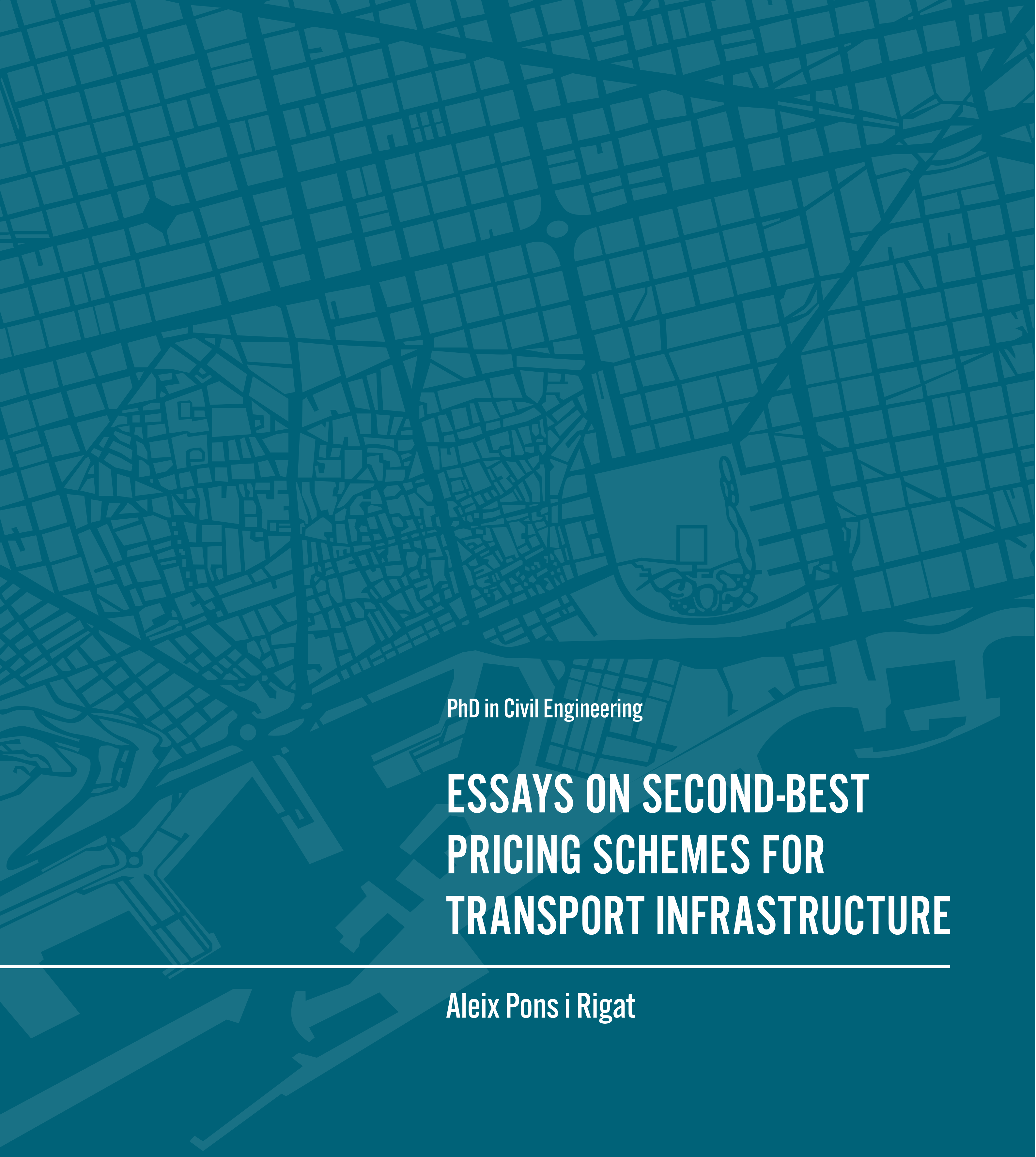

PhD in Civil Engineering

ESSAYS ON SECOND-BEST PRICING SCHEMES FOR TRANSPORT INFRASTRUCTURE

Aleix Pons i Rigat

Universitat Politècnica de Catalunya
Barcelona, 2021

PhD Programme in Civil Engineering

Essays on second-best pricing schemes for transport infrastructure

Doctoral thesis by: Aleix Pons i Rigat

Thesis advisor: Dr. Mateu Turró Calvet

Thesis co-advisor: Dr. Sergi Saurí Marchán

Department of Civil and Environmental Engineering.

Universitat Politècnica de Catalunya

Barcelona, June 2021

Abstract

Pricing has been advocated for a long time as a suitable policy instrument to deal with transport externalities. Recent technological developments enable the implementation of more sophisticated pricing schemes at affordable transaction costs. However, policy makers face numerous constraints and conflicting policy objectives when putting transport pricing schemes into practice. Second-best analysis of specific case studies contributes to translating insights from pricing theory into practical advice in policy design and evaluation. It is in this spirit that this thesis focuses on some critical second-best issues for the definition of transport pricing schemes with three different essays.

There is a strong interdependence between travel behaviour and land use, particularly in urban environments. This causes frictions between pricing instruments to deal with urban transport externalities and other distortions within the urban economy, notably agglomeration economies and urban sprawl.

The first part of the thesis studies this second-best issue in the context of the application of workplace parking policies in Barcelona. The effects on the urban economy of policies addressing current inefficiencies around employer-paid parking are studied through a stylised microeconomic model and a numerical illustration for the metropolitan area of Barcelona. The analytical model indicates that a switch to employee-paid parking has a positive effect on agglomeration economies and urban sprawl, even in dense cities with underground parking facilities. Results from the numerical application suggest that welfare gains from a switch to employee-paid are dominated by

agglomeration effects and to a lesser extent by transport and land use effects. The benefits of a workplace parking levy, however, depend on the extent to which costs are passed on to employees.

The implementation of environmental pricing schemes that favour cleaner traction options in mass public transport often faces a classic dilemma: the internalisation of environmental costs by public transport operators might cause a modal shift towards individual transport forms with a higher environmental footprint.

The second part of the thesis analyses this second-best issue for environmental rail access charges in Europe. Current noise and pollution rail charges implemented in Europe are analysed qualitatively in order to determine the extent to which they address second-best best issues of the rail market, including potential modal shifts to road transport and its imperfectly competitive environment. This analysis suggests that the level of environmental surcharges can be generally increased given the relatively low substitutability between rail and road and that the range of abatement possibilities should be enlarged by further differentiating charges.

Whilst road pricing in urban environments is essentially used to deal with urban traffic externalities, the application of road tolls at regional or national scale is often rather seen as a financial instrument. In this sense, the design of road pricing schemes for interurban networks should balance financial and demand management objectives, and consider public acceptability conditions, such as spatial equity.

The last part of the thesis looks into this second-best issue in the context of a road pricing reform in Catalonia. The proposed model and implementation path builds on a study of revenues and costs for the interurban network, and a qualitative analysis of the trade-offs between financial sustainability, mobility management, and spatial equity. The assessment detects a misallocation of

costs among road users. The proposed reform defines a two-part tariff pricing and a funding model for interurban roads in Catalonia to correct this misallocation.

Resum

La tarifació ha estat defensada durant molt de temps com un instrument adequat per a tractar les externalitats del transport. La tecnologia actual permet l'aplicació de sistemes tarifaris més sofisticats a uns costos de transacció assequibles. Tanmateix, els responsables polítics s'enfronten a nombroses restriccions i objectius polítics contraposats a l’hora de posar en pràctica sistemes de tarifació al transport. L’anàlisi de casos d’estudi des d’una òptica “second-best” contribueix a traduir idees dels marcs teòrics en consells pràctics per al disseny i avaluació de polítiques tarifàries. En aquest sentit, aquesta tesi estudia alguns dels problemes essencials per a la definició d’esquemes tarifaris en infraestructures de transport amb tres assajos independents.

Existeix una forta interdependència entre mobilitat i estructura urbana, especialment en els entorns urbans. Aquest fet causa friccions entre els instruments tarifaris per a fer front a les externalitats del transport urbà i altres distorsions dins de l'economia urbana, especialment les economies d'aglomeració i l'expansió urbana.

La primera part de la tesi estudia aquesta qüestió en el context de l'aplicació de les polítiques d’aparcament en empresa a Barcelona. A través d'un model microeconòmic analític i una il·lustració numèrica per a l'àrea metropolitana de Barcelona s’estudien possibles polítiques que abordin les ineficiències

associades a l’aparcament subvencionat per part de l’empresa. El model analític indica que l’eliminació del subsidi a l’aparcament en empresa té un efecte positiu en les economies d'aglomeració i l'expansió urbana. Els resultats de l'aplicació numèrica suggereixen que els beneficis econòmics estan dominats pels efectes d’aglomeració i, en menor mesura, pels efectes del transport i de l’ús del sòl.

L'aplicació d’una tarifació mediambiental que afavoreixi l’adopció de tecnologies més netes en el transport públic sovint es confronta amb un dilema: la internalització dels costos mediambientals per part dels operadors de transport públic podria causar un canvi modal cap a formes de transport individuals amb una major petjada mediambiental.

La segona part de la tesi analitza aquesta qüestió per als cànons d'accés a la infraestructura ferroviària a Europa. Els actuals cànons relatius al soroll i la contaminació atmosfèrica que s'apliquen a Europa s'analitzen qualitativament per a determinar com s’aborden problemes específics del context ferroviari, incloent el seu entorn imperfectament competitiu i els possibles desplaçaments modals al transport per carretera. Aquesta anàlisi suggereix que el nivell de cànons ambientals pot augmentar-se en general, quan l’elasticitat creuada entre el ferrocarril i el transport per carretera és relativament baixa. A més, es conclou que el ventall de possibilitats de reducció d’externalitats hauria d'ampliar-se a través d'una major diferenciació dels cànons.

Mentre que els peatges urbans s'utilitzen essencialment per a tractar les externalitats del trànsit urbà, l'aplicació dels peatges a escala regional o nacional sovint es considera un instrument financer. En aquest sentit, cal que el disseny d’una tarifació a la xarxa de carreteres interurbanes equilibri els objectius financers i de gestió de la demanda, i consideri condicions d'acceptabilitat pública, com l'equitat espacial.

L'última part de la tesi tracta aquest problema en el context d'una reforma del sistema tarifari de carreteres a Catalunya. El model tarifari i la implementació proposada es basa en un estudi dels ingressos i costos per a la xarxa interurbana, i una anàlisi qualitativa del balanç entre la sostenibilitat financera, la gestió de la mobilitat i l'equitat espacial. L'avaluació detecta una incorrecta assignació de costos entre els usuaris de la carretera. La reforma proposada defineix un model de dues tarifes (fixa i variable) per a la xarxa bàsica i la xarxa de vies d’alta capacitat que millora l’actual assignació de costos i n’assegura el finançament.

Acknowledgements

I am writing these lines while finishing this thesis. Looking backwards, my PhD journey looks like a long and winding road with many ups and downs but with impressive views on the way. This has been an enjoyable journey and at times a solitary one in an effort to explore new areas of knowledge and challenge my own certainties. However, this would not have been possible without the generosity and talent of many people around me during this time. As a part-time student, juggling this major task with other commitments and interests has been a real challenge and I deeply appreciate all the support I have received.

Voldria donar les gràcies en primer lloc al meu director de tesi, Mateu Turró, per haver-me obert la porta al món de la recerca, per la teva paciència, confiança i suport malgrat els meus infinits canvis de rumb i alts i baixos durant aquest temps. Gràcies també per esmolar-me la curiositat a través de revisions, comentaris i llargues converses sobre el món i la política.

He d'agrair també al meu co-director Sergi Saurí la seva confiança en mi i tot el seu suport durant el meu període al CENIT. Voldria també agrair-li a un Lluís Ubalde l'impuls que em va donar en els meus primers passos en el món de la recerca.

I am also sincerely grateful to Stef Proost for his kind welcome to Leuven, my research shelter when I most needed it, and for giving me the opportunity to work with him and other brilliant people at the Economics Department of KU Leuven. Thanks for teaching me the value of simplicity when addressing very complex problems.

This research has received funding from the RAILEX project (TRA2011-23609/RAILEX) granted by the Spanish Ministry of Economy and Competitiveness. Two essays included in this thesis are based on research projects funded by the Autoritat del Transport Metropolità (ATM) de Barcelona and the Department of Territory and Sustainability of the Generalitat de Catalunya.

Voldria també donar gràcies a la Sílvia Aranda per la seva paciència amb mi i pel suport amb els tràmits a distància.

Estic molt agraït a tots els companys del CENIT per tots aquests anys d'aprenentatge i d'estones divertides. Eskerrik asko Sara. Gràcies per entendre'm i per fer-me creure que valia la pena. He d'agrair també a tots els que m'han precedit per ser excel·lents referències de com aconseguir completar una tesi doctoral en aquest camp. Gràcies Pau, Marcel, Albert, Quique, Domingo, Hugo i Mireia. Gràcies també Cisco, Ester, Jaume i a tota la resta de companys que han passat en algun moment pel CENIT pels projectes compartits, els "pinchos de tortilla", els sopars de celebració i de comiats i les bromes que han fet aquests anys molt més interessants.

