception is the performance of the Difference GMM estimator which exhibits noticeably larger biases for pseudo-panel data. Further, the pseudo-panel results indicate a loss in efficiency which is reflected in generally larger standard deviations and root mean square errors. These results allow to conclude that the
results based on pseudo-panels do not suffer from a crucial bias and can hence be interpreted as valid in the context of production functions.

IV Results

IV.I Baseline Results

Table 4.3 reports the findings of the estimations of the static and dynamic production function specifications. Column (1) reports the results for the static OLS production function estimation. All input factors except road stock, which is negative and insignificant, have the expected sign and are highly significant in this specification. It is reasonable to assume that firms require time to adjust to changes in the transportation infrastructure, i.e. extensions to the existing highway network, hence the results from the dynamic production function model are provided in column (2)\(^{36}\). The results show that the coefficients of all the input factors, except highways, have the expected sign and are all highly significant. The coefficients of highways are negative for the contemporaneous and positive for its lagged version, however insignificant for both. Additionally, firms’ output appears to be highly autocorrelated. As the results from the pooled OLS (POLS) estimation may include an upwards bias due to the possible endogeneity issues discussed in Section 4.1 of this chapter, the model is tested additionally with the fixed effects model and two different GMM specifications.

The results of the Fixed Effects estimation model are presented in column (3). Almost all FE coefficients are smaller than those reported under pooled OLS, this particularly affects the coefficients of the lagged variables. As outlined in Section 4.1 of this chapter, the FE estimates are expected to suffer from a downward bias in this context. The results reveal that current transportation infrastructure is

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\(^{36}\) A detailed description of the lag selection can be found in Appendix A2 "The Lag Selection for the Econometric Specification of Chapter 4"
Table 4.3: Empirical Results from Static and Dynamic Production Functions

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)</th>
<th>POLS</th>
<th>POLS Fixed Effects</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Output)_{t-1}</td>
<td>*</td>
<td>0.881*** (0.016)</td>
<td>0.486*** (0.037)</td>
<td>0.512*** (0.056)</td>
</tr>
<tr>
<td>Ln(Capital)_{t}</td>
<td>0.233*** (0.021)</td>
<td>0.093*** (0.019)</td>
<td>0.093*** (0.018)</td>
<td>0.098*** (0.028)</td>
</tr>
<tr>
<td>Ln(Capital)_{t-1}</td>
<td>-</td>
<td>-0.065*** (0.018)</td>
<td>-0.047*** (0.016)</td>
<td>-0.039*** (0.019)</td>
</tr>
<tr>
<td>Ln(Employment)_{t}</td>
<td>0.074*** (0.021)</td>
<td>0.040*** (0.015)</td>
<td>0.040*** (0.016)</td>
<td>0.045** (0.025)</td>
</tr>
<tr>
<td>Ln(Employment)_{t-1}</td>
<td>-</td>
<td>-0.043*** (0.016)</td>
<td>-0.029** (0.017)</td>
<td>-0.032** (0.015)</td>
</tr>
<tr>
<td>Ln(Energy)_{t}</td>
<td>0.090*** (0.019)</td>
<td>0.160*** (0.020)</td>
<td>0.180*** (0.026)</td>
<td>0.203*** (0.049)</td>
</tr>
<tr>
<td>Ln(Energy)_{t-1}</td>
<td>-</td>
<td>-0.147*** (0.020)</td>
<td>-0.082*** (0.021)</td>
<td>-0.099*** (0.020)</td>
</tr>
<tr>
<td>Ln(Materials)_{t}</td>
<td>0.583*** (0.021)</td>
<td>0.625*** (0.021)</td>
<td>0.615*** (0.023)</td>
<td>0.662*** (0.032)</td>
</tr>
<tr>
<td>Ln(Materials)_{t-1}</td>
<td>-</td>
<td>-0.557*** (0.023)</td>
<td>-0.306*** (0.028)</td>
<td>-0.317*** (0.038)</td>
</tr>
<tr>
<td>Ln(Highways)_{t}</td>
<td>-0.020 (0.018)</td>
<td>-0.041 (0.044)</td>
<td>0.026 (0.060)</td>
<td>0.016 (0.084)</td>
</tr>
<tr>
<td>Ln(Highways)_{t-1}</td>
<td>-</td>
<td>0.040 (0.044)</td>
<td>0.150*** (0.049)</td>
<td>0.131** (0.064)</td>
</tr>
<tr>
<td>Cohort FE</td>
<td>N</td>
<td></td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Time FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.265</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.139</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>264</td>
</tr>
<tr>
<td>Observations</td>
<td>4,023</td>
<td>3,490</td>
<td>3,490</td>
<td>3,016</td>
</tr>
<tr>
<td>R²</td>
<td>0.963</td>
<td>0.991</td>
<td>0.855</td>
<td>-</td>
</tr>
</tbody>
</table>

(where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the cohort level are provided in parenthesis)

insignificant whereas the coefficient on the lagged highway stock is positive and significant at the 1 per cent level. This provides evidence for the hypothesis that firms’ adjustment processes to transportation infrastructure expansions require time. These results indicate that a 10 per cent increase in the highway stock of a region results in a private sector output growth of manufacturing firms of 1.50 per cent in the subsequent period.

To correct for the possible biases in the POLS and FE models, the Difference (column (4)) and System GMM estimators (column (5)) are additionally employed. Another crucial advantage of employing the GMM methodology results from its construction of internal instruments. In my model, this allows highways to be treated as an additional input factor whose possible endogeneity is treated by the internal GMM instruments. The Difference GMM specification reports the coeffi-
cients for all input variables with the expected sign. Highway infrastructure, which is only significant in its lagged value, is slightly lower but in line with the results reported under FE. The results from the System GMM specification are reported in column (5). The reported coefficients of capital, labour, energy and materials are all positive in current levels, negative in lagged values and similar in magnitude than those reported under Difference GMM. However, contrary to expectations, the System GMM does not yield much higher estimates for the lagged dependent variable than the Difference GMM estimator does. The estimated coefficient of highway infrastructure is in line with the coefficient estimated with Difference GMM and FE. Current transportation infrastructure appears to be insignificant for the production, while the lagged level indicates a positive and highly significant relationship. A 10 per cent increase in transportation infrastructure would result in an output growth of 1.53 per cent in the manufacturing sector in the following year.

Overall, it is noteworthy that the results only indicate an effect of lagged highways on firm output, there appears to be no effect of contemporaneous highways. In the context of the assumed underlying AR(1) model, a positive effect of lagged highways would mean a negative effect of contemporaneous highways, or alternatively vice versa. The estimation results of Table 4.3 do not consistently show either variable as negative, thus alternative version of the model and its lag structure have been tested to investigate if another specification fits the underlying data better. The analysis of the alternative model specifications have provided support for the prior chosen econometric specification, and given that the point estimates of contemporaneous highway are all insignificant, it cannot be excluded that the true values of these is negative, thus fitting the model’s prediction\(^\text{37}\).

While a negative impact of transportation on firms’ output might appear coun-

\(^{37}\)A graphical presentation of the confidence intervals of contemporaneous highways' estimates is provided in Appendix A3.
terintuitive, there exist possible realistic interpretations of this effect. A possible reason can be found in the construction associated with the new highway segments as the construction work may not have completely finished or been removed by the time the segment is opened to road traffic. This would hinder road traffic, thus having a negative indirect impact on firms’ productions. Additionally, there may also be adjustment costs resulting from any changes being made to the firm’s production following the highway’s extension. Combining this argument with the results of Table 4.3 would indicate that firms have completed the adjustment process of their production within a year, resulting in relatively large positive effects of the highway on the firm’s production after a year. However, (some) firms may also directly benefit from the extended highway network, thus the direction of the overall effect of contemporaneous highways in this context cannot be unanimously determined. The results presented throughout this and the following chapter however support the notion of a possible negative effect, albeit small in magnitude.

The second point to note is the magnitude of this effect. The mean of the reported output elasticities of transportation infrastructure in the context of developed countries is reported to be around 0.06, less than half of the reported coefficient of my analysis. Therefore, the results here provide support for the hypothesis that output elasticities of transportation infrastructure can be substantially higher for developing and emerging economies.

My results further indicate a noticeable similarity between the results of Fixed Effects, Difference GMM and System GMM. This could be indicative for the existence of only weak endogeneity, which may not be substantial enough to cause a significant bias. Alternatively, this could be attributed to ineffective internal instruments employed by GMM.

Generally, the System GMM test statistics of Hansen and Sargan can provide

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38 See Melo et al. (2013) for a comprehensive review of the literature
insight into the over-identification of the model and joint validity of internal instruments used. However, in cases where the number of instruments is relatively large, as is the case of the analyses of this chapter, the statistics are weakened and fail to provide accurate information. Hence, the similarity of the results across FE, Difference and System GMM and provided Hansen statistic may be driven by the weakness of internal instruments employed by System GMM, however it is also likely that the large number of internal instruments employed significantly weakened the strength of the Hansen statistic. In order to investigate the effectiveness of GMM instruments, I examine the reduced form regressions for first differences and for levels as in Blundell and Bond (2000). I find that in the reduced form of first differences which relates the first difference of the variables to its lags, the instruments are jointly significant for all variables, except energy. I would therefore expect that the differenced GMM estimator performs well for all variables except energy. In the reduced form for the levels regression which relates the first lags to lagged differences of the variables, the instruments are jointly significant for all variables except capital. Hence, I expect the System GMM estimator not to perform better than Difference GMM for the capital coefficient and to perform better for energy. Overall, these regressions do not lead to a conclusion that the System GMM should not be employed for the data used here.

IV.II.I Robustness Test I: Additional Controls

To test for the possibility of regional agglomeration economies driving the results of the transportation infrastructure elasticities, employment density and per capita income are included as additional controls. Agglomeration economies describe the productivity benefits that accrue to firms located in areas with a higher density of economic activity. Sharing of input factors, labour pooling and knowledge spillovers are all representatives of these productivity-enhancing benefits
termed as agglomeration economies. Areas that have a higher density of economic activity may also experience higher growth in roads if growth of economic productivity is expected there; hence agglomeration economies, rather than highway stock, may be driving the results. The inclusion of employment density allows to control for this issue. If highways are placed in areas where economic growth is expected, then a positive trend in economic performance rather than changes in the infrastructure may explain the results; the inclusion of per capita income allows to gain insight to this issue. In the context of this study, the inclusion of this variable is of further interest given that the 2002 National Development Plan formulates higher road investments in areas with relatively larger national economic importance measured in GDP\(^{39}\).

Additional time-invariant effects for the presence of a seaport and for the number of large cities within a region are furthermore added to the regression. The former allows to gain insight into the hypothesis that larger benefits of roads may be accrued in regions with an important port due to a possibly larger volume of trade or due to the fact that more productive firms have a preference to be situated near a port to reduce transport times and costs. The latter factor allows to control for the possible importance of the distribution of economic activity and the role of cities in increasing firms output. If increases in the road network result in heightened levels of competition, then a possible result would be that only the most successful firms survive in the market. This would reduce the number of firms in the market and increase the overall productivity level and output growth exhibited by firms. Hence, it may be the increased competition following road network expansion rather than the road expansion itself that drives the results. Preliminary tests have not revealed any strong evidence to support this hypothesis\(^{40}\). I investigate the possibility of this further by adding the number of firms

\(^{39}\)See Section 2.1 of this chapter

\(^{40}\)See Section 2.2
being included in one cohort level observations and the average firm size in terms of its employment pool as additional controls to the estimations.

Table 4.4 reports the results under pooled OLS (column (1)), Fixed Effects (column (2)) and under Difference and System GMM (columns (3) and (4) respectively). The majority of the estimated elasticities under all methods remain similar to those estimated for the baseline model of Table 3. Similar to Table 3, highways are only significant in their lagged and not in their contemporaneous values. The inclusion of additional controls decreases the estimated effect of highways by approximately 0.02 under the FE and System GMM models. Following the introduction of controls to the estimations, a 10 per cent increase in the highway stock would result in an approximate growth in firm’s output of 1.3 per cent under both of these methods. Additionally, while lagged highways remain highly significant under FE and GMM and insignificant under POLS, the estimated effect under Difference GMM becomes insignificant once additional controls are introduced to the model.

The estimated coefficients for employment density are very small and insignificant for both the current and lagged period under all estimation methods, hence it can be concluded that output elasticities of the highway stock reported previously are not explained by agglomeration economies. Per capita GDP however is reported as significant under all models, with Difference GMM being the exception for both contemporaneous and lagged values. The positive and significant results for per capita GDP and the reduction of the estimated highway elasticity, might imply that the magnitude of the estimated highway coefficient is in part due to a general trend of economic growth during the period investigated. However, given the AR(1) structure of the model which generally results in estimates with opposing signs for both periods included, and the similarity in magnitude of the estimates here, it can be argued that while there exists a positive contemporaneous
Table 4.4: Robustness Test I - Additional Controls

<table>
<thead>
<tr>
<th>Dependent Variable: ( \ln(\text{Output}) )</th>
<th>POLS</th>
<th>Fixed Effects</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \ln(\text{Output}) )</td>
<td>0.876*** (0.016)</td>
<td>0.485*** (0.037)</td>
<td>0.485** (0.057)</td>
<td>0.521*** (0.049)</td>
</tr>
<tr>
<td>( \ln(\text{Capital}) )</td>
<td>0.094*** (0.019)</td>
<td>0.093*** (0.018)</td>
<td>0.101*** (0.026)</td>
<td>0.092*** (0.018)</td>
</tr>
<tr>
<td>( \ln(\text{Capital}) )</td>
<td>-0.063*** (0.018)</td>
<td>-0.048*** (0.016)</td>
<td>-0.035*** (0.018)</td>
<td>-0.051*** (0.016)</td>
</tr>
<tr>
<td>( \ln(\text{Employment}) )</td>
<td>0.056*** (0.015)</td>
<td>0.038** (0.017)</td>
<td>0.063** (0.021)</td>
<td>0.039** (0.017)</td>
</tr>
<tr>
<td>( \ln(\text{Employment}) )</td>
<td>-0.044*** (0.016)</td>
<td>-0.029** (0.018)</td>
<td>-0.091* (0.026)</td>
<td>0.031* (0.018)</td>
</tr>
<tr>
<td>( \ln(\text{Energy}) )</td>
<td>0.160*** (0.020)</td>
<td>0.178*** (0.026)</td>
<td>0.164*** (0.038)</td>
<td>0.178*** (0.026)</td>
</tr>
<tr>
<td>( \ln(\text{Energy}) )</td>
<td>-0.147*** (0.020)</td>
<td>-0.081*** (0.021)</td>
<td>-0.098*** (0.020)</td>
<td>-0.087*** (0.022)</td>
</tr>
<tr>
<td>( \ln(\text{Materials}) )</td>
<td>0.624*** (0.021)</td>
<td>0.614*** (0.023)</td>
<td>0.641*** (0.030)</td>
<td>0.614*** (0.023)</td>
</tr>
<tr>
<td>( \ln(\text{Materials}) )</td>
<td>-0.554*** (0.023)</td>
<td>-0.305*** (0.028)</td>
<td>-0.304*** (0.039)</td>
<td>-0.327*** (0.035)</td>
</tr>
<tr>
<td>( \ln(\text{Highways}) )</td>
<td>-0.042 (0.044)</td>
<td>0.021 (0.060)</td>
<td>-0.046 (0.084)</td>
<td>0.022 (0.060)</td>
</tr>
<tr>
<td>( \ln(\text{Highways}) )</td>
<td>0.025 (0.044)</td>
<td>0.130*** (0.050)</td>
<td>0.100 (0.070)</td>
<td>0.131*** (0.049)</td>
</tr>
</tbody>
</table>

Regional Controls

| \( \ln(\text{Employment Density}) \) | 0.004 (0.066) | 0.008 (0.090) | 0.026 (0.106) | 0.012 (0.088) |
| \( \ln(\text{Employment Density}) \) | -0.003 (0.066) | -0.072 (0.075) | -0.077 (0.078) | -0.065 (0.074) |
| \( \ln(\text{GDP/Capita}) \) | 0.234*** (0.112) | 0.235** (0.124) | 0.105 (0.161) | 0.231** (0.122) |
| \( \ln(\text{GDP/Capita}) \) | -0.235** (0.113) | -0.239** (0.117) | -0.174 (0.125) | -0.241** (0.117) |

Seaport FE Y Y Y Y
Urbanisation FE Y Y Y Y

Cohort Controls

| Number of Firms | 0.0001 (0.0001) | -0.0003 (0.00004) | -0.0001 (0.001) | -0.001* (0.004) |
| Average Firm Size | -0.0001 (0.0001) | 0.0001 (0.0002) | -0.0002 (0.0004) | 0.00001 (0.0002) |

Cohort FE Y Y Y Y
Time FE Y Y Y Y

AR1 - - 0.000 0.000
AR2 - - 0.307 0.331
Hansen - - 0.132 0.000

Number of Instruments - - 354 881
Observations 3,488 3,488 3,014 3,488

R² 0.991 0.855 - -

(where *** indicates significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the cohort level are provided in parenthesis)
effect of per capita GDP growth, this effect roughly cancels out after two years.

While the number of firms included in each cohort appears significant under POLS and System GMM, the magnitude and significance of this effect are very small and hence do not lead to a conclusion that this influenced the results of the estimated highway elasticity. Average firm size is very small in magnitude and insignificant across all estimation models\textsuperscript{41}.

Overall, apart from per capita GDP, the introduction of additional controls does not appear to influence the results. The introduction of per capita GDP however shows that the general regional economic growth trend may explain parts of the estimated highway elasticity, but given that the estimated results remain in line with the results of Table \ref{tab:est}, I do not conclude that the results of Table \ref{tab:est} were crucially affected by agglomeration or cohort effects.

IV.II. Robustness Test II: Road Density

In order to account for regionally differing characteristics that could influence the effects of roads heterogeneously across Colombian regions, two specifications of road density are used as alternative measures of transportation infrastructure. First, I use geographic road density, measuring the amount of highway infrastructure (in kilometres) per 100 square kilometres of land surface. This explicitly incorporates the absolute geographic size of each region. This allows to test whether larger states with a larger road stock and an economy possibly growing at a higher rate influence the results. As an alternative road density specification, I construct a population weighted road density variable. This variable measures the amount of highway infrastructure (in kilometres) per 100,000 population. This allows to test whether increased congestion effects, which are expected to be present in areas with low road infrastructure relative to the population, influence the previ-\textsuperscript{41}Developments of the number of firms included and the average output level per firm were additionally investigated, but did not result in any significant results.
Figure 4.2: Average Road Density weighted by geography (left) and population (right) (2000 – 2009)

Source: Own elaboration on the basis of the road infrastructure data provided to the authors by INVÍAS; No consistent road data was available for the islands of San Andrés and Providencia, so that these could not be included in this study.

ous results. Additionally, as this variable measures road infrastructure relatively, this corrects for the effects of possibly higher road infrastructure investments in regions with higher populations. Figure 4.2 provides a graphical representation of both road density variables. The graphs illustrate that while some regions exhibit a geographically dense highway network, predominantly in the centre and towards the coasts, these may not necessarily overlap with those regions that have a dense highway network relative to their population, which are predominantly located towards the East of the country. For those regions, in particular where the geographic road density is relatively high and the population weighted road density is also relatively high, it can be hypothesised that the sole use of the geographic measure might be misleading as in these areas higher levels of congestion should be expected given the large populations. This provides support for the
Table 4.5: Robustness Test II - Road Density

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)</th>
<th>Fixed Effects (1)</th>
<th>System GMM (2)</th>
<th>Fixed Effect (3)</th>
<th>System GMM (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Output)_{t-1}</td>
<td>0.485*** (0.037)</td>
<td>0.536*** (0.048)</td>
<td>0.480*** (0.037)</td>
<td>0.530*** (0.050)</td>
</tr>
<tr>
<td>Ln(Capital)_{t}</td>
<td>0.093*** (0.018)</td>
<td>0.092*** (0.018)</td>
<td>0.093*** (0.018)</td>
<td>0.093*** (0.018)</td>
</tr>
<tr>
<td>Ln(Capital)_{t-1}</td>
<td>-0.047*** (0.016)</td>
<td>-0.051*** (0.016)</td>
<td>-0.048*** (0.016)</td>
<td>-0.052*** (0.016)</td>
</tr>
<tr>
<td>Ln(Employment)_{t}</td>
<td>0.039*** (0.016)</td>
<td>0.039*** (0.016)</td>
<td>0.039*** (0.016)</td>
<td>0.039*** (0.016)</td>
</tr>
<tr>
<td>Ln(Employment)_{t-1}</td>
<td>-0.029 (0.018)</td>
<td>-0.031* (0.016)</td>
<td>-0.029 (0.018)</td>
<td>-0.031* (0.018)</td>
</tr>
<tr>
<td>Ln(Energy)_{t}</td>
<td>0.179*** (0.026)</td>
<td>0.178*** (0.026)</td>
<td>0.179*** (0.026)</td>
<td>0.178*** (0.026)</td>
</tr>
<tr>
<td>Ln(Energy)_{t-1}</td>
<td>-0.081*** (0.021)</td>
<td>-0.090*** (0.022)</td>
<td>-0.081*** (0.021)</td>
<td>-0.089*** (0.022)</td>
</tr>
<tr>
<td>Ln(Materials)_{t}</td>
<td>0.615*** (0.023)</td>
<td>0.615*** (0.023)</td>
<td>0.615*** (0.023)</td>
<td>0.615*** (0.023)</td>
</tr>
<tr>
<td>Ln(Materials)_{t-1}</td>
<td>-0.306*** (0.028)</td>
<td>-0.337*** (0.034)</td>
<td>-0.306*** (0.028)</td>
<td>-0.333*** (0.035)</td>
</tr>
<tr>
<td>Ln(Road Density)_{t}</td>
<td>0.021 (0.052)</td>
<td>0.024 (0.052)</td>
<td>0.039 (0.060)</td>
<td>0.042 (0.060)</td>
</tr>
<tr>
<td>Ln(Road Density)_{t-1}</td>
<td>0.089 (0.042)</td>
<td>0.091*** (0.041)</td>
<td>0.156*** (0.049)</td>
<td>0.157*** (0.047)</td>
</tr>
<tr>
<td>Cohort FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Time FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Per Capita GDP Growth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.357</td>
<td>-</td>
<td>0.316</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td>-</td>
<td>825</td>
<td>-</td>
<td>825</td>
</tr>
<tr>
<td>Observations</td>
<td>3,490</td>
<td>3,490</td>
<td>3,490</td>
<td>3,490</td>
</tr>
<tr>
<td>R²</td>
<td>0.855</td>
<td>-</td>
<td>0.855</td>
<td>-</td>
</tr>
</tbody>
</table>

(where ****, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the cohort level are provided in parenthesis)

necessity to test the effects of these road density variables separately. Table 4.5 reports the results under Fixed Effects in columns (1) and (3) and under System GMM in columns (2) and (4) for geography and population weighted road density respectively\(^{42}\).

The estimated coefficients on all inputs factors, except the road infrastructure

\(^{42}\)Given the difference in construction between the road transportation variables employed in this section and the previous, the interpretation of the results of Table 4.5 do not allow for a direct comparison of these results to those of Tables 4.3 and 4.4. Additionally, the population based road density variables comprises two dynamic components, hence an increase in this road density variable implies a relatively higher growth in the road network to population growth.
variables, remain very similar in magnitude to those of Tables 4.3 and 4.4, allowing for the conclusion that the choice of road infrastructure variable does not alter these estimates. Further, while the road density measure differs from columns (1) and (2) to columns (3) and (4) the results show consistently that road infrastructure density affects output growth positively and significantly, but only with a time lag. An increase in geographic road density of 10 per cent will lead to a 0.89 to 0.91 per cent increase in firms' output in the following year (columns 1 and 2), and an increase in population based road density of 10 per cent will lead to a 1.56 to 1.57 per cent (columns 3 and 4) increase under FE and GMM estimations respectively.

IV.III Industry Specific Results

The manufacturing sector encompasses a diverse range of manufacturing industries that differ greatly in capital and land – use intensity, the amounts of raw materials and electricity consumed in the production process and in the type of final products produced. To test the conjecture that road investments may have a different effect on the different manufacturing sectors due to their production differences, the sample was categorised into heavy and light industries. Heavy industries are characterised by capital and land–use intensive production processes whose final products are often intermediate inputs for other firms, while light industries typically require only limited investment, employ less raw materials and energy than heavy industries, and produce goods that are typically final consumer products. The set of light industries for the analysis consists of manufacturing firms of foods and beverages, textiles, fur and wearing apparel, luggage and leather products, wood and cork products, and furniture. The set of manufacturing firms classified as heavy industries for the analysis includes manufacturing of paper and paper products, publishing, printing and media reproduction, production of coke,
refined petroleum, nuclear fuel, chemicals, plastic, metal and non-metallic mineral products, and basic metals. Furthermore, included in the heavy industry subsample are the production of machinery, equipment, motor vehicles, electric apparatus, radio, TV, communication and transport equipment, and the production of medical instruments.

The industry specific estimation results are presented in Table 4.6. Throughout both estimation methods used, current highway infrastructure remains insignificant, and hence in line with the previous results for both groups of industries. For
light industries, the reported effect of lagged road infrastructure stock has roughly the same magnitude across Fixed Effects and System GMM, and is significant for both specifications. The results indicate that a 10 per cent increase in highways will result in an output growth in the light industries of 0.62 to 0.63 per cent in the subsequent year under System GMM and Fixed Effects estimations respectively. For heavy industries, the effect of lagged road infrastructure is similar in magnitude and remains highly significant across the estimation techniques, but increases substantially in magnitude compared to the results for light industries and for the whole sample provided in Table 4.3. My results suggest that a road expansion of 10 per cent would result in an output growth within heavy industries of 3.51 to 3.58 per cent in the subsequent period (columns (4) and (3) respectively).

It is noteworthy to state that while these results are in line with the previous results in revealing an existing time lag with which road infrastructure expansions affect output growth, the estimated elasticities for heavy industries are more than twice as large as those calculated for the whole sample of manufacturing firms. From these results, I conclude that the benefits from road expansion in Colombia are substantially more accrued to the heavy industries.

These findings can be compared to the elasticities for trade with respect to intercity highway stock identified by Duranton et al. (2014) for the US. Their findings reveal that a 10 per cent increase in the intercity highway stock increases exports by 5 per cent in weight, while it only has a small and weak effect for exports in value. The authors conclude that roads are an important complement to the production of heavy goods. Repeating this analysis using Colombian trade data, Duranton (2015), reports elasticities for the effect of roads on trade of very similar magnitudes in value and in weight. The reported effect on the exports’ value is slightly higher than the author’s results for the US, however no further support for the hypothesis of larger productivity benefits from transportation for heavy
industries is provided in this paper. In contrast to Duranton et al. (2014) and Duranton (2015) who focus their analyses on roads and trade, this study focuses on output growth and roads. My overall findings support the notion that sectors producing heavy goods exhibit a relatively larger sensitivity to transportation infrastructure.

V Conclusion

This paper investigates the relationship between firm performance and transportation infrastructure in Colombia. In comparison to the previous literature researching this relationship, which predominantly focussed on developed countries or on aggregated data, I provide evidence for the effects of road infrastructure on output growth using aggregated firm data in a developing country context. The results suggest that roads have larger effects on firms’ output growth in developing countries than they do in developed countries with dense transportation networks. I furthermore identify a time lag with which a firm’s production reacts to road stock expansions. I find that an increase in the highway stock of 10 per cent results in output growth of 1.3 to 1.5 per cent in the subsequent period. Additionally, I find that the effect of roads on output growth is larger in magnitude for manufacturing firms in heavy industries with an identified elasticity more than double in magnitude of that estimated for the whole sample. Further robustness tests allow to identify that regional per capita income may partly drive the estimated elasticities. Additionally, they allow to reject the hypotheses that the results may be driven by agglomeration benefits, cohort factors or the variable chosen to measure transportation infrastructure.

This paper employs the pseudo-panel methodology as a solution to the absence of true firm-level panel data, which is often a problem for empirical work on developing countries. The use of the pseudo-panel methodology allows for the
investigation of firm level dynamics in the absence of true firm panel data, and hence offers a viable option for research on firms in micro data sparse environments. Further tests do not indicate that a large bias in the coefficients is introduced when using pseudo instead of true panels. Hence, this chapter makes a further methodological contribution by investigating the validity of pseudo-panels in the context of production function estimation using aggregated firm data.

