The sustainable transport system and policy design in metropolitan context: environment facing transport or vice versa?

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Annotation

This habilitation thesis aims to contribute to the topic of sustainable transport planning in an era of continuing metropolisation of society, focusing on the geographically defined area of Central Europe, taking into account several dichotomies in the transport planning process, namely infrastructure and traffic planning, external and internal factors, transport behaviour of inhabitants and passengers, and transport policy at different levels of the public sector. This heterogeneity of perspectives on transport planning allows for unravelling the feedback interactions of the different steps and actors. The thesis focuses successively on metropolisation and the associated economic or environmental burdens; transport systems interacting between and within metropolitan areas, including transport externalities; the last part focuses on the interaction between travel behaviour and transport policy, reflecting the gradual institutional changes in the integrating European area and the long-term changes in the value frameworks of society. The methodological approach is based on regional economics, combining methods from both economic and geographical disciplines, and this way of looking at the topic is one of the fundamental determinants of this work, which is precisely in the field of transport, environment or urban planning a necessary part of dealing with complex and mutually interacting system components.

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Introduction

This habilitation thesis is presented as a collection of already published articles that always reflect individually defined research contexts and objectives and methods addressing specific aspects of the author's research focus. This thesis's following chapters present these research contexts, objectives, methods, and brief individual studies' results. In contrast, space is given here in the introduction to the thesis to the author's key focus and the way of looking at the work's subject matter that defines his research activities.

The goal of this work is to define the perspective challenges of economic policy reflecting long-term transformations of, if possible, economically and environmentally sustainable transportation systems in the Central European context that reflects the economic development determined by the process of creating and empowering metropolitan areas and metropolitan axes while constantly interacting with changes in the differentiated individual value frameworks of end-users of these systems, which are determined by changes in their personal and social value paradigms.

The purpose and ambition of this work are to contribute in the Central European context to the mutual reflection of different methodological approaches used in economics and geography through their collaborative interaction in order to outline the possibilities of the added value of this way of looking at scientific, economic problems (for inspiration see Krugman 1991). This approach is reflected in the long-term goal of achieving a holistic approach in economic research (Sala et al. 2013, Dalton et al. 2015) corresponding with the policy recommendation concept of Leitbild as desired future scenario (Pearson and Gorman 2010, Albert et al. 2012) and using the example of metropolisation processes that transform the design of transportation systems (Rodrigue 2006) not only among metropolitan areas in an increasingly globalised world (Hall et al. 2006, Dodi 2020) but also within these areas (Clark and Kuijpers-Linde 1994) in the interaction of metropolitan cores with its hinterland (Paul 2017). An essential aspect of the metropolisation transformations shaping transport systems is the currently much-debated environmental impacts of these changes, which are a necessary part of such an approach and are significantly reflected and discussed in this work.

The key research question and the motivating question for the author is whether the synergy of innovative development of transportation systems reflecting varying passenger preferences can be achieved through rational transportation policy while minimising conflicts with the environment following the principle of minimising negative externalities. The intensity of internalisation of these external costs into the transport planning process across the entire spectrum of transport modes and even means of transport is an essential issue of transport policy. Furthermore, the respect for non-discrimination of any of these multimodal and intramodal solutions remains an intriguing element. Many of the outcomes of such scientific methodologies might therefore give an inspirational basis for transportation policy design, which is typically constrained by the traditional use of cost-benefit analysis, which is challenging to work with when dealing with broader economic benefits or costs. Thus, this mainly used method needs to be accompanied by other approaches to deal not only with the efficiency of any transport policy decision but even with the effectiveness of such a decision (Drucker 1967).

Metropolisation is the process by which a city or metropolitan area becomes a region's dominant economic and social centre, involving structural, functional, and institutional recomposition and frequently resulting in increased urbanisation, economic growth, and concentration of wealth and resources (Gachelin 1992). The concentration of authority, influence, and economic activity inside a city or metropolitan region characterises this trend, which usually leads to the marginalisation of smaller cities and rural regions. The analysis of the Northeastern seaboard of the United States (Gottman 1957, 1961) was one of the first studies on the metropolisation process, defining the so-called "megalopolis" (originally used in ancient Greek literature) and "megalopolitan process" as areas providing several essential economic functions such as maritime, manufacturing, commercial and financial functions, but also cultural leadership (Gottman 1957). While Gottmann did not use the term "metropolisation" directly in his work, his notion of megalopolis is largely regarded as a predecessor of the phenomena. Original studies of the metropolisation process evolved from geography; thus, these are usually based on the characteristic of population density studied already earlier in the process of urbanisation, defined as a population concentration that can proceed in two ways: the multiplication of points of concentration and the increase in the size of individual concentrations (Tisdale 1941). Although it originates in more geographical or urban studies, this term has considerable economic applications. The primary issue shared by both perspectives is the critical role of population expansion, concentration (Krugman 1993), structure and change in specific regions or countries. Furthermore, even economic growth models deal with population growth and discuss its role in economic development (Headey and Hodge 2009, Peterson 2017).

The process of metropolisation coincides with globalisation (Morin and Hanley 2004, Lang and Török 2017). These two phenomena are interconnected processes with substantial implications on the global economic, social, cultural, and, importantly, political structures (Audikana and Kaufmann 2022) and, thus, policy design (Melkonyan et al. 2020, Ingvardson and Nielsen 2019). The globalisation process refers to the increasing connectivity and interdependence of economies, institutions, and cultures beyond national borders. This process is encouraged by reasons such as technology improvements and innovations (Krugman 1979), trade and investment liberalisation, and the development of novel modes of communication (Moss and Townsend 2000) and transportation (Rodrigue et al. 2009). The interaction between metropolisation and globalisation is reciprocal and challenging to solve regarding action and reaction.

Nevertheless, the rise of large urban centres has been a fundamental driver of globalisation, as cities have become crucial nodes in global commerce, finance, and innovation networks. At the same time, global interconnectivity even accelerated its nodal roles. Globalisation has altered the process of metropolisation by bringing not only new opportunities but also problems for metropolitan areas. The expansion of global supply chains and the increased trade presented by goods and services (Feenstra 1998), furthermore growing mobility flows of people (Freeman 2006), and flexibility of capital (Obstfeld 1998) have altered how countries, regions and cities compete and work with one another what resulted in new patterns of economic inequality. This inequality can occur inside and across cities or regions since certain regions gain more from global economic integration (global cores) than others, which are increasingly becoming the peripheries. In economic words, globalisation affects the location of manufacturing and trade gains, and at high transport costs, all countries have some manufacturing, however when transport costs fall below a critical value, a global core and periphery system spontaneously form, and countries on the periphery suffer a decline in real income (Krugman, Venables 1995). Furthermore, this worldwide process reflects on lower hierarchical structural levels such as mezzo-regional, regional, micro-regional or local. As a result, metropolitan areas become hubs of innovation, creativity, and cultural interchange, considerably contributing to national economic growth and development. However, metropolisation brings new issues, including traffic congestion, socio-economic inequities, and environmental deterioration, which must be addressed with public policy, management and planning.

The metropolisation phenomenon can be studied in several aspects regarding policy and reorganisation of local government (Young 1975); economic production dynamics in metropolitan areas resulting in a dispersal of productive activity to suburban and nonmetropolitan areas as one of the dominant processes shaping the contemporary economic landscape (Scott 1982); technological improvements and innovation activities (Krugman 1979, Sharif 2012) or technological externalities (Fujita el al. 1997). Moreover, Krätke (2007) emphasises the increasing role of the economic specialisation of urban agglomerations in the knowledge economy in the European economic territory. Other studies focus on demographic shifts and their impacts on housing preferences (Patterson et al. 2014) and public spaces planning (Loukaitou-Sideris 2016, Loo et al. 2017) or population segregation in urban centres (Logan et al. 2004). The important role lies in studies on employment activities (McMillen and McDonald 1998) traditionally relying on agglomeration economies in central cities clustering highly educated workers with increases in their wage premium (Ehrlich and Overman 2020) but with growing employment opportunities in various peripheral locations (Hall 1997) which means a significant role for intra-metropolitan work reconfiguration (Wu and Wang 2021). Further approaches discuss the role of general residential relocation preferences (Timmersmans 1984) concerning life cycle changes (Nijkamp et al. 1993, Dökmeci and Berköz 2000) regarding distribution of local amenities (Polinsky and Shavell, 1976). A growing literature is focused on reshaping land use in the city and its neighbourhood (Henderson et al. 2021), including its environmental challenges (Tian et al. 2012). The intersection of the environmental perspective with the perspective of population mobility coming from economic nature is the most relevant paradigm for this work.

In summary, metropolisation is essential in spreading economic performance and profile since major metropolitan regions are frequently the engines of economic growth and development but have different economic backgrounds and varying agglomeration contexts. The concentration of economic, social, and cultural activity in metropolitan regions generates agglomeration economies which are the advantages that result from many economic stakeholders such as public bodies, enterprises, people in business and inhabitants being positioned in the exact location or very close neighbourhoods. These levels of spatial aggregation, including the regional, metropolitan, and even neighbourhood scales resulting in agglomeration effects, have been presented by Rosenthal and Strange (2020). However, these agglomeration economies often cause long-term economic disparities (Glaeser 2013), negatively affecting those not participating. The causes lie in different launching situations and city conditions based on varying spatial-temporal and socio-economic profiles. Thus to formulate reasonable policy, it is necessary to consider the concept of path dependence to understand the evolution of the economic landscape and the regional development process in the local context (Greif 1994, Martin and Sunley 2006). The historical and geographic development and context of individual metropolitan areas and regions determine not only their current state, involving a particular economic specialisation, how to achieve a quality of life through shaping the urban landscape and supporting entrepreneurship in a given area. At the same time, these historical and geographical links also define the inter-relations among and even within metropolitan areas, which can further reinforce their specialised economic and residential profile. According to Quigley (1998) it is the heterogeneity and the diversity of cities that is the source of economic growth which means relations among individual metropolitan areas, at the same time, can be an incentive for the successful development of the whole metropolitan area through exploiting potential opportunities. Nevertheless, in contrast, in some situations, they can lead to stagnation or even degradation of the whole metropolitan region or at least selected parts of metropolitan areas due to the transformation of economic activities because these transformation processes are not only time-consuming but also administratively, economically and in final consequence socially and politically demanding.

It is the process of metropolisation in the context of Central Europe that is the focus of the first chapter 1 of this work, which introduces a typology of Central European metropolises and, at the same time, provides a practical application of metropolisation processes through the identification of metropolitan axes in Central Europe (Viturka et al. 2017). The study of these metropolisation processes based on economic links and reflected in transport and tourism links has been the subject of other publications focused on both inter-metropolitan relations (Šauer et al. 2019) and intra-metropolitan links (Viturka and Pařil 2013) through the introduction of a marginal rate of labour mobility explaining the economic motivation for commuting, reflecting the potential increase of wages by reaching the more attractive job in the metropolitan core (Pařil et al. 2015).

The process of metropolisation of human society and economic activities is both the starting point and the core context of this work. Thus, in the economic framework defined by metropolisation trends, it is necessary to observe the long-term effects and changes that it brings. These effects are the subject of broader literature and research studies, partially already mentioned. The most critical effect of metropolisation is the formation of the duality of the metropolitan core or centre and its hinterland, accompanied by one of the key problematic issues: suburbanisation. Mieszkowski and Mills (1993) consider two classes of theories of suburbanisation, both of which are important: the first, preferred by urban theorists and transportation experts, is the so-called natural evolution theory, and the second stress the fiscal and social problems of central cities. The process of suburbanisation often results in urban sprawl associated with several particular effects. Urban sprawl is a result of the expansion of the metropolitan area and its suburbs, which can result in the spread of development into previously undeveloped areas. This expansion is often driven by factors such as the desire for larger homes, access to green space, and lower housing costs. However, urban sprawl is related to a range of challenges and, in final even economic costs including. According to Nechyba and Walsh (2002) the phenomenon of sprawling cities has created opportunities for significantly higher levels of housing and land consumption for most households. Nevertheless, these benefits have not come without associated costs. These are road congestions related to high levels of car pollution, the loss of open space amenities, and unequal provision of public goods and services across sprawling metropolitan suburbs that can give rise to residential segregation and areas of poverty.

From an economic point of view, social issues are less visible because their impacts are usually not immediately apparent. Somewhat more visible are direct economic costs because they can result in reduced and limited possibilities of public goods management of many different services in a decentralised city, such as transport accessibility, water supply management or waste management. Thus, managing still-growing geographical areas on both metropolitan levels (corresponding institutionally with municipal or regional levels) can immediately lead to increased infrastructure costs, as more roads, sewers, water, and utility lines need to be built to accommodate the geographically expanding residential areas. These infrastructure costs are critical in two specific fields: transportation systems with the goal of accessibility and environmental goods management systems linked to very fundamental human needs. These two sections of the public management framework are often associated with large amounts of public financial expenditure. However, these direct expenses are not solely of an infrastructure nature, as individuals are more likely to rely on cars in hinterland areas, resulting in increased traffic congestion, longer commuting times, and higher fuel consumption. These consequences can result in more extraordinary transportation expenses, even for people and businesses, as well as increased air pollution, noise, and greenhouse gas emissions. Induced environmental costs can have diverse nature and correspond with other issues such as resource consumption, water supply, waste management or land use and habitat fragmentation leading to habitat loss. It is a problem of direct infrastructural and environmental costs in metropolitan areas that is the essential subject of the second chapter 2 that shows the differentiating effects on wastewater, waste management and public greenery management according to the affiliation of metropolitan core, hinterland or periphery (Pařil et al. 2022a).

The process of metropolisation has a significant impact on all transport systems, as the concentration of economic, social, and cultural activities in large metropolitan areas leads to increased demand for transportation infrastructure and services. As metropolitan areas grow and expand, the transportation systems that serve them must adapt to the population's changing needs. Metropolisation can have different impacts on both long-distance transport and short-distance commuting, as the two types of transportation serve different needs and have different characteristics.

Due to globalisation trends, an essential part of metropolisation processes at the macro-regional or international level is the increasing transport interconnectivity of territorially separated metropolitan areas. In Europe, these trends are also supported by political and economic integration within the European Union. Regarding long-distance transport, metropolitan areas are typically connected through various modes of transportation, such as air travel, highways, railways or high-speed railways and maritime systems, more often for freight transport or tourism reasons. These long-distance transportation networks facilitate the movement of people, goods, and information among geographically remoted metropolitan areas and are critical to the functioning of globalised economies. Air travel is a crucial mode of transportation for connecting metropolitan areas far from each other. However, this mode is essential even for middle or short-distance passenger transport where strong demand for fast mobility is determined by tourism or business reasons. When studying the nature of air transport in geographically smaller countries with smaller populations, air transport needs to be placed in a broader international context. Assessing the role of domestic demand in air transport and, in turn, the impact of the border effect is crucial. The border effect is a concept described primarily in international trade (Leamer, Medberry, 1993; McCallum, 1995). Still, it also has important implications for transport planning, as crossing borders brings a significant drop in demand (Klodt, 2004; Hazledine, 2009) that must be considered when planning transportation projects. This effect, in turn, creates the conditions for the emergence of hegemons in air transport at the mezzo-regional level, which shapes the air transport system in Central Europe, where most countries are smaller and international transport is thus highly affected (Pařil et al. 2022b).

Despite the irreplaceable place of air transport, the crucial role in the volumes of goods and passengers transported lies with road transport. The role of car transport is undeniable, both in transport among metropolises and within metropolitan areas. The road infrastructure is thus the essential communication and circulatory system of a global metropolitan organism. A considerable advantage of the road infrastructure is the high hierarchical heterogeneity of the design of the road network, which from the highest level of motorways through the level of national and regional roads, is further linked to various types of local roads, which on the other side of the imaginary scale are terminated by dirt roads used for agricultural or tourist purposes. However, motorways and national roads are essential in meeting the population's long-distance transport needs. The planning of motorway construction is topical in those countries where the motorway network has yet to reach the socially desirable extent. It is a highly complex issue involving direct and indirect economic costs. The issue of a comprehensive assessment of options for the planned sections of the motorway network, including its prioritisation, involves assessing many factors such as relevance, usefulness, integration potential, and economic stimulation of the action or environmental context (Viturka et al. 2012, Viturka and Pařil 2015).

It is the latter criterion, including the environmental context, which is currently gaining momentum in the planning of transport systems and has a significant impact on the two modes of transport mentioned above, namely air and road transport. There are, of course, more reasons for the growing importance of this criterion. The most fundamental one is the contribution of man and his activities to climate change. At the same time, however, other negative externalities causing impacts not only on nature and ecosystems cannot be overlooked. However, due to metropolisation in suburbanisation processes occurring precisely in transport-accessible locations (determined by good road infrastructure), transport externalities significantly negatively impact the population's health. Negative externalities can be divided into two primary groups directly impacting nature or humans. Among those that directly impact nature, in addition to greenhouse gas emissions causing climate change accompanied by well-to-tank costs, are the cost of habitat damage, soil and water pollution, land use and forest and agricultural land grabbing or landscape fragmentation. Costs with a direct impact on human health are accident costs, costs of air pollution, noise, and congestion costs. According to the Handbook on the external costs of transport (Van Essen et al. 2019), road transport is responsible for 83% of external transport costs in EU28. Among these externalities, the most important role is related to accidents (29%) and congestion (27%), followed by air pollution (14%). While accidents and congestion immediately affect a person's health or loss of time, air pollution is a long-run impact, not only on people. The impact on human health must therefore be reflected in research on impacts over the long term. The impact of road transport on human health through the burden of air pollution, including consideration of the variability of impacts according to the demographic structure of the population concerned, is the focus of chapter 3.