M'agradaria donar les gràcies als meus amics, Joaquim, Marc, Artur, Bernat, Laura i a tota la colla de ´felices´. Sense la vostra amistat, la complicitat, les converses sobre tot el que ens envolta, els infinits plans a Barcelona i rodalies i les estones de riure'ns de tot, això hagués sigut molt difícil. Gràcies també a la colla de les "Veïnes", a la Glòria i a tants d'altres pels moments de desconnexió i de compartir estones fantàstiques durant aquests anys de tesi.

I would also like to thank my Ricardo colleagues for their support, friendship and for accepting my "I´m almost there" as a valid response for more than two years.

Gràcies als meus pares i a la Mariona per ser sempre al meu costat i cuidar-me, des de Barcelona i a distancia, i per la seva confiança cega que el que faig

val la pena. Gràcies a tota la família Pons i Rigat, els de Barcelona, els de Manresa, els d'Arenys i els de Berga. Gràcies per les sobretaules, per la complicitat i pel vostre suport durant tots aquests anys.

Gràcies Nora, ens n'hem acabat sortint junts. Gràcies per l'enorme paciència i l'esforç per comprendre'm, per esperar-me, per animar-me, per estimar-me, sempre, sense defallir.

To all of you, my sincere gratitude.

London, April 2021

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Chapter 1 Introduction

1 Research question

The use of transport infrastructure, particularly in the urban context, causes different types of externalities. Road transport is generally associated with significant levels of congestion, while crowding effects are present in many urban public transport systems. The use of fossil fuels to power transport systems contributes to air pollution and climate change. Accidents and noise can also represent significant issues. In addition, since transport activities, and particularly parking, are land intensive, urban transport is linked to significant land opportunity costs.

This thesis focuses on the practical implementation of pricing schemes for transport infrastructure that address these externalities alongside other specific objectives, including the financing of transport infrastructure. Throughout this thesis, the term *pricing* refers to any instrument that puts a price on travel or on access to a transport infrastructure for any mode of transport, i.e. infrastructure charges, tolls, public transport fees, fuel and vehicle taxes, etc.

1.1 First-best benchmark

It is hard to find a piece of work on transport pricing that does not acknowledge Pigou´s pioneering research (Pigou, 1920). He established the theoretical foundations for the application of pricing as an instrument to abate transport externalities.[1] The underlying logic, which is a ramification of the standard

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[1] See Button (2020) for a historical perspective of the evolution of Pigou´s original idea.

economic principle of marginal cost pricing, appears fairly simple now: the externality linked to a transport activity is reduced to its socially optimal level when users pay for (internalise) its marginal external cost. This implies that the traveller´s willingness to pay (marginal benefit) for a trip should be, at least, equal to its marginal social cost.

Non-pricing instruments may also be applied to the transport sector in the form of regulations limiting these externalities. As an example, bans to (older) diesel cars are coming into force in many urban centres to improve air quality. Compared to pricing instruments, these are generally associated with a simpler control technology, with lower transaction costs, and may be a cost-effective instrument to control externalities when heterogeneity of marginal abatement costs is low (Stavins, 2004). However, both travel demand and the abatement capabilities of transport users are highly heterogeneous, so pricing can be considered the most appropriate instrument to deal with transport externalities in the majority of situations.

Furthermore, recent progress in information and communication technologies has enabled the implementation of more sophisticated pricing schemes at affordable transaction costs.[2] This means that the theoretical framework on transport pricing developed one century ago may be now ready to be fully developed in practice.

In a first-best world, the marginal cost pricing principle is applied to the whole transport system. This means that specific pricing schemes for the different transport modes are set at a price level equal to the difference between their marginal social cost and average private cost.[3] For road user costs, for example, this is translated into a congestion charge as marginal social cost is above the average private cost due to congestion effects (Santos and Verhoef, 2011). For

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[2] See de Palma and Lindsey (2011), for example, for a description of developments in road pricing technologies.

[3] See Anas, 2012; Small and Verhoef (2007) for a complete exposition.

public transport agency costs, [4] large economies of scale lead to average costs higher than marginal costs, which may justify a subsidy for the financing of public transport infrastructure and operation (Basso et al., 2011).

Under first-best pricing, transport capacity would be optimally set according to Samuelson's rule for the supply of a public good (Samuelson, 1954), that is, capacity expansion investment continues until the sum of the private marginal benefits over all users of each infrastructure just equals the marginal cost of supplying more of that infrastructure. This can be determined by means of a cost-benefit analysis. Then, the self-financing theorem (Mohring and Harwitz, 1962) ensures that, under constant returns of scale, congestion tolls finance capital costs of transport infrastructure. [5]

Under these conditions, the optimal solution to transport infrastructure pricing, supply and financing appears rather straightforward. However, reality is much more complex and this problem is by no means solved. The first-best benchmark, which was well established more than 50 years ago, is only a useful starting point.

1.2 Second-best issues

In practice, the first-best benchmark is not applicable as policy makers face constraints on pricing instruments, market distortions and conflicting policy objectives when designing and implementing pricing schemes for transport infrastructure. We then enter the world of "second-best", where we study how pricing schemes should be optimised under specific issues or contexts. By nature, a second-best scheme will involve trade-offs linked to multiple constraints, distortions and/or diverging objectives and, as a result, it will lead to sub-optimal outcomes, compared to those of the first-best pricing. We

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[4] Agency costs refer to the supply of public transport services and are separate from user costs, which may include crowding effects.

[5] The classic self-financing theorem for road infrastructure can also be extended to public transport, see Fung et al. (2019).

hereafter outline the main second-best issues found in transport pricing schemes and the main trade-offs involved.

Pricing schemes in practice are, typically, not as flexible as assumed in the first-best framework due to technological limits. Price differentiation to reflect heterogeneous external costs among transport users requires a technology that controls and/or enforces the correct applications of the pricing scheme. Higher levels of price differentiation (e.g. between cars with different GHG emission levels) are associated to more expensive or even not commercially available technologies. In this sense, most pricing schemes face an essential trade-off between efficiency losses due to lack of differentiation and transaction costs of the control technology.

It is also very common that the scope of the pricing scheme is constrained due to political, social or technological reasons. A good example of this is the classic two routes problem, where there are two parallel routes and only one can be tolled (Verhoef et al., 1996). A basic result is that the price of the tolled route should be lower than its first-best value to offset traffic diversion to the untolled route. From a broader perspective, the limited scope issue can also apply to divergent pricing approaches between transport modes. A similar result to the two-route problem applies: transport prices should offset the effect of underpriced externalities in other modes in proportion to the cross-elasticity between them (Arnott and Yan, 2000). This justifies in part the application of subsidies to urban public transport when road traffic is underpriced (Proost and Dender, 2008).

Another second-best issue is associated with distortions in other markets, which are seen as constraints when designing or implementing a transport pricing scheme. Since transport pricing may have an impact on those markets, potential undesired effects should be taken into account. Effects on the labour market are an illustrative example. The implementation of a road pricing scheme, for example, may discourage commuting to work in an already taxdistorted labour market. In urban environments, fewer commuters to the centre may lead to a loss of agglomeration economies, which is a positive externality related to employment density.[6] For this reason, the level of transport prices to the centre may be lowered to offset undesired effects on the labour market.

Another way of offsetting effects on other markets is through an optimised allocation of revenues from the transport pricing scheme, which is known to have significant effects in a general equilibrium context (Parry and Bento, 2001). Revenues from road pricing, for example, could be used to finance road capacity expansion, lower labour taxes in the city centre or finance public transport. An important body of the literature deals with the use of revenue from transport taxes, charges, tolls and fares (de Palma et al., 2007).

Whilst the key point hitherto has been to optimise efficiency linked to a second-best scheme through a welfare function, policy makers and stakeholders may pursue other goals. These could be effectiveness towards pre-existing policy commitments, social and spatial equity, public acceptability and other legitimate interests of stakeholders, including financial restrictions. In fact, the lack of public acceptability and, thus, political hostility towards transport pricing schemes is often associated with an insufficient consideration of social and spatial equity[7] (Eliasson and Mattsson, 2006; Viegas, 2001) and other political economy issues (De Borger and Russo, 2017).

In this sense, efficiency and other policy objectives cannot be disentangled as they all influence the design and implementation of transport pricing schemes in practice. A second-best transport pricing scheme must therefore result from a multi-objective compromise.

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[6] See Proost and Thisse (2019) for a thorough description of agglomeration economies.

[7] See Trannoy (2013) for a review of equity metrics in transport policy.

Since the above-mentioned issues are the norm, rather than the exception, second-best analysis applied to specific case studies is the only way to translate those theoretical insights into practical advice in policy design and implementation. In fact, the path required to implement a transport pricing scheme in practice can be seen as a succession of second-best solutions adapted to a time-varying context (Rouwendal and Verhoef, 2006).

It is in this spirit that this thesis investigates how elements of the second-best pricing framework can be applied to the design and evaluation of specific pricing schemes for transport infrastructure.

2 Thesis overview

2.1 Thesis objective and scope

This thesis aims to contribute to reducing the existing gap between second-best pricing theory and the practical design of pricing schemes for transport infrastructure. Since second-best issues are, by definition, case-specific, research on specific case studies contributes to providing insights into how policy making in the field of transport pricing could benefit from concepts and tools taken from the existing body of theory.

Overall, this thesis focuses on a number of second-best issues: interaction with agglomeration economies (Chapter 2), intermodal competition (Chapters 2 and 3), imperfect competition (Chapter 3), financial constraints (Chapter 4) and spatial equity (Chapter 4). These are analysed for a wide range of transport components: parking (Chapter 2), railways (Chapter 3) and roads (Chapter 4); and at both urban (Chapter 2) and regional (Chapters 3 and 4) scales.

2.2 Thesis methodology

Throughout this thesis, it is assumed that the state-of-the-art theory of second-best pricing in transport infrastructure offers an adequate analysis framework to assess specific pricing schemes for transport infrastructure, both on a quantitative and a qualitative basis. This research reflects the diversity of methods, disciplines and traditions falling under this area of knowledge and combines quantitative (Chapter 2) and qualitative (Chapters 3 and 4) approaches.

Chapter 2 draws from the tradition to use stylised microeconomic models to gain insight on the main trade-offs and effects of transport policies. In particular, an analytical microeconomic model is developed to capture the general equilibrium of the urban economy, including transport, parking and land use components. A numerical application of the model is calibrated for the city of Barcelona to further illustrate the effects and trade-offs of the parking policies analysed.

Chapters 3 and 4 are based on a more qualitative approach, which draws from the underlying theoretical principles of second-best pricing theory to identify relevant issues and inform the assessment. The focus of these chapters is on policy design and implementation through qualitative or semi-quantitative analysis, rather than on microeconomic modelling. In this sense, Chapters 3 and 4 are closer to transportation engineering and regional planning traditions.

2.3 Thesis structure

Following this introductory chapter, the present thesis is structured into the three self-contained chapters (2, 3, 4) described below.

Chapter 2 Workplace parking and second-best policies for commuting trips

There is a strong interdependence between travel behaviour and land use, particularly in urban environments. This causes frictions between pricing instruments to deal with urban transport externalities and other distortions within the urban economy, notably agglomeration economies and urban sprawl.

Chapter 2 studies this second-best issue in the context of the application of workplace parking policies for Barcelona. The effects of policies addressing current inefficiencies around employer-paid parking on the urban economy are studied through a stylised microeconomic model and a numerical illustration for the metropolitan area of Barcelona.

Chapter 2 concludes that a switch to employee-paid parking has a positive effect on agglomeration economies and urban sprawl, even in dense cities with underground parking facilities. Results from the numerical application indicate that welfare gains are dominated by agglomeration effects and to a lesser extent by transport and land use effects. On the other hand, the implementation of a workplace parking levy as a second-best instrument to deal with urban traffic externalities may be counterproductive as it may disincentivise employment in the centre and derive in the loss of agglomeration economies.

Chapter 3 Environmental rail charges in Europe

The implementation of environmental pricing schemes that favour cleaner traction options in mass public transport often faces a classic dilemma: the internalisation of environmental costs by public transport operators might cause a modal shift towards individual transport forms with a higher environmental footprint.

Chapter 3 analyses this second-best issue for environmental rail access charges in Europe. Current noise and pollution rail charges implemented in Europe are analysed qualitatively in order to determine to what extent they address second-best issues of the rail market, including potential modal shifts to road transport and its imperfectly competitive environment.

This analysis suggests that the level of environmental surcharges can be generally increased given the relatively low substitutability between rail and road and that the range of abatement possibilities should be enlarged by further differentiating charges. It is also found that the pricing scope should be adapted to achieve particular cost-efficient allocations for the on-going abatement efforts of rail operators and upstream agents.