While these results support the hypothesis that the effects of transportation infrastructure differ with the state of economic development, further research is required to investigate this relationship in more detail and to examine the underlying mechanisms. It is furthermore important to understand if transportation interacts with the sectoral composition of the economy. In the context of developing countries, it may also be of particular interest to research the relationship of infrastructure and industry shifting.
Chapter 5

The Geographic Heterogeneity within the Relationship of Roads and Firms
I Background and Introduction

Transportation infrastructure is a crucial factor fostering the production and productivity of firms. Transportation connections reduce a firm’s production costs, raise the firms’ productivity level and increase the rate of return on capital. Infrastructure represents an important production component that influences the private sector’s production processes by entering as an additional intermediate input good which subsequently translates to higher output and productivity levels of existing firms. It may further also attract new firms to locate within close proximity to transportation infrastructure links. This may additionally raise the average productivity level within locations. Additionally, if transportation infrastructure, similar to the private capital stock, is assumed to exhibit diminishing marginal returns, then firms in locations with a relatively lower stock of transportation infrastructure are expected to experience relatively higher growth in output and productivity following transportation infrastructure expansions and extensions (for example, Hulten and Schwab, 1993 and Costa et al., 1987 provide evidence across the US, see Puga, 2002 for details across EU countries and Lall, 2007 for analyses of Indian states).

The spatial distribution of the economic activity can be explained by both, regional endowments and increasing returns to scale. It can influence the location choice of firms, foster economic concentration or lead to a geographic dispersion of economic activity. In a setting where transportation costs are relatively high, firms tend to locate within close distance to their final consumer markets so that the overall distribution of economic activity is relatively even across space. However, for lower levels of transportation costs, firms tend to locate and relocate within close proximity of their suppliers leading to an overall economic distribution which

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43 For a detailed discussion see Chapter 2
44 For a detailed discussion see Chapter 4
becomes more concentrated around economic hubs. Given that firms which produce intermediate goods generally supply to final good’s producers of the same industrial sector, industrial clusters tend to become more pronounced and specialised with lower transportation costs. If there exists interregional migration of labour, then workers would relocate in and around regional economic hubs which would result in an uneven distribution of workers, and hence spatial differences in unemployment would ensue. In cases where the degree of interregional migration is low, firms may relocate to those labour markets exhibiting relatively low wage levels. This could additionally foster the emergence of interregional differences in unemployment.

Improvements in transportation connections allow both firms from economically lagging regions to reach the input and relatively larger final consumer markets of economically developed regions faster and at lower costs, and it also allows firms from economically developed regions to reach the markets of less developed regions. Firms from relatively more economically developed regions tend to exhibit higher levels of productivity. Improvements in interregional transportation infrastructure would allow for a better access of these high productivity firms to less developed regions. This would result in an overall heightened level of competition within less developed regions which subsequently leads to an increase in the pressure of firms of less developed regions to survive. Overall, better transportation links reduce and remove the effective geographic distances that allow the survival of lower productivity firms in less developed regions. Hence, transportation infrastructure improvements can hinder the industrialisation process of economically lagging regions.

Investments that increase the capacity and geographic extension of transportation infrastructure networks can thus both foster convergence and reinforce spatial
economic inequality across regions\textsuperscript{45}. Therefore, the investigation into the heterogeneity of the effects of transportation across regions remains important.

This chapter extends the analyses of the previous chapter by investigating the effects of roads across the Colombian regions. I will outline the spatial economy of Colombia in Section 2, and discuss the empirical results in Section 3. Section 4 concludes.

II The Spatial Economy of Colombia

The spatial economy of Colombia is characterised by three predominantly factors: (1) the high degree of urbanisation, (2) the economic importance of natural resources and (3) the persistent regional economic and social disparity between the regions located in the centre and those located along the coasts and the Eastern periphery of the country. Colombia’s three major urban centres, the capital city of Bogotá and the cities of Medellín and Cali, host roughly 41 per cent of the total population and generate 80 per cent of the national GDP\textsuperscript{46}. Further, while the crucial importance of these cities has been a prevailing pattern since the middle of the 20th century, the regional disparity between the central regions, where these cities are located, and the periphery has further increased in the latter part of the 20th and the early years of the 21st century.

Colombia’s economic geography is influenced by the regional economic and social disparity across the central and remaining regions of the country. The poorest and economically least developed regions of Colombia are located along the Pacific and Atlantic coasts in the West and across the wetlands of the Amazon in the East and South East of the country. The rural regions of Colombia are heavily shaped by undiversified local economies and the presence of the decades long civil

\textsuperscript{45}For more details see Faini (1983) and Vickerman \textit{et al.} (1999)

\textsuperscript{46}See Galvis (2001) for further details

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conflict that resulted in the absence of basic public infrastructure (Restrepo et al., 2004). Agriculture, especially the farming of the permanent crops of cocoa and coffee, remains as the main economic activity throughout the rural regions. Notable exceptions to the regional disparity across urban and rural locations are the regions of Arauca, Casanare and La Guajira where the economy of the first two regions has benefitted substantially from large oil fields and the latter region has profited from large coal and salt mines.

Overall, the Colombian concentration of GDP and population is measured as twice the OECD average and its regional Gini coefficient in per capita GDP is higher than the OECD average (OECD, 2014). The absence of efficient transportation networks linking urban centres to each other and to rural areas, and the presence of the civil conflict have further exacerbated the spatial economic disparity. This has lead to a fragmented national economy majorly focused around a few relatively isolated urban hubs with relatively little spillover effects to surrounding regions.

Throughout the literature there exists no clear consensus regarding regional convergence throughout the latter part of the 20th and the early years of the 21st century in Colombia. Cárdenas and Pontón (1995) finds economic convergence for the years 1950 to 1990, but Meisel (1993) only identifies convergence for the period of 1950 to 1960 and no indication for it throughout the following decades. Analysing the more recent years of 1990 to 2005, Royuela and García (2015) find no evidence for economic convergence, but identify convergence in real disposable household income. They argue that given that there was no change in the relative economic importance of regions, the convergence in real household disposable income mostly stems from interregional transfers. Additionally, they identify that the national economic production remained located across the main urban centres named prior. Researching the spatial economy of Colombia for the years of 1999 to
2014, a study by the OECD found that albeit the concentration of population and the economy remained high, Colombia experienced a relatively large reduction in concentration throughout the time period studied (OECD, 2014).

III Results

III.I Results across Geographical Regions

The Colombian regions vary greatly in geographic factors; the Andean mountains run from the northeast to the southwest of the country, they encompass the Amazon region in the south and vast savannah regions in the east of the country. Different topographies and soil types generally benefit different industries, hence given the geographic variety of the country, it cannot be assumed that the effects of transportation infrastructure are homogeneous across the regions. Additionally, the direct and fast access to a seaport may further affect the results. Port cities are often regional or national economic centres with large domestic markets. Furthermore, a location choice closer to a port allows firms to reduce transport costs and times, and hence results in more efficient trading connections. Additionally, given that investment in road infrastructure has not been uniformly distributed across the regions\textsuperscript{47}, it cannot be assumed that its effects are geographically homogeneous. To test for the heterogeneity of transportation infrastructure elasticities across regions, I split the sample into three regional categories: the coastal regions situated on the Atlantic and Pacific coasts, the central regions, and the eastern peripheral regions. Descriptive Statistics for the production variables used for each regional classification are presented in Table 5.1, production function estimation results are listed in Table 5.2.

The estimated coefficients of capital, employment, energy and materials re-

\textsuperscript{47}See Chapter 4, Section 2
main similar across the estimation techniques for each sample, but reveal some degree of variation across the samples. The majority of the results for the peripheral regions however are insignificant. The underlying factor explaining these results can stem from the relatively small sample size for this regional class. The estimated elasticities of highways, similar to all previously tested model variations, remain insignificant in their contemporaneous values across samples and estimations methods chosen. However, the estimated highway coefficients for the lagged values reveal a large degree of heterogeneity across the samples, where while the estimates are in line with the results of Tables 3 – 6 of Chapter 4 and significant for firms located in central regions, they are smaller in magnitude and insignificant for those located in coastal regions. They are negative and insignificant for firms in the peripheral regions. These results indicate that a 10 per cent increase in the highway stock of a region, results in an average output growth of 1.48 to 1.49 per cent for firms in the subsequent period. However, these results are exclusively valid for firms located in central regions. For coastal regions, estimated coefficients on road infrastructure are insignificant for both periods, hence no reliable conclusion can be drawn from these results. Similarly, for firms in peripheral regions, the results indicate that for an increase in the regional highway stock, the firms’ output growth of the subsequent period experiences a negative effect. It could be argued that this may stem from a better access of more productive firms of other regions accessing the region which can lead to demand reductions for the region’s own firms. However, given that the results are not significant, no robust inference can be drawn from these results.

As outlined in Section 2.1 of the preceding chapter, central and coastal regions have been allocated relatively larger shares of the overall road investment budget during the time period analysed. This may lead support to the conclusion that higher investment has resulted in larger economic effects for firms in coastal and
Table 5.1: Descriptive Statistics for Regional Samples

<table>
<thead>
<tr>
<th>Variable</th>
<th>Peripheral Regions</th>
<th>Coastal Regions</th>
<th>Central Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>Output</td>
<td>8,265,689</td>
<td>7,211,915</td>
<td>15,207,354</td>
</tr>
<tr>
<td>Capital</td>
<td>30,286,392</td>
<td>72,151,743</td>
<td>11,330,050</td>
</tr>
<tr>
<td>Employment</td>
<td>35.68</td>
<td>27.40</td>
<td>54.22</td>
</tr>
<tr>
<td>Materials</td>
<td>4,318,460</td>
<td>5,015,697</td>
<td>8,645,404</td>
</tr>
<tr>
<td>Highways</td>
<td>904.18</td>
<td>213.3</td>
<td>863.90</td>
</tr>
<tr>
<td>Observations</td>
<td>66</td>
<td>1,839</td>
<td></td>
</tr>
</tbody>
</table>

central regions relative to those located in peripheral regions. This hypothesis could explain the disparity of estimated elasticities between peripheral, coastal and central regions, but it would not provide an explanation for the differences across coastal and central regions. Hence, the disparity in results cannot be explained simply by a larger amount of investment. Figure 1 of the preceding chapter illustrates the regional disparities across highway growth, but a clear tendency for higher highway growth in central regions cannot be found; additional tests of the data rather show on average higher road growth in coastal regions. Moreover, while the advantage of the employed dataset is that it provides physical infrastructure data, I do not have information on the regional distribution of investments across maintenance and road building projects. For this reason, I cannot exclude the possibility that regional differences in the distribution of funds across road maintenance and new construction projects may influence the results.

The results of this section reveal regional disparities of the role of road infrastructure on firm’s output, and hence highlight the importance of investigating this relationship in more spatial detail. While both the coastal and central regions have received relatively large shares of the national budget, I only find significant results for firms located in the central regions.

48 See Appendix B1. “Graphical Presentation of Regional Highway Growth”
### Table 5.2: Regional Results I: Peripheral, Coastal and Central Regions

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)</th>
<th>Peripheral Regions</th>
<th>Coastal Regions</th>
<th>Central Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Effects</td>
<td>System GMM</td>
<td>Fixed Effects</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Ln(Output)(<em>t)(</em>-1)</td>
<td>0.030(0.262)</td>
<td>0.030(0.191)</td>
<td>0.469(***)</td>
</tr>
<tr>
<td></td>
<td>(0.034)</td>
<td>(0.039)</td>
<td>(0.062)</td>
</tr>
<tr>
<td>Ln(Capital)(<em>t)(</em>-1)</td>
<td>0.006(0.100)</td>
<td>0.006(0.073)</td>
<td>0.077(***)</td>
</tr>
<tr>
<td></td>
<td>(0.021)</td>
<td>(0.021)</td>
<td>(0.021)</td>
</tr>
<tr>
<td>Ln(Utility)(<em>t)(</em>-1)</td>
<td>0.046(0.051)</td>
<td>0.046(0.037)</td>
<td>-0.045(0.027)</td>
</tr>
<tr>
<td></td>
<td>(0.022)</td>
<td>(0.022)</td>
<td>(0.022)</td>
</tr>
<tr>
<td>Ln(Employment)(<em>t)(</em>-1)</td>
<td>0.063(0.105)</td>
<td>0.057(0.077)</td>
<td>0.015(0.022)</td>
</tr>
<tr>
<td></td>
<td>(0.034)</td>
<td>(0.039)</td>
<td>(0.040)</td>
</tr>
<tr>
<td>Ln(Energy)(<em>t)(</em>-1)</td>
<td>-0.129(0.138)</td>
<td>-0.129(0.101)</td>
<td>-0.056(0.026)</td>
</tr>
<tr>
<td></td>
<td>(0.050)</td>
<td>(0.050)</td>
<td>(0.050)</td>
</tr>
<tr>
<td>Ln(Materials)(<em>t)(</em>-1)</td>
<td>0.337(***) (0.119)</td>
<td>0.337(***) (0.087)</td>
<td>0.257(***) (0.041)</td>
</tr>
<tr>
<td></td>
<td>(0.027)</td>
<td>(0.027)</td>
<td>(0.027)</td>
</tr>
<tr>
<td>Ln(Highways)(<em>t)(</em>-1)</td>
<td>1.233(1.000)</td>
<td>1.233*(0.732)</td>
<td>0.055(0.101)</td>
</tr>
<tr>
<td></td>
<td>(0.881)</td>
<td>(0.645)</td>
<td>(0.340)</td>
</tr>
<tr>
<td>Cohort FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Time FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Per Capita Growth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>0.018</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.677</td>
<td>0.145</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td>-</td>
<td>55</td>
<td>578</td>
</tr>
<tr>
<td>Observations</td>
<td>55</td>
<td>55</td>
<td>1,605</td>
</tr>
<tr>
<td>R(^2)</td>
<td>0.905</td>
<td>0.961</td>
<td>-</td>
</tr>
</tbody>
</table>

(Where \(***\), \(**\), * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the cohort level are provided in parenthesis.)

### III.II Results across Economically Lagging and Leading Regions

The results of the preceding subsection only indicated significant effects of highway infrastructure on firms’ output growth for locations in the central part of the country. These results could be supportive of a larger economic importance of the central part of the country. The three classification for the regional categories of the preceding subsection have been chosen based on geographic characteristics and ignored the regional economic differences across the regions. However, given that the large majority of the national GDP is concentrated in the central part of the country, it cannot be excluded that this may also drive the results of Table 5.2. In order to investigate the differing role of highways for firms across economically strong and weak regions in more detail, I analyse this matter further in this subsection.
Table 5.3: Descriptive Statistics for Economically Lagging and Leading Regions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lagging Regions</th>
<th>Leading Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Output</td>
<td>10,277,242</td>
<td>21,075,277</td>
</tr>
<tr>
<td>Capital</td>
<td>9,490,187</td>
<td>28,605,428</td>
</tr>
<tr>
<td>Employment</td>
<td>39.07</td>
<td>49.90</td>
</tr>
<tr>
<td>Energy</td>
<td>2,916,553</td>
<td>10,578,339</td>
</tr>
<tr>
<td>Materials</td>
<td>4,930,987</td>
<td>10,688,217</td>
</tr>
<tr>
<td>Highways</td>
<td>603.96</td>
<td>364.68</td>
</tr>
</tbody>
</table>

| Observations | 1,306 | 1,355 |

I split the sample into three economic categories based on the regional relative average per capita GDP level across the years studied and focus on the effects of highways on firms’ output growth across firms in the economically strongest and weakest third of the sample; I refer to these as the leading and lagging regions respectively. Table 5.3 presents the descriptive statistics for these subsamples.

The spatial economy of Colombia, with the predominant economic role of the main urban centres, suggests that transportation networks may have the largest effects for firms in urban areas. However, given the documentation of a trend of deconcentration for the years of this study (OECD, 2014), firms in lagging regions may also benefit particularly from changes in transportation. This is should especially be expected when the assumption of diminishing marginal returns from transportation infrastructure holds, in which case transportation could be a factor promoting convergence. In the case of this sample, this hypothesis might further hold true as the highway stock (in logs) in lagging regions is lower by approximately a third than the highway stock (in logs) of leading regions. The findings of Hulten and Schwab (1993) and Puga (2002), who analyse the effects of transportation on regional economic characteristics for the US and EU member states
Table 5.4: Regional Results II: Economically Lagging and Leading Regions

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)</th>
<th>Lagging Regions</th>
<th>Leading Regions</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Effects</td>
<td>System GMM</td>
<td>Fixed Effects</td>
<td>System GMM</td>
<td></td>
</tr>
<tr>
<td>Ln(Output)_{t}</td>
<td>0.336*** (0.061)</td>
<td>0.322*** (0.079)</td>
<td>0.472*** (0.070)</td>
<td>0.382*** (0.057)</td>
<td></td>
</tr>
<tr>
<td>Ln(Capital)_{t}</td>
<td>0.062*** (0.020)</td>
<td>0.062*** (0.021)</td>
<td>0.069*** (0.021)</td>
<td>0.067*** (0.020)</td>
<td></td>
</tr>
<tr>
<td>Ln(Capital)_{t-1}</td>
<td>-0.038 (0.027)</td>
<td>-0.037 (0.027)</td>
<td>-0.018 (0.020)</td>
<td>-0.009 (0.019)</td>
<td></td>
</tr>
<tr>
<td>Ln(Employment)_{t}</td>
<td>0.035 (0.023)</td>
<td>0.035 (0.023)</td>
<td>0.031 (0.022)</td>
<td>0.032 (0.021)</td>
<td></td>
</tr>
<tr>
<td>Ln(Employment)_{t-1}</td>
<td>-0.036 (0.027)</td>
<td>-0.034 (0.028)</td>
<td>-0.051*** (0.021)</td>
<td>-0.047*** (0.020)</td>
<td></td>
</tr>
<tr>
<td>Ln(Energy)_{t}</td>
<td>0.257*** (0.058)</td>
<td>0.257*** (0.057)</td>
<td>0.089*** (0.024)</td>
<td>0.102*** (0.026)</td>
<td></td>
</tr>
<tr>
<td>Ln(Energy)_{t-1}</td>
<td>-0.025 (0.026)</td>
<td>-0.022 (0.025)</td>
<td>-0.046*** (0.022)</td>
<td>-0.047*** (0.021)</td>
<td></td>
</tr>
<tr>
<td>Ln(Materials)_{t}</td>
<td>0.583*** (0.046)</td>
<td>0.583*** (0.046)</td>
<td>0.693*** (0.027)</td>
<td>0.691*** (0.026)</td>
<td></td>
</tr>
<tr>
<td>Ln(Materials)_{t-1}</td>
<td>-0.243*** (0.048)</td>
<td>-0.235*** (0.057)</td>
<td>-0.314*** (0.056)</td>
<td>-0.252*** (0.049)</td>
<td></td>
</tr>
<tr>
<td>Ln(Highways)_{t}</td>
<td>0.283(0.329)</td>
<td>0.320(0.321)</td>
<td>0.225(0.297)</td>
<td>0.019(0.223)</td>
<td></td>
</tr>
<tr>
<td>Ln(Highways)_{t-1}</td>
<td>-0.400(0.483)</td>
<td>-0.462(0.487)</td>
<td>0.431** (0.191)</td>
<td>0.242(0.181)</td>
<td></td>
</tr>
</tbody>
</table>

Cohort FE: Y Y Y Y
Time FE: Y Y Y Y
Per Capita Growth: Y Y Y Y
AR1: - 0.002 - 0.000
AR2: - 0.772 - 0.344
Hansen: - 0.000 - 0.000
Number of Instruments: - 524 - 552
Observations: 1,073 1,073 1,226 1,226
R^2: 0.83 0.89

(where *** *, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the cohort level are provided in parenthesis)

respectively, provide further support for this hypothesis of diminishing marginal returns. Table 5.4 provides the estimation results across economically lagging and leading regions.

The results do not provide support for the notion that transportation infrastructure is particularly important for firms of lagging regions. The estimated elasticities of highway infrastructure on output growth are positive for the contemporaneous and negative for the lagged version. The negative coefficient could indicate that an increased market access through growth in regional highways leads to a negative output growth due to increased competition from firms of other re-
regions. Hence, transportation could be assumed to reduce the geographic protection that firms in lagging regions experience. However, given that the results are insignificant, no reliable conclusion can be drawn. For firms of economically strong regions, highway infrastructure is only strongly significant in their lagged value under the Fixed Effects estimation. Given that this elasticity is larger than the elasticities estimated for the whole sample, the industrial classification samples of the preceding chapter and those estimated for the geographic regions in the preceding subsection of this chapter, this result would imply that firms in economically leading regions benefit to a very large degree from transportation infrastructure. However, given that this effect is only identified under one estimator, caution in the conclusions drawn from this result should be advised.

In summary, these results do not provide support for the notion that diminishing marginal returns of infrastructure lead to higher returns from it when its levels are low. In contrast, the estimated elasticities provide some support for the notion that firms' output growth in economically strong regions benefits particularly from growth in transportation.

Overall, there are two possible interpretations explaining the stronger effects of highway infrastructure for firms located in the central relative to those located in the coastal and peripheral regions. The results of Table 5.2 indicate that the benefits of road infrastructure are accrued only by firms located in the central part of the country, while Table 5.4 identifies a tendency of these benefits accruing to firms located in economically strong regions. Within the context of the Colombian economy, the definition of central and economically leading regions partly overlaps, and given that the results of Table 5.2 provide a more consistent pattern, there
exists the possibility that the results of Table 5.4 are indirectly explained by the same pattern exhibited in the results of Table 5.2; thus the following interpretation of the results of this chapter is mostly focused on the interpretation of the results of Table 5.2.

The first argument follows the theoretical outline of the models of economic geography as proposed by Krugman (1980), and Helpman and Krugman (1985), where under the assumption of increasing returns to scale in the industrial production, monopolistic competition along the Dixit-Stiglitz model, and iceberg transport costs, the size of a market is the crucial determinant for economic activity. Within this context, there exists a trade-off between agglomeration forces of better access to final consumer and intermediate input markets and dispersion forces due to lower factor prices and less competitive locations. Changes in transportation costs crucially influence this trade-off, and lead to the prediction of a reinforcement of a more concentrated economy around one or a few economic hubs. The force towards a more concentrated economy, and thus a spatially unequal distribution of economic activity, is predicted to be relatively stronger in regions characterised with particularly asymmetric markets which is often the case for developing economies. Given that the Colombian economy is predominantly concentrated in the central regions of the country, a reduction in transportation costs following extensions of the highway is predicted to lead to an even more concentrated economy by the above outlined theory. Hence, following the theory, the effect of transportation on firms’ output should be particularly strong for firms located in the concentrated central part of Colombia, which is in line with the empirical results of this chapter, particularly those provided in Table 5.2. Empirically, this effect has also been observed in an analysis by Faber (2014), who investigates the economic activity of Chinese districts following the large scale construction of the

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49See Chapter 2, Section 3.3
Chinese highway network. His analysis relies on the comparison of non-connected with connected peripheral districts and identifies reductions in GDP growth of peripheral districts following their connection to the highway network. He finds that this effect is mostly driven by reductions in industrial output and concludes that the prior remoteness of connected peripheral districts had an isolating effect on the district’s local economy. Overall, he finds that the economy becomes more concentrated around agglomeration centres following the construction of the highway network. An alternative interpretation of the empirical results of this chapter might stem from the underlying industrial composition of the Colombian regions. As the results of Table 4.6 of Chapter 4 have illustrated, the positive impacts of transportation on firm’s output are strongly accrued by firms of the heavy industries. Thus, a strong presence of those industries in the central part of the country may drive the results of this chapter rather than a the spatial distribution of economic activity overall. Disaggregating the samples of coastal, central and peripheral regions however does not show a stronger presence of heavy industries within the sample of central regions with relative contributions of heavy industries to these of 40.9, 31.7 and 10.6 per cent respectively.\textsuperscript{50} Within the sample of heavy industries employed for the estimations of Table 4.6, 52.2 per cent are located in the central part of the country, 47.1 per cent are located within the coastal regions, and below 1 per cent is located in the peripheral regions. While this, in combination with the low sample size for peripheral regions, may explain the negligible effects of transportation within the peripheral regions, it does not provide a clear indication that the distribution of heavy industries drives the results of this chapter.

In summary, providing that the regional distribution of heavy industries does not appear to drive the results of this chapter, it follows that the first above

\textsuperscript{50}See also a graphical illustration of this in Appendix B2 “Graphical Presentation of the Geographical Distribution of Heavy Industries”
outlined argument might explain the empirical findings. Hence, the reduction in transportation costs following from the extension of the highway network concentrates the Colombian economy in the central regions of the country further, resulting in larger benefits from road infrastructure for firms located in these.

IV Conclusion

The internal spatial economy of countries is often characterised by an uneven geographic distribution and concentration of economic activity; hence it cannot be assumed that an estimated elasticity of highway infrastructure holds equally for an aggregated national and for disaggregated regional samples. The investigation conducted in this chapter investigates the heterogeneous effects of highways across regions.

The estimated elasticities reveal a large degree of heterogeneity across the regional subsamples defined. Investigating samples of firms in central, coastal and peripheral regions, the estimated elasticities provide support for the notion that firms in the central regions, where the predominant majority of the Colombian economy is generated, benefit particularly from highway infrastructure. Further, it could be argued that highway connections to ports would benefit the country and coastal regions in particular, however the results do not provide any support for this argument. Furthermore, no significant results could be found for firms in peripheral regions. Additionally, investigating the role of highways across economically strong and weak regions, the results do not provide any support for the hypothesis of diminishing marginal returns to infrastructure, and hence it cannot be concluded that highways function as factor promoting convergence in this context.

While overall no definitive pattern emerges, the results indicate that extensions to the highway network resulted in a trend towards an even stronger concentration
of economic activity in Colombia.
Chapter 6

Roads and Productivity: An Investigation of the Effects of Transportation Infrastructure on Firm Productivity Patterns across East and West Germany
I Introduction and Background

The existence of benefits that accrue from economically dense centres to regions, firms and households is strongly supported by the literature. Further, this relationship between economic activity and productivity is generally found to be bidirectional where higher productivity is often attained by firms in economically dense areas and economically dense areas are in turn preferred location choices for high productivity firms (Combes et al., 2012). Transportation networks reduce travel times and costs, and hence increase the accessibility of firms and households to and from economical centres (see for example Ahlfeldt and Feddersen, 2017). Additionally, wider economic benefits arising from economic centres often translate into higher wages, employment and firm productivity (see for example Graham, 2007a; Duranton and Turner, 2012; Holl, 2012 and 2016)\(^{51}\).

Infrastructure is often placed to serve higher expected traffic volumes in regions where higher economic growth is expected. Alternatively, infrastructure is also geographically placed to stimulate growth in low productivity areas. This particularly applies to rail and road transportation networks, given that ports require specific geographical factors, and airports are generally placed around larger metropolitan areas. For the above outlined benefits of transportation, infrastructure investments remain an important topic for policy makers. China and Russia, for example, have agreed on the construction of a 7,000 kilometre high-speed rail network connecting Beijing and Moscow, which is expected to cost around US $230 billion and decrease the average travel time between the cities from 6 to 2 days (AFP, 2014). Another example of a major transportation network is the Spanish high-speed rail programme that was constructed between 2000 and 2010. The target of this programme was to reach 90 per cent of the population within

\(^{51}\)For a detailed discussion, I refer to Chapter 2 of this dissertation
a 50-kilometre radius from a high-speed rail station by 2020. This extensive programme made the Spanish high speed rail network one of the most extensive in Europe. An example of a major highway construction programme is the development of the Chinese national trunk highway network. The highway system, which was built between 1992 and 2005, consisted of the construction of 35,000 kilometres of four-lane highways across the country with a total estimated cost of US $120 billion. Another example of a major transportation project is discussed in Chapter 4 of this thesis.

This chapter analyses the role of highways within regions and its regional spillover effects on firm-level productivity across German NUTS3 districts. This work falls into the greater context of the literature investigating the effects of transportation on various economic measures (examples are provided by D’Costa et al., 2013; Datta, 2012). In detail, this analysis relates particularly to the research investigating the role of roads for firm-level factors (see related work by Gibbons et al., 2017; Holl, 2012 and 2016). Further, this paper also investigates the role of highways across the spatial economic differences of the Western and Eastern districts, the former GDR, of Germany. Hence, this analysis also falls in the context of other research highlighting the economic consequences of the German history of separation and reunification. Ahlfeldt et al. (2015b) for example investigate the spatial distribution of economic activity within the city of Berlin before and during separation, and following reunification. Redding and Sturm (2008) alternatively analyse how the loss in market access during the separation affected the population dynamics of West German towns located closely to the inner-German border. Further details of all referred literature strands can be found in Chapter 2.