Because of the high external costs of road or air transport, the current EU transport policy seeks to shift part of the transport to more environmentally friendly modes and means of transport or even to change car transport through regulatory requirements to limit emissions. Public transport is typically considered a more environmentally friendly mode of transport, and rail transport is politically preferred for long-distance passenger transport. Of course, even planning railway infrastructure, especially high-speed railway infrastructure, requires a complex assessment of these projects (Viturka et al. 2022a), including integration potential (Viturka and Pařil 2020), regional development context (Pařil and Viturka 2020), commuting behaviour change (Pařil and Viturka 2023), relevance and usefulness (Viturka et al. 2022b), capacity planning, economic stimulation (Viturka et al. 2021) and investment or environmental costs. Nevertheless, the latter is considered more favourable and sustainable than road or air transport. Transport policies, therefore, seek to motivate people to switch to more environmentally friendly modes of transport, but this requires knowledge of the transport behaviour of the population in the changing living conditions of a globalised and metropolitan world. Thus, the nature of end-users mobility behaviour of transport modes and means is crucial. Among the essential factors influencing passengers' choices following characteristics are considered significant: the socio-demographic profile, easier accessibility and the need for transfers (Yen et al. 2018), travel time or speed (Fröidh, 2008), traffic congestion (Ben-Akiva and Morikawa 2002), comfort (Allard & Moura, 2018), safety (Si et al., 2009), fares and frequency (Paulley et al., 2006), income (Toro-González, et al., 2020), the opportunity to work (Varghese and Jana, 2018), congestion (Droes and Ritvield, 2015), capacity (Daly et al., 2014) or parking availability (Pagliara et al., 2012). However, in the European context, even the variety of choices has to be taken into account because there is a long-term liberalisation process in all modes of transport that creates a more competitive framework with more opportunities to be used by potential travellers or passengers. The process of liberalisation in transport is broadly discussed in the literature related to air transport (Button et al. 2007, Button 2012), bus transport (Beria et al. 2018) or railway transport (Bergantino et al. 2015). Chapter 4 focuses on the issue of passenger behaviour in public transport in an environment of intermodal competition, taking into account both competition between modes of transport and competition within these modes.

The study of the transport behaviour of the population is often based on the identification of elasticities to various factors influencing passenger behaviour, such as the price or frequency or others mentioned above, as it is widely represented in the literature. From a policy-making perspective, the application of the results of such studies is limited because the elasticities capture behavioural changes at the level of minimal percentage changes. Nevertheless, transport policies can use robust instruments and incentives to motivate passengers to use more environmentally friendly modes of public transport at the expense of individual car travel, e.g. through robust discount schemes or even free fares. However, such transport policy instruments operate at a different level of change, not in the order of percentages but in the order of tens of percentages, and therefore results at the level of percentage elasticities are of very limited predictive power for these instruments and need to be studied in the context of short and long term changes in the context of historical data on transport demand reflecting absolute changes in the volumes and structure but also in the context of overall modal split changes. The introduction of robust discounting with the aim of redirecting transport demand to more environmentally friendly transport modes is the subject of chapter 5, which uses the example of Slovakia and Czechia to present the possibilities of changing the modal split through such robust instruments, as well as their economic consequences or potential impacts on non-included competing transport modes (Tomeš et al. 2022).

The design of the transport system in a globalised world creates a system of metropolitan centres, axes and their hinterland. It reflects the increasing needs of urban life of inhabitants with the possibility to cover greater geographical distances when travelling for work, leisure, holidays, or family is thus a very complex issue. However, it is the setting up of the transport system in terms of not only infrastructure but also technological and regulatory framework (including possible preferences for selected transport segments or selected passenger segments) that has the potential not only for ex-post solutions to transport problems arising from a particular spatial economic situation but is often a stimulus that can be one of the factors determining the further direction of development or a significant factor in mitigating selected negative impacts.

I. The metropolitan process

The first part of the habilitation thesis includes two chapters focused on metropolisation process in Central Europe and its impacts caused by suburbanisation in the metropolitan hinterland reflected on the environmental, both infrastructural and operating costs for public budgets.

1. The Metropolisation Processes A Case of Central Europe and the Czech Republic

In Paper A, the metropolisation process in Czechia is presented with an emphasis on the Central European context. It deals with the strategically important global phenomenon of the metropolis. We present a theoretically based method for evaluating large cities and examine its effectiveness using the example of Central Europe. This method is based on three components: population size (initial assumption), economic profile (linkage to economic performance) general attractiveness (perception of development potential). The results of evaluating a selected sample of 27 identified metropolitan cities were generalised based on the typologies within the framework of these three components. Most metropolitan areas are categorised as Type B (established metropolis), followed by Type C (elementary metropolis), and finally, Type A (dominant metropolis). Next, we use the example of the Czech Republic to demonstrate a practice-oriented conceptualisation. A primary focus was on the strength of economic ties between Prague (and her two other Czech centres) and other central European metropolises.

1.1. Background

Metropolisation is one of the most visible manifestations of long-term changes in the scale and structure of urbanisation occurring in the context of the globalisation process (Hanssens et al. 2012). Generally, it is seen as a higher stage of urbanisation in which the primary focus is no longer on population concentration but on importance concentration in information-knowledge-management. Its growth promotes the strengthening of ties between metropolises and their hinterlands and between metropolises (Hampl 1996). The growing relevance of metropolises in nations' global competitiveness generates a need for theoretical and applied study of this issue. The basic leitmotiv of the further presented approach of assessing metropolisation processes is their understanding from the perspective of the post-industrial fading of the horizontal forms of social organisation and the deepening of vertical forms of this organisation. The position of the metropolis corresponds with the mentioned information as being an ever more dominant part of the national and supranational urban systems integrated not only by operational interactions mediated by the technical, in particular transport infrastructure (Kraft et al. 2014) but also the creative interactions mediated by the knowledge infrastructure. In this context, it is a specific development from the monocentric metropolitan agglomerations to polycentric macrosystems whose manifestation creates supranational axes (Growe, 2012). The described development leads to significant changes in the localisation of production. Thus, it can be considered a renaissance of localisation approaches (Brender and Golden 2007). In addition to the theory of localisation, there are, e.g. the theories of central places, polarised development and cumulative causality, a deeper analysis of which goes beyond the thematic focus of the paper (McCann 2010). In this respect, utilising the working theory of integrated and sustainable regional development is beneficial. This theory (Viturka et al. 2010 and Viturka 2014) stresses that the essence of the social movement is the hierarchical differentiation of social systems and their integration through the territorial division of labour and socio-political links. The resulting arrangement ensures the coherence of the systems, which reflects the balance between the effects of the economic, social and environmental factors, whose results are then accumulated in the quality of the business and social environment. The following decisive driving forces of integration are then considered: labour interactions on a microregional level, production interactions on a mesoregional level, administrative interactions on a macroregional level and trade interactions on a global level. Improving the quality of the business and social environments stimulates the development of different activities, positively impacting innovation and living standards. It is exciting that advances in ICT do not result in the dispersion of information activities (Sassen 1991). This fact can be attributed to the need for face-to-face interactions, which is somewhat unequivocally called the "tyranny of proximity" (Duranton 1999; Bourdeau-Lepage 2004). A controversial issue is a suburbanisation, whose negative impacts are often interpreted in connection with urban sprawl (European Environment Agency 2006). Suburbanisation is an essential tool for reducing the differences in the quality of the business environment between the core and the hinterland. There are even very local issues with potentially significant impacts on the overall attractiveness of cities, such as brownfield regeneration (Frantál et al. 2015). The crucial question is the management of metropolitan regions where solutions to multiscale problems require integrative management (Ianos et al. 2012). The article's main objective is to create a comprehensive method to evaluate a metropolis focusing on Central Europe to verify the possibilities and benefits of the method applications, emphasising the availability of the necessary information and comparing the results. Czechia was chosen for the practically oriented conceptualisation of the research results, including assessing the potential cooperation and policy recommendation. Overall, there is still no consensus on the scientific definition of the metropolisation concept (Abrantes et. al. 2005).

1.2. Data and methods

The publications The World Factbook (2016), the Encyclopædia Britannica (2016) and Brockhaus Enzyklopädie (2016) were used as the primary documents for a definition of the working macroregion of Central Europe. Based on these definitions, Central Europe includes nine countries: Germany, Poland, Czechia, Hungary, Austria, Switzerland (together with Liechtenstein), Slovakia and Slovenia, with a current number of about 163 million inhabitants. The mentioned theoretical ambiguity of the metropolisation concept complicates evaluating the metropolis position, starting with the definition itself. A systematic method of evaluation of the metropolis was created with an analysis, preferring theoretically anchored approaches based on the three components:

1. the population of the metropolis, a sufficient size of which is generally regarded as the initial assumption for starting the metropolisation process;
2. the economic profile, emphasizing the progressivity of the economic structure evolving from the representation of knowledge-based industries;
3. the general attractiveness as a reflection of the high business and residential attractivity.

In the case of population size, there is a lack of clear distinction between the metropolises and other major cities. The size limit of metropolises is influenced by several territorially differentiated factors, including historical development and the achieved degree of urbanisation. They can be seen, from the standpoint of administrative (administrative definition), as urban (continuously built-up areas) and functional (the influential territory of the city). Within this sequence, when the functional approach most corresponds with the metropolitan concept, an increase in the population of the respective units happens. In this context, a boundary of 1 million inhabitants is considered a population limit to be the size of supranationally significant metropolitan regions. Metropolises of global importance occupy the highest hierarchical level (Friedmann, Wulff 1976) - in this respect, London and Paris are the essential global metropolises localised in Europe (Knox et al. 1995). In the case of metropolitan regions of secondary importance, the commonly used limit is a population of 500 thousand (Brezzi et al., 2012). During the evaluation, it is necessary to consider the comparability of their territorial limits. Therefore, the OECD (2015) data were selected as appropriate sources.

The above-mentioned size limit of a metropolis of supranational importance of one million inhabitants was, rather, for the comparatively international solid position of a series of smaller metropolises, reduced to a population of 750 thousand. Two capital cities which do not meet even the reduced limit, Bratislava and Ljubljana were also included. A total of 27 metropolises or metropolitan regions were identified. At this point, it is also appropriate to highlight the problem of the comparability of statistical data in the metropolitan areas of post-socialist Central Europe related to the census data versus the annual population register. Steinführer et al. (2010) found significant statistical variations in the measurements of the population size (influenced by suburbanisation, intraregional and international labour migration). However, these impacts are negligible in terms of the results of our research. Specific data about metropolitan areas are based on the uniform method for defining functional urban areas introduced by the OECD in collaboration with the EU. Here, it is appropriate to mention some fundamental features (Brezzi et al. 2012):

- the basic building blocks of regionalisation are units at LAU 2 level,
- the core of the region is determined based on the minimum population size of a continuously urbanized area,
- in the case of nearby cores, their mutual relations are tested regarding commuting time, due to the identification of the polycentric structure,
- the hinterland of the core consists of the municipalities from which at least 15% of workers commute to work.

Chosen metropolises can be in accordance with their basic demographic importance divided into three size groups: metropolises with a population of more than 2.5 million, metropolises with a population of 1 to 2.5 million and metropolises with a population of less than 1 million.

Big cities logically have suitable conditions for diversification and, thanks to access to knowledge, systematic specialisation in sectors with high added value (OECD 2006). Progressive industry groups taken from the study The Metropolization of the European Urban and Regional System (Krätke 2006) were used in the primary assessment of the given component. A progressive economic profile with a rapidly growing share of knowledge-based high-tech sectors in industry and services is widely regarded as the typical character of a metropolis. Metropolitan regions are the centres for knowledge-based production chains and innovation-strong production clusters (Krätke 2006). The concentration of the corresponding global firms has been analysed at Loughborough University (GaWC 2014). Unfortunately, this database often has gaps for single EU regions and specific periods. Following the available knowledge, the metropolises can be grouped into the following groups:

1. Group A: above average proportion of research-intensive high technology industrial branches (HTI) and research-intensive medium high technology industrial branches (MTI) and knowledge-intensive technology-related services (TS)
2. Group B: above average proportion of knowledge-intensive market-related enterprise services (ES) and knowledge-intensive financial services (FS) and knowledge-intensive services in healthcare, education and the media industry (HEM)
3. Group C: average proportion of knowledge-based industries with a better position of technology-related branches (HTI + MTI + TS)
4. Group D: average proportion of knowledge-based industries with a better position of service-related branches (ES + FS + HEM)
5. Group E: below average proportion of research-intensive and knowledge-intensive branches.

The Eurostat Regio database (2011) was selected to assess the economic profile due to the need to have comprehensive data based on territorial structure (NUTS2 regional level).

Evaluation of general attractiveness is the most complicated matter. Three components are considered: business attractiveness (BA), residential attractiveness (RA), and innovation potential (IP). Business attractiveness (BA) occupies a central position in the case of the evaluation of metropolises' attractiveness. Information from the European Cities Monitor/ECM, presenting the views of approximately 500 respondents from a range of managers of the world's leading companies (Cushman & Wakefield, 2011), was used for its evaluation. Within the framework of the Central European macroregion, at the beginning of the current decade, rankings included 13 cities, whose semantic position was assessed primarily based on data for 1990, 2000 and 2010. This information was accompanied by time-corresponding data obtained from the benchmarking of large cities created by the HWWI/Berenberg bank, emphasising the results of the aggregate rating of location advantages (Neumann, 2013) and further from the database of GaWC, Loughborough University (2014). The researched metropolises can be, based on BA, divided from a broader perspective into three basic categories:

1. metropolises of global importance – five metropolises,
2. metropolises of European importance – seven metropolises,
3. metropolises of Central European importance – fifteen metropolises (ECM database includes only Bratislava).

Data from Mercer, managing the most well-known world database, precisely the average order for freely available surveys of 2011 and 2012 (Mercer, 2012), were used for residential attractiveness (RA). Additional resources are taken from the webpage Numbeo quality of life by the city for 2011 and 2014; in the case of Poland, it was necessary to complete it with information from the database of GaWC (2014) and Bańczyk (2012). The position of a metropolis is rated as balanced in the case of differences compared to the position according to the BA (+/− 1 to 2 places; above this level, it is an unbalanced position with positive or negative deviations). The comprehensively conceived information, taken from the world ranking processed by the 2thinkknow Consulting agency since 2007 (Innovation Cities, 2015), was used as a primary source of information about the IP. An extensive set of used indicators is aggregated here into three factors: cultural assets, human infrastructure and networked markets - the average order for 2011 and 2014. In some cases, this information has been accompanied by Annoni and Dijkstra (2013).

The evaluation results of metropolises form a basic framework for the strategically targeted conceptualisation. In the presented example, we mainly focus on the assessment of the intensity of the links between Prague, accompanied by two following important centres, Brno and Ostrava (the functional regions of Brno and Ostrava reached a population size of 643 and 563 thousand in 2012; OECD 2015), and other Central European metropolises and perceptions of their development potential. The procedure consists of the following steps:

- evaluation of the intensity of ties with an emphasis on the identification of development axes of supranational importance,
- synthesis of obtained knowledge in the context of a spatial model of the development of the Czech economy,
- the final conceptualization of the research results with the use of scenarios of regional development (level NUTS 3).

The evaluation of metropolitan links is based on a gravity model as a standard tool of a qualified estimate of potential interactions:

$$G_{ij} = \frac{M_i \times M_j}{d_{ij}} \ ,$$

where G_{ij} = the gravity force acting between the metropolises i and j, M_{ij} = the economic importance of metropolises and d_{ij} = the distance of metropolises. For measuring the importance, GDP created in metropolitan regions in 2010 were used, and the distance of the metropolis corresponds to the length of the fastest road connection.[1]

[1] During the evaluation, metropolises were preferred that met the criterion of so-called effective distance, that is, in the case of road freight transport as the most important means of transport of goods, in accordance with the relevant EU legislation (regulation of the daily working time of drivers) set at 600 km.

1.3. Results

The typology method, which sorts examined phenomena according to the similarity of the selected characteristics, was chosen due to the problems with the comparability of the data to evaluate the semantic position of the metropolises. We dealt with the degree of similarity in classifying metropolises within individual components - population size, economic profile and attractiveness. The metropolises were classified into dominant, established and elementary types (see Table I.1). The statistical analysis of the results shows that the type classification of the metropolises has the strongest link to the component "attractiveness", with the correlation coefficient on a significance level of 0.05 k = 0.85. We also encounter a similar orientation of the priority links for both remaining components, of which the more powerful dependency shows the component "size". We extended the statistical analysis about the indicator of GDP per capita, finding the strongest link to the component "structure" with k = 0.73, which corresponds with the general premise about the higher added value of the production of knowledge-based industry. In addition, it is helpful to note that we encounter above-average levels of this component only for the dominant and established metropolises.