Chapter 4 Road pricing reform in Catalonia

Whilst road pricing in urban environments is essentially used to deal with urban traffic externalities, the application of road tolls at regional or national scale is often rather seen as a financial instrument. In this sense, the design of road pricing schemes for interurban networks should balance financial and demand management objectives, and consider public acceptability conditions, such as spatial equity.

Chapter 4 looks into this second-best pricing issue in the context of a road pricing reform in Catalonia. The proposed model and its implementation path build on a study of revenues and costs for the interurban network, and a qualitative analysis of the trade-offs between financial sustainability, mobility management and spatial equity.

The assessment detects a misallocation of costs among road users. The proposed reform defines a two-part tariff pricing and funding model for interurban roads in Catalonia to correct this misallocation. The implementation pathway considers policy and technological constraints.

3 Contributions of this thesis

This thesis contributes to the existing body of specialised literature in the following ways:

1. Workplace parking policies

- Urban economy model focused on the effects of workplace parking policies on agglomeration economies in dense cities with underground parking facilities.

- Complementing previous contributions, the model presented in this thesis captures congestion effects on public transport and considers parking spillovers.

- A numerical application of the model to assess the effects of workplace parking policies on transport and parking behaviour, residential and job location and social welfare.

- An important result of the model is that switching to employee-paid parking shifts employment from the suburbs to the city centre and this generates additional agglomeration economies.

- In addition, when parking spillover is limited, the reduced suburbanisation effect of employee-paid parking found in existing literature still holds for dense cities with underground parking facilities.

- Welfare gains from a switch to employee-paid parking are largely dominated by agglomeration effects and to a lesser extent by transport, parking and land use effects.

- The application of a workplace parking levy to deal with urban traffic externalities may be counterproductive in some cases. This policy would benefit from an interaction with other policy measures that favour employee-paid parking.

2. Environmental pricing schemes for railways

- An analytical framework to assess rail pricing schemes in terms of four basic dimensions: charging approach, allocation of abatement efforts, degree of differentiation and intermodal approach.

- Review of implemented noise and air pollution charges on European railways by means of the developed analytical framework.

3. Road pricing

   - Revenues-costs matrix applied to assess the allocation of costs between road classes and road users, along with the coverage of infrastructure and external costs of a network-wide road pricing model.

   - Proposed road pricing reform in Catalonia, which addresses the insufficient coverage of road costs after the finalisation of existing road toll concessions and considers political and technological constraints.

4 Publications and acknowledgements

The three chapters of this thesis have been published in scientific journals and presented at international conferences in the field of transport economics and policy.

Chapter 2 Workplace parking and second-best policies for commuting trips

This paper is co-authored with Prof. Stef Proost, from the KU Leuven, and Prof. Mateu Turró, from the Universitat Politècnica de Catalunya. This work builds on an initial research project supported by the Autoritat del Transport Metropolità (ATM) de Barcelona and in collaboration with Dr. Sergi Saurí. The analytical and numerical model was developed during two research visits at the KU Leuven with guidance from Prof. Stef Proost and other colleagues. This research benefited from the peer-review process following the submission to Economics of Transportation Journal. Finally, comments from Richard Arnott and Albert Gragera at the ITEA conference 2017 in Barcelona contributed to improve this research.

Chapter 2 is published in:

- Pons-Rigat, A., Proost, S., Turró, M (2020). Workplace parking policies in an agglomeration: An illustration for Barcelona. Economics of Transportation, 24, 100194

Part of this research has been presented at:

- Workplace parking and second-best policies for commuting trips: An illustration for Barcelona. Annual Conference and School on Transport Economics, ITEA 2017

Chapter 3 Environmental rail charges in Europe

This paper is co-authored with Prof. Mateu Turró, Dr. Sergi Saurí and Dr. Lluís Ubalde. The research received financial support from the RAILEX project (TRA2011-23609/RAILEX) granted by the Spanish Ministry of Economy and Competitiveness. The paper benefited from the comments from independent reviewers following the submission to Transport Reviews.

Chapter 3 is published in:

- Pons-Rigat, A., Turró, M., Saurí, S. and Ubalde, Ll.(2017) Environmental rail charges in Europe: a review (2017). Transport Reviews, Volume 37, pp. 667-684

Part of this research has been presented at:

- Internalizing noise and pollution externalities into railway charges. The 43rd European Transport Conference (ETC), 2015

- Environmental rail charges in Europe: a critical review, Transportation Research Board, TRB 95th Annual Meeting, 2016

- Applying the polluter-pays principle to rail, XII Congreso de Ingeniería del Transporte, CIT 2016

Chapter 4 Road pricing reform in Catalonia

This paper has been co-authored with Dr. Sergi Saurí and Prof. Mateu Turró. This research builds on a research project on road pricing schemes funded by the Department of Territory and Sustainability of the Generalitat de Catalunya. Feedback from independent reviewers following submission to the Transportation Research Record contributed to improve the presentation of this paper.

Chapter 4 is published in:

- Pons-Rigat, A., Saurí, S., Turró, M. (2017). Matching Funding, Mobility, and Spatial Equity Objectives in a Networkwide Road Pricing Model. Transportation Research Record: Journal of the Transportation Research Board, 2606, pp. 1-8

Part of this research has been presented at:

- A new model for road pricing in Catalonia, European Transport Conference, ETC 2016

- Matching funding, mobility and spatial equity objectives in a network-wide road pricing model: The case of Catalonia, Transportation Research Board, TRB 96th Annual Meeting, 2017.

Chapter 2 Workplace parking and second-best policies for commuting trips

1 Introduction

Employer-paid or highly subsidised parking is a very common practice (Inci, 2015; Small and Verhoef, 2007). In Barcelona, for example, 45% of car trips to work use an employer-provided parking space, which is free for employees in 81% of the cases (ATM, 2015). In non-urban or less densely populated areas, the proportion of employer-provided parking may be much higher. Van Ommeren and Wentink (2012) report that in the Netherlands, 80% of car commuters use employer-provided parking, while, as per Shoup (2005), 95% of car commuters in the US park free at work. In the US, costs of employer-provided parking represent around 1% of the GDP (Shoup, 2005a).

In this context, a key question is why employers provide their employees with such parking benefits, which are rarely offered to those using other transport modes. This is mainly due to two policy distortions (Evangelinos et al., 2018; Shoup, 2005a; Van Ommeren and Wentink, 2012). First, employer-paid parking is generally exempt from fringe benefit taxation, while wages and most perks are subject to income taxation. Hence, wage increases to compensate the loss of the free parking benefit would be more costly for the firm as it should also incorporate the income tax at marginal rates. This provides incentives to employers not to charge parking costs to their employees. Second, land use regulations may impose minimum parking requirements on office buildings. This generally leads to an excessive supply of parking, i.e. the marginal value of parking is below its resource costs (Cutter and Franco, 2012). Even if these regulations may be reviewed,[8] most of the supply of workplace parking in different sectors is still determined by such parking requirements.

Employer-paid parking leads to different types of economic inefficiencies. First there is the distortion in modal choice: car use is made cheaper than it really is. Thus, providing free or low-cost parking to employees clearly exacerbates the problem of urban traffic externalities, such as congestion, air pollution, accidents and noise. Second, too much land and capital resources are dedicated to employer-provided parking (Shoup, 2005b). Van Ommeren and Wentink (2012) use data in the Netherlands to show that exemption from fringe benefit taxation and minimum parking requirements, similar to those applied in the US, would induce, welfare losses of about 10% and 18%, respectively, of parking resource costs.

This chapter studies two policy responses to employer-paid parking: a switch to employee-paid parking by increasing the cost of parking perceived by commuters and a workplace parking levy, whereby employers are charged for the number of parking spaces they provide to their employees.

The analysis of these policies requires a general equilibrium approach where workers can choose residential and workplace locations, mode of transport and type of parking. Employers and land developers can choose where to produce and where to develop housing.

In urban general equilibrium modelling, there are several traditions (Proost and Thisse, 2019). One is the use of computable land use models (Anas and Liu, 2007), more recently there is the quantitative spatial economics tradition (Desmet and Rossi-Hansberg, 2013). These two model approaches do not allow an analytical solution and miss the detail of the parking market. We will use

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[8] Recent research on urban planning recommends eliminating parking requirements completely and replacing them with a more market-based approach (Inci, 2015). Maximum parking regulations are increasingly adopted in European high density areas (Kodransky and Hermann, 2011), such as London (Guo and Ren, 2013).

the third tradition known as the analytical mono-centric model tradition that allows a simplified representation of land used for parking.

Our research builds upon the stylised model of Brueckner and Franco (2018). They use a ‘two regions’ urban model with road and public transport modes and with employers in the central business district providing surface parking. Our model picks up some of their suggestions. First and foremost, we include agglomeration economies by allowing workers to choose between work in the city centre where agglomeration economies are at work and the suburbs where average product is constant. Second, while Brueckner and Franco (2018) focus mainly on surface parking, our model assumes that off-street parking facilities in the city centre are built underground, which is more representative of dense, European-style cities. Third, to capture the potential parking spillover, we consider on-street parking in residential areas as an alternative to employer-provided parking. Fourth, we introduce crowding discomfort in public transport. The introduction of congestible public transport makes the model more realistic: non-congestible public transport sets an unrealistic upper-bound on the commuting cost (the public transport cost). Our commuting cost is convex in the total number of commuters. Fifth, besides the analysis of a switch to employer-paid parking, we include a workplace parking levy as a second-best pricing instrument for urban traffic externalities.

We illustrate our model with a numerical example for the metropolitan area of Barcelona. This aims to quantify the relative importance of the different effects (i.e. agglomeration economies, land use, transport and parking) in a second-best setting. As one of the densest urban areas in Europe,[9] Barcelona is an illustrative example of a compact city with underground parking facilities. Moreover, since 45% of car trips to work use an employer-provided parking

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[9] The city of Barcelona has a very high population density of 16,150 inhabitants per km^2 (Idescat, 2019), with even higher density found in the suburbs of the first ring. According to Eurostat grid data, the highest level of population density in Europe was found in south-western suburbs of Barcelona, within L’Hospitalet de Llobregat and the third highest ratio was also located in the suburbs of Barcelona, within Badalona (Eurostat, 2016).

space and only 19% of employees pay for parking (ATM, 2015), current workplace parking policies in Barcelona are associated to persistent congestion and air pollution issues, while no road tolling scheme has been implemented as of yet. As such, the metropolitan area of Barcelona is an appropriate context for the analysis of a second-best solution to urban traffic externalities based on workplace parking policies.

Compared to Brueckner and Franco (2018), our model illustration allows us to derive two additional insights on the effects of workplace parking policies. Most importantly, we find that, as we introduce agglomeration economies, a switch to employee-paid parking promotes employment in the city centre and increases average productivity. In our numerical analysis for Barcelona, we find that the agglomeration benefits are three times as large as the effects on the transport and land use markets.

Second, while in Brueckner and Franco (2018) the reduced suburbanisation effect of employee-paid parking is only attributed to the availability of surface parking at the workplace, we show that, in cities with underground parking facilities, employee-paid parking also reduces urban sprawl when spillover parking to residential areas is limited. Important to note is that our driver for the increase in number of central residents is a higher generalised cost of commuting (road congestion combined with congestion in public transport) caused by employee-paid parking rather than the generation of more land available for housing in the centre due to the reconversion of surface parking to residential use, as concluded in Brueckner and Franco (2018).

This chapter is structured as follows. Section 2 reviews the literature. Section 3 describes our stylised basic model and its main assumptions. Section 4 derives the social optimum and Section 5 sets the first-best benchmark based on the equilibrium conditions for the parking, transport, labour and housing markets. Section 6 uses comparative statics to analyse the effects of workplace parking policies on travel behaviour, agglomeration economies and residential location. Section 7 deals with the second-best setting of a workplace parking levy when other policy instruments are restricted. Section 8 presents the numerical illustration for the city of Barcelona. Finally, Section 9 concludes.

2 Literature review

Economic theory suggests that, in the absence of other market distortions, urban traffic externalities can be corrected with marginal cost pricing for both the trip and the parking price. For parking, this includes marginal resource and user time costs (Arnott, 2011). In a second-best setting, however, imperfect road pricing and parking charges should be simultaneously determined so that, when parking fees are raised or all employees have to pay for their parking, road charges can be reduced (Calthrop et al., 2000) and one can achieve about half of the benefits of congestion pricing (Proost and Dender, 2008). In this sense, a workplace parking levy can be seen as a second-best alternative to congestion charges in commuting trips, especially when congestion pricing might be too expensive to implement or not readily acceptable by public opinion (Jansson, 2010).

Verhoef et al. (1995) point out that parking fees are only a second-best substitute for congestion charges as they cannot differentiate distance driven, route and time of the trip. According to Glazer and Niskanen (1992), parking fees can only be effective to deal with congestion when parking time is very inelastic, which applies to commuting trips. This makes workplace parking regulation a potentially effective instrument to address congestion. De Borger and Wuyts (2009) find that the presence of employer-paid parking substantially increases the overall efficiency gain of congestion charges, because the inefficiency associated to employer-paid parking is also addressed.