Following roughly a 50 years of separation, the German reunification process started in 1989. However by 2014 the per capita GDP level across Eastern states
still only amounted to 71 per cent of that of the Western states, and productivity in the Eastern states only reached 75 per cent of the productivity observed for the Western states (Brenke, 2014). The absence of qualified workers in the Eastern states was proposed as a possible reason for this absence of convergence. In the years following reunification, the regional unemployment in Eastern states fell particularly, however analyses have shown that this was mostly due to the observed reduction of the workforce resulting from the migration of workers, particularly of the young, to the Western states (Brenke, 2014). The real wage level observed for the Eastern states is estimated to be approximately 85 per cent of that of the Western states, and while qualified workers are crucial to increase regional productivity, and subsequently raise the wage level, lower real wages do not attract qualified workers to relocate to the Eastern states. Further, in the early 1990s, a boost in GDP surpassing the GDP growth of the Western states could be measured for the Eastern states. This however has flattened off and since the mid-1990s the Eastern GDP growth rate remains below the Western one with averages growth rates of 0.9 and 1.4 per cent respectively. The prior mentioned initial economic boost is generally hypothesised to be in part due to the re-structuring of the economy across the Eastern states which resulted, amongst others, in the closure of multiple non-profitable firms. This simultaneously resulted in both an increase in unemployment and in per worker productivity. However, since the mid-2000s this development in per worker productivity has levelled off, so that the current per worker productivity in the Eastern states is approximately 70 per cent of the equivalent variable for the Western states. Hence, another possible source driving this spatial heterogeneity stems from the differences in sectoral composition of the industries. The Eastern states have on average higher relative shares of agriculture and construction industries than the Western states. Both of these industries can generally be observed to have relatively low productivity parameters. Brenke
(2014) has investigated this hypothesis and found no empirical support, but rather identified that the productivity observed for any industrial sector across the Eastern states is behind its equivalent for the Western states. Another source for the spatial disparity stems from the differences in average firm size. Given that it is generally hypothesised that larger firms attain higher productivity (Leung et al., 2008), but across the Eastern states, there is a relatively higher number of small establishments, the conclusion arises that this may be another factor contributing to the spatial heterogeneity in productivity.

This chapter analyses the role of highways for the productivity of firms across German counties. In order to control for the possible endogeneity in placements, I use two historical instrumental variables based on rail and road networks. Additionally, I investigate the differences of these effects across Eastern and Western states, and conduct an ex-ante analysis of highways constructed for better market access across the Eastern states.

This chapter is structured as follows: Section 2 provides an overview of the German highway network, Section 3 describes the data used for this analysis, Section 4 outlines the identification and estimation strategy of this work, and Section 5 discusses the results. Section 6 concludes.

II The German Road Network

Germany has one the most extensive and dense road networks globally. Overall, the German road network spans over 230,517 kilometres across four classes of roads: Federal Highways (Bundesautobahnen), Federal Roads (Bundesstraßen), Country roads (Landes-, Staatsstraßen), and County Roads (Kreisstraßen). The approximately 13,000 kilometres of federal highways and the 39,600 kilometres of federal roads provide direct long distance connections across the states and

52 Throughout this chapter I use the word highway and Autobahn interchangeably
are generally under the direct authority of the federal government. The 86,200 kilometres of country and 91,800 kilometres of county roads primarily facilitate the regional and local traffic. Different from federal highway and roads, country and county roads fall under the authority of the federal state (EU NUTS-1 region) and district (EU NUTS-3 region) respectively.

Given that the German federal highway network represents roughly 6 per cent of the total national road network, but carries more than 32 per cent of the overall traffic volume, its design, implementation and maintenance remain a priority for policy makers. During the years of the existence of two separate German states from 1949 to 1990, the respective East and West German governments however had followed very different transport policy guidelines. This resulted in large discrepancies in the road quality and quantity across the two states. Following the German reunification in 1990, the closing of this infrastructure gap across the East and West German road networks became an important policy priority. The noticeable increase in traffic and transit traffic volume in the East German states following the opening of the border, added further to the importance of the overhaul of the East German federal highway network.

In order to close the infrastructure gap, establish efficient and high capacity transportation links between the former West and East states, and foster economic development and regional employment, in 1991 the federal government decided on 17 priority transportation infrastructure projects under the title of “Transportation Projects German Unity” (Verkehrsprojekte Deutsche Einheit/ VDE). These projects received expedited funding and their implementation process was fast-tracked. Overall, a total budget of roughly €40bn was set, which was distributed across 9 rail, 7 federal highway and 1 waterway project with individual budgets of €20.7bn, €17.3bn and €2bn respectively. The infrastructure projects mostly consisted of the new construction and reconstruction of transportation links in the
Eastern states, but to a minor part also included construction and reconstruction of the connecting transportation infrastructure in Western states.

The rail projects consisted of the construction of new, mostly high-speed, transportation links between metropolitan areas which allowed for crucial reductions of transport times. In 2014, 6 out of the 9 rail projects were constructed and fully operational. The 3 remaining projects were in the finalisation period. The waterway project comprised of the establishment of waterway connections through channels that allow larger vessels to reach destinations further inland. The highway pro-
jects encompassed the construction of 1,954 additional highway kilometres, out of which 97 per cent of this target had been met in 2014 with the construction of another 24 highway kilometres remaining. Five new highways were built and four highways were majorly expanded to allow for an increased capacity and a further reach of the network. The newly constructed highways allow for a better connectivity of Berlin along the Baltic sea towards North Germany and directly towards central West Germany, provide a direct connection between the metropolitan region of Halle and Leipzig with the economically important Rhine, Main and Ruhr regions, and establish efficient transportation links towards Poland in the east and the state of Bavaria in the south. Figure 6.1 provides a graphical representation of the German highway network and the projects of “Transportation Projects German Unity”.

Overall, since 1991 an additional 2,478 highway kilometres have been constructed and the amount of six (or more) lane highway kilometres has been increased by an additional 2,463 to a total of 3,383 kilometres, expanding both the length and capacity of the network.

III Data

III.I Establishment Data

III.I.I The IAB Establishment Panel

The data on establishments used for this analysis stems from the annually conducted IAB Establishment Panel which is based on a survey including all German establishments with at least one employee liable to social security. The survey and resulting dataset are available from 1993 and 1996 for West and East German establishments respectively, and is provided by the Institute for Employment Research of the German Federal Employment Agency. The dataset is derived
Table 6.1: Summary Statistics of Production Function Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>46,898</td>
<td>500,929</td>
</tr>
<tr>
<td>Labour</td>
<td>156.85</td>
<td>970.98</td>
</tr>
<tr>
<td>Capital (between)</td>
<td>17,821</td>
<td>125,810</td>
</tr>
<tr>
<td>Capital (within)</td>
<td>18,171</td>
<td>130,930</td>
</tr>
<tr>
<td>Intermediate Inputs</td>
<td>32,941</td>
<td>421,789</td>
</tr>
</tbody>
</table>

Note: Statistics of Output, Capital (between), Capital (within) and Intermediate inputs are provided in thousands from the survey of interviewed plants according to an optimum stratification principle along 17 industrial sectors, the 16 federal states and 10 plant size categories (Fischer et al., 2009) which results in an approximate annual sample size of 16,000 establishments. The data provide information on the establishment’s revenues, intermediate inputs, investments and numerous additional establishment level data, particularly those relating to employment or the establishment’s workforce.

This stratification process of the data leads to an overrepresentation of large establishments, plants in relatively small federal states and those of the East German manufacturing sector. In order to ensure the representative validity of the sample, I follow Bossler et al. (2017) and control for all four stratification categories across the estimations. The IAB establishment panel offers the benefit of providing a consistent classification of the plant’s industrial sector, which allows the choice of the investigated time period 1999 to 2014 to be independent of the official changes in the German industrial classification system in 2003 and 2008\textsuperscript{53}. For this study, I employ an unbalanced panel for the years 1999 to 2014.

\textsuperscript{53}For further details on the IAB establishment panel see Fischer et al. (2009)
Table 6.2: Yearly Distribution of Number of Firms across East and West German Regions

<table>
<thead>
<tr>
<th>Year</th>
<th>West Germany</th>
<th>Freq.(%)</th>
<th>East Germany</th>
<th>Freq.(%)</th>
<th>Total Number of Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>625</td>
<td>36.89</td>
<td>1,069</td>
<td>63.11</td>
<td>1,694</td>
</tr>
<tr>
<td>2000</td>
<td>1,206</td>
<td>45.56</td>
<td>1,441</td>
<td>54.44</td>
<td>2,647</td>
</tr>
<tr>
<td>2001</td>
<td>1,778</td>
<td>50.87</td>
<td>1,717</td>
<td>49.13</td>
<td>3,495</td>
</tr>
<tr>
<td>2002</td>
<td>1,967</td>
<td>54.94</td>
<td>1,613</td>
<td>45.06</td>
<td>3,580</td>
</tr>
<tr>
<td>2003</td>
<td>2,068</td>
<td>54.96</td>
<td>1,695</td>
<td>45.04</td>
<td>3,763</td>
</tr>
<tr>
<td>2004</td>
<td>2,118</td>
<td>55.55</td>
<td>1,695</td>
<td>44.45</td>
<td>3,813</td>
</tr>
<tr>
<td>2005</td>
<td>1,991</td>
<td>55.05</td>
<td>1,626</td>
<td>44.95</td>
<td>3,617</td>
</tr>
<tr>
<td>2006</td>
<td>1,873</td>
<td>54.45</td>
<td>1,567</td>
<td>45.55</td>
<td>3,440</td>
</tr>
<tr>
<td>2007</td>
<td>1,766</td>
<td>51.25</td>
<td>1,680</td>
<td>48.75</td>
<td>3,446</td>
</tr>
<tr>
<td>2008</td>
<td>1,761</td>
<td>51.89</td>
<td>1,633</td>
<td>48.11</td>
<td>3,394</td>
</tr>
<tr>
<td>2009</td>
<td>1,748</td>
<td>52.30</td>
<td>1,594</td>
<td>47.70</td>
<td>3,342</td>
</tr>
<tr>
<td>2010</td>
<td>1,766</td>
<td>52.43</td>
<td>1,602</td>
<td>47.57</td>
<td>3,368</td>
</tr>
<tr>
<td>2011</td>
<td>1,666</td>
<td>51.97</td>
<td>1,540</td>
<td>48.03</td>
<td>3,206</td>
</tr>
<tr>
<td>2012</td>
<td>1,588</td>
<td>51.42</td>
<td>1,500</td>
<td>48.58</td>
<td>3,088</td>
</tr>
<tr>
<td>2013</td>
<td>1,335</td>
<td>49.94</td>
<td>1,338</td>
<td>50.06</td>
<td>2,673</td>
</tr>
<tr>
<td>2014</td>
<td>1,084</td>
<td>47.65</td>
<td>1,191</td>
<td>52.35</td>
<td>2,275</td>
</tr>
<tr>
<td>Total</td>
<td>26,340</td>
<td>51.81</td>
<td>24,501</td>
<td>48.19</td>
<td>50,841</td>
</tr>
</tbody>
</table>
termediate goods and services purchased from other plants, hence no distinction
between energy and standard intermediate input goods could be made in this ana-
lysis. Further, information on the establishment’s capital stock are not explicitly
provided in the dataset, however I use the data on the plant’s investment behaviour
to derive the capital variable via a (modified) perpetual inventory method\textsuperscript{54}. The
variable for output is the firm’s revenues. The information on intermediate inputs,
the derived capital variable and revenues are provided in monetary units. Labour
is the total number of employees as noted on June 30th of each respective sur-
vey year. I employ data from the German Federal Statistical Office (\textit{Statistisches
Bundesamt/Destatis}) on producer prices to deflate the monetary variables of the
firm’s output, intermediate inputs and capital. The deflation of variables provided
in monetary units allows to adjust these for sector specific price and inflation move-
ments to identify approximate values of physical units. The German FSO gen-
erates producer price indices following a Laspeyres chained index formula which
is based on the sum of the product prices weighted by their relative importance
for total domestic revenue. The base year used for the time when this study was
undertaken was 2010, i.e. all prices were normalised to 100 for 2010. The German
FSO only started a methodical collection of producer prices for service industries
in 2006, thus the majority of the establishments of the service sector could not
be included in this study. For the sectors of hospitality, and retail and wholesale
trade, I use the consumer price indices to correct for price and inflation changes.

Additionally, observations that contain missing data points for those variables
required for production function estimates are further excluded, resulting in the
total sample size of 50,841 observations across the 16 years of this study. Table 6.1
provides summary statistics for the variables employed in the production function
estimation. Table 6.2 provides an overview of the distribution of the observations

\textsuperscript{54}See Section 3.1.2 of this chapter
Table 6.3: Descriptive Statistics of Aggregated Industrial Sectors Included

<table>
<thead>
<tr>
<th>Industry Class</th>
<th>AGRI.</th>
<th>CO.-PE.</th>
<th>FOOD</th>
<th>TEXT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Observations</td>
<td>1,998</td>
<td>383</td>
<td>2,525</td>
<td>894</td>
</tr>
<tr>
<td>Relative Frequency</td>
<td>3.91</td>
<td>0.75</td>
<td>4.97</td>
<td>1.76</td>
</tr>
<tr>
<td>Av. Annual Employment</td>
<td>3,136</td>
<td>8,020</td>
<td>17,399</td>
<td>5,341</td>
</tr>
<tr>
<td>Av. Annual Output</td>
<td>€274m</td>
<td>€4.4bn</td>
<td>€5.4bn</td>
<td>€851m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Industry Class</th>
<th>WOOD</th>
<th>CHEM.</th>
<th>MIN.</th>
<th>MET.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Observations</td>
<td>2,566</td>
<td>3,088</td>
<td>1,751</td>
<td>5,736</td>
</tr>
<tr>
<td>Relative Frequency</td>
<td>5.05</td>
<td>6.07</td>
<td>3.44</td>
<td>11.28</td>
</tr>
<tr>
<td>Av. Annual Employment</td>
<td>15,480</td>
<td>53,972</td>
<td>9,849</td>
<td>68,999</td>
</tr>
<tr>
<td>Av. Annual Output</td>
<td>€3.2bn</td>
<td>€15.1bn</td>
<td>€1.6bn</td>
<td>€21.8bn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Industry Class</th>
<th>ELEC.</th>
<th>MACH.</th>
<th>VEH.</th>
<th>N.E.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Observations</td>
<td>2,547</td>
<td>3,738</td>
<td>1,896</td>
<td>2,235</td>
</tr>
<tr>
<td>Relative Frequency</td>
<td>5.01</td>
<td>7.35</td>
<td>3.73</td>
<td>4.40</td>
</tr>
<tr>
<td>Av. Annual Employment</td>
<td>43,476</td>
<td>58,956</td>
<td>132,051</td>
<td>11,863</td>
</tr>
<tr>
<td>Av. Annual Output</td>
<td>€9.9bn</td>
<td>€12.8bn</td>
<td>€50.9bn</td>
<td>€1.9bn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Industry Class</th>
<th>Energy</th>
<th>CON.</th>
<th>TRADE</th>
<th>HOSP.</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Observations</td>
<td>1,017</td>
<td>9,290</td>
<td>8,853</td>
<td>2,334</td>
<td>50,841</td>
</tr>
<tr>
<td>Relative Frequency</td>
<td>2.00</td>
<td>18.27</td>
<td>17.41</td>
<td>4.59</td>
<td></td>
</tr>
<tr>
<td>Av. Annual Employment</td>
<td>15,153</td>
<td>26,100</td>
<td>45,686</td>
<td>4,633</td>
<td>520,114</td>
</tr>
<tr>
<td>Av. Annual Output</td>
<td>€8.5bn</td>
<td>€4.1bn</td>
<td>€16.1bn</td>
<td>€295m</td>
<td>€157.1bn</td>
</tr>
</tbody>
</table>
across years in East and West Germany. Table 6.3 provides an overview of the
industries included in this analysis aggregated to 16 industrial classifications.

III.I.II The Extrapolation of Capital Data from Firm Investment

The data provided in the IAB Establishment Panel does not include any in-
formation on the capital stock of the establishments. However, given the import-
ance of this variable, it has become a commonly used approach to derive the capital
stock variable from the information on the plant’s investment behaviour included
in the dataset using the perpetual inventory method (Addison et al., 2006; Müller,
2008; Ehrl, 2013). In this chapter, I follow the modified specification of this ap-
proach as drafted by Müller (2008 and 2017). I employ data from the German
national accounts to estimate the average economic lives of the capital stock for
each industrial sector. The subsequent estimation of the plant’s capital stock fol-
lows two assumption: (1) It is assumed that the industry-level depreciation rate is
valid for all plants of the industrial sector. While there exist data on the specific
type of investment undertaken by the firm, this assumption allows to determine
appropriate depreciation rates for all establishment of the given sector, including
those whose observation period in the dataset is relatively short; (2) The assumed
industry-level depreciation rate is linear, and it is assumed to be the reciprocal
of the capital stock’s average economic life. The initial value of each plant’s cap-
ital stock is estimated using the time-average replacement investment of the plant
divided by the industry-level depreciation rate. More specifically, two separate
approaches are used to determine the starting value of capital for each firm: The
augmented proportionality and the modified perpetual inventory approach. The
augmented proportionality approach relies on the information of the moving av-
erages of investment to estimate the firm’s initial capital stock. However, the
reliance on information of moving averages introduces errors into the estimated

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values. These are assumed to be random but not persistent so that on average the estimated capital stocks in levels can be assumed to be of the correct magnitude. The capital stock derived via this method, referred to as Capital (between) throughout this paper, is the more suitable variable for estimators relying on the between dimension of the data (Müller, 2008). The modified perpetual inventory approach computes the firm’s initial capital stock via an augmented proportionality approach which introduces a certain amount of measurement error. Convergence to the true value is expected in the long run, so that this measurement error is of importance for the short run. The noisiness in the data particularly affects the capital variable in its level, so that the measurement error predominantly affects the between dimension of the data. The capital data derived via this method is preferable for estimators relying on the within information of the data. I refer to this variable as Capital (within).

The capital stock for all subsequent periods is approximated via the usual perpetual inventory approach where the capital stock evolves according to \( K_{it} = (1 - \delta_{jt})K_{it-1} + I_{it-1} \) where \( K_{it} \) and \( I_{it} \) are the plant \( i \)'s capital stock and investment at time \( t \) respectively, \( \delta_{jt} \) is the depreciation rate of the industrial sector \( j \) at time \( t \) to which plant \( i \) belongs.

### III.II Regional and Transportation Data

In 2014, Germany consisted of 402 EU-NUTS3 districts, with 295 districts classified as regional districts and 107 districts categorised as district-free cities, which de facto function as their own districts. Between the years of 2007 to 2011, multiple geographical district reforms have taken place. The district reforms were predominantly focused on the former Eastern German states of Mecklenburg-Vorpommern, Saxony and Saxony-Anhalt with a few minor changes also across the former Western states. In the instance where new districts consist of direct merges
of previous districts, the data collected prior to the change was summed to match the new districts; in cases where the districts were subdivided and subsequently split across the new boundaries, the data was aggregated across to ensure consistency. Data on regional population, employment and the district’s size were taken from the Federal Statistics Office (Statistisches Bundesamt), geographical data and positions of county mid-points used for the subsequent estimations were provided by the Federal Agency of Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie).

The detailed information on the yearly kilometre length of federal highways, federal roads, country and county roads were collected from regional statistics offices and regional ministries responsible for transportation. The data was subsequently matched to the data of the IAB establishment panel using the district identifiers. In this analysis, I focus on two separate categories of variables capturing highway infrastructure: district level highway density, and to capture regional spillover effects, I further employ two variables measuring the highway density within the district’s direct vicinity and within a wider regional context. Each district’s highway density is calculated as the amount of highway kilometres per 100 sq. kilometres of geographic area size. Both highway variables capturing spillover effects are generated according to equation (6.1), but differ depending on the pairwise distance between the geographic midpoints of two districts. The variable termed Direct Access only includes the highway density of those districts whose midpoints fall within a 75 kilometre distance band to the given district, while Wider Access includes all remaining districts located further than 75 kilometres away.

$$Highway\ Access_{rt} = \sum_{s \in D} \left( \frac{Highway\ Density_{st}}{Distance_{rs}} \right)$$  \hspace{1cm} (6.1)

where \(r\) and \(s\) are districts, and \(Distance_{rs}\) represents the pairwise distance
between the geographic midpoints of the districts within a 75 kilometre range for *Direct Access* and alternatively those located further away for the *Wider Access* variables respectively. In order to include counties with no highway infrastructure, 0.5 kilometres were added to all observations for the calculation of each district’s highway density.

Figure 6.2 illustrates the average highway density and average annual change of it across the districts\(^{55}\). Overall, from the graphical presentation of highway density allows to note tendencies: The majority of districts with levels of highway density is located in the Western states and around larger agglomeration centres. Further, the largest growth rates however can be observed in districts located in the East and Northeast of the country. The graphical presentation provided in

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\(^{55}\) Equivalent graphs for *Direct Access* and *Wider Access* can be found in Appendix C2 “Graphical Presentations of Highway Density Variables Capturing Direct Access and Wider Access”
Table 6.4: Descriptive Statistics of Highway Variables Employed

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway Density</td>
<td>5.86</td>
<td>5.99</td>
<td>1.000</td>
</tr>
<tr>
<td>Highway Density - Direct Access</td>
<td>3.77</td>
<td>4.40</td>
<td>0.625 1.000</td>
</tr>
<tr>
<td>Highway Density - Wider Access</td>
<td>9.02</td>
<td>1.74</td>
<td>-0.009 0.034 1.000</td>
</tr>
</tbody>
</table>

Appendix C2 further show that when spillovers are included then districts in the West and centre of Germany exhibit the largest values, while the largest growth can predominantly be observed across the districts belonging to the Eastern states. Thus, major improvements are in almost all cases linked to the new highways built under the "Transportation Projects German Unity" across the North-East and as connections of the central part of the former East with the central and southern parts of Germany. Table 6.4 provides summary statistics.

IV Estimation Strategy

IV.I TFP and Production Function Estimation

The motivation for this work is to investigate the influence of highway infrastructure on total factor productivity (TFP) patterns across German firms. Furthermore, I research the "Transportation Projects German Unity" by conducting a subsample analysis of the effect of these on firms.

The empirical strategy to estimate productivity follows a two-step production function estimation process which allows to analyse the role of highway infrastructure affecting firms’ growth through their TFP. Similarly to the methods employed by Holl (2012 and 2016) and Martin et al. (2011), I start with the Cobb-Douglas production function in its standard neoclassical form

\[ Y_{it}(K, L, M) = A_{it}K_{it}^{\beta_K}L_{it}^{\beta_L}M_{it}^{\beta_M} \]  

(6.2)
where $Y_{it}$ represents deflated revenues, $K_{it}$ represents the capital stock, $L_{it}$ the workforce and $M_{it}$ the intermediate inputs of firm $i$ at time $t$. $A_{it}$ represents the firm’s time-varying TFP parameter. The firm’s TFP can further be described as

\[ A_{it} = (H_{rt})^\alpha e^{\epsilon_{it}} \]  

(6.3)

with

\[ \epsilon_{it} = \tau_t + \mu_s + \delta_r + \epsilon_{it} \]  

(6.4)

where $H_{rt}$ represents the highway infrastructure in district $r$ at time $t$. The composite error term $\epsilon_{it}$ is decomposed further into year fixed effects $\tau_t$, which capture any unobservable shocks that affect all firms in a given year, sector specific effects $\mu_s$, which capture any changes that will affect all firms within a sector, and any district specific characteristics affecting firms $\delta_r$. $\epsilon_{it}$ is the true error.

A log-linear transformation of equations (6.2) and (6.3) results in

\[ y_{it}(k,l,m) = a_{it} + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} \]  

(6.5)

and

\[ a_{it} = \alpha h_{rt} + \tau_t + \mu_s + \delta_r + \epsilon_{it} \]  

(6.6)

where lower case letters represent the variables in their logarithmic forms.

The empirical estimation proceeds in two steps: I identify the TFP as the residual of (6.5) with

\[ a_{it} = y_{it} - (\hat{\beta}_k k_{it} + \hat{\beta}_l l_{it} + \hat{\beta}_m m_{it}) \]  

(6.7)

where $\hat{\beta}_k$, $\hat{\beta}_l$ and $\hat{\beta}_m$ are the sector-specific estimated coefficients. Subsequently,
(6.6) is employed to estimate the effects of highway infrastructure on the firms’ estimated TFP parameters from (6.7). Given that the identification of sector-specific coefficients should capture any sector-specific components, I ignore sector specific factors in (6.6), so that $\mu_s = 0$.

Unobservable shocks may affect the firm’s production process both through entering the error term and by influencing the firm’s input choices. The resulting endogeneity issue would bias the estimation under OLS, thus I follow the Levinsohn and Petrin (2003) approach for the identification of the sector-specific coefficients in (6.5). Based on the rationale that firms with increased productivity exhibit increased marginal productivity of their production inputs, Levinsohn and Petrin (2003) propose the firm’s choice of intermediate inputs as a proxy for unobserved productivity. This allows to control for the correlation of the production variables with any unobserved shocks, e.g. productivity or demand shocks\textsuperscript{56}.

### IV.II Identification Issues

For the validity of the empirical estimation it is crucial that possible sources of biases are addressed appropriately. One of the most documented issues within the context of the estimation of the effects of infrastructure investments on firms is the absence of the exogeneity of the firm’s choice of location. Any firm characteristics that determine both the firm’s (re-)location choice, and hence highway access, and the firm’s productivity create endogeneity issues with in the estimation. If these firm factors are time-invariant and unobservable, then the resulting estimation model will ignore these covariates, will hence be misspecified and the resulting estimation will exhibit a bias. Additionally, if there exist firm specific factors that are time variant, then a correlation between the error term and the right-hand side variables will result in a further source of a bias. This source of bias would

\textsuperscript{56}See Chapter 2
occur if there are shocks to productivity which are expected by the firm, and hence affect the firm’s decision of its input factors (Blundell and Bond, 2000). Nocke (2006) highlights this issue by outlining a location choice theory of entrant entrepreneurs, who he finds to be predominantly more efficient than incumbent firms and therefore preferably locate in large markets with increased levels of competition. Saito and Gopinath (2009) empirically find that plants that exhibit relatively high levels of productivity primarily locate in regions with large markets and hence substantially benefit from the self-selection process in Chile. Combes et al. (2012) on the other hand do not find any evidence for the firms’ self-selection process as a driver of geographical advantages to firm’s productivity levels in France.

A further source of estimation bias stems from simultaneity and reverse causality issues. Policies that aim at fostering regions economically, and thus affect the region’s market access directly or indirectly, may consequently also attract firms and workers to locate and relocate to these regions. This will in turn increase the region’s market access further and hence result in a simultaneity between regional economic outcomes and market access. Graham et al. (2010) highlight this issue for the UK. Relying on Vector autoregression (VAR) models to test the mutually dependent relationship between productivity of firms and agglomeration economies, they find that higher levels of TFP can yield growth in industrial and urban environments. They find that this is particularly the case for localisation economies. Ahlfeldt et al. (2015b) investigate this relationship in the context of public transportation and land prices. Using a historic panel of property prices of Berlin to measure the economic productivity of land via land values, they find evidence for a bidirectionality in the relationship between local economic performance and transport infrastructure supply. Baldwin and Okubo (2006) highlight this issue by investigating the effect of market size on the firm’s location choice. They conclude
that productivity is crucially influenced by regional market size and regionally available human capital. Furthermore, regional policies aimed at increasing market size would lead to a location or relocation of the most productive firms to that region, firms with low productivity would locate in peripheral locations.

A third source of endogeneity stems from the endogenous geographic placement of transport infrastructure. Investments in transportation infrastructure may be driven by expected economic growth if roads are placed to meet increased future demand in regions where higher economic growth is expected. Alternatively, transportation infrastructure may also be placed to stimulate economic growth in regions where productivity and economic growth is relatively low.

For a correct estimation it is hence of crucial importance to control for these sources of endogeneity and subsequent biases, thus I discuss instrumental variables based on historical information as an empirical solution in Section 6.4.3.

**IV.III Historical Variables as Instrumental Variables**

In the presence of endogenous explanatory variables, the instrumental variable methodology presents an option to control for any biases which may arise because of it. Any variable to be used as an instrumental variable for the endogenous regressor must fulfil two conditions: the (1) relevance and (2) exogeneity condition. A variable must predict the endogenous variable, i.e. conditional on controls, so that there has to be a non-zero correlation between the endogenous and the instrumental variable. This is the relevance condition. Additionally, it is pivotal that the instrumental variable only affects the dependent variables through its effect on the endogenous variable; this is the exogeneity or exclusion condition. Both conditions ensure the orthogonality of the error term. Further, the conditions require orthogonality conditional on controls, they do not require unconditional orthogonality, hence the inclusion of correlated fixed effects.
other controls, is important. In the context of this work, a variable is hence a suitable instrumental variable if it predicts current highway infrastructure but is uncorrelated with firm-level productivity through any other channel than through its relation with the contemporaneous highway network. I propose three separate instrumental variables, which are based on historical transportation networks, for the contemporaneous German highway network; these are discussed subsequently in Sections 6.4.3.1 and 6.4.3.2. However, there may be factors that may have had an influence on the historical transportation networks as well as an effect on current firm productivity. It appears highly likely that these would be factors relating to specific location characteristics. Hence, I add regional and geographical factors to control for this possible omitted variable bias.