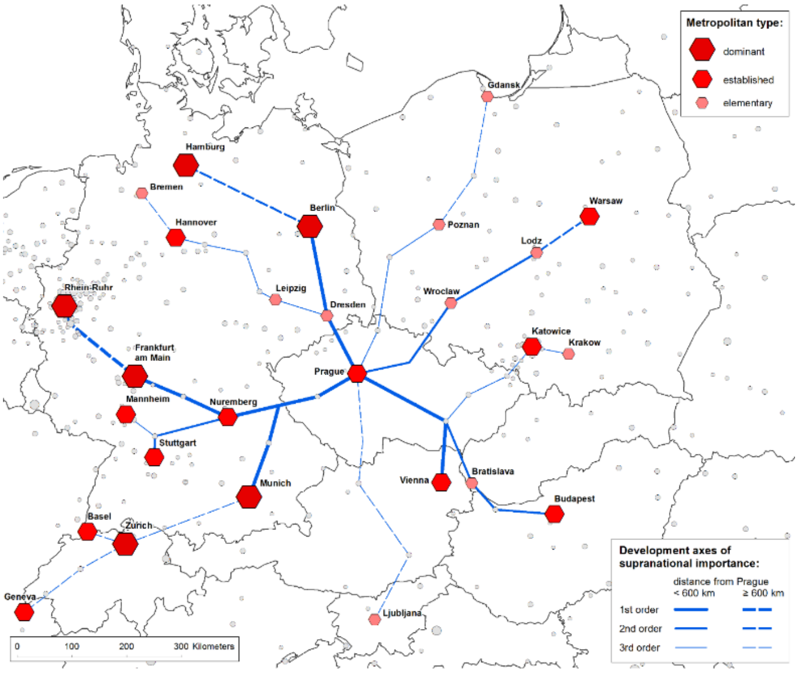
Table I.1: Results on Central European Metropolises

country/area	**population**	**GDP (USD) per capita**	**% share of total GDP**	**economic profile**	**attractiveness (BA order/ RA/IP variation)**	**aggregate group**
Czech Republic	10 505 445	23 712	x		(//)	
Prague	1 868 631	41 543	30,5	Group D	2 (8/▼/●)	II
Germany	81 843 743	33 517	x		(//)	
Berlin	4 386 551	29 971	4,8	Group D	1 (2/▼/●)	I
Rhein-Ruhr	7 089 648	36 366	9,4	Group D	1 (5/●/▼)	I
Hamburg	2 996 750	44 934	4.9	Group B	2 (7/●/●)	I
Munich	2 904 480	51 350	5.3	Group B	1 (3/●/●)	I
Frankfurt a. M.	2 525 458	48 802	4.5	Group B	1 (1/▼/▼)	I
Stuttgart	1 960 286	42 895	3.1	Group A	2 (11/▲/▲)	II
Mannheim	801 951	36 501	1.7	Group A	3 (1/▼/▼)	II
Hannover	1 220 106	36 327	1.6	Group A	3 (2/●/●)	II
Nuremberg	1 168 145	38 548	1.6	Group A	3 (4/▲/●)	II
Bremen	1 026 367	36 431	1.4	Group D	3 (3/●/▼)	III
Leipzig	833 828	25 917	0.8	Group D	3 (6/●/▲)	III
Dresden	842 159	25 383	0.8	Group C	3 (5/●/▲)	III
Poland	38 538 447	17 353	x		(//)	
Warsaw	3 008 921	37 456	16.9	Group D	2 (10/▼/▼)	II
Katowice	2 608 651	20 119	8.0	Group E	3 (4/●/●)	II
Krakow	1 357 206	19 716	4.0	Group E	3 (3/▲/●)	III
Gdansk	1 098 435	20 470	3.4	Group E	3 (5/●/▲)	III
Lodz	947 767	19 642	2.8	Group E	3 (6/▲/●)	III
Poznan	941 914	27 729	3.9	Group E	3 (1/●/▼)	III
Wroclaw	835 403	23 691	3.0	Group E	3 (2/▼/▼)	III
Switzerland	7 954 662	39 351	x		(//)	
Zürich	1 226 332	48 128	19.0	Group B	1 (4/▲/▼)	I
Geneva	807 646	40 039	10.3	Group B	2 (6/●/▼)	II
Basel	773 332	38 635	9.7	Group A	3 (x/▲/▼)	II
Austria	8 443 018	35 400	x		(//)	
Vienna	2 737 753	40 107	36.3	Group D	2 (9/▲/▲)	II
Hungary	9 957 731	16 957	x		(//)	
Budapest	2 862 326	28 417	47.6	Group D	2 (12/▼/●)	II
Slovakia	5 404 322	20 178	x		(//)	
Bratislava	722 106	45 414	29.7	Group D	3 (x/●/●)	III
Slovenia	2 055 496	25 118	x		(//)	
Ljubljana	576 370	34 870	38.5	Group D	3 (x/▼/▲)	III

Source: own research.

The results on metropolitan axes show (Figure I.1) the strongest links of Prague to Berlin and Munich with a value of G = 29 and Vienna with G = 25. From a broader perspective, the metropolitan axis Prague-Nuremberg-Munich seems to be the most important, with the aggregate value G given by the sum of P↔N and P↔M = 41, followed by the axis of the Prague-Dresden-Berlin with G = 40. The importance of these axes shows the current shares of the German federal land concerned with the foreign trade of Czechia with Germany - turnover/import: Bayern 23/29%, Baden-Württemberg 16/20%, Nordrhein-Westfalen 15/14%, Sachsen7/9% and Hessen 6/6% (Statischises Bundesamt, 2012). Brno has the strongest ties to Vienna and Ostrava to Katowice (G = 11 or 7). From a broader perspective, the metropolitan axis Prague-Brno-Vienna (from which a metropolitan axis diverges, pointing over Bratislava to Budapest) plays a decisive role. The metropolitan axis Prague-Munich with the West Bohemia axis Prague-Pilsen, the metropolitan axis Prague-Berlin with the North Bohemia axis Prague-Ústí n. L. and the metropolitan axis Prague-Vienna with the Bohemia-Moravia axis Prague-Jihlava-Brno show strong interactions.

Figure I.1: The metropolitan system of Central Europe from the point of view of Czechia



Source: own research.

Evaluation of the metropolis is an essential basis for creating supranational development concepts, emphasising the metropolitan networks as one of the building blocks of territorial integration. The presented analysis of three components covering the main determinants of the development - the input assumptions (population size), the ability of adaptation (economic profile) and development potential (attractiveness), can be regarded as an inspirational approach to assessing metropolisation process, which can be deepened through generalisation and practically targeted conceptualisation of the results. The suggested approach was demonstrated with the example of Czechia, using the typology of metropolises as the basic design of a long-term strategy for their development. It is necessary to note that several other factors influence metropolises' cooperation. The German metropolises Berlin, Munich and Frankfurt a. M. together with the Austrian metropolis Vienna have crucial importance from the perspective of the Czech metropolises Prague and Brno. Strengthening mutual economic and social ties is a crucial condition for improving the international position of our metropolises which is confirmed by tool of integrated territorial investments (ITI) to support cities and urban areas approved (European Commission 2011, Statutory city of Brno 2015).

2. The cost of suburbanization: spending on environmental protection

The subject of Paper B is an analysis of the suburbanisation costs based on municipal expenditure on protecting the environment in Czechia. The goal is to assess disparities between different municipalities and evaluate the relevance of these differences to suburbs compared to other areas. The analysis is based on a methodological framework of CEPA environmental expenditure corresponding with the Czech public-sector budget financial structure. This study has three essential areas for Czech municipal expenses: water protection (with emphasis on wastewater treatment plant and infrastructure), waste management and biodiversity and landscape protection corresponding with public municipal greenery. We used the Ministry of Finance´s State Treasury Monitor dataset, providing significantly detailed and precise data on municipal expenses for all 6,255 municipalities in 2010–2015. We compared relevant expenses in Czechia's OECD metropolitan and non-metropolitan areas. The results show that municipalities with the most outstanding water protection expenses per capita are exposed to a suburbanisation burden and are situated in neighbourhoods of Czech metropolitan centres. Disparities between municipalities clearly show that less populous municipalities' water protection costs per capita are three times those in bigger towns. The reason lies in the enormous fixed costs of building and operating the required infrastructure. On the other hand, the most extraordinary spending on maintaining public greenery was found in the metropolitan cores, showing more significant demand for public greenery where there is no open countryside. Regarding waste management, there is no apparent relationship with localisation in suburban areas.

2.1. Background

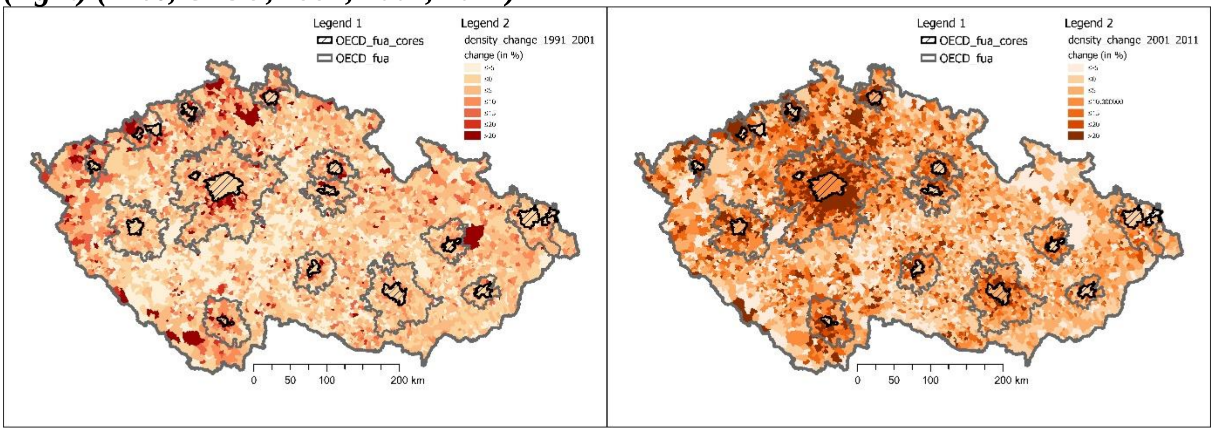
The issue of suburbanisation is primarily discussed in the research literature concerning such areas as land use management (Pendall, 1999), urban studies with a focus on urban sprawl (Ewing, 1997) and transport (Ahlfeldt and Feddersen, 2018). Other studies cover long-term population patterns and public perceptions of living in the suburbs (Goodling et al., 2015). Suburbanisation can be defined as "*a complex and changing process that results in the creation of suburbs with suburbs being a form of land use or a form of development that takes place close to, yet outside of, major cities, and which are substantially influenced materially by the economy and ways of life of these central urban areas"* (Woodbury 1955, p.2). Suburbanisation can be characterised as when urban populations disperse over a larger area encompassing urban neighbourhoods (Edmonston, Davies, 1976). Within a broader definition, the literature usually refers to the following characteristics of suburbanisation, especially in Western countries, namely the internal decentralisation of the population within agglomerations, the expansion of lower-density housing in close proximity to cities, and the blurring of the boundaries between urban and rural areas, including sociological changes in the attitudes of such populations (Tammaru, 2001). In a broader definition, some authors prefer suburbanisation as a situation where the enlargement of areas surrounding cities is more intensive than the city's growth (Hardi et al., 2020). Ewing (1997) distinguished between suburbanisation itself and creating urban sprawl. Ewing (1997, p. 108) defines sprawl as "*leapfrog or scattered development; commercial strip development; and large expanses of low-density or single-use development as well as by such indicators as low accessibility and lack of functional open space*". He also identified issues including excessive public spending, loss of resource lands and a waning sense of community. Pendall (1999) showed that local governments relying on ad valorem property taxes to fund services and infrastructure tended to create more sprawl than those relying on a broader tax base. Brueckner (2000) identified three fundamental forces driving suburbanisation: growing population, rising incomes and falling commuting costs. Qin (2017) showed through the example of high-speed railway network development in China how transportation costs affected urban peripheral patterns. Areas with upgraded railway lines experienced reductions in GDP and GDP per capita following the upgrade, which was largely driven by a concurrent drop in fixed-asset investment.

There is a vast literature on the environmental impacts or consequences of suburbanisation. Burchell et al. (1998) assessed the cost of urban sprawl in several areas: public and private investment and operating costs, transportation and travel costs, land and natural habitat preservation costs, impacts on quality of life, and consequences in social issues related to living in the suburbs. Adelmann (1998) specified before all environmental impacts of suburbanisation with loss of farmland (Liang et al., 2015), excessive removal of native vegetation, and as a result, reduced diversity of species (confirmed by Wang et al., 2017). Associated impacts are an increased proportion of non-permeable surfaces, increased stormwater runoff and a higher risk of flooding (Hardi et al., 2020). Johnson (2001) categorised other environmental impacts corresponding with previous studies with loss of environmentally fragile lands, reduced regional open space, more significant air pollution, higher energy consumption, and decreased aesthetic appeal of landscape corresponding with the monotonous (and regionally inappropriate) residential visual environment. Margules and Meyers (1992) also emphasise ecosystem fragmentation usually associated with the transport infrastructure, but of course, suburbanisation is accompanied strongly by transport network development. Novak and Wang (2004) analysed the impacts of suburban sprawl on Rhode Island's landscape. They found that the land transition in the study area contributed to the scarification of forest land and, consequently, a declination of ecological connectivity. Radeloff et al. (2005) confirmed forest fragmentation by urban sprawl, even in rural areas.

In Czechia, the most suitable case of suburbanisation is the capital Prague and the development of its neighbouring area. Although Ourednicek (2003) presents the post-1990 development in Prague as a shining example of suburbanisation tendencies, in the context of the post-2000 development, the 1990s development can be considered as the relatively slow growth of built-up areas in the Prague hinterland up to 1999. On the contrary, the pervasive development of suburbanisation in the years 1999-2009, when suburban development was recorded not only in the closer hinterland of the capital city but also in areas further away from the border (Franke, 2015). The development in these two periods is represented in Figure II.1, representing the change in population density (in percentage) as an indicator of suburbanisation in two periods corresponding with the national Census in 1991, 2001 and 2011. These two figures emphasise the phenomenon of suburbanisation, especially in the OECD-defined metropolitan areas surrounding their metropolitan cores. The acceleration of the phenomenon after the year 2001 is evident. Regarding other regional centres in Czechia, suburbanisation tendencies in different periods are shown, such as in Brno, followed by Plzeň and České Budějovice. These tendencies have not been statistically demonstrated in Ostrava (Nevedel, Paril, 2014). There is current literature showing continuing residential suburbanisation process after 2010 in the neighbourhood of both the capital Prague (Zevl, Ourednicek, 2021) and regional centres: Brno (Stastna et al., 2018), Olomouc (Biolek et al., 2017), České Budějovice (Kubeš, 2015), Hradec Králové, Liberec and Ústí nad Labem (Obrebalski, 2017).

Spending on the environment is the cornerstone of its protection and a widely debated issue, focusing primarily on corporate or business spending (Vargas-Vargas et al., 2010) and national spending. Less explored is public expenditure at a regional or municipal level. There are many self-governing entities within one national economy – in the case of Czechia, 14 regions and 6,255 municipalities. The management of these entities causes the duplication of some economic activities and involves additional transactional costs (Pannell et al., 2013). This paper examines how the system of municipal environmental accounting is set up (Hajek, 2003) and its relation to environmental protection (Soukopova and Bakos, 2013) with an emphasis on expenditure (Heideri, 2012) and the possibilities of its evaluation (Sarra et al. 2017). It is possible to use financial indicators and their geographical nature to evaluate the effectiveness and to outline other relevant relationships (Hajkowicz et al., 2005). We see a particular gap regarding our specific research focus on municipal environmental expenses concerning population changes in suburban areas. It is partly discussed in the Czech context with results provided by Maštálka and Valíková (2014). They showed in the Pardubice metropolitan area that there is no statistically significant relationship between population increase in suburbs and the increase of total municipal operating profit/result expected by municipalities supporting the development of residential areas. In Spain, Hortas-Rico (2014) analysed the relationship between urban sprawl and local budget using data from 4,000 Spanish municipalities from 1994 to 2005, concluding that sprawl considerably increases demand for new infrastructure. Gielen et al. (2021) calculated the effect of urban sprawl on the expenditure on public municipal services for 542 municipalities in Valencia, showing highly cost-sensitive items to urban sprawl areas: waste management, water supply and distribution, road cleaning or public lighting. We focused on the costs of suburbanisation involved in local government expenditure directly aimed at environmental protection. Evaluating the impact of suburbanisation on municipal budgets is relatively rare, even though such an approach can be found as far back as the mid-twentieth century (Hawley, 1951). Our approach compared spending by municipalities influenced by suburbanisation with those that are not. This approach united assessments from temporal, spatial and financial perspectives in correspondence with the European Union's emphasis on Territorial Impact Assessment (Camagni, 2009; EU Committee of the Regions, 2015; Nosek, 2017) instruments and allowed the economic valuation of long-term socio-geographic patterns. Thus, our research question corresponds with the local costs to develop and manage new residential areas in the municipalities in the vicinity of metropolitan cores compared to other municipalities. Representatives often disregard these costs with the prospect of higher municipal tax revenues that result from a higher municipal population. From our point of view, the direct environmental costs (shown directly in municipal accounting) of such development are not insignificant, but they can occur with some delay.

Fig. II.1. Change in population density in the period 1991 to 2001 (left) and 2001 to 2011 (right) (in %, CZSO, 1991, 2001, 2011)



Source: Census 1991, Census 2001, Census 2011, own elaboration

2.2. Data and methods

Environmental expenditures aim to prevent or eliminate environmental damage (Soukopová, 2011). Environmental-economic accounting (EEA) provides a conceptual framework for integrating environmental statistics and their relationship to finance. The UN Committee of Experts on Environmental-Economic Accounting (UNICEEA) oversees the System of Environmental-Economic Accounting (SEEA, United Nations Statistics Division, 2016). The introduction of the SEEA to the EU member states in 1993 has meant that the above-mentioned internationally comparable indicators have already been developed (CEPA, SERIEE, 1994, the Classification of Environmental Protection Facilities; CEPF, Eurostat, 2002a, 2002b; Classification of Resource Use and Management Activities and expenditure CRUMA, SERIEE, 2002; Falticeli and Ardi, 2007).