There are not as yet many real-world experiments of the two parking policy instruments we study. A first attempt was the cash-out requirement enacted in California in 1992. This requires employers to give commuters the choice between a parking subsidy[10] and its equivalent cash allowance. This leads to a *de facto* switch to employee-paid parking. Evangelinos et al. (2018), Shoup (1997) and Watters et al. (2006) provide empirical evidence on the effects of a cash-out policy on modal choice in terms of a significant reduction in single occupancy car trips. In spite of this, practical implementation of cash-out programs is very limited. Shoup (2005a) associates the limited implementation in the US to prevailing tax distortions.

The city of Nottingham, following previous experiences in cities such as Sydney or Perth, has successfully introduced a workplace-parking levy (WPL) that charges employers for the parking spaces they provide to their employees. This levy has a twofold objective: reduce congestion in commuting trips and generate revenues for public transport financing (Dale et al., 2014). Employers must pay a license for each off-street parking space provided (£415 per year as of December 2018), although they can choose to reclaim part or all of the cost of the WPL from their employees. Dale et al. (2017) find that the WPL contributed to a reduction in congestion while the number of jobs in the city of Nottingham continued to grow. Santos et al. (2020) study the acceptability of a WPL in Cardiff and find that employers would not be very supportive of a WPL, whilst employees would, provided employers were to absorb the costs.

Two common concerns are often raised around workplace parking policies. One is their potential unintended effects on agglomeration economies and, the second, the spillover of parking on residential areas near high-employment districts.

Two papers focus on the effects of introducing congestion pricing rather than parking on the agglomeration effects. Takayama and Kuwahara (2017) show that congestion tolling can cause urban sprawl when commuters are

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[10] Defined as the difference between the out-of-pocket amount paid by an employer to secure the availability of a parking space (not owned by the employer) and the price, if any, charged to an employee for the use of that space.

heterogeneous. Brinkman (2016), with a spatial general equilibrium model using data for Columbus (Ohio), finds that congestion pricing weakens the agglomeration effects through dispersed employment. Both papers use a different model set-up than ours as they have a continuous production density, focus on road pricing rather than parking, do not model parking resources and use models without public transport alternative.

Employers provide staff with free or low-cost parking to attract commuting employees who might otherwise be deterred by the high price of parking in the city centre or other parking-related inconveniences. In this sense, it may be argued that policies limiting the provision of employer-paid parking would cause a decrease in employment in the city centre and induce a loss of agglomeration economies.[11] Shoup (2005a) contradicts this statement by arguing that employee-paid parking (by means of a cash-out policy) would free parking space that could be used for more profitable activities, with even a higher benefit in terms of agglomeration economies. Similarly, Brueckner and Franco (2018) and Franco (2017) show analytically that a switch to employee-paid parking reduces urban sprawl, as it increases available land in the city centre. However, these positive effects on agglomeration economies and urban form would not necessarily apply to urban areas where most of the off-street parking facilities are built underground. Voith (1998) finds that a tax on parking may lower wages and maximise the employment size of the city centre. Nonetheless, this result is subject to assuming that revenue from parking taxes is used to lower public transport fees and that public transport is non-congestible.

This research fills a gap in the existing literature by focusing on the effects of workplace parking policies on agglomeration economies in dense cities with underground parking facilities. In addition, our results on agglomeration

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[11] For a comprehensive review of causes of agglomeration economies see Puga (2010) and Proost and Thisse (2019).

economies capture congestion effects on public transport and are not subject to a specific use of taxation revenues.

A policy-induced increase in the (perceived) price of workplace parking may lead to a spillover effect affecting on-street parking in residential areas, which is often the natural alternative to workplace parking for car commuters when the provision of employer-paid parking is not widely ensured. This effect is also captured in our research.

Following the example of Barcelona, on-street parking is used by 25% of car commuters in the city centre but it grows to 50% in the rest of the metropolitan area. This parking spillover would bring increased parking cruising and, eventually, pressure for more on-street parking supply, with opportunity costs in terms of foregone open public space in residential areas. Gragera and Albalate (2016), using parking data in Barcelona, found that occasional parkers show a clear substitution effect between off-street and on-street parking, with an average on-street premium of €0.55/h. However, off-street parking subscribers do not seem to hold a statistically significant relation with curbside pricing. This empirical result may suggest that spillover parking derived from workplace parking policies may be limited.

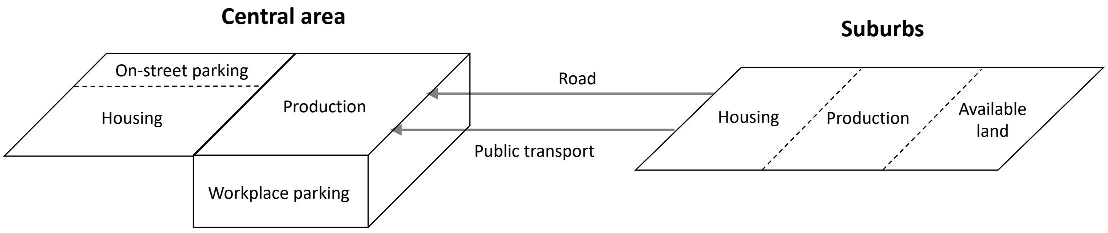
All this means that parking policy must take a comprehensive approach, involving the provision of alternatives to car trips and ad-hoc regulations. In this sense, differentiated on-street parking fees may correct the two main inefficiencies that often arise from the interaction between off-street and on-street parking: a) the externalities from car-cruising linked to on-street parking; and b) the localised market power of off-street facilities (Inci, 2015).

3 Basic model

3.1 Spatial structure

Following Brueckner and Franco (2018), in our model a city is divided into two regions connected by a road and a public transport link. Both the central city (denoted by subscript *c*) and the suburbs (denoted by subscript *s*) have a mixed land use including production and residence.

Figure 2-1: Schematic representation of the model spatial structure



The land supply in the central area is perfectly inelastic, with a fixed land use split between production land $\widetilde{L_p}$ and residential land $\widetilde{L_h}$, and a land rent for residence in the centre r_c.[12] Residential land in the centre includes the land consumption of residents and the space allocated to on-street parking. Zoning typically distinguishes between public open space, which is partly used for on-street parking, and residential land. The value of the residential land is enhanced by the availability of public open space and is actually capitalised by housing prices (Geoghegan, 2002). Based on this and for simplification purposes, we capture the opportunity cost of on-street parking in terms of land resources by considering public open space as part of the resident´s land consumption.

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[12] The land rent for production in the centre will be different from r_c but it is disregarded as it is out of the model scope.

The land supply in the suburbs is perfectly elastic for a given exogenous land rent $\widetilde{r_s}$ (or agricultural rent).

The city is closed, with identical individuals and total working population normalized to 1. The working population is divided into three groups: those with both residence and workplace in the centre n_c, those with residence in the suburbs and workplace in the centre n_{sc}, and those with both residence and workplace in the suburbs n_{ss} (inner city residents working in the periphery are not relevant for our case). Hence, $n_c + n_{sc} + n_{ss} = 1$.

3.2 Resident's preferences

Residents' preferences, defined over land consumption q and other goods e, are assumed to be quasi-linear, with decreasing marginal value. This assumption rules out income effects but facilitates strongly the comparative statics. The utility function is:

$$u_i = e_i + v(q_i), \text{ for } i = c, s, \text{ with } v'(q_i) > 0, v''(q_i) < 0 \tag{1}$$

As individuals can migrate without costs between the zones, in equilibrium, utility has to be equal in both locations. We call this uniform utility level u.

3.3 Production technology

Production technologies both in the central area and the suburbs are assumed to take only labour as a variable input. External economies of scale derived from urban agglomeration economies are present in the centre. We model this in a similar way as (Arnott, 2007). We define e_j as the number of employees at firm j and E_c as the aggregate number of employees in the centre. The aggregate production in the centre is $F_c(E_c)$, with $F_c' > 0, F_c'' > 0$. However, because scale economies are external to the individual competitive firm, each firm views itself as facing the production function $\frac{F_c(E_c)}{E_c} e_j = f_c e_j$ and, therefore, the private marginal product of labour equals the average product f_c while the social marginal product of labour $F_c' > f_c$ captures economies of scale which are external to the firm. The exogenous wage in the suburbs is $\widetilde{w_s}$.[13]

3.4 Supply of workplace parking

All employer-provided parking spaces in the city centre are assumed to be built underground. This assumption is tailored to dense urban centres where production land in the centre is too scarce to allocate it to off-street parking lots or buildings. The total supply of workplace parking in the city centre is modelled as a juxtaposition of many underground facilities where the total floor area $\tilde{A}$ is fixed[14] and, hence, capacity can only be expanded by building more underground floors h. The total number of employer-provided parking places is P_w and each one occupies an area a_w, which includes the relevant proportion of needed access and operational space. From this, it follows that the depth of the underground garage is $h = \frac{P_w a_w}{\tilde{A}}$.[15]

Similar to (Arnott, 2006), the total cost of workplace parking C_w is composed of a cost K per floor:

$$C_w(P_w) = \frac{K a_w}{\tilde{A}} P_w \tag{2}$$

The average cost of workplace parking c_w (equal to the marginal cost) is constant:

$$c_w = \frac{K a_w}{\tilde{A}} \tag{3}$$

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[13] We are aware that our approach of modelling agglomeration economics is a short cut that misses the subtleties of the imperfect competition, matching, sharing and learning effects.

[14] This assumption is coherent with considering a fixed amount of land for production. Underground parking facilities cannot expand horizontally beyond production land

[15] We allow for a non-integer number of floors to simplify the analysis.

We assume that the supply of employer-provided parking spaces is fully adaptable to the demand.[16]

3.5 Commuting costs

For simplicity, transport costs within each island are considered to be zero without loss of generality. Thus, only commuting trips from the suburbs to the central area are modelled. The total demand of commuting trips is perfectly inelastic (a workday requires one round trip)[17] and is equal to n_{sc}. From these, n_r use the road and n_t use public transport. From those who use road transport, P_w use employer-provided parking and P_o on-street parking. Individuals are indifferent between modes of commuting and also between parking alternatives.

It is assumed that each car has only one occupant. The average generalised cost of road use, including time and vehicle costs, for a given road capacity, is $c_r(n_r)$, with $c_r{}' > 0, c_r{}'' \geq 0$ reflecting traffic congestion. For on-street parking, our static model assumes a steady state with unsaturated on-street parking. There is a fixed supply of on-street parking and P_o occupied on-street parking spaces. Since the expected distance that a car cruises before finding a vacant space is increasing with P_o, the average generalised cost for parking search is $c_o(P_o)$, with $c_o{}' > 0, c_o{}'' \geq 0$.[18] Each on-street parking space occupies an area a_o of the public open space assumed to be residential land and does not reduce the space available for traffic. Assuming that road user cost does not depend on on-street parking P_o and that parking search cost does not depend on the

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[16] Employers could achieve this in the short term by renting parking spots from other parking facilities when demand exceeds the available supply or by letting parking spots to other parking uses (e.g. residential, shopping, etc.) when there is excessive supply. An alternative assumption for the long-term supply cost of underground parking would be a marginal cost that is increasing. Starting from the second-best equilibrium with employer paid parking, this alternative assumption would decrease the magnitude of the positive effects of employee paid parking.

[17] This follows other similar papers in the literature such as De Borger and Wuyts (2009) and Parry and Bento (2001).

[18] We assume that parking time is exogenous and equal to the working journey. Hence, the parking occupancy does not depend on parking time but only on total demand. At the same time, an increase in the parking fee will not lead to a reduction in parking time but will be directly translated into increased driving costs (Glazer and Niskanen, 1992).

number of road users n_r ignores the congestion interaction between cars cruising for parking and cars transiting the city.