Within the literature, there exists also other work relying on the information of historical transportation networks as instrumental variables, some of these are provided by Holl (2012 and 2016), Duranton and Turner (2012), Duranton (2015), Duranton et al. (2014), Möller and Zierer (2018), and Volpe Martinus et al. (2017).

IV.III.I The 1938 Highway and Reichsstrassen Network

I base the first two instruments on data from the 1938 highway and Reichsstrassen stock. In Germany, the first roads that followed the idea of long-distance national connections were constructed during the first wave of mass motorisation during the time of the “Weimar Republic” in the 1920s. However, the significant expansion of this road network did not occur until the mid 1930s. Following Hitler’s rise to power in 1933, an intense planning and construction process for a German highway network was initiated. In 1933, a publicly owned company for the nationwide construction, operation and maintenance was founded. The initial plan for a 9,000 kilometres highway network was drafted by the think-tank “Studiengesellschaft
für Automobilstraßenbau / STUFA” and followed predominantly the idea of pairwise connections between important cities rather than a transportation network based concept. Overall, this highway plan was significantly determined by political factors. Exact trajectories were also often decided by Hitler himself, who has been documented to have preferred scenic routes (Voigtlaender and Voth, 2017). The highway project was part of a larger, politically driven plan for the motorisation of Germany which consisted of road constructions, the development of cheaper compact motor vehicles and relevant tax subsidies. The underlying aim for this was largely driven by political and propaganda reasons. Following years of austerity during the 1920s, the construction of a highway network signalled competence, represented a major break from the previous austerity policies and therefore aided the Nazi propaganda. The construction of the highway network was further announced as an employment reducing measure, however ex-post evaluations show that it was predominantly only the employment within the construction of the highway that was affected (Ritschl, 2003). It is often assumed that the highway network was constructed for military purposes, however analyses have shown that the majority of troops and supplies during the second World War were transported by rail (Voigtlaender and Voth, 2017).

Within the year of beginning the highway project, construction started across 22 locations and in 1935 the first segment of the highway was opened. The instrumental variable is based on data from the 1938 highway network at which the network consisted of approximately 4,000 kilometres. Similarly, parallel to the construction of a highway network, the pre-existing network providing national connections, termed Reichsstrassen during the time of the National Socialist’s reign, was also extended. Figure 6.3 illustrates the 1938 German highway and Reichsstrassen network.

Both of the historical highway and and Reichsstrassen networks provide suit-
able instruments for the contemporaneous highway network if they are correlated with the current highway network but do not influence firm-level productivity through any other channel. As much of the current highway network was constructed as replacements or extensions of the previous highways, the 1938 highway data should provide relevant information for the current highway stock. Similarly, following World War 2 various historical Reichsstrassen have been expanded into current highways, and should thus have a non-zero correlation with the contemporaneous highway network. However, the data from 1938 represents information previous to World War 2 and the years of the inner-German division. Both of the
events undoubtedly significantly affected the development and spatial distribution of German economic activity. It can hence be concluded that the existence of a direct effect of the 1938 highway and Reichsstrassen network on current firm-level productivity is highly unlikely. For any geographical components that have influenced both historical highway and Reichsstrassen placements, and current firm-level productivity, controls are included.

In order to generate the instrumental variables based on the information of the 1938 highway and Reichsstrassen network, two digitised versions of the map depicted in Figure 6.3 were generated for the highway and Reichsstrassen networks respectively using GIS software. Subsequently, the generated maps were overlaid with the 2014 geographical borders of German NUTS3 regions to identify the regional lengths of each road category; the digitised maps can be found in Appendix C3, Figures C3 and C4.

The historical highway and Reichsstrassen density, Direct and Wider Access variables were calculated equivalently to those based on the contemporaneous highway network. Table 6.5 provides descriptive statistics of the variables generated from the 1938 highway and Reichsstrassen network.

**IV.III.II The 1849 Rail Network of the German Zollverein**

The second instrumental variable I propose employs data from the 1899 rail road network across the area that is now defined as German territory. Figure 6.4 shows this information. Throughout recent history, German borders have changed particularly often. Further, Germany, as it exists now, is a relatively new construct; for the preceding centuries, Germany did not exist as a national state, rather it was made up of numerous duchies, grand duchies and kingdoms. It was mostly due to the predominance of small state federalism and the absence of a common strategy that Germany had a relatively less developed and limited
railroad network at the beginning of the 19th century (Pierenkemper and Tilly, 2004). In 1815, following the defeat of Napoleon, Germany consisted of 39 states, of which the kingdoms of Prussia, Bavaria, Hannover, and the Austrian empire were the dominating forces. Also during this time, these countries came together for the first time under the common organisation of the German confederation association (Deutscher Bund). During the year 1833, the prominent German economist Friedrich List published the first draft for pan-German railroad links. In combination with the founding of the German customs union between the majority of German states in 1834, which removed trade tariffs and thus increased trade volume between the union’s members, the construction and development of a railroad network received increased importance. Constitutional restrictions prevented any member state from drafting a central plan, however the passing of a law allowed external private entities the construction, operation and maintenance of railroad tracks. The initial construction phase of rail tracks, which lasted until approximately 1850, was focused on establishing pairwise connections between cities, so that in 1835 the first railroad connection between the Prussian cities of Potsdam and Berlin was opened to the transport of people. The first good’s transport occurred in 1836 and consisted of the transport of two kegs of beer. From 1837 onwards, also long-distance connections up to 120 kilometres were established, and with the opening of a rail link to Belgium in 1855/56, also international connections existed. During this phase of the German railway network, rail connections within German states were either under the control of private entities (Privatbahnen) or in the hands of the the state’s monarchy (Staatsbahnen). In the years preceding and those following the founding of the German Reich in 1871, the chancellor of the Prussian empire, Otto von Bismarck, actively promoted the construction of a state-owned network, amongst others also for its expected
military purposes. Parallel to this, other German states also actively expanded their rail network, so that by the end of the 19th century, there existed a wide network of standard-gauge railroads that connected the majority of larger cities.

Figure 6.4: The Railroad Network of the German Zollverein in 1899
Source: Hermann Beyer und Soehne, Langensalza

In order to be a valid instrument for the analysis of this paper, the 1899 railroad network data should be correlated with the contemporaneous highway network. While this connection may not be as direct as the relation to the historical network of the same transport mode, there exist geographical, geological and societal factors that influence the position of both railroad tracks and roads. The railroad and the highway network essentially serve the same purpose, i.e. the long-distance transportation of goods and people. Further, both transportation networks require

\[57\] See for example Brophy, 1998

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a somewhat even levelled and graded surface which provides a stable surface on which road or railroad tracks can be built. Additionally, it is crucial that the 1899 railroad network, conditional on controls, does not affect current firm-level productivity through any other channel than through current highways. As previously outlined, the majority of the construction of the railroad system during the 19th century was undertaken by private entities. These were generally motivated by short-term profits. In combination to these small railroad companies, the structure of federalism, where each ruler was exclusively interested in the economy of his or her territory, prevented any central plan further which could have been driven by national economic arguments; this also particularly shaped the railroad construction during the second half of the 19th century. The organisation of the railroad system during the 19th century was hence predominantly shaped by private profits rather than long term economic plans. This makes an independent effect of the historical railroad network on firm-level productivity unlikely. The railroad was further impacted by the developments of three wars which occurred during the 19th century, the German-Danish war of 1864, the Prussian-Austrian war of 1866, and the German-French war of 1870; these additionally weaken any link between the 1899 railroads and contemporaneous firm-level productivity, but may also decrease its correlation with the contemporaneous highway data. Further, the development of railroads was also affected by the political events that shaped the 20th century as discussed in Section 6.4.3.1. Overall, I do not find any evidence that violates the conditions of a valid instrument.

Information of the 1899 railroad network were extracted equivalently to those of the 1938 highway and Reichsstrassen networks based on the historical map of Figure 6.4. A digitised version of the map overlaid with 2014 NUTS3 regions can be found in Appendix C3 "Digitised Historical Maps and 2014 NUTS3 Regions", Figure C5; summary statistics for variables derived from the 1899 railroad network
are provided in Table 6.5.

Table 6.5: Descriptive Statistics for Infrastructure Variables

<table>
<thead>
<tr>
<th></th>
<th>Autobahn Network</th>
<th>Reichsstrassen Network</th>
<th>Railway Network</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in construction/planned)</td>
<td>2014</td>
<td>1938</td>
</tr>
<tr>
<td>Regions with Direct Access</td>
<td>360</td>
<td>279 (100/76)</td>
<td>348</td>
</tr>
<tr>
<td>Regions without Direct Access</td>
<td>42</td>
<td>121 (302/326)</td>
<td>54</td>
</tr>
<tr>
<td>Total Network Length (km)</td>
<td>12,858.6</td>
<td>4,065.8 (2,534.1/2,129.0)</td>
<td>19,531.1</td>
</tr>
<tr>
<td>Regional Average</td>
<td>32.0</td>
<td>10.1 (6.3/5.3)</td>
<td>48.6</td>
</tr>
<tr>
<td>Regional Standard Deviation</td>
<td>26.7</td>
<td>20.4 (15.8/15.1)</td>
<td>45.4</td>
</tr>
<tr>
<td>Regional Min.</td>
<td>0</td>
<td>0 (0/0)</td>
<td>0</td>
</tr>
<tr>
<td>Regional Max.</td>
<td>142.0</td>
<td>156.9 (142.0/132.0)</td>
<td>261.4</td>
</tr>
<tr>
<td>Regional Density Average</td>
<td>5.9</td>
<td>1.1 (1.0/0.6)</td>
<td>7.9</td>
</tr>
<tr>
<td>Regional Density Standard Deviation</td>
<td>5.9</td>
<td>3.4 (2.7/1.9)</td>
<td>7.8</td>
</tr>
<tr>
<td>Regional Density Min.</td>
<td>0</td>
<td>0 (0/0)</td>
<td>0</td>
</tr>
<tr>
<td>Regional Density Max.</td>
<td>33.5</td>
<td>23.0 (23.3/17.6)</td>
<td>48.7</td>
</tr>
</tbody>
</table>

V Results

V.I IV First Stage Results

The historical highway, Reichsstrassen and railroad information, discussed in Subsections 6.4.3.1 and 6.4.3.2 respectively, are only useful instruments if there exists a relationship with them and current highway levels, and if they do not affect the dependent variable of firm-level productivity through any other channel other than through their effect on current highways. Further, the information extracted from the 1899 railroad, and 1938 highway and Reichsstrassen maps do not offer any time-varying information, however as I am interested in investigating how the change in a district’s highway density affects firms, a time-varying component has to be introduced to the historical data. I use information on the national highway construction rate for the investigation period as a time-varying factor and interact it with the historical instruments to generate a dynamic historical instrument. While the national highway construction rate provides information of the growth rate of the overall national highway network, and as this growth is
not uniformly distributed across all German districts, it is highly unlikely that a
district’s highway growth follows the same pattern. Hence, it can be assumed that
the national construction rate is independent of a firm’s total factor productivity
development in a given district.

In order to investigate the appropriateness of the historical infrastructure data
discussed in Sections 6.4.3.1 and 6.4.3.2, and interacted with the national construc-
tion rate, I run first stage regressions of a district’s current highway density on its
historical values; results are provided in Table 6.6. The table contains three sep-
arate historical highway variables representing the district density of the segments
of the 1938 highway which were in operation, under constructed and planned as it
can be assumed that these highway segments where constructed in the following
years and hence also possibly relate to the highway density of districts throughout
the years of 1999 to 2014. The validity of the instrumental variables requires ortho-
gonality of the dependent variable and the historical infrastructure variables used,
however it does not require unconditional orthogonality but rather requires ortho-
gonality conditional on control variables. Hence, to control for any other factors
influencing a district’s contemporaneous highway, I include additional regional
variables which include information on the district’s average slope and ruggedness
index values,58 dummies for urban, suburban and rural districts, and as highways
may have predominantly been constructed in areas with higher population levels,
the district’s population density is included as a further control. As the unit of
interest across the analyses of this paper is the firm’s productivity, I include this
to test for any possible effects of these on current highways. Additionally included
are dummies that indicate whether a district had highways, Reichsstrassen or rail-
roads passing through it in 1938 and 1899 respectively; an equivalent dummy is
also included for current highways. Further, controls for years, states and 3 digit

58see Appendix C4 “Additional Geographical Variables”
Table 6.6: First Stage IV Regressions

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density)1938</td>
<td>0.282**</td>
<td>0.300**</td>
<td>0.315***</td>
<td>0.054</td>
<td>0.057</td>
<td>0.056</td>
</tr>
<tr>
<td>Ln(Highway Density - segments in construction)1938</td>
<td>0.076(0.059)</td>
<td>0.057(0.062)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - segments planned)1938</td>
<td>-0.035(0.062)</td>
<td>-0.032(0.063)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln(Total Highway Density)1938</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.279***</td>
</tr>
<tr>
<td>Ln(Reichsstrassen Density)1938</td>
<td>0.055(0.037)</td>
<td>0.041(0.039)</td>
<td>0.033(0.036)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Railway Density)1899</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Observations</td>
<td>46,336</td>
<td>46,336</td>
<td>46,336</td>
<td>46,336</td>
<td>46,336</td>
<td>46,336</td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>0.895</td>
<td>0.901</td>
<td>0.879</td>
<td>0.878</td>
<td>0.901</td>
<td>0.895</td>
</tr>
</tbody>
</table>

(In the above the following additional controls have been included: Year, region and 3 digit industrial sector fixed effects, firm productivity (in log), the region average ruggedness index and slope value (in log), population density (in log), dummies for three regional types and for the existence of highways or railways within a district in 1938, 1899 and 1999 - 2014.***, **, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors correct for clustering at the district level are provided in parenthesis)

industry classifications are included.

In Table 6.6, I provide the results of the first stage regressions testing the validity of the historical instruments for a district’s contemporaneous highway density. Column(1) only includes the variable based on those highway segments that were already in operation in 1938, while column (2) adds also those information based on the segments that were under construction or planned in 1938. Columns (3) and (4) alternatively only include the instrumental variables built on data of historical Reichsstrassen and railways respectively. Column (5) includes all of the aforementioned, while column (6) replaces the three variables representing the different 1938 highway information with one composite 1938 highway variable consisting of the sum of the three separate 1938 highway variables. The only variable that is highly significant throughout the specifications, although with differing magnitudes, is the variable of the existing highway segments in 1938. These results are in line, albeit smaller in magnitude, with those reported by Möller and Zierer (2018) who use similar historical information. The information of those segments that were under construction or planned in 1938 is only significant when information on historical Reichsstrassen and railways is also included. The insignificance of these variables is somewhat unexpected. This factor could

59Equivalent estimations for the variables measuring Direct and Wider Access to Highway Density can be found in Appendix C5 “First-Step IV Results for Highway Spillover Variables”
be explained by the possibility of these highway segments having eventually not been constructed, built or abandoned for other highway segments; the results of Appendix C5 however may possibly point towards those segments being placed in neighbouring districts, hence there may have been slight changes in the exact location of these segments. This may also have been a result of its re-construction following the second World War. Further, the discrepancy between the results of column (2) and (5) could potentially be explained by a correlation between Reichsstrassen and/or railways with both of these highway variables. Neither the results of column (3) nor (4), or alternatively (5) and (6), indicate an explanatory component of historical rail and Reichsstrassen for a district’s contemporaneous highway density.

The results of Table 6.6 indicate that the model selection of column (2) is the most suitable for contemporaneous highway density, however the results of Tables C2 and C3 indicate that the combination of the highway density of those segments that were built, under construction and in planning in 1938 with the Reichsstrassen and 1899 rail density variables are the most suited for highway density - direct access, while for the variable of highway density - wider access solely the use of the historical railway density variable provide the most explanatory power of current highways.

V.II First Step Production Function Estimations

The identification of the production function follows the outlined model of (6.5)\(^6\). Table 6.7 lists the results of its estimation with OLS and the Levinsohn-Petrin method. The coefficient of the capital variable of this dataset have often been estimated to be of very small magnitude (Ehrl, 2013). The results here also

\(^6\)The analyses of this chapter focus on the effects of transportation on firm level productivity. However, to provide results comparable to those of Chapter 4, the results of investigating transportation infrastructure as a direct production function input factor are provided in Appendix C6 "Modelling Transportation as an Explicit Production Function Input".
Table 6.7: Production Function Estimation

<table>
<thead>
<tr>
<th>Industry Class</th>
<th>OLS</th>
<th>Levinsohn-Petrin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capital</td>
<td>Labour</td>
</tr>
<tr>
<td>AGRI</td>
<td>0.083*** (0.008)</td>
<td>0.401*** (0.014)</td>
</tr>
<tr>
<td>CO.-PE.</td>
<td>0.035* (0.019)</td>
<td>0.324*** (0.032)</td>
</tr>
<tr>
<td>FOOD</td>
<td>0.056*** (0.006)</td>
<td>0.292*** (0.012)</td>
</tr>
<tr>
<td>TEXT.</td>
<td>0.014*** (0.008)</td>
<td>0.392*** (0.021)</td>
</tr>
<tr>
<td>WOOD</td>
<td>0.014*** (0.005)</td>
<td>0.429*** (0.014)</td>
</tr>
<tr>
<td>CHEM.</td>
<td>0.026*** (0.005)</td>
<td>0.361*** (0.012)</td>
</tr>
<tr>
<td>MIN.</td>
<td>0.020*** (0.007)</td>
<td>0.407*** (0.016)</td>
</tr>
<tr>
<td>MET.</td>
<td>0.005 (0.004)</td>
<td>0.470*** (0.009)</td>
</tr>
<tr>
<td>ELEC.</td>
<td>-0.002 (0.008)</td>
<td>0.493*** (0.021)</td>
</tr>
<tr>
<td>MACH.</td>
<td>0.005 (0.004)</td>
<td>0.529*** (0.011)</td>
</tr>
<tr>
<td>VEH.</td>
<td>0.014*** (0.006)</td>
<td>0.487*** (0.015)</td>
</tr>
<tr>
<td>N.E.C.</td>
<td>0.039*** (0.006)</td>
<td>0.583*** (0.015)</td>
</tr>
<tr>
<td>ENERGY</td>
<td>0.014* (0.008)</td>
<td>0.315*** (0.016)</td>
</tr>
<tr>
<td>CON.</td>
<td>0.030*** (0.003)</td>
<td>0.580*** (0.007)</td>
</tr>
<tr>
<td>TRADE</td>
<td>0.021*** (0.003)</td>
<td>0.289*** (0.007)</td>
</tr>
<tr>
<td>HOSP.</td>
<td>0.031*** (0.005)</td>
<td>0.486 (0.015)</td>
</tr>
</tbody>
</table>

(where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors are provided in parenthesis)

indicate a very small magnitude under OLS, but are significantly larger in magnitude when estimated with the Levinsohn-Petrin method. However, the coefficient of capital is in some cases estimated as insignificant, for which it cannot be excluded that the reason lies in the generation of the capital variable. Capital, for this analysis, has been derived from the firm’s investment behaviour (see Section 6.2.1.2) rather than being directly measured. This can reduce the variability in the data significantly and hence result in insignificant estimated coefficients. The estimated coefficients of labour are of comparable magnitude across the estimation methods. The estimated coefficients of the material input are on average smaller under Levinsohn-Petrin than OLS. As the differences of capital and materials across the estimation methods are of opposite directions, both estimations methods imply roughly constant returns to scale. The estimation of the productivity parameter follows (6.6), and thus employing the sector specific coefficients estimated with Levinsohn-Petrin.
Figure 6.5 illustrates the distribution of log productivity across the Germany. The concentration of high productivity is mostly situated in the West and South of the country, predominantly in the wider metropolitan areas of Frankfurt and Stuttgart and in the Ruhr region around Dortmund. Further, smaller regions with high productivity can be found throughout the southern states of Baden-Württemberg and Bavarian in the South West and East respectively. In the northern part of the country there exist smaller regional centres with high productivity around the cities of Wolfsburg, Hamburg and Bremen. Across the Eastern states, the results indicate relatively lower productivity parameters throughout, with exceptions of the three cities in the South East and the metropolitan area around the city of Leipzig. The estimated productivity around Berlin is slightly above some of its surrounding regions, but still below the productivity estimated for metropolitan areas located in the West.

V.III Second Step Productivity Estimation

I use the residuals from the sector specific Levinsohn-Petrin production function estimations of Table 6.7 and follow equation (6.6) to regress firm-level productivity on highway infrastructure and additional controls variables. The results for the estimation relying on a district’s highway density variable are listed in Table 6.8. The estimates provided in columns (1) to (3) are identified with pooled OLS regressions, columns (4), (5) and (6) provide results obtained with the Fixed Effects, Difference and System GMM methods respectively. Column (1) contains, beside the log of a district’s highway density, a reduced set of controls consisting of year, state, and 3-digit industrial sector fixed effects. It further includes a dummy variable taking the value of 1 if there exist highway segments within the given district. The provided elasticity of highway density is roughly in line, but smaller in magnitude, with those provided in a similar study by Holl (2012). However, as
Figure 6.5: The Spatial Distribution of Productivity
Source: Author’s own calculation

she uses a market potential variable to measure road infrastructure which encompasses both travel time and population data, it is not directly comparable to the results here. Column (2) additionally includes the firm’s age, the number of skilled workers of the firm, both in their logarithmic forms, dummies for different firm sizes, measured in the number of employees, and a dummy for the different German judicial forms of firms. It further includes district-level geographic controls of the district’s area as the log of its square kilometres, and controls for longitude and latitude of the mid-point of each district. Despite the addition of these further variables, the estimated elasticity for the highway density variable remains very
similar in magnitude, however it loses slightly in significance between columns (1) and (2). Following these two results, an increase in a district’s highway density of 1 per cent would raise a firm’s TFP by approximately 0.03 per cent. Furthermore, positive and significant effects are also indicated for both (the log of) firm age and skilled workers, and while both of these estimates are larger in magnitude than the effect of highway density, the effect of skilled workers is significantly larger in magnitude than the effect of firm age. Additionally, benefits from the firm’s size on its TFP can only be identified for firms with a labour pool of 50 or more, where elasticities are generally larger for larger firms. Given that more highways can generally be observed for districts with larger levels of population, column (3) adds a population density variable to the regression to test whether the effect of highway density is driven by population dynamics rather than by infrastructure. The majority of estimated elasticities remains similar in significance and magnitude to those of the previous two columns, the effect of highway density however decreases by approximately a third and becomes insignificant. This may be indicating that the significant results obtained in columns (1) and (2) mostly stem from population dynamics, or agglomeration economies. However, if there exist any omitted time-invariant factors influencing the relationship between highway density and firm TFP, or other issues introducing endogeneity into the estimation, then the results obtained by OLS will be biased. Column (4) thus uses the Fixed Effects method which differences out any (omitted) time-invariant factors and thus controls for any biases stemming from these. The estimated elasticity for the highway variable is larger in magnitude in column (4) relative to column (3), but remains insignificant. While the estimate of the firm’s age’s coefficient remains roughly constant across column (4) and the preceding columns, both the magnitude of the coefficients of population density and skilled workers reduce noticeably, while population density additionally becomes statistically insignificant. The estimates
of the effects of firm sizes also indicate a negative TFP effect for smaller firms and a positive effect for larger firms, although the latter remains below the equivalent estimates of columns (2) and (3). To additionally control for any time-variant issues affecting the estimation, both Difference and System GMM are employed in columns (5) and (6). The estimate obtained for the highway density variable is relatively similar across both columns in magnitude but differs slightly in its significance, where an increase of 1 per cent in a district’s highway density would yield a 0.06 per cent increase in the TFP of firms located in the respective district. In contrast to this, the predominant majority of the remaining elasticities differs noticeably between columns (5) and (6). Both estimators identify insignificant effects for population density, but differ substantially in the estimated magnitude. The effect of a firm’s age on its TFP is roughly similar to those identified in columns (2) to (4) for the System GMM estimate, but the Difference GMM estimate for this variable is noticeably lower. Similarly, the effect of qualified workers estimated by System GMM is comparable to those of columns (2) to (4), but this effect is noticeably smaller and negative but remains significant under Difference GMM. With respect to the firm’s size, System GMM results indicate positive elasticities for larger and insignificant estimates for smaller firms, Difference GMM estimates identify negative effects for all firm sizes, with larger negative impacts for firms employing 20 workers or more. While there exist some similarities across the estimators for specific variables, overall the results cautiously point to an elasticity of 0.03 to 0.06 of a district’s highway density on firm TFP, but do not provide results that are comparable across the estimators employed for any of the variables included.
<table>
<thead>
<tr>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
<th>POLS (1)</th>
<th>POLS (2)</th>
<th>POLS (3)</th>
<th>Fixed Effects (4)</th>
<th>Difference GMM (5)</th>
<th>System GMM (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density)</td>
<td>0.029*** (0.007)</td>
<td>0.030** (0.012)</td>
<td>0.018 (0.013)</td>
<td>0.024 (0.015)</td>
<td>0.064 (0.037)</td>
<td>0.062 (0.025)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>0.067*** (0.018)</td>
<td>0.0002 (0.059)</td>
<td>0.203 (0.274)</td>
<td>-0.049 (0.059)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Firm Age)</td>
<td>0.045*** (0.011)</td>
<td>0.045*** (0.011)</td>
<td>0.050*** (0.099)</td>
<td>0.033* (0.008)</td>
<td>0.043*** (0.010)</td>
<td></td>
</tr>
<tr>
<td>Ln(Skilled Workers)</td>
<td>0.168*** (0.012)</td>
<td>0.168*** (0.012)</td>
<td>0.043*** (0.088)</td>
<td>-0.019*** (0.007)</td>
<td>0.142*** (0.009)</td>
<td></td>
</tr>
<tr>
<td>Firm Size Classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-9 Empl.</td>
<td>-0.028 (0.031)</td>
<td>-0.026 (0.030)</td>
<td>-0.062*** (0.019)</td>
<td>-0.116*** (0.018)</td>
<td>-0.031 (0.024)</td>
<td></td>
</tr>
<tr>
<td>10-19 Empl.</td>
<td>-0.033 (0.038)</td>
<td>-0.031 (0.036)</td>
<td>-0.062** (0.027)</td>
<td>-0.186*** (0.027)</td>
<td>-0.015 (0.030)</td>
<td></td>
</tr>
<tr>
<td>20-49 Empl.</td>
<td>-0.009 (0.041)</td>
<td>-0.006 (0.041)</td>
<td>-0.022 (0.033)</td>
<td>-0.259*** (0.030)</td>
<td>0.027 (0.031)</td>
<td></td>
</tr>
<tr>
<td>50-99 Empl.</td>
<td>0.155*** (0.050)</td>
<td>0.157*** (0.050)</td>
<td>0.017 (0.038)</td>
<td>-0.280*** (0.038)</td>
<td>0.201*** (0.039)</td>
<td></td>
</tr>
<tr>
<td>100-199 Empl.</td>
<td>0.236*** (0.062)</td>
<td>0.240*** (0.061)</td>
<td>0.060 (0.046)</td>
<td>-0.291*** (0.041)</td>
<td>0.303*** (0.047)</td>
<td></td>
</tr>
<tr>
<td>200-499 Empl.</td>
<td>0.352*** (0.069)</td>
<td>0.356*** (0.067)</td>
<td>0.128** (0.053)</td>
<td>-0.277*** (0.047)</td>
<td>0.435*** (0.050)</td>
<td></td>
</tr>
<tr>
<td>500-999 Empl.</td>
<td>0.367*** (0.088)</td>
<td>0.369*** (0.088)</td>
<td>0.216*** (0.066)</td>
<td>-0.246*** (0.056)</td>
<td>0.480*** (0.069)</td>
<td></td>
</tr>
<tr>
<td>&gt; 1000 Empl.</td>
<td>0.478*** (0.105)</td>
<td>0.486*** (0.105)</td>
<td>0.279*** (0.083)</td>
<td>-0.238** (0.092)</td>
<td>0.604*** (0.086)</td>
<td></td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.758</td>
<td>0.335</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.318</td>
<td>1.000</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>478</td>
<td>606</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>46,336</td>
<td>43,811</td>
<td>43,811</td>
<td>43,811</td>
<td>33,509</td>
<td>43,811</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.933</td>
<td>0.953</td>
<td>0.953</td>
<td>0.421</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(Where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parentheses.)
The district’s own highway infrastructure undoubtedly affects the firm’s operations, however as the firm requires access to inputs, employees and output markets, the firm’s performance will also benefit from the highways passing through neighbouring districts, allowing for the access to larger geographical regions. For this reason, I re-examine the relationship between highway density and firm-level TFP by including both highway and population spillover effects into the regressions. The results of these analyses can be found in Table 6.9, where columns (1) to (3) only include those spillover effects referred to as Direct Access and columns (4) to (6) further add those spillover effects termed as Wider Access. Provided the previously discussed issues arising within the context of OLS estimations, the estimations listed in Table 6.9 rely on the previously used panel data methods of Fixed Effects, Difference and System GMM estimations.