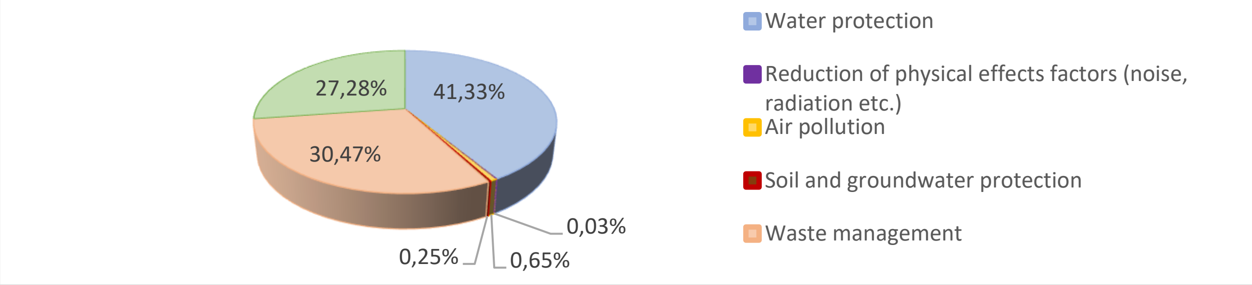
Table II.1. Structure of environmental protection expenditure

Category	Paragraph	Description
Water protection	2321	Drainage and treatment of sewage, sludge
	2322	Prevention of water pollution
	2329	Drainage and wastewater treatment (not elsewhere classified).
	2331	Modifications of water management of watercourses (reconstructions etc.)
	2333	Adjustment of small watercourses
Air protection	2115	Warming and energy-saving programmes
	2542	Meteorology
	3711	Removal of solid emissions
	3712	Gaseous emissions
	3713	Changes in heating technology
	3714	Measures to reduce greenhouse gas production
	3715	Changes in production technologies to eliminate emissions
	3716	Monitoring of air protection
	3719	Other air protection activities
Waste management	2122	Collection and processing of secondary raw materials
	3721	Collection and transport of hazardous waste
	3722	Collection and transport of municipal waste
	3723	Collection and transport of other wastes
	3724	Use and disposal of hazardous waste
	3725	Use and disposal of municipal waste
	3726	Use and disposal of other waste
	3727	Prevention of waste generation
	3728	Waste management monitoring
	3729	Other waste management
Soil and groundwater protection	2342	Anti-rooting protection
	2541	Geology
	3731	Soil and groundwater protection against polluting infiltrations
	3732	Soil decontamination and groundwater purification
	3733	Soil and groundwater monitoring
	3734	Prevention and remediation of salinisation
	3739	Other protection of soil and groundwater
Protection of biodiversity and landscape	1037	Complex socio-economic functions of forests
	2334	Revitalisation of river systems
	3741	Protection of species and habitats
	3742	Protected parts of nature
	3743	Recultivation of land as a result of mining activities
	3744	Anti-erosion, anti-avalanche and fire protection
	3745	Caring for the appearance of villages and public greenery
	3749	Other activities for nature and landscape conservation
Reduction of physical effects factors	3751	Design and application of anti-noise devices
	3753	Monitoring to detect noise and vibration levels
	3759	Other noise and vibration control activities
	3771	Anti-radon measures
	3772	Radioactive waste
	3773	Monitoring to detect the level of radiation
	3779	Other radiation protection activities
Environmental protection administration	3761	Central Government Administration in Environmental Protection
	3762	Other organisations of state administration in environmental protection
	3769	Other ecology management
Other ecological activities	3780	Environmental research
	3791	International cooperation on the environment
	3792	Ecological education
	3793	Environmental programmes in transport
	3799	Ecological issues and programmes

Source: Decree 323/2002 of Ministry of Finance (2017a).

Our research approach corresponds with the most commonly used classification of environmental protection expenditure from CEPA classification (CEPA, SERIEE, Eurostat 1994) regarding Czech specification by types of expenditure created by Soukopová and Bakoš (2013). Reflection of the environmental accounting system in the Czech public accounting system is shown in Table II.1. The dataset used in our study from the State Treasury Monitor of the Ministry of Finance in the Czech Republic (2017b) is based on this accounting scheme. It is our study's critical financial data source. The data presented in Table II.1 covering 2010 to 2015 includes 6,581,924 financial transactions related to self-government expenses and earnings in the Czech 6,255 municipalities. According to the economic importance of the municipal self-government agenda, three principal areas are considered: water protection, waste management and the protection of biodiversity and the landscape. The relevance of these areas is shown in Fig. II.2, which sets out the structure of municipal environmental expenditure. We used the OECD metropolisation database (OECD, 2020) to define three municipal categories: OECD functional urban cores (comprising 15 cities or towns); OECD functional urban hinterland areas (2,480 FUAs); and others (3,760 NON-FUAs). This categorisation allows for identifying the cost differences and answers whether it is more costly for a municipality to be near a metropolitan centre.

Fig. II.2. Share of expenditure on the environment 2010–2015 (%).

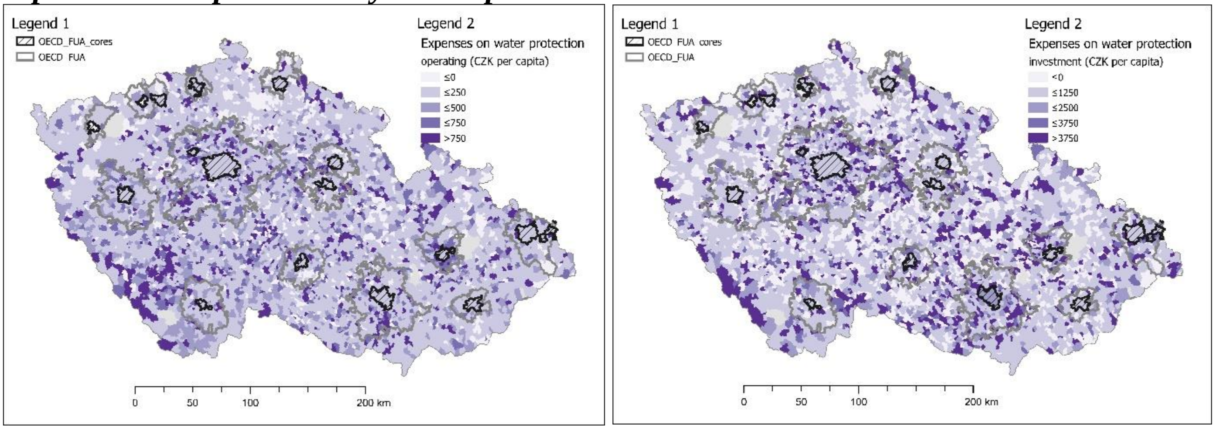


Source: Ministry of Finance (2017b).

2.3. Results

In the following part, we consequently provide results on three key areas where municipalities spend their expenses: water protection, waste management and biodiversity and landscape protection corresponding with municipal public greenery. Water management is becoming a strategic issue for most countries due to resource depletion and continuing metropolisation that creates suburban zones and affects water quality (Yang et al., 2013). Fig. II.3 shows the average municipal operating and investment expenditure on water protection. The black hatched areas at the location of large cities (OECD metropolitan core centres) and their surroundings indicate values up to CZK 250 per inhabitant for operating expenditure and up to 1,250 CZK per inhabitant for investment, the former including around Prague and Brno but not Ostrava. Overall results show that municipalities in functional urban areas (FUAs), on average, pay up to 17% more for water protection than municipalities not situated in FUAs. On the other hand, metropolitan centres pay only 19% as much as NON-FUA municipalities, which means there are large economies of scale. The highest additional costs for suburban water protection are paid near Olomouc (76% more), Prague (50%) and Brno (47%).

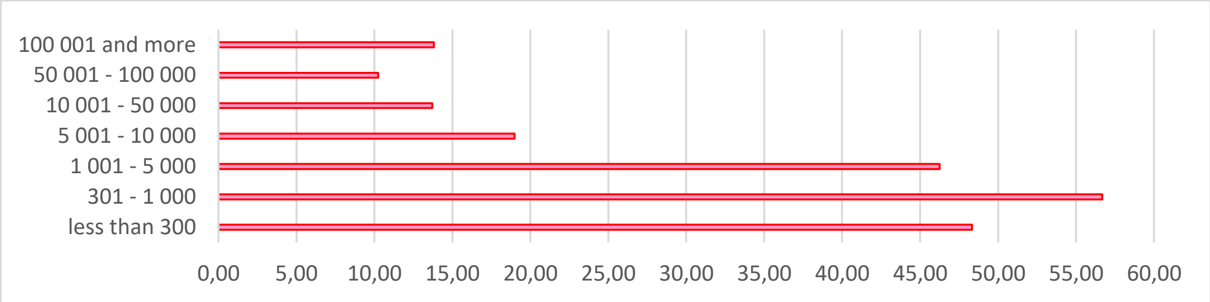
Fig. II.3. Yearly arithmetic average of operating (left) and investment (right) expenditures per capita on water protection by municipalities in Czechia in 2010 to 2015



Source: Eurostat (2020), CZSO (2020), Ministry of Finance (2017b), own elaboration.

The available data show that the expenditure on water protection is inversely related to the municipality's population – the smaller the population, the greater the average per capita expenditure. There is an uneven distribution of municipal size categories, and most municipalities in Czechia are small, with 300 to 1,000 inhabitants. Fig. II.4 shows the average results for all municipalities by size category in 2010–2015, with the link between the municipality's population and the average expenditure per capita. There is a step-change at the 5,000-inhabitant level. Large municipalities spend less per capita on water protection on average due to the fixed costs of constructing wastewater treatment plants; for large municipalities, economies of scale are confirmed.

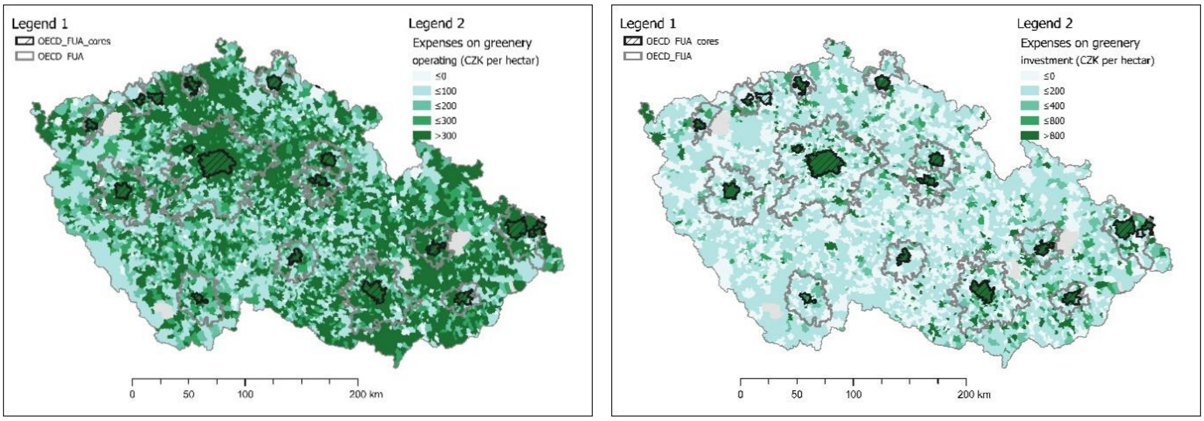
Fig. II.4. The average expenditure per capita on water protection according to municipality population category (EUR).



Source: Ministry of Finance (2017b), CZSO (2020), own elaboration.

The next case is biodiversity protection. FUA core areas and municipalities in urbanised areas spend considerable amounts on public green maintenance to improve people's quality of life and on bio-corridor systems that serve as the green infrastructure (Peimer et al., 2017; Grodzinska-Jurczak and Cent, 2011). Fig. II.5 shows many areas with a zero or very small average amount of operating and investment expenditure on biodiversity and landscape protection, indicating that investment in this category is only a high priority for FUA cores. The overall results on protecting biodiversity and landscape indicate the significance of this environmental component as municipalities in FUAs show 30% more costs, but this significance seems to be restricted to urban centres, which spend 20 times more than non-urban areas.

Fig. II.5. Yearly average operating (left) and investment (right) expenditure per hectare on protecting biodiversity and landscape by municipalities (2010 to 2015)



Source: Eurostat (2020), CZSO (2020), Ministry of Finance (2017b), own elaboration.

Our results regarding expenditure on waste management show that, unlike the previous case study on water protection, this service is provided at a lower cost in functional urban areas (FUAs) compared to NON-FUAs. FUAs provide this service at 1.87% less costly compared to the nationwide municipality average, while for NON-FUAs, it is 1.32% more expensive. The difference is low. The highest costs compared to the municipality average can be found in the following FUA areas: Most (64%), then Zlín (16%) and Chomutov (15%). In Prague, costs are higher but only by about 7%. FUA centres again confirm the importance of economies of scale in providing waste services – they reach an average level of 78% compared to the nationwide municipality average.

Analysis revealed that from 2010–2015, Czech municipalities allocated most environmental spending to water protection, waste management and biodiversity and landscape protection. In contrast, the protection of soil and groundwater, air quality protection and the reduction of physical factors were only marginal categories. The annual total municipal spending oscillated around 18 billion CZK for operating expenditures and 16 billion CZK for investment. Total municipal operating expenditure on environmental protection exceeded the investment amount; the only exception was in 2015, when the investment was higher by about CZK 200 million due to the final draw-down of finance from European structural funds for 2007–2014. Analysis of this expenditure reveals that most of it target drainage and sewage treatment. When constructing wastewater treatment plants, fixed costs are similar for all municipalities, so they are proportionately cheaper for large cities than for less populous municipalities. A point of step-change was found with municipalities with less than 5,000 inhabitants, which showed significantly higher average expenditure. The environmental expenditure for the protection of biodiversity and landscape, meaning care of the area's appearance and public greenery, showed the most significant expenditure in functional urban cores. A different situation was found in the case of waste management. Here, the main expenditure is on waste collection and disposal, which is directly proportional to the amount of waste produced, which depends on the number of residents. The average per capita expenditure on waste management in the municipalities of Czechia was approximately the same for all size categories. The cost of waste management showed a growing trend, which can be expected with increasing consumption and thus increasing waste.

The paper shows a fundamental approach to comparing a large number of municipality budgets and provides an essential evaluation framework that reveals it is possible to increase the quality of municipality financial management not only given "efficiency as doing things right") but also in the view of "effectiveness as doing the right thing" (Drucker's 1967). Our results provide evidence that suburbanisation leads to higher direct environmental costs and burdens municipal budgets in relevant areas over the long term. Public sector representative often disregards this effect. Our findings also show potential in the public sector budgetary framework to find a more effective system of financing environmental services on the municipality level. Simply, general budgetary rules are not respecting significant municipal disparities corresponding with local conditions and population categories. Our results raise some follow-up questions for further research. One of these areas is, of course, analysing an even more extended period of at least one decade between two population Censuses, 2011 and 2021, as a critical research enlargement is also to enrich the analysis of more factors leading to higher costs, such as altitude or slope of the terrain or other relevant costs that correspond with the approach of Guilen et al. (2021).

II. The transport system design and externalities

The second part of the habilitation thesis focuses on transportation system design with emphasis on road transport on inter-metropolitan level of connectivity, with particular emphasis on the environmental externalities of transport caused by air pollution.

3. Assessment of the burden on population due to transport-related air pollution: The Czech core motorway network

The need for human mobility is responsible for many negative environmental impacts, including human health. Negative externalities of transport are one of the crucial issues in environmental discussion and policy. Paper C aims to assess transport externalities related to air pollution from particulate matter (PM10) using the example of the Czech highway D1 in 2007–2016. The geographical assessment method distinguishes varying elevations in which different buffer zones are identified to assess PM10 concentration changes according to distance from the road. An econometric analysis then discusses the resulting relation between PM10 and highway proximity. In the final step, we assess the size and demographic structure of the population affected by the highway PM10 pollution, and we compare several evaluation methods to assess related morbidity. The results show falling levels of PM10 pollution, not only with increasing distance but also in intertemporal comparison, with concentrations lower by 2μg.m3 in the 2012–2016 period than in 2007–2011 despite increasing road traffic on the highway, which means both a very significant reduction in the number of cases and economic value.

3.1. Background

The context of assessing the external effects of transport is primarily related to construction and maintenance. The most crucial benefits concern the time saved and improvements in the overall level of accessibility (Martens and Di Commo, 2017; Forslund and Johansson, 1995). Cost-benefit analysis (CBA) is considered to be one of the best possible methods for transport project assessment, and it generally provides significant results for differentiated transport solutions. CBA is used differently according to country and policy-making decision processes (Hansson and Nerhagen, 2019). Recently, the emphasis on long-term strategic planning in the EU was enriched by a territorial impact assessment (TIA; 2020), which makes it possible to measure the regional impacts of strategic planning. However, Czechia still needs to introduce this instrument as an integral part of the general planning process. Instead, it is used only for separate assessments of regional development, regardless of whether it involves environmental or transport policy. The application of CBA is a critical way that can provide better results in long-term transport project assessment because it provides a way to integrate CBA with a TIA (2020) approach, emphasising dynamic and long-term data (Schade and Rothengatter 2003). This approach is used to assess specific problems linked to road transport and human health (de Campos et al., 2019), such as noise (Serrano-Hernández et al. 2017; Hammer et al. 2014) and air pollution (Watkiss et al. 2001; Rotaris et al. 2010, Le Boennec 2017, Cavallaro et al. 2018). The research focus is usually in the field on air transport emissions (Monks et al., 2009), but for human health, the concentration of pollutants in the environment is crucial.