Finally, we assume that the public transport link is segregated from road transport (e.g. a suburban rail line) and its frequency is already at its technical limit, which is a typical situation in many suburban rail systems at peak hour. Thus, public transport capacity can only be increased with large infrastructure investments, which, like road capacity expansion, are out of the scope of the model. User time costs $c_t(n_t)$ in public transport are affected by crowding discomfort. In a similar way to de Palma et al. (2017), crowding costs are assumed to be linear and $c_t{}' > 0, c_t{}'' = 0$ holds.[19]

4 Social optimum

The optimal allocation from a social planner's perspective is reached when the uniform utility u is maximised subject to a resource constraint of the city's economy. The production of the city and the suburb sets the available resources for land and non-land consumption and for transport and parking. The optimal allocation can be studied by the following constrained optimisation of the uniform utility level:

$$\begin{aligned} L_1 = u + \delta * \{ & F_c(n_c + n_{sc}) + \widetilde{w_s} * n_{ss} \\ & - [n_c * e_c + (n_{sc} + n_{ss}) * e_s + \widetilde{r_s} \\ & * (\widetilde{L_p} + n_c * q_c + a_o * P_o + (n_{sc} + n_{ss}) * q_s) + n_r * c_r(n_r) \\ & + P_w * c_w + P_o * c_o(P_o) + n_t * c_t(n_t)]\} \\ & + \theta_c * [e_c + v(q_c) - u] \\ & + \theta_s * [e_s + v(q_s) - u] \end{aligned} \tag{4}$$

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[19] Most empirical studies find that crowding costs are approximately linear above a threshold load factor or passenger density, see e.g. Tirachini et al. (2013) and Wardman and Whelan (2011). We assume that this threshold has been exceeded.

$$+\omega * \left(\widetilde{L_h} - n_c q_c - a_o P_o\right)$$

$$+\varphi * (P_w + P_o - n_r)$$

$$+\mu * (n_r + n_t - n_{sc})$$

$$+\lambda * [1 - (n_c + n_{sc} + n_{ss})]$$

We simultaneously optimise for non-land consumption $(e_c,\ e_s)$, land consumption $(q_c,\ q_s)$, central and suburbs´ population and number of commuters (n_c, n_{sc}, n_{ss}), modal choice (n_r, n_t), and parking choice (P_w, P_o).

The first constraint (multiplier δ) is the resource constraint of the city. This means that the production in both the centre and the suburbs is spent entirely on land and non-land consumption, transport and parking costs.

The second and third constraints (multipliers θ_c and θ_s) make sure utility is equalized among the two zones.[20]

The constraint with multiplier ω guarantees that the total residential land equals land dedicated to housing plus land for on-street parking.

The constraint with multiplier φ guarantees that total parking needs to be satisfied by employer provided underground parking and on street parking.

The next constraint with multiplier μ makes sure total commuting equals car commuting and public transport commuting.

The last constraint with multiplier λ fixes total population and total employment.

The first order conditions for an interior optimum yield the following equations (details in the Appendix A):

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[20] This ensures location equilibrium where migration is costless, as typically assumed in the mono-centric model see e.g. Brueckner (2011).

$$q_c v'(q_c) - v(q_c) = q_s * \widetilde{r_s} + c_r + n_r c_r' + mc_w - v(q_s) \tag{5}$$

$$F_c'(n_c + n_{sc}) - c_r - n_r c_r' - mc_w = \widetilde{w_s} \tag{6}$$

$$c_r + n_r c_r' + mc_w = c_t + n_t c_t' \tag{7}$$

$$mc_w = c_o + P_o c_o' + a_o v'(q_c) \tag{8}$$

Equation (5) describes the optimal allocation of residents between the centre and the suburbs, which is optimal when the resource consumption of an extra resident is equal in the two zones[21]. Equation (6) characterizes the optimal work location choice by equalising the social marginal benefit of an extra worker in the centre (marginal product of labour minus commuting costs) to the marginal product of labour in the suburbs. Equation (7) states that the optimal mode share will be achieved when marginal road costs plus marginal parking costs equal marginal costs of public transport. Finally, equation (8) determines the optimal allocation between workplace parking and on-street parking. The marginal costs of an extra workplace parking space should be equal to marginal parking search costs for on-street parking plus the opportunity costs of on-street parking in terms of land resources.

5 Equilibrium and first-best decentralisation

The social optimum can be decentralised as a competitive equilibrium if sufficient policy instruments are available. The following policy instruments can be potentially applied to reach a first-best decentralisation:

- a wage subsidy in the centre s_c
- a user fee on public transport per round trip τ_t
- a road toll per round trip τ_r
- a policy measure that eliminates employer-paid parking
- a workplace parking levy per day for employer-provided parking spaces τ_w

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[21] If we substitute $v(q_i)$ by $u - e_i$, u cancels out and both sides of the equation represent total resource consumption, in the city centre and the suburbs respectively, including transport, land and other goods.

- an on-street parking fee per day τ_o

5.1 Equilibrium conditions for residents

In order to analyse the market equilibrium, we need to specify the price formation and the budget equations.

We distinguish five different types of workers: 1) residents living and working in the centre (c); 2) those commuting from the suburbs by public transport (sc, t); 3) those commuting from the suburbs by road and using workplace parking (sc, r, w); 4) those commuting from the suburbs by road and using on-street parking (sc, r, o); and 5) those living and working in the suburbs (ss). Once they have chosen their category, each type of worker is confronted to a specific budget constraint that is a function of the particular commuting costs of each area, transport mode, and parking choice. These commuting costs, which include the relevant taxes and fares, are subtracted from the gross income. The gross income is composed of the wage plus an average extra income $\bar{y}$ equal for the whole city that includes lump-sum government transfers, additional rent incomes, and available time for commuting. The wage in the centre w_c adds to the wage subsidy s_c whereas the wage in the suburbs is the exogenous wage $\widetilde{w_s}$. Budget (and time) constraints for the five categories are the following:

$$w_c + s_c + \bar{y} = e_c + r_c q_c \tag{c}$$

$$w_c + s_c + \bar{y} - c_t(n_t) - \tau_t = e_s + \widetilde{r_s} q_s \tag{sc, t}$$

$$w_c + s_c + \bar{y} - c_r(n_r) - \tau_r - \beta * (c_w + \tau_w) = e_s + \widetilde{r_s} q_s \tag{sc, r, w}$$

$$w_c + s_c + \bar{y} - c_r(n_r) - \tau_r - c_o(P_o) - \tau_o = e_s + \widetilde{r_s} q_s \tag{sc, r, o}$$

$$\widetilde{w_s} + \bar{y} = e_s + \widetilde{r_s} q_s \tag{ss}$$

Where $\beta \in [0,1]$ represents the proportion of the costs of workplace parking that employers pass-on to their employees. We assume that when $\beta = 1$, employers, as profit maximisers, charge the full average cost of workplace parking c_w to their employees along with the workplace parking levy τ_w. When employers have exogenous incentives for employer-paid parking ($\beta < 1$),[22] the parking cost passed-on to employees who use workplace parking is $\beta * (c_w + \tau_w)$.

Under these budget (and time) constraints, the first-order conditions for an interior utility maximum for residents both in the centre and the suburbs always contain the condition for the optimal land consumption:

$$v'(q_i) = r_i, \;\; i = c, s \tag{9}$$

Then, by substituting $e_i, \; i = c, s$ from each budget constraint into the general expression for utility (1) and taking into account equation (9), the utility level for each resident type can be written as:

$$u_c = w_c + s_c + \bar{y} + v(q_c) - v'(q_c) \cdot q_c \tag{10}$$

$$u_{sc,t} = w_c + s_c + \bar{y} + v(q_s) - \widetilde{r_s} q_s - c_t(n_t) - \tau_t \tag{11}$$

$$u_{sc,r,w} = w_c + s_c + \bar{y} + v(q_s) - \widetilde{r_s} q_s - c_r(n_r) - \tau_r - \beta * (c_w + \tau_w) \tag{12}$$

$$u_{sc,r,o} = w_c + s_c + \bar{y} + v(q_s) - \widetilde{r_s} q_s - c_r(n_r) - \tau_r - c_o(P_o) - \tau_o \tag{13}$$

$$u_{ss} = \widetilde{w_s} + \bar{y} + v(q_s) - \widetilde{r_s} q_s \tag{14}$$

As we focus on an interior optimum, the utilities for different areas must be equal to ensure the location equilibrium where migration is costless. Then:

$$u = u_c = u_{sc,t} = u_{sc,r,w} = u_{sc,r,o} = u_{ss} \tag{15}$$

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[22] These incentives are mainly related to fringe benefits of workplace parking and other market distortions such as minimum parking requirements as described in Section 1.

The equalisation of utilities for commuters (11,12,13) is equivalent to a Wardropian user equilibrium, where the different transport and parking choices are deemed to be perfect substitutes.

5.2 Equilibrium conditions for firms

Firms are profit-maximisers. Normalising the market price of the final good to one, the aggregate profit of the firms in the centre Π_c can be written as the total output minus the labour costs and minus the proportion of workplace parking costs that are borne by the firm, including the workplace parking levy. Note that the perfectly competitive firms perceive the average product of labour f_c as an exogenous parameter.

$$\Pi_c = f_c * (n_c + n_{sc}) - w_c * (n_c + n_{sc}) - (1 - \beta) * (c_w + \tau_w) * P_w,$$

$$\text{with } f_c = \frac{F_c(n_c + n_{sc})}{n_c + n_{sc}} \tag{16}$$

And the profit maximising condition is:

$$\frac{\partial \Pi_c}{\partial n_{sc}} = 0 \tag{17}$$

5.3 Equilibrium conditions for the government

The government plays a passive role here. It collects tolls, on street parking fees, employer parking fees and pays subsidies for work in the city and redistributes the net revenues in a lump sum way to all the workers so that the government budget is in equilibrium. As we use quasi-linear utility functions, we can neglect the income effect of this lump-sum redistribution. The policy instruments are set exogenously, and we do not aim to explain the selection of policies by a political equilibrium model.

5.4 General equilibrium

It is instructive to understand the general equilibrium of the city's economy as a two-step procedure. In the first "short run" step, the equilibrium in the transport mode and parking market is reached for given work and residential locations. In the second "long term" step, the labour and land market reach a new equilibrium.

5.4.1 Short-term: Transport mode and parking equilibrium

In the short-term, employment and number of residents in the centre, n_{sc} and n_c respectively, are exogenous variables. From equations (11, 12, 13, 15) we find the conditions for the choice of commuting mode; the Wardrop conditions for the choice of mode and for the choice of parking options are:

$$c_r(n_r) + \tau_r + \beta * (c_w + \tau_w) = c_t(n_{sc} - n_r) + \tau_t \tag{18}$$

$$\beta * (c_w + \tau_w) = c_o(n_r - P_w) + \tau_o \tag{19}$$

The solutions of equations (18,19) are $n_r^*(n_{sc}; \tau_w, \beta)$ and $P_w^*(n_{sc}; \tau_w, \beta)$, which are functions of n_{sc} and the relevant parameters of the problem τ_w and β.[23] With this, we obtain the generalised price of transport p that results from the transport and parking behaviour:

$$p = c_r(n_r^*) + \tau_r + \beta * (c_w(P_w^*) + \tau_w) \tag{20}$$

From equation (15) and replacing with equation (20), the gross wage (unit labour cost) in the city centre is:

$$w_c(n_{sc}; \tau_w, \beta) = p(n_{sc}; \tau_w, \beta) + \widetilde{w_s} - s_c \tag{21}$$

Equation (21) describes the supply of labour to the city centre. Because $\frac{\partial p}{\partial n_{sc}} > 0$, as shown in Appendix A, labour costs in the city centre increase with the

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[23] The complementary variables $n_t^*(n_{sc}; \tau_w, \beta)$ and $P_o^*(n_{sc}; \tau_w, \beta)$ can be derived by considering that total parking needs to be satisfied by employer provided underground parking and on street parking and total commuting consists of car commuting and public transport commuting.

number of commuters n_{sc}, as firms have to compensate commuters for the increased generalised price of transport to compete with the alternative of working in the suburbs. Note that, as the gross wage in the centre is independent of the residence of the workers, residents in the centre also see their gross wage increased with more commuters.

5.4.2 Long-term: Work and residential location equilibrium

In the long term, the number of commuters and the residence of all the workers becomes endogenous. The number of commuters in the city centre will be driven by the gross wage and the gross wage will depend on the number of workers via the agglomeration effect.

The profit maximising condition in equation (17) applied to equation (16) and expressed as a function of p leads to:

$$f_c - \frac{\partial p}{\partial n_{sc}} * (n_c + n_{sc}) - p - \widetilde{w_s} + s_c - (1 - \beta) * (c_w + \tau_w) * \frac{\partial P_w^*}{\partial n_{sc}} = 0 \tag{22}$$

By combining equation (21) and equation (22) we obtain that, in equilibrium, the gross wage in the city centre w_c^* is equal to:

$$w_c^* = f_c - \frac{\partial p}{\partial n_{sc}} * (n_c + n_{sc}^*) - (1 - \beta) * c_w * \frac{\partial P_w^*}{\partial n_{sc}} \tag{23}$$

This means that, in equilibrium, the gross wage in the city centre is the average productivity minus the marginal labour costs of an extra commuter (because of increased cost for transport) and minus the marginal workplace parking costs of an extra commuter borne by firms.

When firms pass-on a proportion of parking costs to their employees ($\beta > 0$), those using a workplace parking space bear an extra cost $\beta * c_w$, but all employees see their wage increased by $\beta * c_w * \frac{\partial P_w^*}{\partial n_{sc}}$. It follows that the part of workplace parking costs borne by firms is allocated to all employees in a lump-sum way through wage decreases whereas the part of workplace parking costs passed-on to employees is only paid by workplace parking users.