Across columns (1) to (3), all estimators yield positive and significant effects of a district’s highway density, however they differ noticeably in magnitude, where a 1 per cent increase in a district’s highway density is associated with firm-level TFP increases of 0.03, 0.06 and 0.04 for Fixed Effects, Difference and System GMM results respectively. Furthermore it is to note that the significance level of these estimates is generally lower than those provided for the same variable in Table 6.8. The effect of the highway density of districts located in close proximity (Highway Density - Direct Access) does not appear to have a significant effect of firm-level TFP across all estimators. Similarly, the coefficient of a district’s population density is not estimated to be statistically significant across. The coefficient of the population density of surrounding districts is only significant under Fixed Effects which may point to a possible negative spillover effect, the coefficient of this variable is statistically insignificant under both of the alternative methods. The estimated effect of a firm’s age remains similar, or directly identical, to the

---

61 See Section 6.3.2 for specifics of their underlying calculation
62 See Chapter 3
estimates obtained with the equivalent method in Table 6.8. This pattern can also be observed for the variables of skilled workers and firm size classes. Overall, columns (1) to (3) do not point to a large presence of spillover effects, both with respect to highway infrastructure as well as to population levels.

Columns (4) to (6) allow to test for the presence of spillover effects further by additionally including effects of farther districts. The estimated coefficients of highway density remain relatively stable in magnitude and statistically significant. This stability, in combination with the equivalent coefficients of columns (1) to (3), possibly indicates that any possible presence of highway spillovers of farther districts does not affect the estimates of columns (1) to (3). Additionally, within the specification of columns (4) to (6) the effect of highway density of closely located
districts remains insignificant, albeit changed in magnitude which is particularly noticeable for the GMM estimators. For the coefficient of highway density of farther districts, only the Fixed Effects method provides significant results. It is to note that this variable, similar to the variable representing highway density of districts within close geographic location, presents an index and can thus not be interpreted in a direct way equivalent to the interpretation of the coefficient of a district’s own highway density. Therefore, the estimate of the effect of highway density of farther districts in column (4) signals that for an increase in the underlying index of 1 per cent, a firm’s TFP of a respective district would experience a growth of 0.8 per cent. In line with the majority of previous results, the three estimation methods all point to a non-significant effect of a district’s population density on firm’s TFP, however they offer quite disparate results for the coefficients of the population density of district’s located within close proximity, where Fixed Effects points to a negative, significant effect, Difference GMM does not point to a statistically significant effect, and System GMM points to a positive and significant effect. Therefore, no conclusion can be drawn from the results of columns (4) to (6). However in combination with the preceding estimates of columns (1) to (3), resulting in 66.6 per cent of the results pointing to insignificant effects, it can cautiously be concluded that there do no exist any (strong) population spillover effects from districts in close proximity. For the population density of districts located further away, only the System GMM estimator points to significant results, both of the alternative methods yield insignificant results, thus similarly not allowing for a robust overall conclusion. In line with the results of columns (1) to (3) and those of Table 6.8, columns (3) to (6) point to positive and significant effects of firm age on firm productivity, however with differing magnitudes. A similar pattern is presented for the effect of qualified workers, where results are in line with the one obtained for other specifications with the same method.
Overall, the results of Table 6.9 confirm the conclusion of Table 6.8 of positive and significant effects of a district’s highway density on firm-level TFP, where estimates point to elasticities between 0.03 to 0.07 across the different techniques. Furthermore, the discussed results do not indicate the presence of substantial spillover effects, both for highway infrastructure or population density. Further, the estimated results of a district’s highway density variable are generally in line with the literature of this field (see for example Melo et al., 2013 for an overview), but exact comparisons are not possible given the absence of a large literature body focusing on the level of the firm. Additionally, the variables representing transportation infrastructure are often defined differently across studies, while I use highway density and indexes representing its spatial spillovers, Holl (2016) for example uses the distance to the closest highway ramp as the variable signifying transportation infrastructure. Noteworthy is further the magnitude of the highway infrastructure variable in relation to other factors influencing the firm’s productivity. In the context of the variables chosen for this analysis, the effect of highway infrastructure is roughly in line with the magnitude of the effect of firm age on the firm’s productivity, which remains relatively stable across the specifications and across Tables 6.8 and 6.9. However, relative to the productivity effects of the firm’s stock of skilled employees, the effect of highway infrastructure is significantly smaller. The effect of firm size is not smooth across the firm size classes. With the exception of Difference GMM, the regressions do not report any significant productivity effects following from the firm’s size for firms with an employee stock below 50, however a highly significant effect of the firm’s size is reported for firms with an employee level above 50. Further, this productivity effect stemming from the firm’s size increases noticeable with the size of the firm. Hence, this would result in higher productivity levels for larger firms. This notion is a generally established phenomenon of the literature with findings across countries
(see for example Leung et al., 2008). Given that it can be hypothesised that firms benefit substantially from the local density of population and economic activity firm’s productivity may be endogenous in cases where higher productivity firms have located in high population and/or highway districts, the overall findings of little or no effect of population density on TFP is therefore somewhat unexpected. As agglomeration economies often indicate skilled workers as a crucial component, and given that this is included as a separate variable here, the insignificance of the population density could possibly indicate that while the firms benefit from its skilled workforce, they do not necessarily derive productivity benefits solely from larger populations. However, given the higher levels of skilled workers in cities, it is to note that high density or access areas are generally also those that allow for a higher density and access to high skilled employees. However, the low R² of the Fixed Effects estimations and the perfect Hansen statistic should leave the avid reader with some degree of caution in the interpretation of these results.

V.III.I Alternative Highway Variables

The previously discussed results point towards the crucial importance of skilled labour for the TFP of a firm, however they also indicate an insignificance of the mere effect of population density. In order to investigate this issue further, two alternative variables measuring highway infrastructure are used in the estimations of this subsection. I construct the Market Access variable as the product of population and highway density, hence positive changes of this compound variable can stem from increases in either of the aforementioned variables, however it will remain (mostly) unchanged if there exist developments in the underlying variables in opposing directions. This variable is derived to more accurately measure market access rather than just the pure effect of highway infrastructure, i.e. the accessibility of labour as both an input market for employees, and an output market for
consumers. I repeat a selection of the analyses of Tables 6.8 and 6.9 for this Market Access variable, estimation results are listed in Table 6.10, where columns (1) and (2) only include a district’s own variables, columns (3) and (4), and columns (5) and (6) add the market access variables of districts in close proximity and those located farther away respectively. The estimates of columns (1) and (2) provide very similar results across all firm control variables to their previous estimates, however the regressions differ crucially in the estimated market access elasticity. While System GMM provides a positive and significant effect, that is in line with its result in Table 6.8, but larger than the one of Table 6.9, the Difference GMM coefficient is substantially smaller in magnitude and insignificant. An increase of 1 per cent in the market access of a district, either through highway and/or population density changes, yields a positive impact on firms’ TFP of approximately 0.07 per cent. Holl (2012) similarly uses a market access variable to estimate its effect on TFP for Spanish firms, but constructs it based on travel time and population data instead. Despite the difference in the variable’s construction, her estimates are relatively close to those obtained with System GMM in column (1). The disparity between System and Difference GMM persists across columns (3) and (4), however under this specification, the Difference GMM results are estimated to be positive, albeit they remain insignificant. System GMM alternatively points towards positive and significant effects for a firm’s TFP stemming from both the market access of a district and that of its neighbours, where the magnitude of the effect of the district’s own market access remains relatively similar to that of column (2). The estimates of firm control variables remain similar across all columns, and to those of the previous tables of this subsection. The results of those specifications further adding the market access of farther districts in columns (5) and (6) however alter both the Difference and System GMM results,

\footnote{Provided the low levels of R^2 and aforementioned complications with OLS, I limit the selection of the estimation techniques to GMM regressions}
where the Difference GMM estimates of market access become slightly larger in magnitude, albeit remaining insignificant. The System GMM results decrease in magnitude and can no longer assumed to be significant. Both estimates however provide negative effects of the market access variable of farther districts, possibly pointing towards negative spillovers from districts with larger population and/or highway density located farther away. One hypothesis may be that those regions that have low levels of either of the aforementioned variables are particularly negatively impacted by the economy and regional competitiveness of those districts with high levels of either variable and thus market access, and as districts with very low levels of either variables are generally located somewhat remotely from high population and/or highway districts, this could be reflected in the negative TFP effect of the market access of farther districts. However, as this result is only indicated to be significant under one estimator, this conclusion should be seen with caution. Similar to the previous columns and tables, the estimates of the firm-level control variables remain similar to those previously produced with the same regression methods. Overall, the regressions relying on the market access variable as representing highway infrastructure, possibly point to a positive impact of highways on TFP. However, these results are only obtained with System GMM, and do not remain robust under all specifications. Further, this variable does not allow to separate between highway and population changes.
Table 6.10: Second Step Productivity Estimations - Alternative Highway Variable I: Market Access

<table>
<thead>
<tr>
<th>Market Access</th>
<th>Difference GMM</th>
<th>System GMM</th>
<th>Difference GMM</th>
<th>System GMM</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Market Access)</td>
<td>-0.013 (0.054)</td>
<td>0.063*** (0.029)</td>
<td>0.028 (0.047)</td>
<td>0.061*** (0.025)</td>
<td>0.038 (0.044)</td>
<td>0.032 (0.023)</td>
</tr>
<tr>
<td>Ln(Market Access - Direct Access)</td>
<td>0.008 (0.055)</td>
<td>0.086*** (0.035)</td>
<td>0.013 (0.044)</td>
<td>0.051 (0.033)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Market Access - Wider Access)</td>
<td>-1.354 (1.022)</td>
<td>-0.555*** (0.272)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Firm Age)</td>
<td>0.013* (0.008)</td>
<td>0.088*** (0.009)</td>
<td>0.014* (0.008)</td>
<td>0.042*** (0.010)</td>
<td>0.041* (0.008)</td>
<td>0.041*** (0.010)</td>
</tr>
<tr>
<td>Ln(Skilled Workers)</td>
<td>-0.019*** (0.007)</td>
<td>0.143*** (0.007)</td>
<td>-0.019*** (0.007)</td>
<td>0.142*** (0.009)</td>
<td>-0.019*** (0.007)</td>
<td>0.142*** (0.009)</td>
</tr>
<tr>
<td>Firm Size Classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-9 Empl.</td>
<td>-0.115*** (0.018)</td>
<td>-0.027 (0.024)</td>
<td>-0.116*** (0.018)</td>
<td>-0.025 (0.024)</td>
<td>-0.117*** (0.018)</td>
<td>-0.029 (0.024)</td>
</tr>
<tr>
<td>10-19 Empl.</td>
<td>-0.186*** (0.027)</td>
<td>-0.011 (0.031)</td>
<td>-0.186*** (0.027)</td>
<td>-0.006 (0.030)</td>
<td>-0.188*** (0.027)</td>
<td>-0.012 (0.030)</td>
</tr>
<tr>
<td>20-49 Empl.</td>
<td>-0.257*** (0.030)</td>
<td>0.031 (0.032)</td>
<td>-0.259*** (0.030)</td>
<td>0.036 (0.032)</td>
<td>-0.261*** (0.030)</td>
<td>0.032 (0.032)</td>
</tr>
<tr>
<td>50-99 Empl.</td>
<td>-0.278*** (0.037)</td>
<td>0.204*** (0.040)</td>
<td>-0.279*** (0.038)</td>
<td>0.207*** (0.039)</td>
<td>-0.280*** (0.037)</td>
<td>0.205*** (0.039)</td>
</tr>
<tr>
<td>100-199 Empl.</td>
<td>-0.289*** (0.041)</td>
<td>0.308*** (0.048)</td>
<td>-0.290*** (0.040)</td>
<td>0.314*** (0.048)</td>
<td>-0.292*** (0.041)</td>
<td>0.316*** (0.047)</td>
</tr>
<tr>
<td>200-499 Empl.</td>
<td>-0.277*** (0.047)</td>
<td>0.436*** (0.051)</td>
<td>-0.276*** (0.047)</td>
<td>0.443*** (0.051)</td>
<td>-0.278*** (0.047)</td>
<td>0.443*** (0.051)</td>
</tr>
<tr>
<td>500-999 Empl.</td>
<td>-0.245*** (0.056)</td>
<td>0.473*** (0.070)</td>
<td>-0.245*** (0.056)</td>
<td>0.488*** (0.069)</td>
<td>-0.245*** (0.056)</td>
<td>0.486*** (0.069)</td>
</tr>
<tr>
<td>&gt; 1000 Empl.</td>
<td>-0.236*** (0.093)</td>
<td>0.603*** (0.084)</td>
<td>-0.235*** (0.092)</td>
<td>0.619*** (0.085)</td>
<td>-0.240*** (0.093)</td>
<td>0.617*** (0.086)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>0.770</td>
<td>0.361</td>
<td>0.765</td>
<td>0.363</td>
<td>0.797</td>
<td>0.353</td>
</tr>
<tr>
<td>Hansen</td>
<td>0.000</td>
<td>0.949</td>
<td>0.345</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
<td>358</td>
<td>471</td>
<td>478</td>
<td>606</td>
<td>598</td>
<td>741</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>33,509</td>
<td>43,811</td>
<td>33,509</td>
<td>43,811</td>
<td>33,509</td>
<td>43,811</td>
</tr>
</tbody>
</table>

(where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis)
An alternative option to measure population and highway infrastructure within one combined variable is the population weighted version of highways as used in Chapter 4 of this thesis. This variable allows to identify the amount of highways relative to the population in a district, and thus provides implicit information on highway (under-/over-) demand and possible congestion issues, where areas with low values of this variable are expected to have higher congestion. I replicate the analyses of Table 6.10, replacing the market access variable with the population weighted highway density variable in Table 6.11. Similar to columns (1) and (2) of Table 6.10, columns (1) and (2) of Table 6.11 indicate positive and significant effects under System GMM, and negative and insignificant effects under Difference GMM for the variable including highway infrastructure. The elasticity implicated by System GMM shows an increase of firm-level TFP of approximately 0.09 for a 1 per cent growth of the population weighted highway variable used, where positive changes in the variable could stem from either decreases in population or increases in highways, or both. The magnitude of this effect is larger than the one implied by the estimate of column (2) of Table 6.10; exact comparisons are however not directly possible given the different construction of the highway infrastructure variables. Columns (3) and (4) additionally add the version of this variable for districts located in close proximity. Under this model, Difference GMM indicates a positive and significant effect of a relatively large magnitude for the district’s own variable, while System GMM only points to a positive and significant effect from the population weighted highway density variable of neighbouring districts. A positive impact could potentially be interpreted as low congestion levels within a district, which is possibly independent of the district’s own highway variable, but influenced by this parameter of surrounding regions. For the estimate of column (3) this would be interpreted as positive TFP effects for firms located in

\footnote{Given the stability of the estimated coefficients of the firm-level control variables within each estimation technique, its discussion would be a mere repetition and is thus omitted here.}
districts where congestion is relatively low, and for the System GMM estimate of column (4) it would mean that firms experience positive TFP effects if congestion in neighbouring districts is relatively low. Both version of this interpretation are not unrealistic. Noticeable is further that the magnitude of each respective estimate is larger than previous estimates of Table 6.8, 6.9 and 6.10. The further inclusion of the version of the highway variable for farther districts in columns (5) and (6) of Table 6.11 does not change the tendency of the Difference GMM estimates of column (3) with an implied positive and significant effect of the own population weighted highway density variable of a district. However, results under System GMM have changed, where the estimates of column (6) are in line with those of Difference GMM under this version of the model. Albeit the estimate of System GMM is substantially lower in magnitude than the Difference GMM estimate, it similarly implies a positive and significant effect of a districts own population weighted highway density for a firm’s TFP. No firm-level TFP effects are identified from the population weighted highway variable of districts located in close proximity or from those located farther away.
Table 6.11: Second Stage Productivity Estimations - Alternative Highway Variable II: Population weighted Highway Density

| Highway Density - weighted by pop. | Difference GMM System GMM Difference GMM System GMM Difference GMM System GMM |
|-----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| (1)                               | (2)                              | (3)                              | (4)                              |
| Ln(Highway Density (pop. weighted)) | -0.013**(0.052)                  | 0.098*****(0.035)                | 0.116**(0.049)                   | 0.039(0.030)                    | 0.138*****(0.051)               | 0.047*(0.025)                   |
| Ln(Highway Density (pop. weighted) - Direct Access) | -0.178(0.114)                    | 0.222**(0.074)                   | -0.014(0.100)                    | 0.018(0.065)                    |
| Ln(Highway Density (pop. weighted) - Wider Access) | -1.045(1.182)                    | -0.011(0.682)                    |                                    |                                  |
| Ln(Firm Age)                      | 0.013**(0.009)                   | 0.046*****(0.010)                | 0.012(0.008)                     | 0.042*****(0.010)               | 0.013(0.009)                    | 0.043*****(0.010)               |
| Ln(Skilled Workers)               | -0.019*****(0.007)               | 0.144*****(0.009)                | -0.019*****(0.007)               | 0.141*****(0.009)               | -0.018*****(0.007)              | 0.141*****(0.009)               |
| Firm Size Classes                 |                                  |                                  |                                  |                                  |                                  |                                  |
| 5-9 Empl.                         | -0.115**(0.018)                  | -0.030(0.024)                    | -0.115**(0.018)                  | -0.031(0.024)                   | -0.116**(0.018)                 | -0.032(0.024)                   |
| 10-19 Empl.                       | -0.186**(0.027)                  | -0.015(0.031)                    | -0.186**(0.027)                  | -0.007(0.031)                   | -0.188**(0.027)                 | -0.016(0.031)                   |
| 20-49 Empl.                       | -0.257*****(0.030)               | 0.026(0.032)                     | -0.259*****(0.030)               | 0.033(0.032)                    | -0.260*****(0.030)              | 0.026(0.032)                    |
| 50-99 Empl.                       | -0.278*****(0.038)               | 0.199*****(0.040)                | -0.284*****(0.037)               | 0.207*****(0.040)               | -0.281*****(0.037)              | 0.199*****(0.039)               |
| 100-199 Empl.                     | -0.296*****(0.041)               | 0.300*****(0.048)                | -0.299*****(0.041)               | 0.312*****(0.049)               | -0.291*****(0.041)              | 0.301*****(0.048)               |
| 200-499 Empl.                     | -0.277*****(0.047)               | 0.430*****(0.051)                | -0.278*****(0.047)               | 0.442*****(0.051)               | -0.280*****(0.047)              | 0.434*****(0.054)               |
| 500-999 Empl.                     | -0.245*****(0.056)               | 0.476*****(0.070)                | -0.242*****(0.055)               | 0.486*****(0.070)               | -0.248*****(0.056)              | 0.482*****(0.069)               |
| > 1000 Empl.                      | -0.236*****(0.092)               | 0.589*****(0.085)                | -0.234*****(0.093)               | 0.601*****(0.086)               | -0.247*****(0.093)              | 0.604*****(0.087)               |
| Year, Region, Industrial FE       | Y                                | Y                                | Y                                | Y                                | Y                                | Y                                |
| Firm Controls                     | Y                                | Y                                | Y                                | Y                                | Y                                | Y                                |
| Geographic Controls               | Y                                | Y                                | Y                                | Y                                | Y                                | Y                                |
| AR1                               | 0.000                            | 0.000                            | 0.000                            | 0.000                            | 0.000                            | 0.000                            |
| AR2                               | 0.770                            | 0.353                            | 0.727                            | 0.380                            | 0.773                            | 0.330                            |
| Hansen                            | 0.000                            | 0.954                            | 0.214                            | 1.000                            | 1.000                            | 1.000                            |
| Number of Internal Instruments    | 358                              | 471                              | 478                              | 606                              | 598                              | 741                              |
| Number of Observations            | 33,509                           | 43,811                           | 33,509                           | 43,811                           | 33,509                           | 43,811                           |

*(where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis)*
In summary, the estimates of Tables 6.10 and 6.11 confirm the conclusions drawn from the results of Tables 6.8 and 6.9 where positive firm-level TFP effects from a district’s highway infrastructure are indicated. The evidence for regional spillover effects from highway infrastructure located in districts in close or far locations is inconsistent and weak. However, based on the specific construction of the highway variables used in this section, direct comparisons of an elasticity’s magnitude are not possible. Furthermore, given that the highway variables employed in this subsection are variables consisting of the combination of highway and population data, it cannot be distinguished if changes affecting firm-level TFP stem from population or highway changes. Despite this however, the results presented in the subsection provide support for the previous results of positive impacts of highways on firm’s TFP.

V.III.II  IV-Estimations

To investigate the possibility of endogenously placed highways further, I use the historical variable specifications of column(2) of Table 6.6 as instruments for the possibly endogenously determined highway levels of districts. The low first stage F-statistics identified in the context of the chosen historical information leads me to conclude that the instrumental variable specification of limited information maximum likelihood (LIML) is better suited than two-stages least squares (TSLS) in this context of relatively weaker instruments. I replicate the specifications of columns (3) to (6) of Table 6.8 in IV-LIML regressions; results are listed in Table 6.12, columns (1) and (2) where the former only includes a limited amount of control variables and the latter contains the full set. The highway elasticity identified in column (1) is significantly larger in magnitude compared to those pre-

\(^{65}\) While the set of firm-level control variables employed is identical to the one of Subsections 5.3 and 5.3.1, given the identified robustness of their elasticities, the repeated reporting and discussion is omitted for the remainder of this Chapter.
Table 6.12: Second Step Productivity IV Estimations

<table>
<thead>
<tr>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
<th>IV-LIML (1)</th>
<th>IV-LIML (2)</th>
<th>IV-GMM (3)</th>
<th>IV-2SLS (4)</th>
<th>IV-2SLS (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density)</td>
<td>0.107***</td>
<td>-0.003(0.031)</td>
<td>0.001(0.014)</td>
<td>-0.006(0.028)</td>
<td>-0.009(0.027)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.070(0.063)</td>
<td>-0.093(0.065)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>-1.404***</td>
<td>(0.664)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>0.074***</td>
<td>0.077***</td>
<td>0.077***</td>
<td>0.088***</td>
<td>0.097***</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>0.069(0.045)</td>
<td>0.107***</td>
<td>0.097***</td>
<td>0.108***</td>
<td></td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>1.290***</td>
<td>(0.618)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>First Stage F-Stat</td>
<td>34.19***</td>
<td>6.85***</td>
<td>906.144**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Eigenvalue Statistic</td>
<td>474.67**</td>
<td>1091.19**</td>
<td>757.37**</td>
<td>695.67***</td>
<td></td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>171.28***</td>
<td>174.78***</td>
<td>169.92**</td>
<td>167.85***</td>
<td></td>
</tr>
<tr>
<td>Shea’s adj. partial R² - Ln(Highway Density)</td>
<td>0.210</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shea’s adj. partial R² - Ln(Highway Density - Direct Access)</td>
<td>0.293</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shea’s adj. partial R² - Ln(Highway Density - Wider Access)</td>
<td>0.301</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Observations</td>
<td>46,336</td>
<td>43,811</td>
<td>43,811</td>
<td>43,811</td>
<td></td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.933</td>
<td>0.953</td>
<td>0.953</td>
<td>0.953</td>
<td></td>
</tr>
</tbody>
</table>

(Where ***,**,* indicate significance at the 1%, 5% and 10% level respectively. The significance of the Eigenvalue is determined according to the LIML Wald test, for 2SLS estimations the Sargan test is used alternatively, overidentification tests used are the Anderson-Rubin statistic for IV-LIML, the Hansen’s J statistic for IV-GMM and the Sargan statistic for IV-2SLS estimations. Robust standard errors corrected for clustering at the district level are provided in parenthesis.)

Previously identified throughout this chapter. The inclusion of the full set of controls in column (2) results in a noticeable reduction of the estimated highway density elasticity, further it leads to the full loss of significance. Hence, the low magnitude and insignificance of the highway density elasticity of column (2) indicates a non-existent effect of highways on firm-level TFP. Furthermore, in this specification population density is reported to be highly statistically significant and roughly in line with the magnitude of highway density elasticities identified with Difference and System GMM in Table 6.8, albeit larger than those reported in Table 6.9.

Similar to the previous estimations ignoring the historical instrumental variables, I employ the IV-GMM method to additionally control for any firm-specific time-invariant factors possibly driving the results; results are provided in column (3) of Table 6.12. The consistence of the identified results of IV-LIML and IV-GMM across columns (2) and (3) is noticeable, both for the population density and highway density variables used. Both results point to an importance of a
district’s population density for firm-level TFP of the same district, but they do not point towards the importance of a district’s highway density. However, while these results are similar for columns (2) and (3) of Table 6.12, they are noticeably distinct from those of Section 5.3 of this Chapter, which point towards the importance of highways and if anything, only to a very weak and inconsistent effect of population density. The results of Subsection 5.3.1 on the other hand are in line with both possible channels, the firm-level TFP effect of highway density as implied by the results of 5.3 and the population density effect as suggested by the results of this subsection.

The reported first stage F-statistics of Table 6.12 are in line with the critical values reported for IV estimations, the significance of the overidentification statistic however does not provide strong support for the validity of the instrumental variables used and model specified, hence caution in the interpretation of the results should remain.

V.IV Results across Eastern and Western Districts

As discussed in Section 6.1, Germany exhibits a large degree of spatial heterogeneity across the states of the former German Democratic Republic (GDR) in the East and the Western states of the former version of the Federal Republic of Germany as it existed until 1990. In this subsection, I investigate whether highway infrastructure played a role in fostering the spatial convergence of firms’ productivity levels across districts located within the border of the former GDR and the former geographic boundaries of the Federal Republic of Germany. For this, I split the total sample of observations into two subsamples depending on the location of a district. Overall, the number of observation of each subsample is relatively stable so that the results should not be driven by differences in sample size. I re-estimate the elasticities of highway infrastructure and population and report
Table 6.13: Second Step Productivity Estimations - Eastern and Western Districts

<table>
<thead>
<tr>
<th></th>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Western Districts</td>
</tr>
<tr>
<td></td>
<td>Fixed Effects System GMM</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>0.042(0.032)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.265***(0.100)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>-0.031(0.044)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>-0.013(0.076)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>-0.136(0.181)</td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>-0.344(1.047)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>21,981</td>
</tr>
<tr>
<td>R(^2)</td>
<td>0.425</td>
</tr>
</tbody>
</table>

Note: ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis.

the results in Tables 6.13 and 6.14 for non-IV and IV estimations respectively.

In the context of firms and highways, two hypotheses could be possible: (1) if there exist relatively lower levels of highway infrastructure across the districts in the former GDR, and diminishing returns to highway infrastructure, then firms located in those districts should experience relatively higher productivity benefits from increases in the highway infrastructure. Alternatively, (2) given that firms across those districts are reported to exhibit lower levels of productivity, increases in the district’s highway infrastructure could expand the geographical reach of more productive firms, and therefore heighten the survival pressure within those districts with more pre-existing lower level productivity firms, and therefore result in a negative elasticity of highways on firm’s productivity levels.

For districts located in the Western states, the results of Table 6.13 imply a positive TFP effect of a district’s highway density. The identified coefficients imply that an increase of a district’s highway density of 1 per cent is followed by an increase of 0.05 per cent of firm-level TFP, or similarly, that a 10 per cent highway density increase results in a 0.5 per cent firm-level TFP growth. The identified average magnitude of the highway density elasticities is in line with those iden-
tified for the whole sample in Table 6.9, however none of the highway density coefficients can assumed to be statistically significant. The coefficient of measuring the highway density of districts located in close proximity is estimated to be negative and statistically significant across both columns (3) and (4). While it might be assumed that firms also benefit from highways of neighbouring districts, this result does not support this notion but rather points to a negative effect. This effect can possibly stem from competition effects, where higher highway density of neighbouring districts allows for more incoming competition from (higher productivity) firms located in other districts which would depress the TFP levels of firms in the given district. For the Western states, the results of columns (1) to (4) further estimate all population variables to be negative and insignificant, thus not pointing to any TFP effects stemming from the population other than those resulting from the firm’s skilled labour force.