According to the World Health Organization (WHO, 2000), common pollutants from transport include nitrogen dioxide, ozone, other photochemical oxidants, particulate matter, and sulfur dioxide. In our paper, we focus on PM10, which is considered one of the primary pollutants (Maibach et al., 2008), usually bounding polycyclic aromatic hydrocarbons (PAHs) (Yin and Xu, 2018) and suggested as a suitable pollution indicator by Künzli et al. (2000). Based on the WHO (2000) recommendation, we did not set any lower limit for PM10 to indicate the level of pollution that is detrimental to health. Adverse effects on health have been observed at levels not far from natural background concentration values of about 6 μg/m3 (Correia et al., 2013). Many epidemiological studies have demonstrated negative health consequences from excessive PM10 in the child and adult populations (Kirshnan et al., 2019; Sánchez et al., 2019; Gouveia et al., 2018; Künzli et al., 2001; Abbey et al., 1999; Englert, 1999). The most frequent impacts of PM10 are related to cardiovascular, respiratory, cancer, and cerebrovascular effects, which are manifested in increased morbidity and mortality. A long-term concentration of particulate matter is associated with natural-cause mortality (Beelen et al., 2014), especially for cardiovascular disease mortality or morbidity (Kirrane et al., 2019; Dabass, 2018; Haikerwal et al., 2015; Mills et al., 2009; Metzger et al., 2004). PM10 also has respiratory health effects that can lead to increased mortality and morbidity (Kim et al., 2018; Mathew et al., 2015; Gehring, 2013; Hoek et al., 2012; Zanobetti et al., 2009; Ostro et al., 2005). A relationship has also been shown between exposure to PM10 and cancer, primarily lung cancer (Dimitriou and Kassomenos, 2018; Raaschou-Nielsen et al., 2013; Pope et al., 2002; Nyberg et al., 2000) and cerebrovascular disease (Wettstein et al., 2018; Staffogia et al., 2014; Zhang et al., 2011; Torén et al., 2007). Meisner et al. (2015) assessed the magnitude of health impacts and economic costs of fine particulate matter pollution in Macedonia using Disability-Adjusted Life Years (DALYs). Martinez et al. (2018) obtained particulate matter concentration data from air quality monitoring stations in the Skopje metropolitan area, applying relevant concentration-response functions and calculating the burden of disease and societal mortality cost attributable to particulate matter. Künzli et al. (2000) and Seethaler et al. (2003). estimated the impact of outdoor traffic-related air pollution on public health in Austria, France, and Switzerland, using attributable cases of morbidity and mortality. The often used is the health impact assessments (HIA) method in the area of traffic air pollution (Khreis et al. 2018, Tobollik et al. 2016, Chartasa and Gibson 2015, Boldo et al. 2006). Korzhenevych et al. (2014) consider the following two studies on the assessment of the external costs of transport to be essential at the European level: HEATCO – Developing Harmonised European Approaches for Transport Costing and Project Assessment (Bickel et al., 2006) and CAFÉ CBA – Clean Air for Europe Cost-Benefit Analysis (Hurley et al., 2005), which were evaluated in the HEIMTSA project – Health and Environment Integrated Methodology and Toolbox for Scenario Assessment (Friedrich et al., 2011). Both studies use the impact pathway approach, which was developed under the External Cost of Energy project (ExternE), with its own “ExternE Methodology” calculating external environmental costs (Bickel and Friedrich, 2005). The impact pathway analysis identified the most significant impacts of emissions, their quantifiability and the monetary valuation of costs. The main emphasis in this field of research is focused on the emission measuring approach, while our study brings a concentration-based approach. The research objective is to assess the effect of road transport on air pollution considering accurate spatiotemporal characteristics with impacts on population morbidity regarding the demographical structure and, finally, bringing monetised values determined by PM10 concentration changes.

3.2. Data and methods

The research approach lies in assessing ten years of the Czech core highway D1 and its traffic-related air pollution, as indicated by PM10, emphasising long-term trends. Using the example of Czech core highway D1, this paper seeks to establish the long-term influence of road traffic on health precisely. The average daily intensity of vehicles on the D1 highway is around 38,000 cars per day, with certain parts exceeding 100,000 vehicles per day (RSD, 2016). The first methodological point outlines the specific geographical route of Czechia's most significant highway, the D1, connecting three main urban areas: Prague, Brno, and Ostrava (RSD, 2010). The D1 highway is an incomplete road project, with one part currently under construction between Říkovice and Lipník nad Bečvou (a segment of approximately 25 km is routed on first-class road number 47 which was included in the study). We defined four distance zones to compare variations in PM10 concentrations based on distance from the D1 highway. The first zone was designated as the 100-meter distance zone (intersected area). It is based on a significant reduction in PM10 exposure at a distance of 100 m (Karner et al., 2010). The second distance zone is 250 m (neighbouring area) based on Yazdi et al. (2015) precise analysis of distance from highway exposure depending on wind speed and rain circumstances, demonstrating that high-speed wind (velocity >10 m/s) might raise PM10 concentration to a distance of roughly 250 m, after which it begins to drop. The third distance zone of 500 m (closer burdened area) is used under the European Commission (2019) approach in the development of a methodology to assess populations exposed to high levels of noise and air pollution close to major transport infrastructure (Ritchie et al., 2006). The last category defines the average pollution level in the appropriate geographical location with a 2,500-meter distance zone (broader areas). The following methodological step uses a static approach to determine the relevant impacted population (Mommens et al., 2019). We performed this identification based on the 2011 Population and Housing Census (CSO, 2011), which provided the most thorough information based on population in basic units of settlement (22,505 units in Czechia) according to the census registry's cadastral regions (CSO, 2018). Then we intersected the D1 motorway-defined zones with the residential cadastral areas of individual basic settlement units to identify the affected population, including the demographic structure. In contrast, the dynamic approach reveals that commuting during the day varies but is primarily directed towards larger cities in their proximity (Census, 2011). As a result, our final estimate of long-term exposure may be slightly underestimated.

The critical methodological step lies in the pollutant concentration analysis based on the historical data on long-term air pollution focusing on PM10 (CHMI, 2018) from 2007 to 2016. These datasets provide long-term averages of pollutant concentrations in the grid network. Datasets are based mainly on the Air Quality Monitoring System (CHMI, 2019). These data are processed in three dispersion models, one Gauss model SYMOS (CHMI, 2017, defined in Decree No 330/2012 of the Ministry of Environment) and two Euler method-based models following the dispersion approach according to the methodology of Kuenen et al. (2014). These three dispersion models are used in the Czech national REZZO pollutant categorisation system. The outcomes include a countrywide grid network for PM10, PM2.5, benzopyrene, nitrogen oxides, ground-level ozone, benzene, heavy metals, and sulfur dioxide. We isolated PM10 concentrations and overlapped the Czech grid network with appropriate distance zones and residential areas. The following numbers of concerned basic settlement units were obtained for distance zones: the 100-meter zone contained 820 residential areas, the 250-meter zone included 1,011 locations, the 500-meter zone included 1,293 areas, and the 2,500-meter zone included 2,640 areas.

In the next step, we investigated whether roads influenced PM10 air pollution concentrations, principally using the indicator of transport intensity (Transport Census, 2010 and 2016). We intersected 22,505 basic settlement units in Czechia with the Transport Census based on 54,944 traffic counting sections and 80,151 pollution monitoring polygons. The final detailed dataset concerning traffic, air pollution, and population provides 271,882 local observations. To explain the significance of the model, we ran a multivariate regression analysis where the explained variable is an average annual concentration of PM10 particles from 2012 – 2016 (PM10_rp). Other factors, including traffic intensity, population, population density, and average altitude, were explanatory variables (US EPA, 1978; Hoek et al., 2008). The power of influence of the non-standardised regression coefficients is estimated by controlling the effect of other independent variables in the model (Mareš et al., 2015). We can formally write the multiple regression model as:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \varepsilon_n \quad (1)$$

where Y is a dependent variable, b_0 is a constant, b_1, b_2, b_3 are regression coefficients, X_1, X_2, X_3 are independent variables, and ε is random error.

Parameters are estimated by the ordinary least squares method:

$$min\ \sum(Y_i - \beta_0 - \beta_1 X_{i1} - \ldots - \beta_n X_{in})^2 \tag{2}$$

This method aims to find those parameters β (estimates for b) for which the error term is minimized:

$$\hat{\beta} = \min_{\beta} \sum_{i=1}^{n} (y_i - \beta_0 - \beta X_i)^2 = \min_{\beta} \sum_{i=1}^{n} \varepsilon_i{}^2 \tag{3}$$

Finally, we determine significant PM10 health consequences based on population groups and distance zones. We derived the essential consequences on the long-term health impact of PM10 from three European studies using the exposure-response function (ERF cases / (year · person · µg / m3)]. We used their monetary valuation per case or day based on individual health effects and risk groups to determine the health impacts on the population living near the D1 motorway, focusing on acute and chronic morbidity. These studies are the following: EEA 2013 (European Environment Agency) - Road user charges for heavy goods vehicles (HGV) - EEA Technical Report 1/2013 (Andersen, 2013); HEIMTSA (Health and Environment Integrated Methodology and Toolbox for Scenario Assessment) - EU Sixth Framework Program, runtime 2007–2011 (Friedrich, 2011); HEATCO – Developing harmonized European approaches for transport costing and project assessment, 2006 (Bickel et al., 2006). An overview is given in Table III.1 (Korzhenevych et al., 2014).

Table III.1: Description of priority health effects

Health effect	Notes
Chronic bronchitis	change in new persistent cases per year per 10 µg/m^3 PM_{10}
Respiratory hospital admissions	change in attributable emergency admissions per 10 µg/m^3 PM_{10}
Cardiac hospital admissions	change in attributable emergency admissions per 10 µg/m^3 PM_{10}
Restricted activity days (RAD)	change in RADs per year per 10 µg/m^3 $PM_{2.5}$ amongst the working-age population
Respiratory medication use among adults	change in the probability of daily bronchodilator usage per 10 µg/m^3 PM_{10}
Respiratory medication use among children	change in the probability of daily bronchodilator usage per 10 µg/m^3 PM_{10}
Lower respiratory symptoms (LRS)	increase in the average daily occurrence of LRS (including cough) per 10 µg/m^3 PM_{10}
Bronchodilator use	change in the probability of daily bronchodilator usage per 1 µg/m^3 PM_{10}

Source: Andersen, 2013; Friedrich, 2011; Korzhenevych et al., 2014; own elaboration

The following formula (Bickel and Friedrich, 2005) is used to calculate the increase in the impact of air pollution from traffic on the population:

$$\Delta I = \sum s_i\ \Delta c_i \tag{4}$$

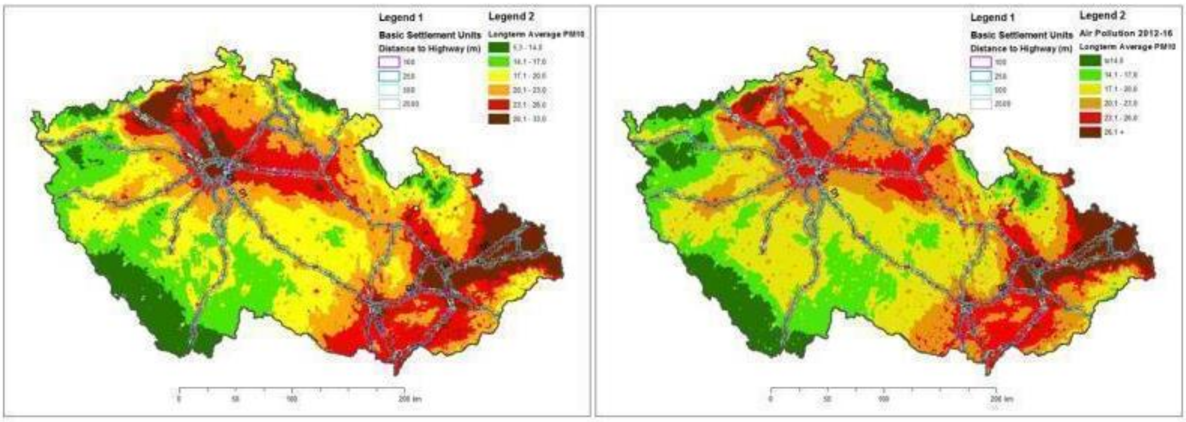
I is case per year per average person. The c_i is PM_{10} concentration, and s_i is the slope of ERF.

We converted this result into Czech prices for 2017 expressed in euro (based on the ExternE methodology). We considered inflation with the EU harmonized consumer price index (Eurostat, 2018) and the exchange rate based on the PPP-adjusted exchange rate (OECD, 2018).

3.3. Results

Figure III.1 shows all the basic settlement units affected by the motorway infrastructure close to the intersection (zones 100/250/500/2,500 m) with the motorway network. In individual risk areas, there are residential zones of about 6,000 (100 m zone), 14,000 (250 m zone), and 31,000 (500 m zone) residents affected by increased air pollution due to the motorway. The results show a slight improvement in air quality in terms of PM10. This improvement amounts to about 2 μg/m3 over ten years. The improvement is reflected in Table III.2, which shows the difference in the degree of pollution between the individual distance zones (100/250/500/2,500 m) and the different comparison periods. Long-term improvements are seen for all distances (with an overall improvement of 7.56% on average). The improvement when comparing 2007–2011 and 2010–2014 is, on average, 0.71%. However, when comparing the 2012–2016 period and 2010–2014, there is an average improvement of 6.89%. In the same period, the Traffic Censuses for 2010 and 2016 show the average traffic intensity increased from 33,544 to 38,025 cars a day, an increase of 13.36%.

Figure III.1: Basic settlement units according to the distance from the motorway network and PM_{10} pollution in 2007–2011 vs 2012–20116



Source: own elaboration

Table III.2. The concentration of PM_{10} ($\mu g.m^3$) in the vicinity of the D1 motorway and its decrease (in %)

Period	Zone				Difference with zone 2,500 m		
	100 m	250 m	500 m	2,500 m	100 m	250 m	500 m
2007–2011	27.105	27.050	26.799	26.033	1.072	1.017	0.766
2010–2014	26.862	26.712	26.667	25.978	0.884	0.734	0.689
2012–2016	25.097	24.972	24.624	24.203	0.894	0.769	0.421
Period differences			**100 m**	**250 m**	**500 m**	**2,500 m**	**Average**
2010–2014 vs 2007–2011			0.90%	1.25%	0.49%	0.21%	0.71%
2012–2016 vs 2010–2014			6.57%	6.51%	7.66%	6.83%	6.89%
2012–2016 vs 2007–2011			7.41%	7.68%	8.11%	7.03%	7.56%

Source: own elaboration

Considering only PM_{10} concentration and traffic intensity, the observed improvement achieves a pollutant decrease weighted by traffic intensity of 18.95%[2]. However, more factors influence pollutant concentration, so we cannot attribute this improvement only to transport.

We ran a multivariate linear regression analysis to determine the impact on the level of PM10 air pollution with these variables: transport intensity (trans_int), the population in the vicinity of road infrastructure (popul_num), population density in the area of 500 m (popul_dens), and average altitude (alt_avg). To fulfil the assumption of normality, variables were logarithmised. The results show that a set of estimated independent variables explains 53.1% of the variance of the dependent variable. According to the F Test in one-way analysis of variance, we can reject the null hypothesis about the insignificance of the model. In other words, the model including these variables is useful. According to the model results (Table III.3) the average value of air pollution by PM_{10} particles should be 26.654 $\mu g/m^3$. Coefficient B represents the influence of the independent variable on the dependent variable. We see a

[2] According to the 2010 level of pollution and pollutant concentration, the expected pollutant concentration with the 2016 traffic intensity level corresponds to 30,379. But the real concentration is 24,624, which means an 18.95% improvement.

positive relationship between the PM10 concentration and transport intensity and population density and a negative relationship between the PM10 concentration and average altitude and population. According to the standardised beta coefficient, average altitude is the most critical indicator influencing PM10 concentration. 53.1% of the variance in the average PM10 concentration near road infrastructure in Czech data is explained by studied variables.