From residents' equilibrium conditions in equations (9,10,14) and considering that L_h equals $n_c q_c + P_o a_o$ we obtain:

$$p + v\left(\frac{L_h - P_o^* a_o}{n_c}\right) - v'\left(\frac{L_h - P_o^* a_o}{n_c}\right) * \left(\frac{L_h - P_o^* a_o}{n_c}\right) = v(q_s) - q_s v'(q_s) \tag{24}$$

$$v'(q_s) = \tilde{r}_s \tag{25}$$

Equations (22, 24, 25) solve for $n_{sc}^*(\tau_w, \beta)$ and $n_c^*(\tau_w, \beta)$.

5.5 First-best decentralisation

Equilibrium conditions (18, 19, 22, 24, 25) are compared to the social optimal conditions (5,6,7,8) to derive a first-best decentralisation. It can be shown that the following are necessary conditions for a decentralisation of the first-best allocation (the subscript FB means that the variable is set at the first-best allocation value):

a) $s_c^{FB} = F_c{}'(n_c^{FB} + n_{sc}^{FB}) - w_c^*$; a subsidy (in the form of lower labour taxes, for example) is provided to workers in the centre equal to the uninternalized effect of agglomeration economies, i.e. difference between social productivity and the gross wage in equilibrium;
b) $\tau_t^{FB} = n_t^{FB} c_t{}'(n_t^{FB})$; public transport users pay a fare equal to the crowding externality;
c) $\tau_r^{FB} = n_r^{FB} c_r{}'(n_r^{FB})$; road users pay a congestion toll equal to the congestion externality;
d) $\beta = 1$; a regulation on workplace parking induces a switch to employee-paid parking;
e) $\tau_w^{FB} = 0$; no workplace parking levy is applied;
f) $\tau_o^{FB} = P_o^{FB} c_o{}'(P_o^{FB}) + a_o v'(q_c)$; on-street parking users pay a fee equal to the parking search externality plus the opportunity costs of land.

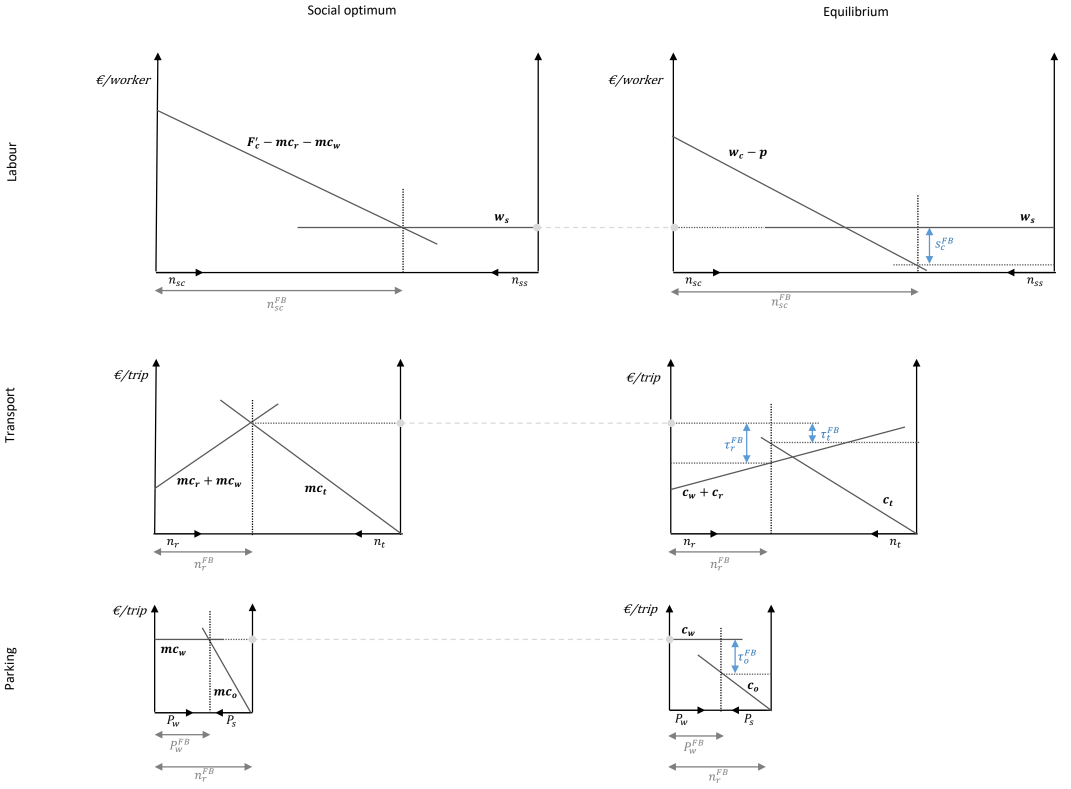
Condition *d* requires further explanation. The switch to employee-paid parking can be achieved by introducing a cash-out program such that firms are legally obliged to offer a cash compensation equal to c_w to their employees in lieu of their employer-paid parking space. Then, free parking has an opportunity cost for employees which is equal to the forgone cash c_w. However, if income is taxable but employer-paid parking is not, the additional income tax applied to the cash compensation can be viewed as a cost of not choosing the employer-paid parking option. This reduces the amount employees perceive for an employer-paid parking space (Brueckner and Franco, 2018; Shoup, 2005a). Therefore, employees will only get the full marginal cost of workplace parking if the cash-out programme is complemented by a modification of fiscal legislation making employer-paid parking as a taxable fringe benefit.

The first best decentralisation is illustrated in Figure 2-2, with social optimum to the left and corrections needed for the equilibrium to the right. The top-left diagram shows the social optimum conditions in the labour market, i.e. productivity in the centre minus marginal commuting costs are equal to the exogenous wage in the suburbs. For simplicity, the profit maximising condition in the top-right diagram is expressed in terms of the equilibrium wage as $w_c^* - p - s_c = w_s$, by combining equations (21) and (23). Because agglomeration economies are external to firms, *laisse-faire* equilibrium results in excessive employment in the suburbs, which can be corrected with a subsidy to employment in the centre (condition *a*).

The second part of the diagram shows the modal choice for the commuters and how it needs to be corrected by tolls and crowding charges (conditions b and c in this section). The third (bottom) part shows the optimal use of the two parking options in the city centre and the on-street parking fee that is necessary to implement the first best optimum (conditions d, e, f).

Figure 2-2: Marginal costs under social optimum conditions (left) and average costs and first-best taxes and fares under equilibrium conditions (right) in the labour, transport and parking markets. Notation: Marginal user cost of road

$\boldsymbol{mc_r = c_r + n_r c_r{}'}$; marginal user cost of public transport $\boldsymbol{mc_t = c_t + n_t c_t{}'}$; marginal cost of on-street parking $\boldsymbol{mc_o = c_o + P_o c_o{}' + a_o v'(q_c)}$



6 Analysis of the effects of workplace parking policies

In this section, we use comparative statics, to analyse the effect on travel behaviour, agglomeration economies and residential location of the two analysed policy instruments related to workplace parking: a switch to employee-paid parking and a workplace parking levy. The order of magnitude of these effects will be illustrated numerically in section 8.

6.1 Effects on travel behaviour

If we differentiate equations (18,19,21) with respect to the parameters of the problem, β, τ_w and we solve the resulting system of equations, we obtain the following (details in the Appendix A):

$$\left\{\frac{\partial p}{\partial \beta} > 0; \frac{\partial n_r}{\partial \beta} < 0; \frac{\partial n_t}{\partial \beta} > 0; \frac{\partial P_w}{\partial \beta} < 0; \frac{\partial P_o}{\partial \beta} > 0\right\} \tag{26}$$

$$\left\{\frac{\partial p}{\partial \tau_w} > 0; \frac{\partial n_r}{\partial \tau_w} < 0; \frac{\partial n_t}{\partial \tau_w} > 0; \frac{\partial P_w}{\partial \tau_w} < 0; \frac{\partial P_o}{\partial \tau_w} > 0\right\} \tag{27}$$

Equation (26) shows that a higher pass-on rate of workplace parking costs to employees causes a shift from road use to public transport and from workplace parking to on-street parking. As per equation (27), a workplace parking levy produces the same effects on travel behaviour, but, in this case, the magnitude of the effect depends on the pass-on rate β, such that if $\beta = 0$, the workplace parking levy τ_w has no impact on the transport and parking split.

It should also be noted that both the switch to employer-paid parking and the workplace parking levy cause an increase in the generalised price of transport, which means that the increased charge for parking is not offset by a reduction in travel time costs.

We analyse the effect of more commuting trips by differentiating equations (18,19,21) in terms of n_{sc}, which yields the following:

$$\left\{\frac{\partial p}{\partial n_{sc}} > 0; \frac{\partial n_r}{\partial n_{sc}} > 0; \frac{\partial n_t}{\partial n_{sc}} > 0; \frac{\partial P_w}{\partial n_{sc}} > 0; \frac{\partial P_o}{\partial n_{sc}} = 0\right\} \tag{28}$$

Because road and public transport are both congestible, in terms of increased travel time and increased discomfort respectively, more commuting trips to the city centre will lead to an overall increase in the generalised price of transport and to more users both in road and public transport modes, as shown in equation (28).

By further differentiating in terms of the policy parameters τ_w and β, we obtain the following results (proof in the Appendix A):

$$\frac{\partial^2 p}{\partial n_{sc} \partial \beta} < 0 \tag{29}$$

$$\frac{\partial^2 p}{\partial n_{sc} \partial \tau_w} < 0 \tag{30}$$

Equations (29) and (30) show that both workplace parking policies induce a reduction in the marginal transport price of an extra commuter. This effect is achieved by decreasing road use and the resulting mitigation of congestion effects.

6.2 Effects on agglomeration economies

We use comparative statics on $\frac{dn_{sc}}{d\beta}$ and $\frac{dn_{sc}}{d\tau_w}$ to evaluate the effect of workplace parking policies on agglomeration economies.

Proposition 1:

Under the assumptions of the model:

a) A full switch to employee-paid parking ($\beta = 1$) increases employment in the city centre and, consequently, agglomeration economies;
b) A workplace parking levy has only positive effects on agglomeration economies when the pass-on rate β of parking costs is high.

The details of the proof are included in the Appendix A. The basic rationale behind Proposition 1 is the following: In a switch to employee-paid parking (proposition 1a), because employers are indifferent on the proportion of parking costs passed-on to employees (increased parking costs are compensated with wage decreases and vice versa), only second-order effects are relevant. As per equation (29), a switch to employee-paid parking mitigates congestion effects by decreasing road use. This promotes employment in the city centre as the marginal labour cost of an extra commuter, which internalises the price for transport, will decrease. Since we assume that the switch to employee-paid parking is achieved through a fiscal reform that considers parking as a taxable fringe benefit, the income tax consideration would not modify this result.

However, when a workplace parking levy is applied (proposition 1b), this represents an extra cost for firms that cannot be compensated and that will be borne by firms either in terms of wage increases (if employee-paid parking) or in the form of extra parking costs (if employer-paid parking). The overall effect on agglomeration economies of a workplace parking levy will result from the juxtaposition of two effects. On the one hand, a workplace parking levy increases marginal labour costs (either in terms of wages or parking costs), which obviously discourages employment in the city centre. On the other hand, as per equation (30), a workplace parking levy disincentivises road use and lessens congestion effects as a second-order effect, which may offset the direct increase in marginal cost of labour caused by the levy. The second effect is more significant when β is higher. This means that a workplace parking levy is more likely to have a positive effect on agglomeration economies when the pass-on rate of parking costs to employees is higher (β is closer to 1). The numerical illustration will show the relative importance of the two effects.

6.3 Effects on residential location

As shown in the Appendix A, the effect of a switch to employee-paid parking on residence in the city centre (sign of $\frac{dn_c}{d\beta}$) is ambiguous in general. However, when we disregard the effect of spillover parking ($a_o \rightarrow 0$), we find that a switch to employee-paid parking leads to an increase of residents in the city centre. Brueckner and Franco (2018) reach a similar conclusion. The increase of residents in their study is due to more available land for central residences that was previously used for parking, but this argument does not apply to our analysis as we consider off-street facilities built underground. Our driver for the increase in central residents is different, for us it is the higher generalised cost of commuting caused by employee-paid parking. Thus, when parking spillover is limited, the reduced suburbanisation effect of employee-paid parking still holds for dense cities with underground parking facilities.

However, if a switch to employee-paid parking leads to significant spillover parking $a_o > 0$, this may take residential land and offset the increase in central residents described above. Again, the numerical illustration will provide more insight on the relative importance of these effects.

7 Second-best workplace parking levy

Suppose that we cannot count on all the policy instruments required to reach the first-best decentralisation. It seems interesting to analyse if the application of a workplace parking levy could be a second-best policy instrument to deal with road congestion.

Say that, for example, because of political constraints, road tolls cannot be introduced ($\tau_r = 0$). In such case, a workplace parking levy ($\tau_w > 0$) may be regarded as a second-best policy instrument to discourage road use and reduce the road congestion externality. The drawback is that this would induce spillover parking, increase the parking cruising externality and require more residential land for on-street parking in the long run. Another countereffect is that this could raise the cost of transport, reduce the attractiveness of the centre for work and cause a loss in agglomeration economies. Hence, a second-best setting for a workplace parking levy should trade-off the effects on congestion, on-street parking and agglomeration economies.