Similar to the estimates obtained for the districts of the Western states, columns (5) to (8) imply positive effects of highway density for firm-level TFP for districts located in the East German states. The average magnitude of this effect however is approximately half of its equivalent estimate across columns (1) and (4), and thus noticeably smaller. The results identify an average TFP increase of 0.02 per cent following a 1 per cent raise in a district’s highway density, albeit all estimated elasticities cannot assumed to be statistically significant. The elasticity of the highway density of closely located districts is estimated to be negative across both columns (7) and (8). Similar to its equivalent estimate for districts of the Western states, this might imply negative competition effects, however given its smaller magnitude, competition effects might be less harsh across the districts of the Eastern states. For both versions of columns (7) and (8), the estimate is not reported to be statistically significant. The variable of wider highway density is reported as positive, but parallel to all population related variables also reported
Table 6.14: Second Step Productivity IV Estimations - Eastern and Western Districts

<table>
<thead>
<tr>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
<th>Western Districts</th>
<th>Eastern Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV-LIML (1)</td>
<td>IV-GMM (2)</td>
</tr>
<tr>
<td></td>
<td>IV-2SLS (3)</td>
<td>IV-2SLS (4)</td>
</tr>
<tr>
<td></td>
<td>IV-LIML (5)</td>
<td>IV-GMM (6)</td>
</tr>
<tr>
<td></td>
<td>IV-2SLS (7)</td>
<td>IV-2SLS (8)</td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>0.018(0.045)</td>
<td>0.032(0.025)</td>
</tr>
<tr>
<td></td>
<td>0.022(0.044)</td>
<td>0.017(0.043)</td>
</tr>
<tr>
<td></td>
<td>0.015(0.037)</td>
<td>0.019(0.038)</td>
</tr>
<tr>
<td></td>
<td>0.017(0.031)</td>
<td>0.014(0.030)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.100(1.28)</td>
<td>-0.100(1.137)</td>
</tr>
<tr>
<td></td>
<td>0.018(1.092)</td>
<td>0.003(1.087)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>-0.821(0.895)</td>
<td>-0.801(0.946)</td>
</tr>
<tr>
<td></td>
<td>0.059***</td>
<td>0.044***</td>
</tr>
<tr>
<td></td>
<td>0.056***</td>
<td>0.048***</td>
</tr>
<tr>
<td></td>
<td>0.043</td>
<td>0.062</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>0.100(0.109)</td>
<td>0.147(0.119)</td>
</tr>
<tr>
<td></td>
<td>-0.003(0.049)</td>
<td>0.022(0.056)</td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>0.100(0.209)</td>
<td>0.147(0.119)</td>
</tr>
<tr>
<td></td>
<td>0.413(0.571)</td>
<td></td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographical Controls</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Min. Eigenvalue Statistic</td>
<td>535.30**</td>
<td>563.02***</td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>0.100(1.28)</td>
<td>0.100(1.137)</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density)</td>
<td>0.292</td>
<td>0.297</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density - Direct Access)</td>
<td>0.245</td>
<td>0.319</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density - Wider Access)</td>
<td>0.305</td>
<td>0.491</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>21,981</td>
<td>21,981</td>
</tr>
<tr>
<td>F-Stat</td>
<td>4.41***</td>
<td>4.41***</td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>0.100(1.28)</td>
<td>0.100(1.137)</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density)</td>
<td>0.292</td>
<td>0.297</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density - Direct Access)</td>
<td>0.245</td>
<td>0.319</td>
</tr>
<tr>
<td>Shea's adj. partial H^2. Ln(Highway Density - Wider Access)</td>
<td>0.305</td>
<td>0.491</td>
</tr>
<tr>
<td>Hansen's J statistic for IV-GMM and the Sargan statistic for IV-2SLS estimations. Robust standard errors corrected for clustering at the district level are provided in parenthesis.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

as statistically insignificant. Furthermore, similar to prior results of this chapter and those of the preceding Chapters 4 and 5, the estimated Hansen statistic does not allow for a conclusion on the appropriateness and suitability of the internal instruments used by the System GMM estimation procedures.

Given the afore discussed issues with the majority of the estimation procedures used when endogeneity issues are present, the regressions of Table 6.13 are repeated with the use of external instrumental variables in Table 6.14. The IV-estimation results for the variables of highway density and highway density - Direct Access across Western states confirm the results of Table 6.13, however the latter variable is reported as statistically insignificant in Table 6.14. The estimate of the variable highway density - Wider Access is reported to be positive in Table 6.13, but is identified as negative in Table 6.14. This is possibly in line with the outlined competition dynamics which might affect firm TFP negatively through the highway variables. However, similar to Table 6.13, this variable is reported to be statistically insignificant in Table 6.14. The estimated elasticities of all population variables listed in Table 6.14, columns (1) to (4) are reported to be positive, thus contrasting those of the previous table where they were all estimated as negative.
The results of Table 6.14 therefore suggest TFP effects stemming from population
density in addition to those derived from the skilled workforce of a firm across
districts of the Western states. This supports the notion cautiously identified by
the majority of the results provided in Tables 6.8 and 6.9. The positive effect
of population density on firm-level TFP may also be driven through the role of
population density as the final consumer market and the effect of its proximity to
the firm’s location. This effect however can only be statistically significantly iden-
tified for a district’s own population density, the elasticities of population density
- direct and wider access cannot assumed to be statistically significant.

The estimates obtained for firms located in the districts of the Eastern states
in columns (5) to (8) of Table 6.14 for the variable of highway density are in
line with those obtained via the non-IV estimations of Table 6.13. However, given
that the magnitude of the elasticity is either of similar size to its equivalent for the
Western states, or smaller than it, the results provide no support for the hypothesis
that increases in highway levels across the Eastern states can aide the economic
convergence of TFP levels across the East and West of Germany. The elasticity of
highway density - direct access is reported to be negative in Table 6.13 and positive
in Table 6.14, albeit this difference, both estimates are statistically insignificant.
Similarly, the estimate of highway density - wider access is listed as positive in
Table 6.13 and negative in Table 6.14, and reported to be statistically insignificant
across both. With regards to a district’s population density, the results obtained
for districts of East Germany are positive, similar to those obtained with the non-
IV estimations and in line with those identified for the Western states. However,
unlike those results of columns (1) to (4), the estimates for the Eastern states are
only reported to be statistically significant in half of the IV-estimations. Given the
lower levels of district-level population densities across the East German districts,
the impact on firm-level TFP through district population will overall be lower
than throughout the Western states. The population variables of direct and wider access are reported to be statistically insignificant.

For both the estimations of the Western and Eastern states, the first stage F and Eigenvalue statistics provide necessary parameters supporting the validity and appropriateness of the external instruments employed, the overidentification statistics however, similar to the prior discussed IV results in Section 5.3.2, do not provide the required estimates supporting the notion of the suitability of the external instruments. Hence, the robustness and reliability of results discussed and provided in this section should be interpreted with caution.

Overall, the results of this subsection provide tentative support for the importance of a district’s highway and population density for a firm’s TFP growth. However, they also point to possible negative TFP effects stemming from increased incoming competition through higher highway density of surrounding districts, and do not provide support for the notion that increased highway levels can foster convergence within TFP levels across the districts located in East and West Germany.

V.V Urban, Suburban and Rural Districts

In this subsection, I further the estimation results of the preceding subsections by analysing the productivity effects of highways across firms located in urban, suburban and rural districts. I split the sample according to the classification of districts into the before mentioned three categories which are based on the classification of districts by the German Federal Institute for Research on Buildings, Urban Affairs and Spatial Development (Bundesinstitut für Bau-, Stadt- und Raumforschung) and re-estimate a sub-set of the calculations of Tables 6.8, 6.9 and 6.12 for firms located in each of three categories separately; results are provided in Tables 6.15 and 6.16 for non-IV and IV estimations respectively.

Overall, the results of Table 6.15 support the notion that a district’s high-
way density has a positive effect on the TFP level of firms located within the given district, independent of whether the district is of an urban, suburban, or rural nature. The estimated elasticities are of similar magnitude across the different estimation procedures and regional classifications indicating that a 1 per cent increase in a district’s highway density yields an average firm-level TFP increase of 0.03 to 0.04 per cent. However, none of these estimated highway density elasticities across columns (1) to (12) are reported to be statistically significant. For urban districts, the results of column (1) to (4) indicate a negative estimate for the highway density of neighbouring districts, which may possibly indicate relocations of high TFP firms from urban to neighbouring districts if these exhibit higher highway densities, and thus better accessibility, to circumvent the high urban costs. This would represent a decrease in the average TFP level of urban firms. However, these estimates are not statistically significant, and thus the preceding interpretation is a cautious one. The results of the variable of highway density - direct access across suburban and rural districts within columns (5) to (12) are mixed, so no consistent conclusion can be drawn. The variable measuring the wider highway accessibility of a district, highway density - wider access, however is reported to be positive, of relatively large magnitude across and statistically significant in two of the three regional classifications, thus indicating that firms benefit from increased inter-regional highway connectivity. This effect might particularly stem from increased international connectivity through better access to ports, which are generally located in a few national hubs, and increased accessibility to intermediate input suppliers which can generally not hypothesised to be entirely located within the same district. For the effect of a district’s population density, the results across columns (1) to (12) include positive and negative, and statistically significant and insignificant estimates. For the urban districts, the identified elasticities are mostly positive, but low in magnitude, and
thus do not provide any support for a positive TFP effect through the channel of agglomeration economies stemming solely from the size of a city or its population density levels. For the suburban districts, the estimates of the effect of population density are negative across all four estimation procedures, larger in magnitude compared to those generated across columns (1) to (4) for urban districts and statistically significant in one specification. These estimates indicate that districts with higher population densities depress firm-level TFP growth, and while this might appear counterintuitive, negative congestion issues stemming from higher population density may explain this effect. This might particularly be driven by the relatively large fraction of the suburban population working within cities, but residing within suburban districts, thus not being part of the suburban workforce but contributing to negative congestion matters. For the rural districts, identified elasticities are mostly positive and slightly larger than those found for urban districts, therefore possibly indicating that any positive TFP effects derived from the local population density outweigh associated negative congestion effects. However, given the absence of statistical significance across these estimates of column (9) to (12), caution should prevail. The effect of the population density of neighbouring districts on firm-level TFP is reported negative for all estimation procedures across the three regional classification but with differing magnitudes. The largest magnitudes, and only statistically significant estimates, are found for urban districts, which might provide support for the notion of negative congestion effects given that the population residing in neighbouring (suburban) districts often also use the infrastructure of urban districts, thus adding to congestion effects of cities beyond that stemming from its own population. The estimates reported for the population density - wider access variable are very mixed across the three regional classes, and thus no conclusion can be drawn.
Table 6.15: Second Step Productivity Estimations - Urban, Suburban and Rural Districts

<table>
<thead>
<tr>
<th></th>
<th>Urban Districts</th>
<th></th>
<th>Suburban Districts</th>
<th></th>
<th>Rural Districts</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density)</td>
<td>0.019(0.041)</td>
<td>0.037(0.042)</td>
<td>0.032(0.042)</td>
<td>0.030(0.041)</td>
<td>0.030(0.041)</td>
<td>0.034(0.043)</td>
</tr>
<tr>
<td></td>
<td>0.101(0.076)</td>
<td>0.037(0.042)</td>
<td>0.032(0.042)</td>
<td>0.030(0.041)</td>
<td>0.030(0.041)</td>
<td>0.034(0.043)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.069(0.127)</td>
<td>-0.097(0.125)</td>
<td>-0.031(0.076)</td>
<td>0.001(0.076)</td>
<td>-0.003(0.046)</td>
<td>0.037(0.046)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>1.744** (1.017)</td>
<td>1.081(0.843)</td>
<td></td>
<td></td>
<td>2.004*** (0.897)</td>
<td></td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>-0.078(0.168)</td>
<td>0.021(0.126)</td>
<td>0.018(0.170)</td>
<td>0.045(0.180)</td>
<td>-0.375*** (0.094)</td>
<td>-0.368(0.229)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.368(0.229)</td>
<td>-0.268(0.221)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.043(0.095)</td>
<td>0.045(0.094)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>-1.146*** (0.400)</td>
<td>0.024*** (0.404)</td>
<td></td>
<td></td>
<td>-0.368(0.387)</td>
<td>-0.000(0.402)</td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>3.885(2.603)</td>
<td></td>
<td></td>
<td></td>
<td>-0.615(1.329)</td>
<td></td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>0.000</td>
<td></td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.935</td>
<td></td>
<td>-</td>
<td>0.042</td>
<td>-</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>1.000</td>
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<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
<td>- 577</td>
<td>-</td>
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<td>-</td>
<td>584</td>
<td>-</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>12,918</td>
<td>12,918</td>
<td>12,918</td>
<td>12,918</td>
<td>14,754</td>
<td>14,754</td>
</tr>
<tr>
<td>R²</td>
<td>0.449</td>
<td>0.450</td>
<td>0.453</td>
<td>0.442</td>
<td>0.442</td>
<td>0.395</td>
</tr>
</tbody>
</table>

Dependent Variable: Firm-Level Total Factor Productivity (Ln)

Notes: ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis.
To test the robustness of the estimates identified in Table 6.15, the regressions are repeated with IV methods in Table 6.16. The elasticities identified for the effect of a district’s highway density on firm-level TFP in urban districts is estimated to be negative across all four methods, and highly significant in half of them. While this finding might be relatively surprising, combining it with the positive effects identified for the highway density of districts located within proximity and also with those located further away possibly indicates that firms do not generate TFP benefits from interregional highways within urban environments, but mostly generate benefits from the urban connectivity with other districts. While this interpretation suits the findings of Table 6.16, it contrasts those reported for urban districts in Table 6.15, and additionally given that only two of the seven highway density variables’ estimates are reported to be statistically significant, caution in the robustness of this interpretation should remain. For suburban districts, the estimates for all highway density variables are reported to be positive, albeit also all statistically insignificant, and therefore in line with those identified for suburban districts in Table 6.15. For rural districts, all highway variables’ estimates are identified as positive in columns (9) to (12). These elasticities are found to be larger in magnitude than those reported for urban districts, statistical significance is reported for approximately half of the estimates. Therefore, it suggests itself that firms located in rural districts benefit particularly from highway infrastructure, both located within their location districts, but also within those in close proximity. Given the statistical significance of both of the variables of highway density - direct access, the TFP effect stemming from the highway density of neighbouring districts, firms in rural regions possibly benefit particularly from their connectivity to surrounding districts. The estimates found for the variable of highway density - wider access are positive but statistically insignificant with a noticeably smaller magnitude for suburban districts. The variable of a district’s population density
is found to be positive and, for seven of the twelve estimates, statistically significant across all regional classes. For the urban population density, positive and significant elasticities are found in columns (1) and (2), but these become smaller in magnitude and insignificant once the population spillover effects are introduced into the regression in column (3) and (4). For suburban districts, positive estimates are found for a district’s own population density, and negative elasticities are found for the effect stemming from the population density of neighbouring districts, where the latter are possibly in line with the negative congestion effects discussed prior. For rural districts, positive and statistically significant results are identified across all estimation methods, thus suggesting that firms located in rural areas benefit relatively more from the district’s population density than those firms located in suburban districts. Further, negative and significant effects are found for the population density - direct access variable, possibly indicating the rural districts located further away from higher density districts benefit from a more insulated economy. For the variable of population density - wider access negative and statistically insignificant results are found for all three regional categories. Overall, given the prevailing issues with the Hansen statistic for System GMM estimations and the overidentification parameter for the IV estimations, caution should persist regarding the robustness of the estimated elasticities.
Table 6.16: Second Step Productivity IV Estimations - Urban, Suburban and Rural Districts

<table>
<thead>
<tr>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
<th>Urban Districts</th>
<th>Suburban Districts</th>
<th>Rural Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV-LIML (1)</td>
<td>IV-GMM (2)</td>
<td>IV-2SLS (3)</td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>-0.107(0.060)</td>
<td>-0.096*** (0.042)</td>
<td>-0.065*** (0.048)</td>
</tr>
<tr>
<td></td>
<td>-0.065*** (0.071)</td>
<td>0.014 (0.026)</td>
<td>0.016 (0.015)</td>
</tr>
<tr>
<td></td>
<td>0.021 (0.023)</td>
<td>0.022 (0.024)</td>
<td>0.045 (0.048)</td>
</tr>
<tr>
<td></td>
<td>0.065** (0.025)</td>
<td>0.040 (0.044)</td>
<td>0.030 (0.044)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>0.039 (0.167)</td>
<td>0.137 (0.184)</td>
<td>0.040 (0.146)</td>
</tr>
<tr>
<td></td>
<td>0.053 (0.152)</td>
<td>0.136** (0.058)</td>
<td>0.190** (0.082)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>0.860 (1.687)</td>
<td>0.167 (1.420)</td>
<td>1.183 (1.080)</td>
</tr>
<tr>
<td></td>
<td>0.092 (0.054)</td>
<td>0.099*** (0.036)</td>
<td>0.076 (0.054)</td>
</tr>
<tr>
<td></td>
<td>0.040 (0.061)</td>
<td>0.030 (0.044)</td>
<td>0.039*** (0.021)</td>
</tr>
<tr>
<td></td>
<td>0.022 (0.046)</td>
<td>0.023 (0.046)</td>
<td>0.090*** (0.043)</td>
</tr>
<tr>
<td></td>
<td>0.109** (0.026)</td>
<td>0.084 (0.045)</td>
<td>0.075 (0.046)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>0.030 (0.147)</td>
<td>0.043 (0.163)</td>
<td>0.039 (0.136)</td>
</tr>
<tr>
<td></td>
<td>-0.049 (0.148)</td>
<td>0.028 (0.044)</td>
<td>0.088*** (0.002)</td>
</tr>
<tr>
<td></td>
<td>0.016*** (0.051)</td>
<td>0.016*** (0.051)</td>
<td></td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>-1.466 (1.433)</td>
<td>-1.391 (1.400)</td>
<td>-1.406 (1.571)</td>
</tr>
<tr>
<td></td>
<td>0.040 (0.147)</td>
<td>0.043 (0.163)</td>
<td>0.039 (0.136)</td>
</tr>
<tr>
<td></td>
<td>-0.049 (0.148)</td>
<td>0.028 (0.044)</td>
<td>0.088*** (0.002)</td>
</tr>
<tr>
<td></td>
<td>0.016*** (0.051)</td>
<td>0.016*** (0.051)</td>
<td></td>
</tr>
<tr>
<td>First Stage F-Stat</td>
<td>12.30***</td>
<td>5.63***</td>
<td>15.67***</td>
</tr>
<tr>
<td></td>
<td>1837.89***</td>
<td>522.68***</td>
<td>344.44***</td>
</tr>
<tr>
<td>Min. Eigenvalue Statistic</td>
<td>645.02***</td>
<td>522.68***</td>
<td>199.51***</td>
</tr>
<tr>
<td></td>
<td>1491.78***</td>
<td>417.21***</td>
<td>334.74***</td>
</tr>
<tr>
<td></td>
<td>429.51***</td>
<td>355.51***</td>
<td>310.26***</td>
</tr>
<tr>
<td></td>
<td>286.93***</td>
<td>70.37***</td>
<td>74.58***</td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>74.65***</td>
<td>34.68***</td>
<td>109.17***</td>
</tr>
<tr>
<td></td>
<td>105.62***</td>
<td>54.83***</td>
<td>48.15***</td>
</tr>
<tr>
<td></td>
<td>116.95***</td>
<td>116.95***</td>
<td>42.97***</td>
</tr>
<tr>
<td></td>
<td>116.95***</td>
<td>42.97***</td>
<td>116.95***</td>
</tr>
<tr>
<td></td>
<td>70.37***</td>
<td>74.58***</td>
<td>74.58***</td>
</tr>
<tr>
<td>Shea's adj. partial R²: Ln(Highway Density)</td>
<td>0.340</td>
<td>0.273</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>0.432</td>
<td>0.194</td>
<td>0.192</td>
</tr>
<tr>
<td>Shea's adj. partial R²: Ln(Highway Density - Direct Access)</td>
<td>0.536</td>
<td>0.390</td>
<td>0.262</td>
</tr>
<tr>
<td></td>
<td>0.262</td>
<td>0.354</td>
<td>0.362</td>
</tr>
<tr>
<td>Shea's adj. partial R²: Ln(Highway Density - Wider Access)</td>
<td>0.249</td>
<td>0.241</td>
<td>0.480</td>
</tr>
<tr>
<td></td>
<td>0.241</td>
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<td></td>
</tr>
<tr>
<td>Number of Observations</td>
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<td>12,918</td>
<td>12,918</td>
</tr>
<tr>
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<td>12,918</td>
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<td></td>
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<td>16,139</td>
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<td></td>
<td>16,139</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.951</td>
<td>0.951</td>
<td>0.951</td>
</tr>
<tr>
<td></td>
<td>0.951</td>
<td>0.959</td>
<td>0.959</td>
</tr>
<tr>
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<td>0.959</td>
<td>0.953</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>0.953</td>
<td>0.929</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>0.953</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*, **, *** indicate significance at the 10%, 5% and 1% level respectively. The significance of the Eigenvalues is determined according to the LIML Wald test, for 2SLS estimations the 2SLS relative bias test is used alternatively; overidentification tests use the Anderson-Rubin statistic for IV-LIML, the Hansen’s J statistic for IV-GMM and the Sargan statistic for IV-2SLS estimations. Robust standard errors corrected for clustering at the district level are provided in parenthesis.)
In summary, the estimations results listed in Tables 6.15 and 6.16 point to the spatial heterogeneity of firms located within urban, suburban and rural districts. Further, the results point to particularly large benefit for firms located in rural regions, both those stemming from highway and population dynamics. Additional results are provided in Appendix C7 "Estimation Results for Urban, Suburban and Rural Districts across East and West Germany", where the estimations of this Subsection are repeated for districts located in East and West Germany separately.

V.VI High and Low Density Districts

The results of the preceding subsections point to a possible beneficial effect of highway infrastructure for the firm’s productivity across Germany. However, the preceding analyses of Chapter 5 have highlighted the differences between aggregate and disaggregate effects, and the possible heterogeneity of effects across different spatial units. I investigate this in this context of German data by splitting the sample into four percentiles and comparing the estimated elasticities identified for the percentile of the districts with the highest and lowest highway density; Tables 6.17 and 6.18 report the estimation results across non-IV and IV estimation methods employed.

For the non-IV estimations listed in Table 6.17, I cannot identify any significant elasticities for the sample of those districts with the highest reported levels of highway density. However, the results provide some weak evidence for a positive effect on firm TFP from the highway densities of districts located farther away. In addition, some evidence is found pointing to negative population density effects of districts located within close proximity. The latter might possibly be interpreted as higher population density of neighbouring counties increasing congestion of a given districts, and thus affecting firm TFP negatively. However, given the low values of R² of the Fixed Effects estimations, one shouldn’t interpret this finding...
Table 6.17: Second Step Productivity Estimations - High and Low Density Districts

<table>
<thead>
<tr>
<th>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</th>
<th>Low Density Districts</th>
<th>High Density Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Effects System GMM</td>
<td>Fixed Effects Fixed Effects System GMM Fixed Effects Fixed Effects</td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>-0.022*** (0.027)</td>
<td>0.076*** (0.029)</td>
</tr>
<tr>
<td></td>
<td>-0.021(0.026)</td>
<td>-0.013(0.026)</td>
</tr>
<tr>
<td></td>
<td>0.168(0.046)</td>
<td>-0.071(0.144)</td>
</tr>
<tr>
<td></td>
<td>0.118(0.079)</td>
<td>0.118(0.078)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.044(0.059)</td>
<td>-0.005(0.060)</td>
</tr>
<tr>
<td></td>
<td>-0.010(0.010)</td>
<td>-0.005(0.017)</td>
</tr>
<tr>
<td></td>
<td>-0.033(0.143)</td>
<td>-0.035(0.140)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>1.331(1.221)</td>
<td>3.101*** (1.335)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>0.122(0.088)</td>
<td>0.135(0.088)</td>
</tr>
<tr>
<td></td>
<td>0.135(0.088)</td>
<td>0.135(0.088)</td>
</tr>
<tr>
<td></td>
<td>-0.349(0.293)</td>
<td>0.002(0.100)</td>
</tr>
<tr>
<td></td>
<td>-0.144(0.222)</td>
<td>-0.144(0.222)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>-0.233(0.402)</td>
<td>-0.222*** (0.500)</td>
</tr>
<tr>
<td></td>
<td>-0.087(0.220)</td>
<td>-0.163*** (0.490)</td>
</tr>
<tr>
<td></td>
<td>-1.224*** (0.500)</td>
<td>-1.181*** (0.490)</td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>-7.617*** (4.125)</td>
<td>0.566(3.333)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
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<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.088</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
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<td>581</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>11,137</td>
<td>11,137</td>
</tr>
<tr>
<td>R²</td>
<td>0.260</td>
<td>0.260</td>
</tr>
</tbody>
</table>

(where *** *, indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis)

as robust. Similarly, investigating the impact of highway density within those districts with relatively high levels of this variable in further detail in Table 6.18, columns (5) to (8), also does not provide any more evidence for the impact of highway density of firm-level TFP within these districts; some weak evidence for the importance of a district’s population density for firm-level TFP however is found in one specification in column (7). Furthermore, no evidence for spillover effects, either through population or highway density, can be identified.

This could possibly present the higher relative importance of the district’s population as an important factor for firms in those regions with high levels of highway density. It could be argued that districts with high transportation density are those which are densely populated where more highways have been constructed to serve the higher population levels, so population would be the relevant factor for the firm’s productivity. However, as this effect is only found in one estimation, caution in the reliance on this estimate should prevail.

The elasticities identified for the sample consisting of the districts with the lowest reported levels of highway density hint at a different matter. The estimations of Table 6.17 provide evidence for both positive and negative TFP elasticities
of highway density. The Fixed Effects estimation of column (1) implies a negative effects, the System GMM specification of column (2) a positive estimate, where both of these estimated coefficients are highly significant. The Fixed Effects specifications of columns (3) and (4) furthermore imply negative firm-level TFP effects of a district’s highway density, however these results are not statistically significant. Additionally, the results of Table 6.17 do not provide any robust evidence for spillover effects, neither for population nor highway density. Some weak evidence is found for a positive effect of population density in column (2). However, given the prior discussed econometric issues with the employed methods, Table 6.18 retests the estimations with the inclusion of the external instruments. All estimation methods employed estimate positive elasticities of highway density on firm TFP, however only the estimates obtained via 2SLS provide significant results where the magnitude of the estimates is in line with those found for the whole sample in Table 6.12 under IV-LIML. These results would imply that an increase in a district’s highway density of 10 per cent would lead to a TFP increase of approximately 1 per cent at the firm-level. These results could point towards higher productivity benefits following highway extensions in districts with relative low highway stocks. In addition to the prior discussed results identified for the whole sample, the results of Table 6.18 possibly point to diminishing returns of a district’s highway density where there exists satiation of the effects of highways for firm’s productivity in districts with high levels of existing highways. Furthermore, the results may imply that the results identified for the whole sample are purely driven by those effects found in relatively low highway density districts. Overall, the results indicate that districts with low levels of highway density predominantly benefit from increases in the district’s own highway stock, increases in the overall access to highways, as measured by the variables of Direct and Wider Access do not reveal a consistent effect across estimation specifications at this point. Fur-
thermore, the estimations of column (1) and (2) also find statistically significant evidence for the importance of a district’s population density for the dependent variable, where the elasticity identified with IV-GMM is noticeably larger in magnitude than the estimate obtained with IV-LIML.

Analysing the test statistics of Table 6.18 reveals that all First stage F-statistics imply valid explanatory effects of the instrumental variables employed. Furthermore, the identified Eigenvalues and Wald tests also do not provide evidence for weak instruments. However, the overidentification tests hint at possible structural issues within the estimations. The significance of this test statistic implies that either the instruments used are not valid, or that there exists a structural mis-specifications, or alternatively also that heteroskedastic errors are presents, which would violate the assumptions of i.i.d. errors of the underlying overidentification test. Hence, given this, caution should remain in the reliance of the results of this section.
VI Conclusion

The aim of this research work was the investigation of the role of highways for the spatial distribution of firm-level productivity across the economic geography of Germany. An additional focus of this work was the investigation of the effect of regional highway stocks in explaining the persistent productivity differences across the Eastern and Western states of Germany and if additional highway investments in the East could foster a trend of convergence in productivity.

While there exist a few papers investigating the role of transportation and geographical access related variables on the spatial economy of Germany, the extensive dataset used for this work, allows for the first investigation of transportation for the whole of Germany; previous work has almost exclusively only used information for the Western states of Germany. Further, this work adds to the investigation of firm-level effects of transportation, which up to date remains relatively limited due to data constraints.

In this work, I use historical variables to control for the possibility of the endogenous placement of highways in areas with high productivity firms and identify productivity elasticities of approximately 0.05 depending on the econometric specification chosen and control variables included. While the results across disaggregated subsamples reveal a large degree of heterogeneity, two tentative conclusions can be drawn: (1) there exists differences in the effect of highways on productivity across districts with relatively high and low levels of highway density; these points to the existence of diminishing returns and satiation effects of highway infrastructure, and (2) highways affect the spatial distribution of productivity in dissimilar directions across districts in the Eastern and Western states and across urban, rural and suburban districts. The named methodological issues discussed, which the estimations suffer from at this point, do not allow for a final robust conclusion
of the effects of highways on firm-level productivity, hence the improvements of validity of the estimated elasticities remain as next steps of this work.
Chapter 7

Conclusion
I Introduction

In this final chapter, I provide a summary of the results identified throughout the analyses of this dissertation. I further discuss their contribution and relevance for policy making. Further, I provide an outline for the future direction of this research.