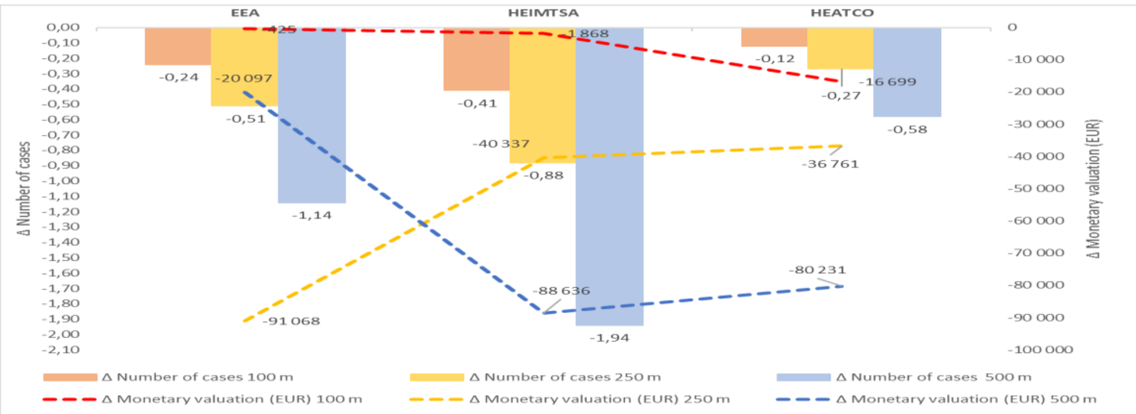
Table III.3: Model Results

	Unstandardized Coefficients		Standardized Coefficients			95 % Confidence Interval for B	
	B	**Std. Error**	**Beta**	**t**	**Sig.**	**Lower Bound**	**Upper Bound**
Constant	26.654	0.063		420.395	0.000	26.530	26.778
Trans_int_ln	0.518	0.007	0.115	78.102	0.000	0.505	0.531
Popul_num_ln	-0.050	0.002	-0.034	-22.715	0.000	-0.054	-0.045
Popul_dens_ln	0.401	0.004	0.171	108.512	0.000	0.394	0.408
Alt_avg	-0.022	0.000	-0,617	-427.798	0.000	-0.022	-0.022

Source: own elaboration

Figure III.2 declares that the decrease in concentration has a significant effect on the reduction of cases of chronic bronchitis. From the results, we can deduce that reducing PM10 in the air by 1 µg/m3 will reduce cases or days of all health endpoints and monetary costs by 4%. Even though we observed long-term improvements in air pollution, the resulting condition still carries high economic value. The results of our study show that the PM10 concentration during the reference period, comparing the average of 2007 – 2011 and 2012 – 2016, has decreased on average by 2 µg/m^3. This positive change brought a reduction in the number of cases and days of health endpoints and associated monetary values. A relatively small change in PM10 concentration significantly changes the number of cases and days in most health endpoints and monetary values, decreasing the financial burden between EUR 485,056 and 842,891 (in Czech prices of 2017) per year. Thus, monetised costs related to chronic bronchitis mean a monetary decrease in the range of EUR 33,400 to 85,000 a year in the zone up to 100 m, EUR 73,600 to 182,000 and in the zone up to 250 m, and EUR 160,400 to 202,000 in the zone up to 500 m.

Figure III.2: 1 µg/m^3 improvement change of PM$_{10}$ concentration in the number of cases of chronic bronchitis and associated monetary valuation in Czech prices of 2017 in euro



Source: own elaboration

Künzli et al. (2000) used a similar approach to estimating the air pollution health impacts in three European countries. They modelled population exposure for each square kilometre with traffic-related fraction separation and concluded that the public-health consequences are considerable. Ostro and Chestnut (1998) showed that decreased PM10 concentration has substantial health benefits. Danielis and Chiabai (1998) estimated the cost of air pollution imposed by various types of vehicles in urban areas in Italy through increased premature mortality from exposure to suspended particulate matter derived from the exposed population multiplied by the statistical value of life. Using the unit values of various health endpoints of morbidity and mortality, Guo et al. (2010) computed the economic costs of transport-related air pollution in Beijing. Similarly, using high-density PM10 and population data, Hou et al. (2016) assessed the effect of PM10 on human health in Beijing from 2008 to 2012. They estimated the average economic cost of five years inside the most urbanised ring road was USD 4.55 billion. Mueller et al. (2017) emphasised health costs of exposure caused by transport could be avoided with exposure recommendations. Regarding the research limits, it is necessary to consider the quality of secondary data used for both air pollution and traffic intensity. We used the most precise territorial units statistically monitored in Czechia (basic settlement units). Population data are based on the 2011 Census (CSO, 2011). A further limitation comes from the actual daily mobility and temporality because inhabitants may commute to work in another settlement unit and not be exposed to the highest emissions in their place of residence. A related limitation is the accuracy of the extrapolation air pollution model, as the measuring station is not always located near the road. Regarding air pollution assessment regarding human health, the results of our study are limited by several factors. We took into account the linear exposure-response function, resulting in equally significant gains in the number of cases of health endpoints, even though a non-linear relationship is observed in reality (e.g., Liu et al., 2014), which may also vary due to air pollution mix, climate, and the health of the population (Samoli et al., 2006). Exposure-response functions were then taken from particular epidemiological studies (recommended projects HEATCO, EEA, and HEIMTSA), which do not reflect the detailed specific socio-demographic characteristics of the population in the area, but only relevant target age groups.

Although there is no safe, acceptable threshold of PM10, neither is there any generalised approach to PM10 limitation worldwide; there are different recommendations and regulatory frameworks. However, results show that decreases in PM10 concentration lead to lower morbidity rates and decreases in relevant health symptoms with significant annual cost savings in healthcare systems. Since 2005, the WHO has recommended a limit of 20 μg/m3 annual mean, and 50 μg/m3 24-hour mean (WHO, 2006), while European Air Quality Standards are even stricter and define the limit as 40 μg/m3 per year (EU, 2008). The US EPA cancelled the annual limit established in 1987 at 50 μg/m3 in 2006, leaving only a daily limit (US EPA, 2020). A very similar situation is in Japan (MOE, 2020). This study found that high PM10 concentrations along the D1 highway substantially influence morbidity in the affected population, implying a significant cost burden. The existence of highways with traffic intensity from 30,000 to almost 100,000 cars a day near residential areas decreases air quality concerning PM10 in the range of 0.421 to 1.072 μg/m3 compared with the outer zone of 2,500 m. The abovementioned impact is relevant for at least 30,868 inhabitants living less than 500 m from the D1 highway. A long-term comparison of 2007–2011 and 2012–2016 shows a decrease between 7.41% and 8.11%. Policy recommendations can be aimed at long-term reductions in air pollution exposure through various tools, such as incorporating health information into the impact assessment of infrastructure projects (Seethaler et al. (2003) or applying the polluter-pays principle by internalising the externalities. Furthermore, the COVID-19 crisis showed through mobility changes the total potential of transport improvements relevant to air quality (decreases of PM10, PM2.5, and nitrogen oxide, which should be studied further (Collivignarelli et al. 2020).

III. The mobility behaviour and policy

The last part of the habilitation thesis is based on assessing mobility behaviour in passenger transport concerning individual preference variability and its reflection in intermodal choice (with emphasis on the shift to rail). Finally, this part finishes with the transport policy design assessment presented by robust discount schemes for particular modes of transport.

4. Competition in long-distance transport: Impacts on prices, frequencies, and demand in the Czech Republic

Paper D assesses different entry regulations' effects on company conduct and mobility behaviour. The paper reflects three railway markets with significantly other entry policies using data on prices and frequencies and a survey conducted to obtain revealed preferences. The study employs data from the three main routes in Czechia. The two open-access markets tended to provide significantly higher connection frequencies than the line with regulated entry did. Surprisingly, low price variation across the rail and bus markets suggests low monopoly power for the monopolised incumbent and its uniform price strategy across markets with different entry regulations. Conversely, high price sensitivity among travellers confirms the substance of intramodal competition.

4.1. Background

Open access competition on the railway is gradually becoming more widespread, especially after the Fourth Railway Package of the European railway reforms (European Commission, 2016), mainly in Central Europe. The market structure is slowly changing, as is passenger behaviour. This ongoing process of deregulation and market restructuring offers a unique opportunity to compare markets with different levels of transformation. However, the railway industry has several specifics. Therefore, it is necessary to be careful about the impacts of competitors on the market and demand. First, intramodal and intermodal competition plays a vital role in transport behaviour. Therefore, the regulated entry in the case of one transportation mode can be partially offset by deregulation in other modes, which is often the case for intercity bus and railroad competition. Second, vertical integration of railways and high fixed costs can make entries socially undesirable. Third, from the traveller's perspective, rail services will always remain heterogeneous due to such factors as the importance of departure times. Therefore, some non-zero market power always exists and may be challenging to regulate if desired. For these reasons, open access for railroads remains the subject of ongoing discussion. The Czech transportation market provides a specific opportunity for cross-section comparison due to the variability of competition across different routes. The markets to compare include the following long-distance transport routes. The Prague–Ostrava market has been a competitive open access line since 2011, including three train providers (Czech Railways, RegioJet since 2011, and LeoExpress since 2013). The Prague–Brno market is a case of intermodal competition. It has represented a mixed market since 2016, with the incumbent providing public service obligation (PSO) services and open access competitor RegioJet operating at its own risk (and also providing bus services via the parallel motorway in competition mainly with FlixBus). The last market Brno–Ostrava, was operated as a PSO by a state-owned company (Czech Railways, in December 2019, the incumbent Czech Railways was replaced on this line by RegioJet). This paper aims to analyse the effects of different types of railway competition on firms' conduct and travellers' behaviour using price and frequency information together with elasticity analysis.

Several studies have analysed free entries on railroads and their effect on the given market. Almost all of these studies have confirmed a positive effect from competition on prices, higher service quality and product differentiation – Cascetta & Coppola (2013), Bergantino et al. (2015), Beria et al. (2016), and Desmaris & Croccolo (2018) for Italy; Tomeš et al. (2016) for Czechia; Kvizda & Solnička (2019) for Slovakia; Tomeš & Jandová (2018) for Czechia, Slovakia, and Austria; and Vigren (2017) for Sweden. However, competition is not the only factor determining prices, but also demand, capacity or willingness to pay (Beria & Bertolin, 2019). Competition also contributed to increased ridership (Fröidh & Nelldal, 2015). Accusations of unfair practices were not rare: price war in Czechia (Tomeš et al., 2016), Slovakia (Kvizda & Solnička, 2019), and Austria (Tomeš & Jandová, 2018) or political action in Poland (Król et al., 2018). On the other hand, Bergantino et al. (2015) do not find evidence of predatory pricing by the incumbent, and Desmaris & Croccolo (2018) show that there is no blatant evidence of anti-competitive behaviour against the new operator in Italy. However, lower prices meant slowly growing revenues, which can cause problems with profitability. Pressure on infrastructure capacity and the coexistence of open access and PSOs are other significant problems (Tomeš & Jandová, 2018). These case studies' findings align with the modelled situation for a duopoly market in Broman & Eliasson (2019), finding equilibrium with one dominant firm holding more than two-thirds of the market. Such asymmetry stems from the natural differentiation of companies through the heterogeneity of departure times. However, such an outcome is still preferable concerning overall welfare compared to a profit-maximising monopoly. On the other hand, Wheat et al. (2018) found cost disadvantages for firms operating in open-access markets, which stemmed from both comparable costs for franchised operators and the loss of the advantage to profit from increasing returns to scale common to monopolised markets and partially confirmed in a market with three competitors (Tomeš et al., 2016). Fares (Finez, 2014; Paulley et al., 2006), travel time or speed (Behrens & Pels, 2012; Fröidh, 2008), comfort (Fröidh & Byström, 2013, Allard & Moura, 2018), safety (Si et al., 2009), frequency (Raturi & Verma, 2019, Paulley et al., 2006), income (Toro-González, et al., 2020), the opportunity to work (Varghese & Jana, 2018), congestion (Droes & Ritvield, 2015), capacity (Daly et al., 2014), and station location and parking availability (Eagling & Ryley, 2015; Pagliara et al., 2012) have been among the most important factors that influence passengers' choices. Yen et al. (2018) emphasised trip and socio-demographic characteristics, frequency, transfer need, and easier accessibility. Ben-Akiva & Morikawa (2002) discussed traffic congestion and parking space shortages. Attitudes and perceptions have also affected how individuals choose between different transport modes (Bahamonde-Birke et al., 2014). Rail and bus intermodal competition led to price decrease on routes with intermodal competition compared to monopolistic routes (Gremm, 2018). In Aarhaug et al. (2018), competition from low-cost air carriers was significant for long-distance coach lines, whereas improved road infrastructure and rail services led to increased competition from private cars and rail for shorter coach lines. Beria et al. (2018) showed that intermodal competition matters. The bus routes overlapping with rail PSO are priced less, but interestingly this happens also for high-speed lines in Italy, which means that the two markets are not independent. In France, the level of intermodal long-distance passenger competition among coaches, BlaBlaCar, highspeed rail, and low-cost airlines is high (Crozet & Guihéry, 2018). New deregulated bus services represent only about 2% of long-distance transport, but intramodal competition is solid. Burgdorf et al. (2018) analyse long-distance bus services in Germany and show that price, speed, reliability, convenience, and luggage carriage are the most critical determinants of modal choice.

Most papers analysed the effects using individual case studies of a single route or by analysing partial characteristics of the examined markets. Paper contributes to the existing empirical literature on competition and regulatory effects in long-distance passenger transport by comprehensively analysing the effects of different regulatory regimes and competition, with the regulatory framework as an essential element. Therefore the research question is to determine what effects bring open access to railways and how different institutional frameworks influence the behaviour of competitors and travellers from intermodal and intramodal points of view.

4.2. Data and methods

We carried out a survey collecting data on passengers' mobility choices. We gathered data on prices and frequencies, and departure times for three different markets with different regulatory regimes to analyse the firm's conduct. Then we carried out elasticity analysis using discrete choice models. Furthermore, we used mobile operator data to verify our survey sample composition. The first step was based on frequency and price data collection for the relevant transport markets during the same period from 9 November to 22 November 2019. We collected standard ticket purchases without any special tariffs or discounts. The data set consists of more than 12,000 bus and train connections and ticket prices on the relevant routes provided by Czech Railways, RegioJet, LeoExpress, and FlixBus. We merged these data with the mobility survey to adjust for possible changes from special tariffs because the Czech Ministry of Transport guaranteed a level of senior and student discounts on public transport tickets of 75%. The mobility survey aimed to identify the factors determining the use of a particular transport service by inspecting passengers' preferences. The survey results served as feedback on the opinions, attitudes, and reasons why passengers "choose" or "do not choose" a specific mode of transport or company. The survey was conducted via systematic sampling, arranging the study population under selected routes and modes during October and November 2019. Interviewers collected data via face-to-face paper and pen interviews localised in trains and buses or at train stations, bus stops, or motorway rest areas. In the case of bus and train passengers, there were two phases of field data collection. In the first phase, the form and content of the questionnaire were verified by a pilot survey of fifty passengers. In the second phase, the survey was conducted using an optimised questionnaire. In the case of modal choice focused on car passengers, there were also two phases, but with a different designs. The data collection was followed by verification with 10% of car respondents. Randomly selected respondents were queried through telephone inquiries and e-mail correspondence based on screening questions to select respondents who had been on a car journey on a relevant route (Prague–Brno, Brno–Ostrava, or Prague–Ostrava) within the previous 14 days. Our research comprises data for three train operators and two bus operators. The original sample achieved 1,887 respondents, but the final sample with complete answers reached 1,521 responses; thus, the error rate was less than 20% of the sample.

We used a standardised methodology of discrete choice models (Greene, 2009; Tomeš & Fitzová, 2019) concerning different numbers of alternatives. All of our models were based on logistic regressions: Brno–Ostrava (BRQ–OSR; binary logistic regression), Prague–Ostrava (PRG–OSR; McFadden's conditional logistic regression), Prague–Brno (PRG–BRQ; nested multinomial logistic regression). The monopolised line Brno–Ostrava had the simplest model. The single alternative train (the choice) was predicted relative to individual car transportation, which was the unchosen alternative. Therefore, the model is closed in the sense of travelling, and we did not consider outside alternatives, comprising people currently not travelling at all. The Prague–Ostrava market was modelled with McFadden's conditional logistic regression (McFadden, 1973). The three alternatives (trains) compete within the line; therefore, a binary choice is no longer relevant. There are two options to model such a market. The more common option is multinomial logistic regression, which is focused on the individual unit and uses only the individual's characteristics to explain a choice. The less common is conditional logistic regression (Hoffman & Duncan, 1988). The second option has two independent variables: alternative-specific (varying across and within cases, e.g. price) and case-specific (constant within cases, e.g. travel purpose). Our explanatory variables included both types and so we used the conditional option. The last market, Brno-Prague, according to the well-known problem of the independence of irrelevant alternatives (McFadden, 1974), can be solved by grouping similar alternatives into groups or nests. There are two bus alternatives and two train alternatives. This methodological approach was standardised based on the available literature, such as Koppelman & Bhat (2006) and applications in Forinash & Koppelman (1993) and Polydoropoulou & Ben-Akiva (2001). Finally, the elasticities were calculated the same way across different models. First, the original fitted values and adjusted fitted values were calculated. In the case of price elasticities, all observations were adjusted by increasing price and frequency by 1%. The individual elasticity for the given mode and company was then calculated by subtracting the original and adjusted fitted value. The market elasticities for transport mode were calculated as the average across individual elasticities. In our research, the elasticity analysis represents a means of identifying the relationship between the level of competition on the markets and behaviour using revealed preferences obtained through a survey of all analysed markets. Due to the different specifications of the models, the predictors differed slightly. We generally controlled for mode and company-specific variables, including ticket price and frequency. Elasticities were calculated concerning these variables. The model specification for the last market did not enable frequency use. The existing alternative to Czech Railways between Brno and Ostrava was only car transport, which is inconsistent with any frequency information. Second, the socio-demographic characteristics were specific to individuals and did not vary across modes or companies. The variables of travel purpose and passenger travel frequency were used in all three models. In addition, the Prague–Brno model used the highest completed education to better distinguish among the available options. Last, the need to change was captured as a dummy variable at the departure, the origin, or both. Detailed variable descriptions are in Table IV.1.