In this section, to focus on the analysis of the mentioned trade-off for an optimal workplace parking levy, we only consider the short-term and mid-term equilibrium. Thus, the number of residents in the city centre $\widetilde{n_c}$, the land consumption $\widetilde{q_c}$ and the land rent $\widetilde{r_c}$ are exogenous. Besides, for the sake of simplicity, we consider only the case of employee-paid parking ($\beta = 1$). This means that both the costs of parking and the workplace parking levy are fully borne by employees in our analysis of the second-best setting. Finally, we assume that policy instruments other than the workplace parking levy are exogenous. The road toll, the public transport fee, the on-street parking fee and the wage subsidy in the city centre are fixed respectively at $\widetilde{\tau_r}$, $\widetilde{\tau_t}$, $\widetilde{\tau_o}$ and $\widetilde{s_c}$, which can be either zero or positive values. Thus, we consider a context where these policy instruments are either not applicable or cannot be modified because of political, social or technical constraints.

The optimal second-best workplace parking levy τ_w^{SB} from a social planner's perspective is reached when the total utility is maximized subject to the equilibrium conditions of the model. The resulting Lagrangian can be written as:

$$L_2 = F_c + \widetilde{w_s} * (1 - \widetilde{n_c} - n_{sc}) - n_{sc} * p - a_o * \widetilde{r_c} * P_o^* + P_w^* * \tau_w + n_r^* * \widetilde{\tau_r} + n_t^* * \widetilde{\tau_t} + P_o^* * \widetilde{\tau_o} + \lambda * \left(f_c - \frac{\partial p}{\partial n_{sc}} * (\widetilde{n_c} + n_{sc}) - p - \widetilde{w_s} + \widetilde{s_c}\right) \tag{31}$$

The objective function in equation (31) is the total utility of the city, which is composed of the total output of the city minus the transport costs, minus the opportunity costs of land for on-street parking plus the revenues generated by tolls and fees. We assume that the wage subsidy is implemented through a revenue-neutral difference in labour taxes between the centre and the suburbs and so it is not part of the utility. The constraint multiplied by λ is the equilibrium condition for firms (22). We derive the first order conditions for equation (31) in terms of n_{sc} and τ_w^{SB}.

Proposition 2: Under the assumptions of the model, the optimal second-best workplace parking levy τ_w^{SB} offsets the price deviation in road transport with respect to its first best value, but also accounts for potential price distortions in public transport, on-street parking and labour, in terms of the following expression:

$$\tau_w^{SB} * \frac{dP_w^*}{d\tau_w} = (\tau_r^{FB} - \widetilde{\tau_r}) * \frac{dn_r^*}{d\tau_w} + (\tau_t^{FB} - \widetilde{\tau_t}) * \frac{dn_t^*}{d\tau_w} + (\tau_o^{FB} - \widetilde{\tau_o}) * \frac{dP_o^*}{d\tau_w} - (s_c^{FB} - \widetilde{s_c}) * \frac{dn_{sc}}{d\tau_w} \tag{32}$$

Details of the proof are presented in the Appendix A. Note that the second-best workplace parking levy τ_w^{SB} results from the weighted sum of the differences between the current levels of the other policy instruments and their respective first-best values. The weighting coefficients are the total derivatives of the relevant variables of the problem with respect to τ_w. This means that, for example, $\frac{dP_w^*}{d\tau_w} = \frac{\partial P_w^*}{\partial \tau_w} + \frac{\partial P_w^*}{\partial n_{sc}} * \frac{dn_{sc}}{d\tau_w}$. Based on the comparative statics analysis of section 6, $\frac{\partial P_w^*}{\partial \tau_w} < 0$, $\frac{\partial P_w^*}{\partial n_{sc}} > 0$ and $sign\left(\frac{dn_{sc}}{d\tau_w}\right)$ depends on the context. Therefore, $sign\left(\frac{dP_w^*}{d\tau_w}\right)$ can be positive or negative, and no general conclusions can be drawn. The same can be argued for the other variables.

This result can be seen as an extension of the Doi problem (Doi, 1986) as presented in Arnott and Yan (2000). The Doi problem seeks the optimal price of a public transport mode when road transport is underpriced and capacities are fixed. We have expanded this by considering externalities also in the public transport mode and by including parking alternatives and agglomeration economies of the labour market into the model.

In practice, this result means that a workplace parking levy is only efficient as a second-best instrument when road traffic externalities are sufficiently high to compensate for unintended effects or when on-street parking, public transport and the labour market are optimally regulated. In addition, when a workplace parking levy has positive effects in terms of agglomeration economies, its optimal level will be higher.

8 Numerical illustration for Barcelona

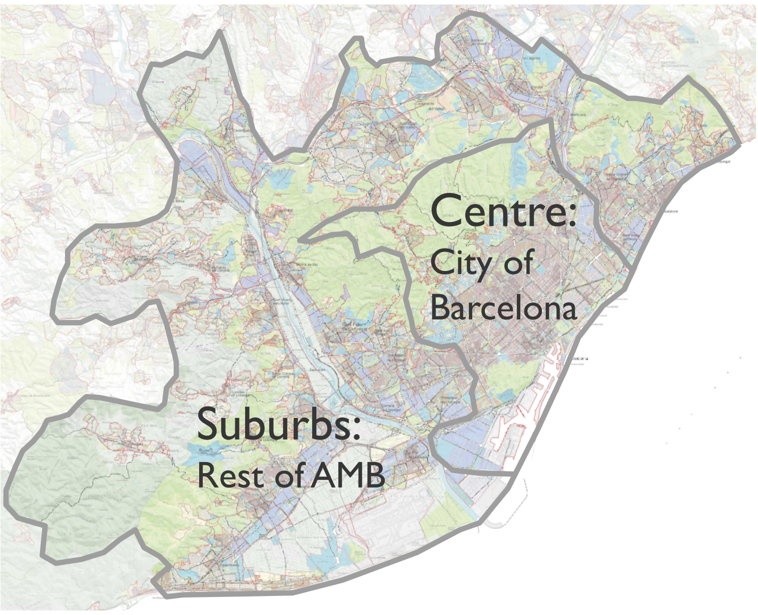
In this section, we illustrate our theoretical model with a numerical example for the city of Barcelona. In this way we can determine the relative importance of the different effects. This is particularly important when we are in a second-best environment because the first best is not always providing the correct policy guidance. We start by outlining the setting and the functional forms of the numerical case, we then present the data and the calibration process and, finally, we discuss the results (details of data and calibration of parameters are presented in Appendix B).

8.1 Outline of the numerical example

The city is divided into two areas, the centre is represented by the administrative limits of the municipality of Barcelona, while the suburbs include the rest of the AMB, the public administration of the metropolitan area of Barcelona. According to the most recent census data (EMO 2011), 688000 people work in the centre and 181000 of these commute from the suburbs. 289000 inhabitants in the suburbs also work in the suburbs. According to a recent mobility survey (EMQ 2016), 49% of the commuters use a car, while the rest use public transport. Among those who park in the centre, 52% have a workplace parking space provided by their employer, 25% park on-street and the rest use other parking facilities. This means that there are 46000 commuters from the suburbs who use an employer-provided parking space, only 19% of these are employee-paid. The city centre of Barcelona has a good public transport system, so city residents use almost no cars to travel to work.

No congestion charging scheme has been implemented in Barcelona and the percentage of employee-paid parking is relatively low (19%), which makes it an ideal example for the analysis of a second-best solution based on workplace parking policies. The numerical illustration is calibrated to the current situation (baseline) with observed data from a range of sources and current policy instruments in place.

Figure 2-3: Geographical limits of the numerical example



8.2 Functional forms

The numerical illustration for Barcelona is based on functional forms and parameters shown in Table 2-1. The utility function of residents keeps the quasi-linear form of the theoretical model. For simplicity, we assume $v(q_c)$ to be a logarithmic function of the house size q_c. The exogenous suburbs land rent r_s is constant.

For the labour productivity, we assume that the elasticity of the total factor productivity with respect to employment density is constant, which is a typical assumption in the literature to quantify agglomeration economies (e.g. Ciccone (2002), Combes et al. (2012)). Therefore, the average productivity has an elasticity with respect to city employment equal to δ. The exogenous suburbs wage w_s is constant.

As in the theoretical model, road transport to the city centre is represented by a single congestible road link. Road user costs within this link are based on the

Bureau of Public Roads (BPR) function,[24] a simple time-averaged speed–flow function where travel time is proportional to the fourth power of the flow over capacity. Public transport is also modelled as a single congestible link. For this, we assume a description of crowding costs taken from Tirachini et al. (2013). The crowding discomfort is linear to the load factor once a load factor threshold ε_t is exceeded.

The price of workplace parking is represented by the proportion of average cost of workplace parking and workplace parking levy that is charged to employees, plus the parameter $\emptyset$ representing the difference in access time with respect to on-street parking, which is used for calibration purposes.

Following Inci et al. (2017), the time of cruising for on-street parking is assumed to be linear with the number of parkers (i.e. commuters searching for parking) once an occupation level threshold is exceeded. The price of on-street parking has to consider current regulations and tariffs applied to curbside parking in the city of Barcelona on top of search costs. Most parking spaces are subject to a fee under the AREA system;[25] however, there are still some spaces which are not subject to a fee or time regulation. Our function to represent the price of on-street parking assumes that unregulated parking spaces are filled in the first place. When the number of parkers P_o exceeds the available unregulated parking spaces Ω_o, parkers have a uniform probability of having to park in a regulated space and pay the corresponding fee. Based on this, their perceived price is the tariff in regulated areas σ_o, multiplied by the probability of parking in a regulated space $\frac{P_o - \Omega_o}{P_o}$.

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[24] As described in Small and Verhoef (2007), for example.

[25] The AREA system includes Area Blava and Area Verda. The Area Blava spaces are intended to encourage a high turnover of vehicles in the vicinity of service areas (tariffs 1-2.5 €/h) while Area Verda spaces aim to prioritise the parking for residents (tariff for non-residents 2.75-3 €/h).

Table 2-1: Functional forms and parameters of the numerical illustration

Module	Functional forms	Parameter	Description
Residential	Utility of land consumption: $v(q_c) = \alpha * \log{(q_c)}$	α	Utility parameter
		r_s	Suburbs land rent (€/m2/day)
Labour	Average labour productivity: $f_c(n_{sc}, n_c) = \theta * (n_{sc} + n_c)^{\delta}$	θ	Index of total factor productivity
		δ	Elasticity of productivity with respect to employment density
		w_s	Average daily gross wage in the suburbs (€/day)
Road transport	Average cost of road use: $c_r(n_r) = 2 * \left[c_F + V_T * T_r * \left(1 + \left(\frac{n_r}{k_r}\right)^4\right)\right]$	c_F	Fuel costs per trip (€)
		V_T	Value of time (€/hour)
	Generalised price of road use: $p_r(n_r) = c_r(n_r) + \tau_r$	T_r	Free-flow travel time (hours)
		k_r	Index of road capacity
		τ_r	Road toll per road trip
Public transport	Average cost of public transport use: $c_t(n_t) = \begin{cases} 2 * T_t * \left(V_T + \rho * \left(\frac{n_t}{k_t} - \varepsilon_t\right)\right), & \frac{n_t}{k_t} > \varepsilon_t \\ 2 * T_t * V_T, & \frac{n_t}{k_t} \leq \varepsilon_t \end{cases}$	T_t	Public transport travel time (hours)
		V_T	Value of time (€/hour)
		ρ	Index of crowding discomfort
		ε_t	Load factor threshold

Module	Functional forms	Parameter	Description
	Generalised price of public transport use: $p_t(n_t) = c_t(n_t) + \tau_t$	k_t	Index of public transport capacity
		τ_t	Public transport fee per round trip
Workplace parking	Generalised price of workplace parking use: $p_w(P_w) = \beta * (c_w + \tau_w) + \emptyset$	c_w	Average cost of workplace parking (€/day)
		$\emptyset$	Index of parking access time
On-street parking	Average cost of on-street parking use: $c_o(P_o) = \begin{cases} \frac{V_T * (P_o - \varepsilon_o)}{k_o}, & P_o > \varepsilon_o \\ 0, & P_o \leq \varepsilon_o \end{cases}$ Based on Generalised price of on-street parking use: $p_o(P_o) = \begin{cases} c_o(P_o) + \tau_o + \sigma_o * \left(\frac{P_o - \Omega_o}{P_o}\right), & P_o > \Omega_o \\ c_o(P_o) + \tau_o, & P_o \leq \Omega_o \end{cases}$	V_T	Value of time (€/hour)
		ε_o	Occupation level threshold
		k_o	Index of on-street parking capacity
		σ_o	Daily on-street parking price in payment areas
		Ω_o	Number of available free on-street parking spaces
		τ_o	Global daily on-street parking fee

8.3 Data and calibration

In this section we outline the calibration process to generate the numerical illustration in the baseline (i.e. current policy instruments in place). The process starts by calibrating the equilibrium conditions for the transport and parking markets in terms of the calibration parameters $\{\emptyset, \varepsilon_o\}$. From this we calculate the generalised price of transport p and its derivatives. We then proceed to calibrate the work location equilibrium for parameters $\{\theta, w_s\}$ and, finally, the residential location equilibrium conditions to obtain the exogenous parameters $\{\alpha, r_s\}$. The details of data and results of the calibration are presented in Appendix B.