This chapter is organised as follows: Section 7.2 provides an overview of the research findings of this work, Section 7.3 highlights the research contribution of this work, Section 7.4 relates the findings of Section 7.3 to current policies, and Section 7.5 concludes with an overview of the next steps for this body of research.

II Overview of Research Findings

The overarching theme of this dissertation is the investigation of the relevance of transportation infrastructure for the development and performance of the private sector. I analyse this relationship for both firms located in developing and developed countries to highlight similarities and disparities of the importance of transportation networks for the performance of the private sector. For the examination of this relationship, I have chosen two countries that differ substantially on various economic and social factors: Colombia and Germany. Investigating the role of highways in Colombia allows for an analysis of the importance of transportation in a developing country context for an economy with considerably low levels of transportation infrastructure. The analysis of the role of highways in Germany highlights the role of transportation for a mature economy with a relatively dense transportation network. These empirical analyses are provided throughout Chapters 4 to 6.

Research on developing countries is often limited by the absence of reliable panel data, this especially applies to data on firms. Some researchers attempt to
circumvent this problem by designing different proxy variables, for example the proxy of night light satellite data as a proxy for income (Henderson et al., 2012). I alternatively use aggregated Colombian data of input and outputs of industries across regions to identify a pseudo-panel that can be used to simulate the analysis of firm-level effects in the absence of true firm panel data; these analyses are discussed in Chapter 4 and 5. The findings of Chapter 4 are twofold: (1) it provides support for the use of pseudo-panels in the context of firm-data and (2) it quantifies the effects of transportation for the private sector output in a developing country. I conduct a Monte Carlo simulation to test the validity of pseudo-panels. The results of this exercise provide support for the usefulness of pseudo-panels in the context of firm-level data, and further identify the suitability of different estimators to be used in combination with pseudo-panel data. The subsequent investigation of the pseudo-panel of Colombian firms and the Colombian highway network reveal two noteworthy points: The elasticity of highway infrastructure on the growth of a firm’s output is significant and positive, however the identified magnitude of this effect of approximately 0.13 to 0.15 is substantially larger than the average effect identified in similar studies for developed countries. The results further show a time lag of this effect of one year. These results are noticeably constant across different specifications and remain relatively stable independently of the inclusion of various additional control variables. I test the robustness of these results further by employing two alternative density based transportation variables: highway density weighted by the geographic size of a region and highway density weighted by the region’s population. The estimations employing these alternative transportation measures provide further support for the robustness of the previously identified elasticities. An additional investigation reveals that transportation benefits particularly accrue to firms of the heavy industries.

I analyse the role of the Colombian highway network further by shifting the
focus to the spatial heterogeneity of this effect across regions. The aim of this
analysis is further to identify indicators for possible diminishing returns from high-
ways and the impact of transportation networks on regional economic convergence.
Colombia’s spatial economy is characterised by two predominant factors: the high
levels of concentration of the population and economy and the persistent spatial
inequality between the central regions and the remainder of the country. I invest-
igate the role of highways across geographically and economically heterogeneous
regions separately. The geographical samples of central, coastal and peripheral re-
gions only identify significant effects for those firms belonging to the pseudo-panel
of firms in central regions in which the majority of economic output is generated.
The direction and magnitude of these results is reported to be around 0.150 and
hence in line with the elasticities identified for the whole country in Chapter 4. No
significant results were obtained for the pseudo-panels of firms located in coastal
or peripheral regions. For the further examination of the role of transportation
for economic convergence, I split the sample into economically strong and weak
regions. The estimated elasticities only provide a weak indicator for a larger effect
for the pseudo-panel of firms located in economically strong regions and hence do
not provide any notion for the importance of transportation for fostering economic
convergence in Colombia.

I subsequently shift the focus towards the investigation of the impact of high-
ways on the spatial distribution of total factor productivity across Germany. For
this research, I employ data on firms across German NUTS3 districts. Germany
offers a unique setting for the investigation of the role of transportation for the
spatial economy given its unique recent history and the impact of this on the
economic geography of Germany. Germany additionally invested heavily in ad-
ditional highways predominantly exclusively throughout the states of the former
GDR which offer an additional interesting context to analyse the impact of high-
ways on the private sector. For this analysis, I generate instrumental variables from historical transportation networks to control for the possible endogeneity of the placements of highways according to economic variables. I employ a two-step estimation procedure relying on the Levinsohn-Petrin methodology to investigate the impact of a district’s highway density on the productivity level of the firms located in the district. In line with previous studies investigating firms located in Germany, I find spatial differences in productivity levels where larger levels are generally found in the districts of the South and West of the country, and around the Northern city of Hamburg, relatively lower productivity levels are identified for the majority of the districts of the Eastern states and throughout some areas of the North of the country. The investigation of the whole country identifies positive and significant effects of highways for firm level productivity levels. The estimates range from 0.02 to 0.12 for highway density, representing an increase of the firm’s productivity of 0.02 to 0.12 per cent following a 1 per cent increase in the district’s highway density; further evidence for positive firm-level TFP effects are found for the highway density of districts located in close proximity and farther away. This indicates that firms derive benefits from both the highways located in its own district and those located in the surrounding regions and the remainder of the country. The results further highlight the relative importance of highways for the firm’s productivity; while the elasticities identified for highway variables are significant for the firm’s productivity levels, the elasticities identified for the firm’s skilled employees are generally larger in magnitude. This is particularly the case with respect to highway density elasticities. The investigation of subsamples designed to capture districts with relatively high and low highway density points towards diminishing returns of transportation infrastructure and satiation effects in high transportation density districts. While no consistent and robust differences in the estimated effects could be identified across districts of
the Eastern and Western states further disaggregate results show that highways particularly benefited firms in rural districts. Overall, the robustness of the results of this chapter requires further analyses, however they tentatively point towards productivity enhancing benefits of transportation and additionally reveal a large degree of heterogeneity of this effect.

Overall, the combination of those two settings for the analyses allowed for the investigation of two important notions: (1) Is there evidence to support the hypothesis of positive and diminishing returns to highway infrastructure? and (2) Do marginal changes in highway infrastructure foster spatial economic convergence, or push the economy towards geographic concentration? The combined results of Chapters 4 to 6 both provide evidence for diminishing returns to highway infrastructure. The analyses relying on Colombian data provide noticeably larger estimates than equivalent ones for the developed world, thus suggesting highway infrastructure investments have larger economic benefits in countries with sparse highway networks. Further, within the work with German data, analyses comparing the TFP effects of highway infrastructure within districts with relatively high and low highway densities confirm this notion. With regards to hypothesis (2), regional estimations throughout Chapter 4 and 5 reveal that highway infrastructure expansions resulted in a push towards a concentrated economy, by particularly benefitting firms in dense regions. For the analyses of German data however, the relatively largest benefits from transportation infrastructure are found for firms located in rural regions. While this might appear contradictory, these two separate findings can be explained by one underlying rationale. In cases where transportation infrastructure is relatively sparse, and thus transportation costs relatively high, reductions in transportation costs will push the economy towards higher levels of concentration. However, in cases where transportation infrastructure is already dense, expansions of the highway network increase the accessibility of sub-
urban and rural regions, and thus allowing firms to circumvent the high urban costs by (re-)locating to well-connected suburban and rural districts. Thus concluding, low absolute levels of highway density are often accompanied by high marginal effects on the economy, however these will often also be accompanied by lower urban costs where benefits of locating in dense areas outweigh negative congestion effects. This will lead to a push towards geographic economic convergence. At absolute higher levels of highway density, marginal changes are expected to be lower, but given that low levels of transportation costs are also associated with a concentrated economy, further highway expansions within countries with high levels of highway densities can also lead to relocations of firms to suburban and rural district to circumvent the high costs associated with urban locations.

III Research Contributions

The analyses contained in this thesis aim to complement the existing literature through the following:

1. The provision of investigations relying on firm-level data. The majority of studies investigating the role of infrastructure for various economic variables predominantly rely on aggregate economic information. While this provides an indicator for the overall effect, it does not allow to draw any conclusions as to the distribution of this effect across smaller disaggregate units. The use of firm-level data hence allows to investigate the effect of transportation in more detail and across smaller economic and geographic units.

2. The methodological investigation of the validity of pseudo-panels. The absence of specific required data forms often limits the scope and scale of empirical investigations. In this work, I test the validity of the pseudo-panel methodology in the context of firm-data. The results indicate that pseudo-
panels offer a viable alternative for analyses in the absence of true panel data. This investigation further highlights the relative suitability of different panel estimation methods to be used to analyse pseudo-panels.

3. The quantification of the economic effects of transportation infrastructure for a developing country. The above named absence of suitable data often results in the absence of quantifiable effects for developing countries. However, given that developing and developed countries differ on a wide range of economic, social and political factors, it cannot be assumed that effects identified for developed countries generally similarly hold for developing countries. It is therefore of crucial importance to conduct separate analyses for developing countries to quantify the relationship between infrastructure and economic factors in this context. I provide an example of this.

4. The identification of the effects of transportation and its geographical spillovers for TFP. I construct separate highway variables to highlight the effects of both access to the immediate highway density located within the firm's own districts, those highway infrastructures located within relative close proximity and those situated farther away on the performance of firms. I identify that the different highway measures affect the firm's productivity.

5. The examination of the spatial heterogeneity. I further contribute to the existing literature by providing insight into the spatial heterogeneity of the economic effects of transportation infrastructure and its disparities across distinct economies.

IV Policy Implications

The analyses conducted in this work, can be summarised into three main policy implications which are discussed in following paragraphs.
Firstly, the relatively large magnitudes identified for the economic effects of transportation in developing countries highlight the crucial importance of continued investment in the physical transportation infrastructure of developing countries.

Secondly, the results reveal a large degree of spatial heterogeneity which shows that transportation infrastructure alone does not automatically result in a trend of spatial economic convergence but its economic effects may rather predominantly accrue to those regions already exhibiting relatively stronger economies, and thus aiding spatial economic concentration. If a policy is targeted towards economic convergence within a country, then it is of high importance that infrastructure investments are accompanied by further economic policies targeting the country’s economically lagging regions. If transportation infrastructure investments are not part of a wider economic policy bundle, then transportation infrastructure can benefit some regions at the expense of other and result in exacerbated spatial inequality.

Thirdly, the construction of additional highway kilometres alone is not sufficient to generate large productivity increase for firms. While the results of the preceding chapter show that transportation infrastructure generally benefits a firm’s productivity, they also show the importance of additional factors influencing productivity where the largest benefits are derived from the existence of skilled workers. Hence, improvements in transportation do overall affect a firm’s performance positively, however additional policies ensuring the availability and access to high skilled labour, for example through labour market policies, are important to lead to a significant increase in the firm’s productivity parameter.
V Directions for Future Research

The economic investigations conducted for this dissertation adds to the existent literature of this field, but further also indicate directions for future research.

Foremost, future research should strengthen the robustness of the results of Chapter 6 to identify consistent economic effects of transportation networks for firm-level productivity.

Further, while it is generally established that transportation infrastructure is beneficial for economic development, this relationship should be investigated in further detail to highlight the exact channels through which transportation infrastructure affects the economic performance of firms. This direction of future research investigations could examine the relative importance of transportation for the transportation of goods and people for the firm’s performance to highlight the underlying factors resulting in the positive economic effect of transportation infrastructure.

Additional research would also be required to investigate the substitutability and complementarity of different transport modes for the firm’s productivity levels and further economic parameters. This work only employs information on roads, however it can be hypothesised that alternative transport modes also influence firms. Hence, this should be analysed in further detail.

Moreover, the research of this thesis focuses on the economic effects of transportation on output and productivity, however it would be of further interest to investigate the effect of transportation networks on a firm’s levels of exports and imports.
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Conference Presentations

The work of this thesis has been presented, in full or in parts, at the following conferences:

**hEART** - 2nd Symposium of the European Association for Research in Transportation, KTH Stockholm/SE (2013)


**TRB** - 95th Annual Meeting of the Transportation Research Board, Washington D.C./USA (2016)

**ERSA/UEA** - 6th European Meeting of the Urban Economics Association at the 56th European Regional Science Association Congress, Vienna/AT (2016)
Appendix
Appendix A

A1. Additional Descriptive Statistics

The below Table A1 provides additional descriptive statistics of factors employed for this work. The average number of cohorts, firms and employees lists the number of industry-region cohorts, the average number of firms and employees averaged to the regional level across all years employed for the analysis. The average highway growth shows the average growth of the regional highway stock, average geographic road density growth lists the average growth of highway kilometres per 100 sq. kilometres and the average population weighted road density growth measures the average growth of highway kilometres per 100,000 population in each region, all in their natural logarithms, across the years employed for this study.
<table>
<thead>
<tr>
<th>Departamento</th>
<th>Average Number of Cohorts</th>
<th>Average Number of Firms</th>
<th>Average Number of Employees</th>
<th>Highway Growth</th>
<th>Geographic Road Density</th>
<th>Population Weighted Road Density Growth</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antioquia</td>
<td>49.13</td>
<td>1.460.85</td>
<td>82.169.88</td>
<td>7.33</td>
<td>2.39</td>
<td>0.027</td>
<td>12.20</td>
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<td>Atlántico</td>
<td>30.82</td>
<td>360.96</td>
<td>17.191.45</td>
<td>5.48</td>
<td>8.00</td>
<td>0.011</td>
<td>7.66</td>
</tr>
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<td>Bogotá, D.C.</td>
<td>54.63</td>
<td>2.653.63</td>
<td>117.247.6</td>
<td>6.69</td>
<td>3.32</td>
<td>0.009</td>
<td>13.57</td>
</tr>
<tr>
<td>Bolívar</td>
<td>16.86</td>
<td>120.37</td>
<td>6.326.60</td>
<td>6.21</td>
<td>1.93</td>
<td>0.027</td>
<td>4.18</td>
</tr>
<tr>
<td>Boyacá</td>
<td>7.48</td>
<td>57.62</td>
<td>4.200.42</td>
<td>6.94</td>
<td>4.49</td>
<td>0.083</td>
<td>1.64</td>
</tr>
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<td>Caldas</td>
<td>21.84</td>
<td>172.02</td>
<td>6.403.30</td>
<td>5.73</td>
<td>3.91</td>
<td>0.032</td>
<td>5.39</td>
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<tr>
<td>Caquetá</td>
<td>1.00</td>
<td>4.10</td>
<td>69.4</td>
<td>6.08</td>
<td>0.49</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>Cauca</td>
<td>16.32</td>
<td>103.54</td>
<td>6.072.59</td>
<td>7.21</td>
<td>4.60</td>
<td>0.11</td>
<td>4.03</td>
</tr>
<tr>
<td>Cesar</td>
<td>5.55</td>
<td>30.84</td>
<td>1.616.64</td>
<td>6.48</td>
<td>2.91</td>
<td>0.074</td>
<td>1.37</td>
</tr>
<tr>
<td>Córdoba</td>
<td>5.63</td>
<td>29.69</td>
<td>1.778.96</td>
<td>6.38</td>
<td>2.36</td>
<td>0.040</td>
<td>1.34</td>
</tr>
<tr>
<td>Cundinamarca</td>
<td>27.53</td>
<td>329.67</td>
<td>25.517.26</td>
<td>6.69</td>
<td>3.32</td>
<td>0.009</td>
<td>6.79</td>
</tr>
<tr>
<td>Chocó</td>
<td>1.00</td>
<td>3.00</td>
<td>31.50</td>
<td>5.62</td>
<td>0.59</td>
<td>0.063</td>
<td>0.05</td>
</tr>
<tr>
<td>Huila</td>
<td>9.22</td>
<td>50.68</td>
<td>816.28</td>
<td>6.74</td>
<td>4.25</td>
<td>0.084</td>
<td>2.29</td>
</tr>
<tr>
<td>La Guajira</td>
<td>1.18</td>
<td>3.55</td>
<td>20.55</td>
<td>5.87</td>
<td>1.70</td>
<td>0.054</td>
<td>0.27</td>
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<td>Magdalena</td>
<td>8.32</td>
<td>50.30</td>
<td>1.660.90</td>
<td>6.45</td>
<td>2.74</td>
<td>0.055</td>
<td>2.04</td>
</tr>
<tr>
<td>Meta</td>
<td>5.44</td>
<td>48.11</td>
<td>1.937.63</td>
<td>6.90</td>
<td>1.16</td>
<td>0.13</td>
<td>1.34</td>
</tr>
<tr>
<td>Nariño</td>
<td>8.14</td>
<td>57.36</td>
<td>1.039.94</td>
<td>6.65</td>
<td>2.36</td>
<td>0.050</td>
<td>2.01</td>
</tr>
<tr>
<td>Norte de Santander</td>
<td>14.19</td>
<td>146.99</td>
<td>2.550.68</td>
<td>6.76</td>
<td>3.85</td>
<td>0.069</td>
<td>3.50</td>
</tr>
<tr>
<td>Quindío</td>
<td>8.08</td>
<td>61.85</td>
<td>621.39</td>
<td>5.11</td>
<td>9.03</td>
<td>0.031</td>
<td>1.99</td>
</tr>
<tr>
<td>Risaralda</td>
<td>23.79</td>
<td>182.82</td>
<td>6.832.83</td>
<td>5.71</td>
<td>7.27</td>
<td>0.034</td>
<td>5.89</td>
</tr>
<tr>
<td>Santander</td>
<td>30.35</td>
<td>363.19</td>
<td>8.677.85</td>
<td>7.11</td>
<td>4.00</td>
<td>0.063</td>
<td>7.53</td>
</tr>
<tr>
<td>Sucre</td>
<td>2.57</td>
<td>14.00</td>
<td>455.61</td>
<td>5.62</td>
<td>2.59</td>
<td>0.036</td>
<td>0.57</td>
</tr>
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<td>Tolima</td>
<td>11.07</td>
<td>120.40</td>
<td>3.204.84</td>
<td>6.33</td>
<td>2.38</td>
<td>0.041</td>
<td>2.68</td>
</tr>
<tr>
<td>Valle del Cauca</td>
<td>45.72</td>
<td>1,064.56</td>
<td>48.610.51</td>
<td>6.52</td>
<td>3.05</td>
<td>0.017</td>
<td>11.36</td>
</tr>
<tr>
<td>Casanara</td>
<td>2.00</td>
<td>10.00</td>
<td>228.00</td>
<td>6.65</td>
<td>1.73</td>
<td>0.241</td>
<td>0.05</td>
</tr>
</tbody>
</table>
A2. The Lag Selection for the Econometric Specification of Chapter 4

While it is often hypothesised that within a production function context a firm’s contemporaneous output is influenced by its past realisations, the empirical validity of this hypothesis for the used data requires an evaluation. The empirical analysis of the aforementioned hypothesis is oriented along two criteria: the identification of (1) a possible auto-correlated structure and (2) the suitable amounts of lags to be included in the estimations. Given that the employed pseudo-panel is an unbalanced data set, only a Fisher-type unit test in combination with either the augmented Dickey-Fuller or alternatively with the Phillips-Perron unit-root test can provide the appropriate statistical parameters required. The underlying hypotheses of this test are a null hypothesis of all panels containing unit-roots and the alternative hypothesis that at least one panel exhibits a unit-root. However, given that this test requires $T \rightarrow \infty$, but the data only contains 10 years, a Fisher-type test in either combination could not compute the required statistics for a large number of the time-series included. Instead both the Levin-Lin-Chu and the Im-Pesaran-Shi tests combined with the augmented Dickey-Fuller regression have been used to analyse the unit-root behaviour of the data. The determination of the suitable lags was identified via the Akaike and Bayesian information criteria (AIC and BIC respectively). Both of these tests follow the null hypothesis of all included time-series exhibiting a unit-root, but while the Levin-Lin-Chu test has an alternative hypothesis of all time series being stationary, the Im-Pesaran-Shi test uses a less stricter version of the alternative hypothesis where some, but not necessarily all included time-series have unit-roots. Both tests can only be conducted on a balanced panel set, thus cohort units where data was not available for all years had to be dropped for the conduction of these. In total, this resulted in a loss of 583 observations which is equivalent to 14 per cent of the total data.
Table A2: Unit-Root tests conducted

<table>
<thead>
<tr>
<th>Employed Unit-Root Test</th>
<th>Statistic</th>
<th>p-value</th>
<th>Determined Optimal Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levin-Lin-Chu</td>
<td>Adjusted t</td>
<td>-17.82</td>
<td>0.000</td>
</tr>
<tr>
<td>Levin-Lin-Chu</td>
<td>Adjusted t</td>
<td>-15.839</td>
<td>0.000</td>
</tr>
<tr>
<td>Im-Pesaran-Shin</td>
<td>$W_{t-bar}$</td>
<td>-2.37</td>
<td>0.009</td>
</tr>
<tr>
<td>Im-Pesaran-Shin</td>
<td>$W_{t-bar}$</td>
<td>-1.61</td>
<td>0.054</td>
</tr>
</tbody>
</table>

set. Furthermore, to control for a possible cross-sectional correlation biasing the estimation, cross-sectional means were removed for the Levin-Lin-Chu and the Im-Pesaran-Shin tests. The results of both tests are listed in Table A2 below.

Overall, both the Levin-Lin-Chu and the Im-Pesaran-Shin unit-root tests allow to reject the null hypothesis at the 1 per cent significance level, thus indicating that none or not all included time-series exhibit unit-roots. Furthermore, the closest integer to the optimal lag length as determined by the AIC and BIC is 1, thus providing support for the assumed AR(1) structure of the model.

A3. Confidence Interval Presentations Relating to Table 4.3

The discussion outlined in Section 4.1 of Chapter 4 and the estimation results provided in Table 4.3 do not indicate a clear direction of the effect of contemporaneous highways on firms’ output growth. However, the auto-correlation in the error structure of the underlying model specification would predict that either the contemporaneous or lagged version of a variable is negative. While this is clear in the estimated coefficients of all other input factors included, for the variable relating to highways, only the lagged version of it implies a significant and positive effect which is relatively consistent throughout the estimation techniques used.
Thus, it would follow that the effect of contemporaneous highways on the dependent variable must be negative in order for the estimates to be in line with the econometric specification assumed. The point estimates identified for contemporaneous highways via POLS (columns (1) and (2) of Table 4.3) have the expected negative sign, however, the point estimates of Fixed Effects, Difference and System GMM (columns (3) to (5)) are neither negative nor significant. Given that these estimates are not significant, it cannot be assumed beyond doubt that the true point estimates are positive, hence they may indeed by negative thus fitting the econometric specification. Graph A1 graphically presents the range of possible estimates of contemporaneous highways across the models used in columns (2) to (4) in Table 4.3; a possible interpretation of this effect is provided in Section 4.1 of Chapter 4.
Appendix B

B1. Graphical Presentation of Regional Highway Growth

The graph B1 illustrates the average highway growth, in the logarithmic form, for the regional subsamples defined in Subsection 5.3.

![Figure B1: Average Regional Highway Growth](image-url)
B2. Graphical Presentation of the Geographical Distribution of Heavy Industries

Following the discussion of the regional distribution of heavy industries across Colombia, the below graph provides a graphical presentation of this across the sample of peripheral, coastal and central regions.

Figure B2: Geographic Distributions of Heavy Industries
Source: Author’s own calculation based on aggregated plant information from the Colombian Manufacturing Census conducted by the Colombian National Statistics Office (Departamento Administrativo Nacional de Estadística/DANE)
Appendix C

C1. Industrial Class Abbreviations

The below information lists the full details and abbreviations for industrial classifications used in Chapter 6.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGRI.</td>
<td>Agriculture, Forestry and Fishery</td>
</tr>
<tr>
<td>CO.-PE.</td>
<td>Manufacture of Coke and Petroleum Products; Mining</td>
</tr>
<tr>
<td>FOOD</td>
<td>Manufacture of Food, Beverages and Tobacco</td>
</tr>
<tr>
<td>TEXT.</td>
<td>Manufacture of Textiles, Leather and Wearing Apparel</td>
</tr>
<tr>
<td>WOOD</td>
<td>Manufacture of Wood and Paper Products; Printing</td>
</tr>
<tr>
<td>CHEM.</td>
<td>Manufacture of Chemical, Pharmaceutical and Plastic Products</td>
</tr>
<tr>
<td>MIN.</td>
<td>Manufacture of Non-Metallic Mineral Products</td>
</tr>
<tr>
<td>MET.</td>
<td>Manufacture of Basic and Fabricated Metals</td>
</tr>
<tr>
<td>ELEC.</td>
<td>Manufacture of Electric, Electronic and Optical Equipment</td>
</tr>
<tr>
<td>MACH.</td>
<td>Manufacture of Machinery and Equipment</td>
</tr>
<tr>
<td>VEH.</td>
<td>Manufacture of Vehicles and Transport Equipment</td>
</tr>
<tr>
<td>N.E.C.</td>
<td>Manufacture n.e.c.</td>
</tr>
<tr>
<td>ENERGY</td>
<td>Energy and Water Supply</td>
</tr>
<tr>
<td>CON.</td>
<td>Construction</td>
</tr>
<tr>
<td>TRADE</td>
<td>Retail and Wholesale Trade</td>
</tr>
<tr>
<td>HOSP.</td>
<td>Hospitality</td>
</tr>
</tbody>
</table>
C2. Graphical Presentations of Highway Density Variables

Capturing Direct Access and Wider Access

The analyses of Chapter 6 rely on three separate variables capturing the a district’s own highway density and those within its direct vicinity and further away locations. As graphical presentations of the first variable are presented in Chapter 6, for completeness graphical presentations of the latter two variables are provided below.

Figure C1: Average Direct Access to Highway Density (left) and Its Relative Changes (right)

Source: Author’s calculation based on information of the regional statistics offices, regional transportation ministries and the Federal Agency of Cartography and Geodesy

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Figure C2: Average Wider Access to Highway Density (left) and Its Relative Changes (right)

Source: Author’s calculation based on information of the regional statistics offices, regional transportation ministries and the Federal Agency of Cartography and Geodesy
C3. Digitised Historical Maps and 2014 NUTS3 Regions

Based on the information extracted from Figure 6.3 and 6.4, Figure C3, C4 and C5 show the historical 1938 Autobahn, 1938 Reichssstrassen and 1899 Rail networks over 2014 boundaries of NUTS3 districts.

Figure C3: The 1938 Highway Network projected across current NUTS3 Regions
Source: Author’s own calculation based on information in the Reichsautobahnatlas (1938) published by the Meinhold-Karten-GmbH - Dresden
Figure C4: The 1938 Reichstrassen Network projected across current NUTS3 Regions
Source: Author’s own calculation based on information in the Reichsautobahnatlas (1938) published by the Meinhold-Karten-GmbH - Dresden

Figure C5: The 1899 Rail Network of the German Zollverein
Source: Author’s own calculation based on information of the Stahlstich und Verlag v. F. Sporer, Nürnberg
C4. Additional Geographical Variables

As additional geographical controls, variables based on the geographical slope and the ruggedness index have been computed. The calculation of the slope variable is based on the comparison of a location’s pixel value relative to the pixel values of its eight surrounding neighbours. This allows to generate a measure of the steepness. A graphical presentation is provided in Figure A4. For the subsequent use of this variable for the regression, district average have been computed.

The calculation of the Ruggedness Index follows Riley et al. (1999). The index is based on elevation differences for every 3 by 3 pixel grid, so that this variable captures the change in elevation of within locations. Subsequently, the estimated index of a location is categorised into seven categories of ruggedness ranging from levelled to extremely rugged. The calculated Ruggedness Index is represented in Figure A5. Similar to the variable based on the geographical slope, district averages of the ruggedness index have been calculated to be used throughout the regressions.
Figure C6: The Geographical Slope
Source: Author’s own calculation based on data from the German Federal Ministry of Cartography and Geodesy/Bundesamt für Kartographie und Geodäsie

Figure C7: The Geographical Ruggedness Index
Source: Author’s own calculation based on data from the German Federal Ministry of Cartography and Geodesy/Bundesamt für Kartographie und Geodäsie
C5. First-Step IV Results for Highway Spillover Variables

In Section 6.5.1 of Chapter 6, the First Stage IV results for the highway infrastructure variable measuring a district’s own highway density are provided. To complete the analysis of the identification of the most suitable instrumental variable relying on historical transportation networks, this subsection adds to the aforementioned subsection by providing the First Stage IV results for the variables of Highway Density - Direct Access and Highway Density - Wider Access.