Table IV.1: Variable description

	Individual specific	Alternative specific	Variable description
Ln_price	Yes	Yes	Log of price in EUR, adjusted for discounts
Ln_frequency	Yes	Yes	Log of number of connections per day
Old_X_public	Yes	Yes	Interaction variable 1 for people born before 1977 and using Czech Railways at the same time, otherwise 0.
One_day_travel	Yes	No	1 if travel duration < one day, otherwise 0
Origin_change	Yes	No	1 if origin municipality for traveller is not equal to resident municipality for traveller, otherwise 0
Destination_change	Yes	No	1 if destination municipality for traveller is not equal to resident municipality for traveller, otherwise 0
Change	Yes	No	1 if destination or origin municipality for traveller is not equal to resident municipality for traveller, otherwise 0
Weekend	Yes	No	1 if day of travel is Saturday or Sunday, otherwise 0
Travel purpose fixed effects	Yes	No	A) Business trip; B) travel to work; C) study; D) family, friends; E) tourism – 1 day; F) tourism – overnight; G) private affairs; H) other
Education fixed effects	Yes	No	Elementary, secondary without qualifications, secondary with qualifications, tertiary
Travel frequency fixed effects	Yes	No	4+ times per week, 2–3 times per week, once per week, 1–3 times per month, 2–10 times per year, once per year

4.3. Results

Regarding prices, the route from Prague to Ostrava shows the most significant price volatility. This is an important finding because this passenger transport market is the only fully open

Czech train market. The price strategy of LeoExpress was the most flexible, and prices varied between 1 and 7 euro cents per km, while those of the incumbent and RegioJet were mostly 3.5–4 euro cents per km. The lowest volatility was observed on the Prague–Brno route for trains and RegioJet buses, especially compared to the more flexible FlixBus. Operators offered different types of services. Czech Railways' fast trains offered second, first, and business classes. RegioJet offered four services: Low cost, Standard, Relax, and Business. LeoExpress provided Economy, Business, and scarce Premium tickets, thus excluded from the sample. The inclusion of tariffs, discounts, and classes had a substantial impact on the minimum and first quartile prices, which were much lower than standard tickets, possibly due to the composition of the population sample. LeoExpress prices showed the narrowest interquartile range and the highest final ticket price per kilometre, as students and seniors represented a minimal share of the passengers. In summary, almost one-third of passengers took advantage of 75% discounts. In addition to prices, the frequency of connections is another essential variable influenced by the level of intramodal and intermodal competition and the openness of the railway markets. On average, there was a train or bus connection every 20 minutes between Brno and Prague and every 32 minutes between Prague and Ostrava but only every 74 minutes between Brno and Ostrava.

Table IV.2 Estimation results

Variable	**Company/mode**	BRQ–PRG		PRG–OSR		OSR–BRQ	
Ln_price		−1.575**	(0.73)	−0.565***	(0.212)	−1.749***	(0.435)
Ln_frequency		0.35	(0.38)	1.176***	(0.278)		
Old_X_public		0.607***	(0.203)				
One_day_travel	Bus	−0.704***	(0.165)				
Origin_change	Bus	−0.299*	(0.166)				
Constant	FlixBus bus	−1.952**	(0.85)				
Constant	RegioJet bus	−1.851**	(0.836)				
Constant	RegioJet train	0.249	(0.463)				
Tau	Bus	0.983	(0.778)				
Tau	Train	0.603**	(0.239)				
Origin_change	LeoExpress Train			−0.275	(0.368)		
Destination_change	LeoExpress Train			−2.965***	(0.684)		
Weekend	LeoExpress Train			−0.435	(0.329)		
Constant	LeoExpress Train			0.718	(0.485)		
Origin_change	RegioJet Train			0.403	(0.376)		
Destination_change	RegioJet Train			−0.833*	(0.427)		
Weekend	RegioJet Train			−0.084	(0.262)		
Constant	RegioJet Train			0.005	(0.426)		
Change	CD Train					1.419***	(0.519)
Constant	CD Train					1.895**	(0.953)
Observations		3,036		1,584		205	

*Note: standard errors in parentheses; asterisks (***, **, and *) correspond to the significance level (1%, 5%, and 10%, respectively).*

Table IV.2 presents estimations for the final models. The Brno–Prague market model contains both mode-specific and company-specific variables. The variables are interpreted in comparison to a benchmark, which is the omitted option in all three cases. For example, the statistically significant variable One_day_travel refers to trips shorter than one full day. These consumers had lower utility for using the bus than the train. The constants were significantly lower for both bus options compared to Czech Railways trains. In the case of RegioJet trains, the constant utility was higher but not statistically significant. The constant utility could, with some caution, be interpreted as unobserved comfort. Lastly, the parameter Tau in the case of the nested version of the discrete choice model, captures the dissimilarity between options (companies) in the specified groups (modes). Tau is always lower than one, although for the bus mode, it was close to one (however, statistically insignificant), which can be interpreted as showing a high dissimilarity between bus alternatives. Model for Prague–Ostrava market shows that in both cases, the constant was not significantly higher in comparison to the state-owned provider. Except for the variable Destination_change, all of the other predictors were not significantly different from zero. For both private companies, consumers had significantly lower utility when there was a change in destination. Model for Ostrava–Brno market does not show the binary variables for travel purposes and travel frequency. Contrary to expectations, the need to change at the destination or origin positively affected the traveller's utility, which the poor alternatives can explain. Thus, the time schedules of regional trains are smoothly integrated with the schedule of fast trains.

The coefficients for prices and frequencies from Table IV.2 provide little explanatory value due to unobserved and individual-specific utility. Therefore, the market demand elasticities for travel alternatives were estimated. Table IV.3 gives the calculated elasticities for price. Three interesting results are observed. First, intermodal competition seems to have had a stronger effect on the elasticity of demand than another intramodal competitor did. Second, the results do not provide any sign of brand loyalty on the part of consumers. Third, the market power of the incumbent within the Brno–Ostrava connection seems to have been low regarding price. Even though elasticity analysis is not stand-alone proof of any of these conclusions and requires separate investigation, the direct- and cross-price elasticities are essential indicators of the findings. Regarding elasticities concerning frequency, percentual changes of connections by a 1% increase for FlixBus connections on the Prague–Brno route would increase the company's market share by 0.25%. Such an increase would reduce the market shares of RegioJet buses by 0.10%, RegioJet trains by 0.07%, and Czech Railways by 0.09%. In this case, the elasticities for the Prague–Brno market are not statistically different from zero. The elasticities for the Brno–Ostrava market were not estimated due to the model specification. In general, the lower the frequency was, the higher the elasticity of change was. Therefore, even though we cannot estimate elasticity for frequency for the Brno–Ostrava line, the expectation would be findings of a highly elastic market.

Table IV.3 Elasticities with respect to price (frequency)

Company/Route	FlixBus	RegioJet bus	RegioJet train	Czech Railways
BRQ–PRG				
FlixBus	−1.12 (0.25)	0.47 (−0.10)	0.32 (−0.07)	0.30 (−0.07)
RegioJet bus	0.44 (−0.10)	−1.15 (0.26)	0.30 (−0.07)	0.28 (−0.06)
RegioJet train	0.29 (−0.07)	0.29 (−0.07)	−1.68 (0.37)	0.74 (−0.16)
Czech Railways	0.39 (−0.09)	0.39 (−0.09)	1.05 (−0.24)	−1.33 (0.30)
PRG–OSR				
Czech Railways	−0.28 (0.58)	0.20 (−0.42)	0.22 (−0.46)	
LeoExpress train	0.10 (−0.20)	−0.40 (0.84)	0.11 (−0.24)	
RegioJet train	0.18 (−0.38)	0.20 (−0.42)	−0.33 (0.69)	
OSR–BRQ				
Czech Railways	−0.38			

The results for prices and frequencies for different entry setups provide a surprising contradiction. First, we observe little variability in price across markets with significantly different market structures, but the frequencies vary significantly across markets. There is almost no geographic price discrimination from the incumbent Czech Railways (expecting the uniform price strategy). Together with conditions based on PSOs, this leaves very little space for price manoeuvres by the incumbent on the monopolised Brno–Ostrava market. Therefore, we did not observe higher prices (on average) within the monopolised market compared to more competitive routes. However, the connection frequency is a different story. There was significant variation in the number of connections across markets, which aligns with previous findings of equilibria with one dominant firm (most likely the incumbent) and smaller entrants. Not only was the number of connections per day higher in the case of open access routes, but also, more of the day was served. This suggests that players tended to compete for both peak and off-peak times. The elasticity analysis of market demand both confirmed previous findings and opened new questions. First, the lack of differences in price elasticities between the monopolised market and the market with three railway companies confirmed the results of the price analysis itself (little price discrimination and overall low market power on the monopolised Brno–Ostrava market). However, there was a striking difference in price elasticities between the Prague–Brno and Prague–Ostrava markets. Three possible reasons are discussed here. First, the price war on the Prague–Brno line occurred before the survey, which may have contributed to travellers' price sensitivity. Second, the intense competition on this route was even intensified by equally tough competition between bus alternatives. Finally, on average, there were 82 connections between Brno and Prague during a regular workday. Thus, a specific connection has minimal market power, generally due to departure time differentiation. Therefore, market demand was highly elastic to price even for negligible changes. The market structure enabled us to test for consumers' brand loyalty. However, we did not find any tendency to prefer a brand alternative to a mode alternative from a competitor.

We have comprehensively analysed the effects of different entry regulations on competition and travellers' decision processes with the example of three different Czech lines, which differed significantly in railway entry policies and market structure. Moreover, intramodal competition with bus alternatives further intensified the intense railway competition in the Prague–Brno market. Our findings align with the existing literature describing the positive effect of railway competition on consumers. However, we could not find significant price level differences across markets with varying entry regulations. We believe that this is an effect of the low monopoly power of the incumbent Czech Railways. It seems that the incumbent's pricing policy does not distinguish between routes. Given the estimated price elasticity, the policy is not profit-maximising. The pricing strategy is based on what is fair rather than what is profitable, making it seem unacceptable to discriminate by the route. On the other hand, we identified a clear relationship between entry setup and increased connection frequency. Both findings are further supported by estimated market demand and firm-specific elasticities. In the case of price sensitivity, there seems to have been a significant effect from the intramodal competition. Furthermore, intense competition increased the number of connections per day significantly. In summary, the paper contributes to the existing empirical literature on the competition and regulatory effects in long-distance passenger transportation. The paper has the potential to provide new arguments for ongoing policy discussions on trade-offs between open access regimes and more traditional regulation on railways. Moreover, by collecting a vast amount of supplementary data on prices and frequencies, together with conducted surveys, we fulfil the existing gap in the academic literature on comparisons of markets under different regulatory regimes.

5. Fare Discounts and Free Fares in Long-distance Public Transport in Central Europe

Free fare transport schemes have been increasingly used in many cities. They are utilised to stimulate public transport market share and promote transport equity and justice. These policies have been applied in two countries in Central Europe on the national level. The authorities in Slovakia and Czechia have introduced generous fare discount policies for long-distance transport which is the crucial subject of Paper E. Slovakia has launched free rail fares for children, students, and pensioners since November 2014. Czechia has introduced 75% discounts for the same target groups but for both trains and buses from September 2018. These schemes are unique in their broad coverage and application to long-distance transport. These policies were motivated by social, transport, and political factors, but the social goals dominated. This article aims to review ridership and the development of modal shares due to these policies. The results show that policies significantly increased ridership and the modal share of railways. The mobility of the targeted groups was significantly affected, and the share of young and elderly riders increased. However, the policies were costly and had some undesirable side effects that could have been prevented by better policy design.

5.1. Background

Policymakers are trying to diminish car usage and promote public transport through various measures to struggle with congestion and environmental issues. The much-debated factors in promoting public transport usage are fare discounts and free-fare schemes. Slovakia and Czechia recently introduced ambitious fare policies in long-distance public transport in 2014 and 2018. Thus, it is now possible to analyse what effect these measures have had on the market and determine whether they meet their goals. These policies were not designed only to reach higher public transport usage. Their main aim was to improve mobility for younger and elderly people and achieve higher equity and justice in access to transport services. These policies are costly, and there has been an ongoing debate about their effectiveness. We aimed to assess the consequences of these policies. Our analysis focused on: transport volumes, modal shares, changes in mobility among different groups, and the total cost. Our paper contributes to the existing literature by comparing two wide-scale policies' impacts. Due to their recent implementation, they are not systematically captured in the academic literature and are unique in their nationwide coverage.

Fare reduction policies aim to make transport cheaper, improve its affordability, and stimulate ridership. However, the crucial issue is the price elasticity of demand in long-distance travel. Based on the existing evidence, short-run elasticity is relatively low, in the range of 0.2–0.4 (Baum 1973, Scheiner – Starling 1974, Litman, 2004, Paulley et al. 2006, Oum et al. 1990, Ivaldi – Seabright 2003). Long-run elasticity is higher, usually in the range of 0.6–0.9 (Litman 2004, Paulley et al. 2006, Ivaldi – Seabright 2003). Recent estimates of price elasticity from the rail market in Czechia were identified in the range of 0.6–1.7 (Fitzová et al. 2021). However, elasticities are of limited value when it comes to radical changes, and existing research has also suggested that price is not the most critical factor determining transport ridership. The most significant factors are service quality, time, route, and status attributes. Switching car users has been particularly problematic, as it has been argued that negative fares would have to be introduced to motivate car users to change (Baum 1973). The general conclusion is that forcing significant ridership changes through fare declines is difficult and costly, and especially car users are hard to persuade (Wardman et al. 2018, Fearnley et al. 2017). However, these studies did not distinguish the price elasticity of younger and elderly people. There are cases where fares in public transport were abolished; for example, Studenmund – Connor (1982), who described the result of a free-fare experiment in Trenton, New Jersey (US), where off-peak bus fares were eliminated. The authors claimed that net ridership went up by 15% (off-peak ridership by 45%). De Witte et al. (2006) analysed the impact of free fares in Brussels on the included and non-included populations. They concluded that residential determinants were more important than fares. Van Goeverden et al. (2006) focused on motives for introducing free fare by presenting four urban case studies from Belgium and the Netherlands. The free-fare experiment in Tallinn showed that general ridership went up by 14%, specific groups of youth by 21%, and elderly by 19% (Cats et al. 2017). Tomanek (2017), Štraub (2019) and Štraub – Jaroš (2019) reviewed the introduction of free-fare schemes in municipalities in Poland and analysed the four key areas that municipalities try to influence through free fares. There has been a program of free fare for old-age pensioners in the UK that is well established and covers both rail and bus travel modes (Kębłowski 2019, Fearnley 2006). An inspiring case is Luxembourg, where a free-fare system was introduced nationwide, including metro, rail, and buses (Carr – Hesse 2020).

Some attempts have been made to conceptualise these findings from case studies dedicated to free-fare systems. Perone (2002) analysed the advantages and disadvantages of free fares in three areas: costs and impacts on transit service and quality of service distinguishing temporary and permanent systems. She concluded that a free-fare policy could be recommended for smaller systems, but whether it could be recommended for larger systems is questionable. Storchmann (2003) pointed out that the reasons for introducing free-fare schemes (in Germany) were mainly environmental to change the modal shift. Kębłowski (2019) analysed the broader consequences of free-fare public transport, distinguishing partial and complete free-fare systems, including economic, sustainability, and politically transformative aspects. He concluded that it could not be analysed as a sole transport instrument. Baum (1973) argued that launching free fares has two goals: to overcome income inequality and relieve traffic congestion. However, the diversion factor from cars is usually only 15–20%, and it seems that the more effective method to reach the stated goals is to improve the quality of public transport. Scheiner – Starling (1974) analysed the political economy of free-fare transport, arguing that four issues are critical: demand elasticity and responsiveness, the costs and financial sources, the benefits, and the political feasibility. Fearnley (2013) analysed the impact of free-fare policies on modal shares regarding other policy goals (economic, political, and environmental). He argued that although these policies seem attractive, their goal achievement rate is poor and comes at high costs. The effects on car ridership are marginal and typically offset by a few years of growth. Successful free-fare traffic schemes are those that concentrate only on public transport ridership growth. Other goals are best achieved with targeted measures. Thus, the critical parameter is how free fares and discounts have contributed to transport equity and justice. Church et al. (2000) distinguished seven social exclusion factors related to transport: physical, geographical, services, economic, time-based, based on fear, and based on space management. There is significant research on the issue of transport poverty (see Banister 2018, Mattioli 2016), but it tends to concentrate on short-distance travel and long-distance travel is significantly less covered. Existing research has concentrated on mobility differences for different classes (Cass et al. 2005) and their environmental impacts (Ivanova – Wood 2020). The temporality issue is also crucial (Moyano – Dobruszkes 2017). Free fare schemes' distributional and equity impacts are an evolving issue and deserve further investigation. The application of free fare schemes to long-distance transport nationwide is unique and has not been applied (except for Luxembourg). We aimed to analyse the impact of this unique system on ridership and modal shares.

Launching these nationawide systems started in Slovakia that became, on 17 November 2014 (symbolically International Students' Day and Struggle for Freedom and Democracy Day), a pioneer in providing free transport for selected population groups on a national scale, but only for rail and only for public-service obligations (PSOs; mostly the incumbent operator ZSSK with the single exception of RegioJet on the Bratislava–Komárno line). The launch of free-fare rail discount scheme (Table V.1) was presented as a fulfilling political strategy for Prime Minister Robert Fico's Implementation of Financial, Economic and Social Measures in Rail Passenger Transport (Government of the Slovak Republic 2014a).

Table V.1. Rail Discount Scheme in Slovakia

Group	**Original tariff** (before 17 November 2014)	**Discounted tariff** (after 17 November 2014)
Child/student		
0–5 years	50% discount (ticket needed)	100% discount (no ticket needed)
6–14 years	50% discount (ticket needed)	100% discount (ticket needed)
Student		
15–26 years	50 % discount (student ID needed)	100% discount (student ID needed)
Elderly	**70+ years;** around 80% discount according to train and class (or €0.15 for each 50 km)	**62+ years** 100% discount (senior ID needed)

Data sources: Government of the Slovak Republic (2014a); ZSSK (2014); ZSSK (2021).
Note: Discounts valid only on ZSSK trains for 2nd class tariffs (not valid on IC trains, nor RegioJet or Leo Express trains).

In March 2018, the Czech government approved a proposal to introduce 75% fare discounts on buses and 2nd class trains for specific groups (Government of the Czech Republic 2018). Table V.2 reflects the system of discounts eligible for the elderly, children and students under 26. Before the start of the discount policy, children and students already had discounts limited to journeys between their residences and the location of their school. Newly they received a discount for any long-distance route at any time of the year. The state also continues to order a 100% discount on fares for children under 6.

Table V.2 Rail Discount Scheme in Czechia

Group	**Original tariff** (before 1 September 2018)	**Discounted tariff** (after 1 September 2018)
Child/student		
0–5 years	0–5 years 100% discount (maximum of 2 free-fare children)	100% discount if accompanied by a person at least 10 years old (maximum of 2 free-fare children); 75% discount otherwise
6–14 years	50% discount (student ID card) 62.5% discount specific route (student ID card)	75% discount (student ID not needed – no confirmation of age)
Student		
15–26 years	40% discount (ID card)	75% discount (ISIC or student ID needed)
Elderly		
65+ years	50% discount (ID needed; up to 2011) 25% discount since 2012 (open-access lines excluded)	75% discount (ID needed)

Data sources: Government of Czechia (2018); ČD (2018, 2021).
Note: Discounts are valid since 1 September 2018 for all public transport, buses, and trains at 2nd class tariffs (2nd class for ČD; low-cost, standard, and relax for RegioJet; and economy for Leo Express).

5.2. Data and methods

We first analyse the development of total ridership using passenger-km and changes in railway modal share on the passenger market. We further analyse the composition of travellers regarding age and fare type used, i.e. children and students, pensioners, and standard-fare adults, based on detailed data from both national rail operators. Finally, we assess the fiscal consequences, focusing on how revenues from fares, PSO compensation, and compensation for fare discounts have developed. Finally, we discuss future sustainability and compare the two countries approaches. To identify the long-term impacts of discounts on the transport market, we use standard data from Eurostat (2021). As our primary data on ridership and finances, we work with both Czech Railways (České dráhy, a.s.; ČD) and the Railway Company of Slovakia (Železničná spoločnosť Slovensko, a. s.; ZSSK) company yearbooks (ČD 2010–2019; ZSSK 2010–2019) including profit and loss statements. We identify the yearly amount of PSOs and other compensation from the Ministry of Transport. Consequently, we use Finstat's (2021) data in Slovakia to analyse the financial impacts on the bus market. We checked the discount systems on their websites (ČD 2021, ZSSK 2021) and official government documents and press releases where the changes were defined when discounts were launched (Government of the Czech Republic 2018; Government of the Slovak Republic 2014a, 2014b; ZSSK 2014; ČD 2018). We used official government press releases, press conferences, and news in traditional media to analyse the social and political context. We use official Czech Transport Yearbooks (Transport Yearbooks 2010–2019) to identify regional differences in ridership.

5.3. Results

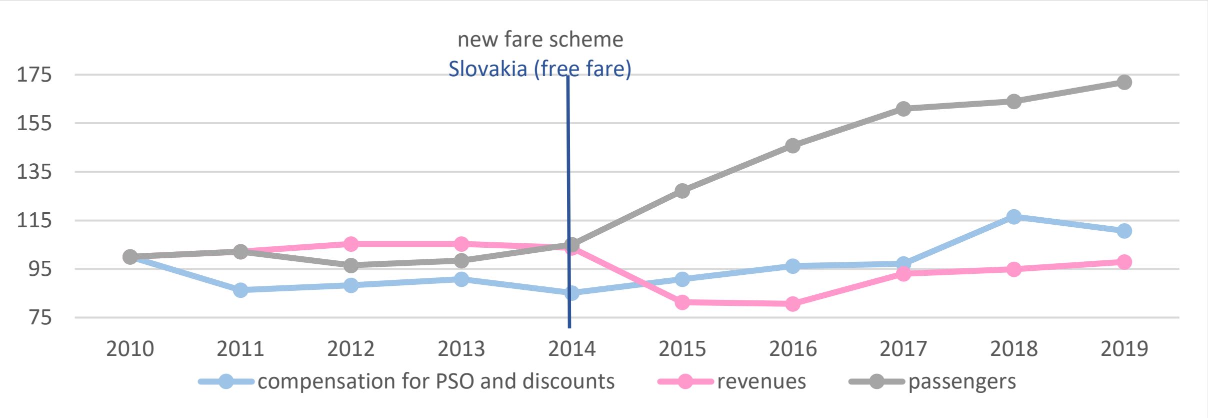
The results show that the total growth in ridership in the passenger rail market during the entire period of interest was much higher in Slovakia and Czechia than in the EU-28. The Czech transport market grew from 2009 to 2018 at an average rate of 5.2%. Slovak market growth was slightly higher at 5.9%, while EU-28 growth was only 1.6%. In particular, a sharp jump in Slovakia appeared in 2015 when the free-fare policy was introduced. The modal share of passenger rail transport in the EU-28 was nearly the same during 2010–2018 (around 7.5–8%). However, the development in both Czechia and Slovakia is different. Two reasons are identifiable – first, the entries of new competitors (in 2011 on the Prague–Ostrava line and in 2016 on the Prague–Brno line in Czechia; in 2012 on the Prague–Ostrava–Žilina–Košice line in Slovakia); second, the introduction of fare discounts. However, the exact shares of these two factors are not easy to distinguish. There is head-on competition on two main routes – with the two operators Czech Railways and RegioJet competing on the Prague–Brno line (Tomeš – Fitzová 2019) and even three operators (Czech Railways, RegioJet, and Leo Express) operating on the Prague–Ostrava line (Tomeš – Jandová 2018). The impact on the rail share of free fares in Slovakia is noticeable (from 7.3 to 9.3%, accompanied by a car share drop of almost 2%). The changes in modal shares in passenger railway transport and the number of passengers are positive in both countries, which implies that a similar goal may be achieved in different ways.

Regarding ridership, the total number in Slovakia increased in the launch year of 2014 by nearly 7%, followed by more than 21% in 2015, 15% in 2016, and 10% in 2017. The senior passenger group in Slovakia grew by about 349% from 2013 to 2019, of which the initial change from 2013 to 2015 covered 248%. Student travel rose from 2013 to 2019 by 126%, while the initial change was almost 88%. In Czechia, the total ridership grew, but Czech Railway's market share decreased because demand was partly diverted to other new operators. The last year of 2019 (the first complete year with the implemented discounts) had a growth rate of 1.62%. The number of students and children was decreasing by 1.11% per year before

2018. This trend changed in 2018 when the number grew by 13% and then even by 44% in 2019, so the total increase from 2017 to 2019 was 63%. Before the discounts were implemented, the number of seniors was decreasing by 9.48% per year, but this number increased by almost 16% in 2018 and by more than 24% in 2019, which means the overall increase from 2017 to 2019 was 44%.

However, it is also necessary to consider the financial costs of those approaches as they differed significantly. The results show that PSO and free-fare compensation from the Ministry of Transport to the Railway Company of Slovakia varied throughout the period. While the sum of both (PSO and discount) compensations stagnated or slightly decreased on average by 1.5% during 2010–2014, it increased more than four times during 2015–2019. The change in 2015 is worth mentioning. Revenues from domestic and foreign passenger tickets decreased by EUR 19.2 million (meaning 22%; in domestic transport, 27%), compensated for by an increase in PSO and other compensation by EUR 13.5 million. Comparing the last year without discounts (2013) with the last year of the relevant period (2019) reveals a decrease in revenue from both domestic passengers and passengers abroad (EUR 1.4 million) accompanied by a substantial increase in PSO and discount compensation (reaching EUR 66.1 million). Figure V.1 captures the significant increase in passengers and compensation and a sharp decrease in total revenues in the first two years after introducing the free-fare scheme, followed by a slight increase in the next three years. In 2019 the revenues are still below the level of the year 2014. The critical point is the overall financial impacts on the bus sector in Slovakia, represented by the 15 members of the Slovak Bus Association. In 2013, total revenues were EUR 141 million (FinStat 2021), but these bus companies' "revenues from sales of own products and services" gradually decreased to EUR 119 million in 2019 (a decrease of more than 15%).

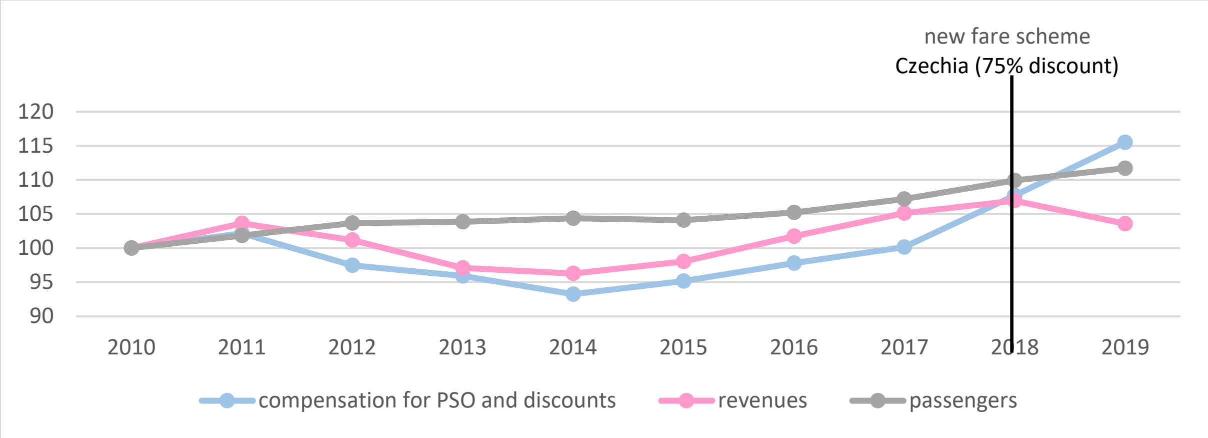
Figure V.1 Financial impacts and rail passengers in Slovakia (index; 2010=100)



Data source: ZSSK (2010–2019), Eurostat (2021)
Note: Adjusted for inflation using the Harmonised Index of Consumer Prices.

The experience is very recent in Czechia, so it is impossible to compare long-run effects over a five-year horizon as in Slovakia. Figure V.2 shows the overall impacts on PSO and other discount compensation, revenues, and passengers in the period indexed to 2010. We can only observe the immediate effects as the only year with 75% discounts is 2019. The compensation for discounts grew more sharply than it did in Slovakia, and revenues from passengers abroad increased in 2019. The public compensation for discounts during 2010–2017 was, on average, over EUR 1 million per year. In 2018, which includes four months of effective fare discounts, there was a sharp increase in public compensation to more than EUR 28 million, then in 2019, an increase to EUR 90 million. At the same time, PSO compensation was stagnating, so the fiscal effect of the new discounts is visible. Furthermore, compensation for Czech Railways is strictly related to the number of student and senior tickets sold. There is no compensation for losses from previous years, as in the Slovak case. A common feature for both cases is immediately falling revenues from domestic transport; however, accompanied by increasing revenues from international transport in Czechia. The difference between Slovakia and Czechia lies in the sharp compensation increase in Czechia, where the original level was almost zero.

Figure V.2. Financial impacts and rail passengers in Czechia (index; 2010 = 100)



Data source: ČD (2010–2019), Eurostat (2021)
Note: Adjusted for inflation using the Harmonised Index of Consumer Prices.

Introducing free fares in Slovakia and fare discounts in Czechia has made public transport in both countries more attractive and more used. On the other hand, Czech and Slovak fare levels are lower than those in Western Europe, even when corrected for lower economic levels and purchasing powers. Both countries' low absolute fare levels diminished the potential of free fares or fare discounts. Nevertheless, the existing monetary costs may still have been high for some population groups. In this respect, the free-fare policy in Slovakia may have had better starting conditions because the fare decrease was higher, and purchasing power was lower. Therefore, out-of-pocket outlays for public-transport fares constituted a higher proportion of disposable income.

In addition to the differences in the total fare discounts (100% vs. 75%), the crucial difference lies in coverage. Slovakia included only trains, not buses, significantly affecting the entire transport market. The bus market was hit hard with an outflow of passengers, a worsening financial situation, and reduced long-distance services (zeleznicne.info 2017). The preference for rail over a bus in Slovakia had some unintended consequences helping marginalised groups with access to the rail network. However, it has worsened the accessibility for people reliant on bus transport. The policy design in Czechia seems to be more sophisticated. However, both designs did little to differentiate between peak and off-peak travel and had no stimulation for travel from or to disadvantaged regions. Thus, the potential of these policies to mitigate inequalities in access to transport services was not fully utilised. The fiscal costs of these policies were significant; however, they are manageable in the context of the total subsidies for rail/public transport. The policies successfully increased total ridership, especially ridership among the targeted groups of elderly and young people. However, whether subsidising fares is the best way to help them with their mobility is still an open question. In conclusion, the policies aimed at supporting public transport only and did almost nothing to accompany this measure to decrease the attractiveness of individual car transport.

Conclusion

In conclusion, this habilitation thesis seeks to contribute to sustainable transport planning in the context of metropolisation tendencies manifested globally, macro-regionally, regionally and locally. At these different levels, metropolisation raises different challenges in terms of research niches and policy implications. The need for transport is one of the basic needs of the human population, which is at the same time one of the necessary but not sufficient conditions for economic development at the global, international or regional level. However, the way of meeting this need is changing along with the changes in society as a whole, whose preferences are influenced by urban lifestyle trends with the possibility of cross-border mobility for work and leisure, but all this in the knowledge of climate change and the overall impact of transport on the living environment of people spending most of their lives in metropolitan centres or their hinterland. Therefore, the development of sustainable transport systems raises challenges in the field of research on transport between metropolises and in the connectivity of the metropolis with its hinterland, as well as in their interconnectivity. However, in order to make policy recommendations, it is necessary to take into account not only the planning of infrastructure with very long-term implications for the future development of transport systems but also how these systems are operated or regulated, which must take into account the preferences and behaviour of residents and passengers.

This habilitation thesis focuses on the interrelationship of the formation of an internationally integrated economic space and their mutual influence on the design of transport systems taking into account infrastructure and traffic, with a focus on the economic assessment of the environmental impacts of these processes and capturing changes in passenger preferences shaping the demand for specific modes and means of transport. Such a focus is always central to successful policy formulation, which may, however, operate concerning the nature of supply and demand ex-post and ex-ante. The following research challenges occur from work presented in this thesis regarding potential future challenges. In particular, the identification of long-term changes in transport demand from the perspective of longitudinal studies and focusing on changes in people's preferences over their individual life cycle to evaluate the significant factors that influence their mobility and residential behaviour. Because residential behaviour is the determinant of commuting behaviour, i.e. the precondition for regular commuting demand, which creates significant transport demands, especially in terms of spatial distribution and temporality, on the other side of this process is the stage of regulatory or supportive public policy instruments and the evaluation not only of their immediate response but also of their long-term impact, including the inclusion of long-term and broader economic costs that may not be obvious at first sight when implementing a given instrument, at all levels of the urban system, i.e. international, taking into account the border effect in transport, national, targeting the interconnectivity of the most important economic areas, and local, responding primarily to the distribution of the population in the metropolitan core-hinterland context.

Authorship contribution statements

Here relevant author contribution statements according to relevant papers are listed.

A. The Metropolisation Processes: A Case of Central Europe and the Czech Republic

List of authors: Milan VITURKA, Vilém PAŘIL, Petr TONEV, Petr ŠAŠINKA a Josef KUNC.

Author´s contribution share: 20 % (corresponding author).

Author´s relevant contribution is: Resources; Data curation; Investigation; Formal analysis; Writing – original draft; Writing – review & editing.

B. The cost of suburbanization: spending on environmental protection

List of authors: Vilém PAŘIL, Barbora ONDRŮŠKOVÁ, Aneta KRAJÍČKOVÁ a Petra ZELENÁKOVÁ.

Author´s contribution share: 45 %.

Author´s relevant contribution is: Term; Conceptualization; Funding acquisition; Project administration; Supervision; Methodology; Resources; Data curation; Investigation; Formal analysis; Validation; Visualization; Writing – original draft; Writing – review & editing.

C. Assessment of the burden on population due to transport-related air pollution: The Czech core motorway network

List of authors: Vilém PAŘIL a Dominika TÓTHOVÁ.

Author´s contribution share: 50 %.

Author´s relevant contribution is: Term; Conceptualization; Funding acquisition; Project administration; Methodology; Resources; Data curation; Investigation; Validation; Visualization; Writing – original draft; Writing – review & editing.

D. Competition in long-distance transport: Impacts on prices, frequencies, and demand in the Czech Republic

List of authors: Hana FITZOVÁ, Richard KALIŠ, Vilém PAŘIL a Marek KASA.

Author´s contribution share: 33 %.

Author´s relevant contribution is: Term; Conceptualization; Funding acquisition; Project administration; Supervision; Resources; Data curation; Investigation; Validation; Visualization; Writing – original draft; Writing – review & editing.

E. Fare Discounts and Free Fares in Long-distance Public Transport in Central Europe

List of authors: Zdeněk TOMEŠ, Hana FITZOVÁ, Vilém PAŘIL, Václav REDERER, Zuzana KORDOVÁ a Marek KASA

Author´s contribution share: 32,6 %.

Author´s relevant contribution is: Conceptualization; Funding acquisition; Data curation; Formal analysis; Investigation; Visualization; Writing – original draft; Writing – review & editing.

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