Table C2: First Stage IV Regressions - Highway Density - Direct Access

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>0.111*** (0.024)</td>
<td>0.060*** (0.024)</td>
<td>0.065*** (0.023)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access - segments in construction)</td>
<td>-0.052 (0.034)</td>
<td></td>
<td>-0.084*** (0.031)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access - segments planned)</td>
<td>0.108*** (0.036)</td>
<td></td>
<td></td>
<td>0.066*** (0.029)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Reichsstrassen Density - Direct Access)</td>
<td>0.336*** (0.075)</td>
<td></td>
<td></td>
<td></td>
<td>0.076*** (0.028)</td>
<td></td>
</tr>
<tr>
<td>Ln(Railway Density - Direct Access)</td>
<td>0.108*** (0.030)</td>
<td>0.096*** (0.029)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of Observations: 46,336
Adjusted R²: 0.944

In the above the following additional controls have been included: Year, region and 3 digit industrial sector fixed effects, firms productivity (in log), the average average wages index and wage values (in log), population density - direct access In log), distance for three regional types and for the existence of highway or railway within a district in 1938, 1899 and 1999 - 2014. **, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors corrected for clustering at the district level are provided in parenthesis.

Table C3: First Stage IV Regressions - Highway Density - Wider Access

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>-0.043 (0.031)</td>
<td>-0.022 (0.025)</td>
<td></td>
<td>-0.066*** (0.023)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access - segments in construction)</td>
<td>0.022*** (0.019)</td>
<td></td>
<td></td>
<td>-0.052 (0.018)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access - segments planned)</td>
<td>0.120*** (0.022)</td>
<td></td>
<td></td>
<td>0.065*** (0.022)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Reichsstrassen Density - Wider Access)</td>
<td>0.246*** (0.028)</td>
<td></td>
<td></td>
<td></td>
<td>-0.057*** (0.033)</td>
<td></td>
</tr>
<tr>
<td>Ln(Railway Density - Wider Access)</td>
<td>0.108*** (0.029)</td>
<td>0.060*** (0.030)</td>
<td></td>
<td></td>
<td>0.045*** (0.033)</td>
<td></td>
</tr>
</tbody>
</table>

Number of Observations: 46,336
Adjusted R²: 0.944

In the above the following additional controls have been included: Year, region and 3 digit industrial sector fixed effects, firms productivity (in log), the average average wages index and wage values (in log), population density - direct access In log), distance for three regional types and for the existence of highway or railway within a district in 1938, 1899 and 1999 - 2014. **, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors corrected for clustering at the district level are provided in parenthesis.
C6. Modelling Transportation as an Explicit Production Function Input

The analyses of Chapter 6 focus solely on investigating the effects of highways on the TFP of firms across Germany. This methodological approach differs substantially from the one employed in Chapters 4 and 5 to identify the effects of highways as a direct input factor into firm’s production function. Thus, to further the analyses of Chapter 6, and to provide a nexus of the analyses of both approaches, I estimate models following the methodology of Chapters 4 and 5 and apply these to the data used in Chapter 6.

Table C4 is a replica of Table 4.3, columns (2) to (5), for the sample of German establishments, however parallel to Tables 4.4 to 4.6, in Tables 5.2 and 5.3, the log of GDP growth has been added to the regression as an additional control variable. Similar to the results of Table 4.3, there exists a large disparity in the estimated coefficients of the lagged dependent variable. POLS provides the largest estimate, Fixed Effects the lowest and both the GMM estimators provide an estimate that lies in between the two aforementioned. Overall, the magnitude of the effect of lagged log output on current output growth appears to be lower for the German than for the Colombian sample, particularly those that are indicated by the GMM estimates. The reported capital coefficients are particularly low, and while this provides a stark contrast to those reported for capital in Table 4.3, they are in line with those reported in Table 6.7 for the same underlying sample using OLS. Similar low estimates for the capital coefficient in this context of this data have also been previously reported (see for example Ehrl, 2013), hence while this provides a significant disparity to the results of Table 4.3, it is not unexpected for this sample. A different pattern is provided for the labour variable, where all of the estimated coefficients are substantially larger than those of Table 4.3. Further,
they are reported to be both positive in their contemporaneous and lagged versions, and while the reported results of Table 4.3 in some cases exhibited lower levels of significance, in this sample they are highly significant throughout all estimation methods. This could be indicative of a large heterogeneity in the structuring of the input factors within a firm’s production process, and also for large differences in the labour market of Germany and Colombia. The results of Table C4 provide a compound intermediate inputs variable, encompassing, amongst others, both energy and intermediate inputs if purchased. Given that it was possible to measure intermediate inputs and energy separately in the Colombian dataset, the results of this variable cannot be directly compared. However, the estimated coefficients for the intermediate inputs, similarly to those identified for materials in Table 4.3, exhibit the largest magnitude and thus the largest relative importance for the firm’s production. However, while this applies to the materials’ coefficient of the contemporaneous period in Table 4.3, for the German data sample of Table C4, this emerges for the estimates for the lagged period. Overall, there exists one noteworthy disparity for the estimated coefficients of the standard production function input factors across Tables 4.3 and C4: While the results of Table 4.3 are mostly in line with the model’s prediction of positive and negative estimates, those provided in this section, are mostly positive throughout both periods; an exception is capital, where all estimates for the lagged period are reported to be negative. The highway variable used for the estimations of Table C4 is directly equivalent to the one used in Table 4.3, and despite this direct comparability in the construction of this variable, the results indicate a significant disparity in the estimated results. The results provided in Table 4.3 indicate a significant importance of highways for the firm’s production, although exclusively in their lagged version. The results of Table C4 however do not provide any support for this notion, neither in their contemporaneous nor lagged version. Furthermore, the
magnitude of these coefficients is significantly lower than those reported in Table 4.3. Similar to the results of Chapters 4 and 5, the Hansen statistic fails to provide accurate information\textsuperscript{67}. Furthermore, the $R^2$ for the Fixed Effects estimation and the AR2 statistics of the Difference GMM estimation of Table C4 are significantly below the ones reported in Table 4.3.

Table C4: Direct Output Effects of Highways

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)\textsubscript{t}</th>
<th>POLS</th>
<th>Fixed Effects</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Output)\textsubscript{t-1}</td>
<td>0.590*** (0.009)</td>
<td>0.239*** (0.013)</td>
<td>0.178*** (0.013)</td>
<td>0.244*** (0.010)</td>
</tr>
<tr>
<td>Ln(Capital)\textsubscript{t}</td>
<td>0.044*** (0.004)</td>
<td>0.024*** (0.005)</td>
<td>-0.025** (0.012)</td>
<td>0.045*** (0.005)</td>
</tr>
<tr>
<td>Ln(Capital)\textsubscript{t-1}</td>
<td>-0.028*** (0.004)</td>
<td>-0.022*** (0.004)</td>
<td>-0.012** (0.005)</td>
<td>-0.027*** (0.004)</td>
</tr>
<tr>
<td>Ln(Labour)\textsubscript{t}</td>
<td>0.205*** (0.013)</td>
<td>0.178*** (0.013)</td>
<td>0.124*** (0.038)</td>
<td>0.165*** (0.013)</td>
</tr>
<tr>
<td>Ln(Labour)\textsubscript{t-1}</td>
<td>-0.088*** (0.013)</td>
<td>0.118*** (0.014)</td>
<td>0.156*** (0.013)</td>
<td>0.097*** (0.014)</td>
</tr>
<tr>
<td>Ln(Interm. Inputs)\textsubscript{t}</td>
<td>0.011** (0.005)</td>
<td>0.018*** (0.005)</td>
<td>-0.018 (0.014)</td>
<td>0.084*** (0.005)</td>
</tr>
<tr>
<td>Ln(Interm. Inputs)\textsubscript{t-1}</td>
<td>0.276*** (0.007)</td>
<td>0.368*** (0.008)</td>
<td>0.391*** (0.010)</td>
<td>0.413*** (0.008)</td>
</tr>
<tr>
<td>Ln(Highways - km Length)\textsubscript{t}</td>
<td>-0.005(0.008)</td>
<td>-0.00001(0.006)</td>
<td>0.029(0.024)</td>
<td>-0.013(0.010)</td>
</tr>
<tr>
<td>Ln(Highways - km Length)\textsubscript{t-1}</td>
<td>0.006(0.008)</td>
<td>0.003(0.006)</td>
<td>-0.008(0.007)</td>
<td>0.015(0.010)</td>
</tr>
<tr>
<td>GDP Growth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Year FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>State FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>-</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>-</td>
<td>0.040</td>
<td>0.314</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>-</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td>-</td>
<td>-</td>
<td>778</td>
<td>964</td>
</tr>
<tr>
<td>Observations</td>
<td>36,578</td>
<td>35,717</td>
<td>27,249</td>
<td>35,717</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.990</td>
<td>0.611</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(***, ***, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors corrected for clustering at the district level are provided in parenthesis)

Given that the spatial units employed in Chapters 4 and 5 differ from the one used in Chapter 6, where the latter employs NUTS3 districts and the former employs Colombian departamentos, which are more comparable to the NUTS1 definition used within the European Union, I repeat the analyses of Table C4

\textsuperscript{67}See pages 124 and 125 for a discussion.
Table C5: Direct Output Effects of Highways - Alternative Highway Variables

<table>
<thead>
<tr>
<th>Dependent Variable: Ln(Output)</th>
<th>Fixed Effects</th>
<th>Difference GMM</th>
<th>System GMM</th>
<th>Fixed Effects</th>
<th>Difference GMM</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted by sq. km</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>Ln(Output)</td>
<td>0.239***</td>
<td>0.179***</td>
<td>0.243***</td>
<td>0.239***</td>
<td>0.178***</td>
<td>0.243***</td>
</tr>
<tr>
<td>(0.013)</td>
<td>(0.013)</td>
<td>(0.010)</td>
<td>(0.013)</td>
<td>(0.013)</td>
<td>(0.011)</td>
<td>(0.010)</td>
</tr>
<tr>
<td>Ln(Capital)</td>
<td>0.024***</td>
<td>-0.025***</td>
<td>0.046***</td>
<td>0.024***</td>
<td>-0.025***</td>
<td>0.045***</td>
</tr>
<tr>
<td>(0.005)</td>
<td>(0.012)</td>
<td>(0.005)</td>
<td>(0.005)</td>
<td>(0.011)</td>
<td>(0.005)</td>
<td>(0.005)</td>
</tr>
<tr>
<td>Ln(Labour)</td>
<td>-0.022***</td>
<td>-0.012***</td>
<td>-0.027***</td>
<td>-0.022***</td>
<td>-0.012***</td>
<td>-0.027***</td>
</tr>
<tr>
<td>(0.004)</td>
<td>(0.005)</td>
<td>(0.004)</td>
<td>(0.004)</td>
<td>(0.005)</td>
<td>(0.005)</td>
<td>(0.004)</td>
</tr>
<tr>
<td>Ln(Interm. Inputs)</td>
<td>0.118***</td>
<td>0.156***</td>
<td>0.096***</td>
<td>0.118***</td>
<td>0.157***</td>
<td>0.097***</td>
</tr>
<tr>
<td>(0.014)</td>
<td>(0.013)</td>
<td>(0.014)</td>
<td>(0.013)</td>
<td>(0.013)</td>
<td>(0.038)</td>
<td>(0.014)</td>
</tr>
<tr>
<td>GDP Growth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Year FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>State FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ARI</td>
<td>-</td>
<td>0.000</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.047</td>
<td>0.316</td>
<td>-</td>
<td>0.039</td>
<td>0.325</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>1.000</td>
<td>0.000</td>
<td>-</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td>-</td>
<td>778</td>
<td>964</td>
<td>-</td>
<td>778</td>
<td>964</td>
</tr>
<tr>
<td>Observations</td>
<td>35,717</td>
<td>27,249</td>
<td>35,717</td>
<td>35,717</td>
<td>27,249</td>
<td>35,717</td>
</tr>
<tr>
<td>R²</td>
<td>0.611</td>
<td>-</td>
<td>0.611</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(*, **, *** indicate significance at the 1%, 5% and 10% level respectively. Standard errors corrected for clustering at the district level are provided in parenthesis.)

but employ highway variables that incorporate the spatial dimension. Similar to Table 4.5, these are highway densities as weighted by the geographic size and by the population of the respective geographic unit. Table C5 provides the results employing the geographic weighing highway density variable in columns (1) to (3) and those employing the population weighted version in columns (4) to (6).

The results of Table C5 are strongly in line with those reported in Table C4, and similarly exhibit a disparity with the equivalent estimates reported for the Colombian sample in Table 4.5. The reported estimates for the standard input factors are predominantly similar, or in some cases directly equal, to those of Table C4 for the same estimation method. Additionally, despite the change in highway variables employed, the results of Table C5 do not indicate that highway infrastructure affects the firm’s production. Hence, in stark disparity to the results investigating the direct effects of highways on firm’s productions, the results of both Tables C4 and C5 do not support the notion that within the German data
sample, highway infrastructure enters firms’ productions directly. Further, the results do not indicate that this is driven by the selection of the highway variable employed.

Table C6: Direct Output Effects of Highways - Manufacturing Subsample

<table>
<thead>
<tr>
<th>Highway Variable</th>
<th>Kilometre Length Density - weighted by sq. km Density - weighted by population</th>
<th>Fixed Effects</th>
<th>System GMM</th>
<th>Fixed Effects</th>
<th>System GMM</th>
<th>Fixed Effects</th>
<th>System GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent Variable: Ln(Output)</td>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>Ln(Output)</td>
<td>0.268*** (0.019)</td>
<td></td>
<td></td>
<td>0.262*** (0.015)</td>
<td></td>
<td>0.260*** (0.015)</td>
<td></td>
</tr>
<tr>
<td>Ln(Capital)</td>
<td>0.025*** (0.007)</td>
<td>0.052*** (0.007)</td>
<td></td>
<td>0.025*** (0.007)</td>
<td></td>
<td>0.025*** (0.007)</td>
<td></td>
</tr>
<tr>
<td>Ln(Labour)</td>
<td>-0.020*** (0.006)</td>
<td>-0.032*** (0.006)</td>
<td></td>
<td>-0.020*** (0.006)</td>
<td></td>
<td>-0.032*** (0.006)</td>
<td></td>
</tr>
<tr>
<td>Ln(Labour)</td>
<td>0.204*** (0.019)</td>
<td>0.159*** (0.018)</td>
<td></td>
<td>0.204*** (0.019)</td>
<td></td>
<td>0.159*** (0.018)</td>
<td>0.204*** (0.019)</td>
</tr>
<tr>
<td>Ln(Labour)</td>
<td>0.098*** (0.0022)</td>
<td>0.079*** (0.019)</td>
<td></td>
<td>0.098*** (0.022)</td>
<td></td>
<td>0.080*** (0.019)</td>
<td>0.098*** (0.022)</td>
</tr>
<tr>
<td>Ln(Interm. Inputs)</td>
<td>0.024*** (0.006)</td>
<td>0.085*** (0.007)</td>
<td></td>
<td>0.024*** (0.006)</td>
<td></td>
<td>0.085*** (0.007)</td>
<td>0.024*** (0.006)</td>
</tr>
<tr>
<td>Ln(Interm. Inputs)</td>
<td>0.036*** (0.011)</td>
<td>0.036*** (0.012)</td>
<td></td>
<td>0.036*** (0.011)</td>
<td></td>
<td>0.037*** (0.012)</td>
<td>0.036*** (0.011)</td>
</tr>
<tr>
<td>Ln(Sector)</td>
<td>0.001(0.008)</td>
<td>-0.006(0.013)</td>
<td></td>
<td>0.004(0.008)</td>
<td></td>
<td>-0.001(0.012)</td>
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</tr>
<tr>
<td>Ln(Sector)</td>
<td>0.001(0.011)</td>
<td>0.010(0.012)</td>
<td></td>
<td>0.002(0.007)</td>
<td>0.010(0.012)</td>
<td>0.003(0.007)</td>
<td>0.010(0.017)</td>
</tr>
<tr>
<td>GDP Growth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Year FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>State FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<td>Y</td>
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<tr>
<td>Industrial FE</td>
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<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AR1</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>AR2</td>
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<td>0.072</td>
<td>-</td>
<td>0.076</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>Number of Instruments</td>
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<td>922</td>
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</tr>
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<td>20,051</td>
<td>20,051</td>
<td>20,051</td>
<td>20,051</td>
<td>20,051</td>
<td>20,051</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.641</td>
<td>-</td>
<td>0.641</td>
<td>-</td>
<td>0.641</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

(***, **, * indicate significance at the 1%, 5% and 10% level respectively. Standard errors corrected for clustering at the district level are provided in parentheses)

Another factor that might affect the comparability of the results based on German establishment data with those using Colombian manufacturing data, stems from the industrial composition of the underlying data. The German establishment data employed throughout the thesis includes establishments within the industries of agriculture, forestry and fishery, manufacturing, mining, energy generation and water supply, construction, retail and wholesale trade, and hospitality, in contrast to the Colombian data set used in this thesis which solely encompasses plants within the manufacturing sector. The results presented in Table 4.6 highlight the heterogeneity of the effects of transportation solely within the manufacturing sample, thus it cannot be assumed that the results obtained hold independently of the industrial composition of the data used. Hence, to invest-
igate whether the estimation results of Tables C4 and C5, and their disparities with Tables 4.3 and 4.5, are driven by the industries included in the underlying data set, I repeat the analyses of Tables C4 and C5 for the subsample of manufacturing industries included within the German dataset employed throughout this dissertation. Table C6 reports the results. As the reported results predominately serve as comparison estimates to those reported in C4 and C5, I limit the analysis to the Fixed Effects and System GMM estimation methods. While both the test statistics for the Difference and System GMM methodologies in Tables C4 and C5 do not indicate that either of these estimators can be assumed to outperform the other, for the sole reason of a better comparability of these results with those of Chapter 4, the GMM results listed in Table C6 are derived with the System GMM estimator. The listed results of Table C6 are for the majority in line with those of Tables C5 and C4, both in magnitude and significance. Small deviations can be noted for the variables of the lagged dependent variable and the lagged labour variable, where both of their coefficients are estimated to be slightly larger in magnitude than those of the previous two tables for the whole sample. Furthermore, similar to those results listed in the previous two tables, the coefficients estimated for the highway variables are small in magnitude and insignificant throughout the estimation methods and variations of the variable employed. Additionally, the $R^2$ of the Fixed Effects estimations and the AR2 of the System GMM versions are significantly lower than those reported in Tables 4.3 and 4.5. In summary, while the results only encompassing German manufacturing establishments indicate some differences to those reported for the whole sample, these are predominantly limited to the estimates of the lagged dependent and lagged labour variables. No significant changes in the magnitude or significance of the highway variable can be observed.

Overall, the results of this section allow for a more direct comparison of the res-
ults employing the German establishment data to those identified for the Colombian manufacturing dataset used throughout this thesis. Throughout the production function estimations of this section, disparities in both magnitudes and significance levels can be observed throughout all estimated coefficients reported, in particular for the highway variables. The results of Chapters 4 and 5 point towards the crucial importance of the highway infrastructure for a firm’s output growth, the results of this section however do not provide any support for this notion across German establishments. Furthermore, given the results provided in Chapter 6, Section 5 for the effects of transportation on a firm’s productivity parameter, it can be concluded that the effects of transportation on a firm’s performance are rather driven through their productivity than through a direct effect on output growth for German firms.
C7. Estimation Results for Urban, Suburban and Rural Districts across East and West Germany

In addition to the results obtained in Subsections 5.4 and 5.5 investigating the firm-level TFP effects stemming from highway density across districts located in the East and West of Germany, and across districts classified as urban, suburban and rural, the estimation results reported in this section provide a combination of the aforementioned by re-estimating the estimations of Subsections 5.4 and 5.5, for urban, suburban and rural districts separately for districts of East and West Germany. Tables C7 and C8 provide results for West German districts, and Tables C9 and C10 provide results for East German districts.\textsuperscript{68}

\textsuperscript{68} Due to insufficient overidentifying restrictions, no IV estimates and test statistics could be obtained for urban districts located within East Germany.
### Table C7: Second Step Productivity Estimations - Urban, Suburban and Rural Districts - West Germany

<table>
<thead>
<tr>
<th></th>
<th>Urban Districts</th>
<th>Suburban Districts</th>
<th>Rural Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Effects</td>
<td>System GMM</td>
<td>Fixed Effects</td>
</tr>
<tr>
<td>ln(Highway Density)</td>
<td>0.139(0.127)</td>
<td>0.078(0.124)</td>
<td>0.163(0.123)</td>
</tr>
<tr>
<td>ln(Highway Density - Direct Access)</td>
<td>-0.260(0.178)</td>
<td>-0.234(0.177)</td>
<td>-0.522(0.222)</td>
</tr>
<tr>
<td>ln(Highway Density - Wider Access)</td>
<td>1.250(1.342)</td>
<td>0.241(1.499)</td>
<td>1.250(1.342)</td>
</tr>
<tr>
<td>ln(Population Density)</td>
<td>-0.028(0.193)</td>
<td>0.147(0.098)</td>
<td>0.055(0.180)</td>
</tr>
<tr>
<td>ln(Population Density - Direct Access)</td>
<td>-0.524(0.471)</td>
<td>-0.456(0.477)</td>
<td>-1.077(0.739)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ARI</td>
<td>-</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>AR2</td>
<td>-</td>
<td>0.671</td>
<td>-</td>
</tr>
<tr>
<td>Hansen</td>
<td>-</td>
<td>1.000</td>
<td>-</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
<td>-</td>
<td>570</td>
<td>-</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>9,970</td>
<td>9,970</td>
<td>9,970</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.450</td>
<td>0.450</td>
<td>0.451</td>
</tr>
</tbody>
</table>

(Notes: ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis.)
Table C8: Second Step Productivity IV Estimations - Urban, Suburban and Rural Districts - West Germany

<table>
<thead>
<tr>
<th></th>
<th>Urban Districts</th>
<th>Suburban Districts</th>
<th>Rural Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV-LIML</td>
<td>IV-GMM</td>
<td>IV-2SLS</td>
</tr>
<tr>
<td>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>-0.058(0.082)</td>
<td>-0.037(0.047)</td>
<td>-0.026(0.085)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>0.296(0.176)</td>
<td>0.414* (0.239)</td>
<td>0.043(0.176)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>2.367* (2.130)</td>
<td></td>
<td>-0.746(1.608)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>0.082(0.063)</td>
<td>0.081*** (0.034)</td>
<td>0.040(0.063)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>-0.202(0.167)</td>
<td>-0.315(0.226)</td>
<td>0.019(0.152)</td>
</tr>
<tr>
<td>Ln(Population Density - Wider Access)</td>
<td>-1.424(1.957)</td>
<td>1.004(1.690)</td>
<td></td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y Y Y Y</td>
<td>Y Y Y Y</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>First Stage F-Stat</td>
<td>8.79***</td>
<td>393.05***</td>
<td>16.51***</td>
</tr>
<tr>
<td>Min. Eigenvalue Statistic</td>
<td>541.91**</td>
<td>421.59**</td>
<td>172.19**</td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>88.10***</td>
<td>48.43***</td>
<td>120.05***</td>
</tr>
<tr>
<td>Shea’s adj. partial $R^2$: Ln(Highway Density)</td>
<td>0.347</td>
<td>0.273</td>
<td>0.286</td>
</tr>
<tr>
<td>Shea’s adj. partial $R^2$: Ln(Highway Density - Direct Access)</td>
<td>0.066</td>
<td>0.386</td>
<td>0.488</td>
</tr>
<tr>
<td>Shea’s adj. partial $R^2$: Ln(Highway Density - Wider Access)</td>
<td>0.236</td>
<td>0.340</td>
<td>0.340</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>9,970</td>
<td>9,970</td>
<td>9,970</td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>0.954</td>
<td>-</td>
<td>0.954</td>
</tr>
</tbody>
</table>

Notes: ***, **, * indicate significance at the 1%, 5% and 10% level respectively. The significance of the Eigenvalues is determined according to the LIML Wald test, for 2SLS estimation the 2SLS relative bias test is used alternatively; overidentification tests used are the Anderson-Rubin statistic for IV-LIML, the Hansen’s J-statistic for IV-GMM and the SARGAN statistic for IV-2SLS estimations. Robust standard errors corrected for clustering at the district level are provided in parenthesis.
Table C9: Second Step Productivity Estimations - Urban, Suburban and Rural Districts - East Germany

<table>
<thead>
<tr>
<th></th>
<th>Urban Districts</th>
<th>Suburban Districts</th>
<th>Rural Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Effects</td>
<td>System GMM</td>
<td>Fixed Effects</td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>0.006 (0.046)</td>
<td>0.121 (0.064)</td>
<td>0.031 (0.046)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>0.140 (0.245)</td>
<td>0.301 (0.243)</td>
<td>-0.156 (0.097)</td>
</tr>
<tr>
<td>Ln(Highway Density - Wider Access)</td>
<td>10.62 (5.518)</td>
<td>-4.180 (2.586)</td>
<td>2.063 (1.418)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>-0.425 (0.543)</td>
<td>-0.193 (0.594)</td>
<td>-0.372 (0.175)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>-2.112 (0.716)</td>
<td>-1.579 (1.243)</td>
<td>0.999 (0.498)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Geographic Controls</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>AR1</td>
<td>- 0.000</td>
<td>-</td>
<td>0.000</td>
</tr>
<tr>
<td>AR2</td>
<td>- 0.325</td>
<td>-</td>
<td>0.393</td>
</tr>
<tr>
<td>Hansen</td>
<td>- 1.000</td>
<td>-</td>
<td>1.000</td>
</tr>
<tr>
<td>Number of Internal Instruments</td>
<td>- 521</td>
<td>-</td>
<td>567</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>2,948 2,948 2,948</td>
<td>2,948 2,948 2,948</td>
<td>7,313 7,313 7,313</td>
</tr>
<tr>
<td>R²</td>
<td>0.465</td>
<td>0.465</td>
<td>0.553</td>
</tr>
</tbody>
</table>

(where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. Robust standard errors corrected for clustering at the district level are provided in parenthesis)
### Table C10: Second Step Productivity IV Estimations - Urban, Suburban and Rural Districts - East Germany

<table>
<thead>
<tr>
<th></th>
<th>Urban Districts</th>
<th>Suburban Districts</th>
<th>Rural Districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV-LIML (1)</td>
<td>IV-GMM (2)</td>
<td>IV-2SLS (3)</td>
</tr>
<tr>
<td>Dependent Variable: Firm-Level Total Factor Productivity (Ln)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln(Highway Density)</td>
<td>0.021(0.018)</td>
<td>0.023(0.018)</td>
<td>0.010(0.030)</td>
</tr>
<tr>
<td>Ln(Highway Density - Direct Access)</td>
<td>-0.185(0.124)</td>
<td>-0.179(0.137)</td>
<td>-0.093(0.073)</td>
</tr>
<tr>
<td>Ln(Population Density)</td>
<td>-0.079(0.078)</td>
<td>-0.094(0.050)</td>
<td>-0.005(0.058)</td>
</tr>
<tr>
<td>Ln(Population Density - Direct Access)</td>
<td>0.164(0.127)</td>
<td>0.156(0.182)</td>
<td>-0.086(0.043)</td>
</tr>
<tr>
<td>Year, Region, Industrial FE</td>
<td>Y Y Y Y Y Y</td>
<td>Y Y</td>
<td>-1.038(1.787)</td>
</tr>
<tr>
<td>Firm Controls</td>
<td>Y Y Y Y Y Y</td>
<td>Y Y</td>
<td>Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>Geographi Controls</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
<td>Y Y</td>
<td>Y Y Y Y Y Y Y Y Y Y Y Y</td>
</tr>
<tr>
<td>First Stage F-Stat</td>
<td>15.87***</td>
<td>250.23***</td>
<td>2.89***</td>
</tr>
<tr>
<td>Min. Eigenvalue Statistic</td>
<td>2517.65***</td>
<td>299.50***</td>
<td>249.49***</td>
</tr>
<tr>
<td>Overidentification Statistic</td>
<td>29.15***</td>
<td>25.37***</td>
<td>18.39***</td>
</tr>
<tr>
<td>Shea’s adj. partial R²</td>
<td>Ln(Highway Density)</td>
<td>0.683</td>
<td>0.732</td>
</tr>
<tr>
<td>Shea’s adj. partial R²</td>
<td>Ln(Highway Density - Direct Access)</td>
<td>0.321</td>
<td>0.543</td>
</tr>
<tr>
<td>Shea’s adj. partial R²</td>
<td>Ln(Highway Density - Wider Access)</td>
<td>0.694</td>
<td>0.624</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>7,313</td>
<td>7,313</td>
<td>11,569</td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.959</td>
<td>0.959</td>
<td>0.959</td>
</tr>
</tbody>
</table>

(Where ***, **, * indicate significance at the 1%, 5% and 10% level respectively. The significance of the Eigenvalue is determined according to the LIML Wald test; for 2SLS estimations the 2SLS relative bias test is used alternatively; overidentification tests used are the Anderson-Rubin statistic for IV-LIML, the Hansen’s J statistic for IV-GMM and the Sargan statistic for IV-2SLS estimations. Robust standard errors corrected for clustering at the district level are provided in parenthesis.)

**S.Barzin - Doctoral Dissertation**