The value of time used to calibrate transport functions is taken from the Catalan transport appraisal guidance (DGIMT, 2015). The capacity parameter k_r within the BPR function is calibrated with data on average congestion time in Barcelona´s access roads as per RACC (2016). In public transport, crowding parameters are taken from Tirachini et al. (2013) and the capacity parameter k_t is directly obtained from assuming the average load factor at peak hour is equal to the load factor threshold from which crowding happens. The public transport fee τ_t is based on a weighted average of prices for multiticket travel cards for trips from AMB municipalities to Barcelona.

The estimated capacity index k_o within the on-street parking function assumes a reference value for the marginal cost of parking cruising taken from Inci (2017). The daily cost of workplace parking is based on typical prices for 8 hours parking time in off-street parking facilities in Barcelona. To the best of our knowledge, there is no available data on the proportion of the costs of workplace parking that employers pass-on to their employees (β) for Barcelona. For the purpose of our numerical illustration, we assume the average pass-through rate is equal to the aggregate share of employee-paid parking (19%). We use this short cut to avoid discontinuities and simplify the numerical application. This can be interpreted as a case where employer-paid ($\beta = 0$) and employee-paid ($\beta = 1$) parking spaces were allocated randomly to employees, such that the probabilised cost employees perceive ($c_w * 0.19$) is equivalent to the parking cost passed on to employees with $\beta = 0.19$.

With these values for variables and parameters, the unknown parameters $\emptyset$ and ε_o are obtained by solving the equilibrium conditions for the transport and parking markets (18,19).

The average production f_c is obtained by applying to equation (23) the value of the average gross wage in the city centre according to the municipality of Barcelona and the derivates of transport functions already calibrated. We then take the value of elasticity of productivity with respect to employment density δ from Ciccone (2002) and fully calibrate the average production function in terms of the remaining parameter θ. We also obtain the wage in the suburbs w_s with equation (20).

To calibrate the functional forms adopted for the residential module we use data on average rent prices per square meter and total residential land provided by the municipality of Barcelona. The average house size q_c is then obtained by dividing total residential land by the number of workers living in the city centre n_c, and parameters α and r_s are derived from applying equation (24, 25) with these values.

8.4 Numerical results

The model is solved by using the equilibrium conditions (18, 19, 22, 24, 25) for the relevant variables of the model taking the functional forms and parameters described above.

We introduce some further notation to decompose the total welfare effect in different components. We define average commuting costs c_{sc}, including both transport and parking costs, and average commuting costs at agglomeration level c as:

$$c * n = c_{sc} * n_{sc} = n_r * c_r(n_r) + P_w * c_w + P_o * c_o(P_o) + n_t * c_t(n_t) \tag{34}$$

The average productivity at agglomeration level f is:

$$f * n = f_c * (n_c + n_{sc}) + \widetilde{w_s} * n_{ss} \tag{35}$$

The surplus associated to land consumption in the centre l_c is defined as the total utility from land consumption minus land resource costs in the centre:

$$l_c * n_c = n_c * v(q_c) - \widetilde{r_s} * \left(\widetilde{L_p} + n_c * q_c + a_o * P_o\right) \tag{36}$$

Similarly, the surplus associated to land consumption at agglomeration level l is defined as:

$$l * n = l_c * n_c + (n_{sc} + n_{ss}) * (v(q_s) - \widetilde{r_s} * q_s) \tag{37}$$

With this notation, residents' utility can be expressed as a sum of agglomeration, land use and transport and parking effects:

$$u = f + l - c \tag{38}$$

8.4.1 Effects of a switch to employee-paid parking

The numerical illustration is used to assess the different effects of a switch to employee-paid parking. Table 2-2 below presents the results for the current situation ($\beta = 0.19$) and for variations within the range of the pass-on rate β and decomposes the total effect into transport and parking effects, agglomeration effects and land use effects.

The numerical application confirms the effects on the transport and parking markets from our theoretical analysis in Section 6. Increasing levels of employee-paid parking (higher β) lead to a shift to public transport and an increase in on-street parking use. Under the assumption that transport modes are perfect substitutes, the road share decreases from 49% to 38% when parking is fully paid by employees ($\beta = 1$).

Our results show a convex relationship between average commuting costs c_{sc} and the pass-on rate. Since average costs of commuting by public transport are lower than those of a commute by road with parking, the shift to public transport leads to efficiency gains in terms of reduced commuting costs when the pass-on rate increases from the current situation (0.19) to 0.5. However, because both road and public transport are congestible and as the new situation entails more commuters to the centre, efficiency gains from a shift to public transport are offset by additional congestion and crowding effects, in both modes. This explains why average commuting costs increase when the pass-on rate increases from 0.5 to 1.

The spillover parking effect leads to a 30% increase in on-street parking spaces used by commuters when workplace parking is fully paid by employees. However, since unregulated parking spaces in Barcelona are mostly located in the periphery and often far from workplaces, the additional intra-city transport costs from the parking space to the workplace, which are not considered in our aggregated model, would clearly limit this effect.[26]

Regarding agglomeration effects, results of Proposition 1 are confirmed with up to almost 10% more commuters to the city centre and higher productivity in the centre as the pass-on rate increases. Average productivity in the city centre increases by 0.4% with respect to the current situation as a result of the switch to employee-paid parking.

Next we turn to the land-use effects. A switch to employee-paid parking makes more residents live in the centre. This is the direct result of the increased price for commuting (road and public transport) and where the spillover effect of residential land taken by on-street parking remains limited. More residents to the centre leads to lower land consumption per resident and a reduction in the surplus from land consumption.

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[26] In addition, empirical evidence from Barcelona (Gragera and Albalate, 2016) suggests that there is no clear substitution effect between off-street and on-street parking for recurrent users, while our stylised model assumes perfect substitution between transport and parking modes. Therefore, our numerical illustration may overestimate the unintended parking spillover, which is likely to be more limited in practice.

Table 2-3 presents the decomposition of the overall welfare effect for different pass-through rates. Overall, our numerical application shows that a switch to employee-paid parking ($\beta = 1$) is clearly a welfare enhancing measure. Efficiency gains achieved by increased productivity are the dominant source of the welfare gain. These are three times larger (74%) than the welfare changes in the transport (16%) and land use market (9%) together.

We test the sensitivity of these results to agglomeration effects by considering a lower elasticity of productivity with respect to employment density δ (see Appendix B for detailed results). When we reduce δ from 4.5% to 2%, the number of commuters to the centre is slightly less sensitive to the pass-on rate of parking costs, while the effect on average productivity in the centre is clearly mitigated. This leads to somewhat lower welfare gains from a switch to employee-paid parking. However, the relative importance of agglomeration economies, commuting costs and land use on welfare remains fairly constant.

To understand the robustness of the relative importance of agglomeration economies in our numerical illustration, we need to look at the drivers of overall productivity. Effects on average productivity at agglomeration level are composed of both changes in the productivity of the centre and changes in the number of commuters working in the centre, where productivity is in any case higher than in the suburbs. A lower elasticity δ mitigates the first, but the latter remains significant and becomes the main driver of increased productivity at agglomeration level from a switch to employee-paid parking.

Table 2-2: Effects of a switch to employee-paid parking. Monetary values in euros per day. Baseline equilibrium for $\boldsymbol{\beta} = \mathbf{0.19}$

	Pass-on rate (β)			
	0	0.19	0.5	1
Transport and parking effects				
Road transport share (%)	52%	49%	45%	38%
Used on-street parking spaces ($* 10^3$) (P_o)	15.0	22.1	24.4	28.9
Average commuting costs (c_{sc})	16.7	16.5	16.3	16.6
Agglomeration effects				
Number of commuters ($* 10^3$) (n_{sc})	176.2	180.6	188.1	204.7
Average productivity in the centre (f_c)	171.9	172.0	172.2	172.6
Land use effects				
Number of residents in the centre ($* 10^3$) (n_c)	504.6	507.9	518.9	541.2
Surplus from land consumption in the centre (l_c)	85.7	85.5	85.1	84.5

Table 2-3: Welfare effects of a switch to employee-paid parking. Monetary values in euros per day. Baseline equilibrium for $\boldsymbol{\beta} = \mathbf{0.19}$

	Pass-on rate (β)				Welfare change β from 0.19 to 1	
	0	0.19	0.5	1	Dif.	% Abs. variation
Utility per resident ($u = f + l - c$)	242.4	242.7	243.4	244.8	+2.1	
Average productivity at city level (f)	157.5	157.9	159.0	161.2	+3.3	74%

	Pass-on rate (β)				Welfare change β from 0.19 to 1	
	0	0.19	0.5	1	Dif.	% Abs. variation
Surplus from land consumption at city level (l)	87.9	87.8	87.6	87.1	-0.7	16%
Average commuting costs at city level ($-c$)	-3.01	-3.05	-3.14	-3.47	-0.4	9%

8.4.2 Effects of a workplace parking levy

The application of a workplace parking levy of 1 €/space-day and 2 €/space-day for different pass-on rates of parking costs is tested. Results are presented in Table 2-4 and Table 2-5. These can be compared to the equilibrium baseline ($\beta = 0.19$ and $\tau_w = 0$) presented in Table 2-2 and 2-3.

In the current situation ($\beta = 0.19$), the application of a workplace parking levy, within the range considered, has little effect on the economy of the city. The cost of the levy is mostly borne by employers, which leads to an increase in costs of labour. As a result, there are fewer commuters to the city centre and a slight loss in agglomeration economies. At the same time, road transport is somewhat disincentivised because a part of the levy is passed-on to employees. This leads to small efficiency gains in terms of lower transport and parking costs. In Table 2-5 we see that passing from a workplace levy of 1 to 2 €/day has a negative agglomeration effect that is compensated by the efficiency gain on the transport market.

When workplace parking is fully paid by the employer ($\beta = 0$), the application of a workplace parking levy is very counterproductive. As in the previous case, higher marginal costs of labour in the centre decrease the number of commuters and induce a much larger loss in agglomeration economies. As there is a decrease of employment in the centre, there will be fewer commuters to the centre. Since these commuters do not see an increase in car commuting costs, the share of car commuting increases, but overall there is a small gain in commuting costs. Also, the number of residents decreases. Overall, a workplace parking levy results in a welfare loss. As shown in Table 2-5, welfare losses are now largely dominated by the decrease in productivity.

When the pass-on rate increases to 0.5 or more ($\beta \geq 0.5$), the application of a workplace parking levy becomes a welfare enhancing measure. It increases agglomeration economies with more commuters to the centre and also discourages suburbanisation. Average transport and parking costs per commuter decrease because demand is shifted from road to public transport. However, at the city level, the higher number of commuters means that the average expenditure on transport and parking per city resident is higher. The only negative side effect is the increase in on-street parking use. It should be noted again that the parking spillover effect may be lower in practice; limitations described above for the switch to employee-paid parking also apply here.

These numerical results are consistent with our theoretical analysis in Proposition 1b. A workplace parking levy is more likely to have a positive effect on agglomeration economies when the pass-on rate of parking costs to employees is higher. Since the numerical application shows that welfare changes are largely dominated by agglomeration effects, a workplace parking levy is also more likely to be welfare-enhancing with a higher pass-on rate of parking costs to employees.

Table 2-4: Effects of the application of a workplace parking levy. Monetary values in euros per day

	$\beta = 0$		$\beta = 0.19$		$\beta = 0.5$	
	Workplace parking levy (τ_w) (€/day-space)					
	1	2	1	2	1	2
Transport and parking effects						
Road transport share (%)	52%	52%	49%	48%	43%	42%
Used on-street parking spaces ($* 10^3$) (P_o)	15.0	15.0	22.4	22.7	25.3	26.3
Average commuting costs (c_{sc})	16.6	16.6	16.4	16.3	16.3	16.2
Agglomeration effects						
Number of commuters ($* 10^3$) (n_{sc})	174.7	173.1	179.9	179.3	189.7	191.5
Average productivity in the centre (f_c)	171.9	171.8	172.0	172.0	172.2	172.3
Land use effects						
Number of residents in the centre ($* 10^3$) (n_c)	503.4	502.1	508.1	508.3	522.1	525.5
Surplus from land consumption in the centre (l_c)	85.8	85.8	85.5	85.4	85.0	84.9
Welfare						
Utility per resident ($u = f + l - c$)	242.3	242.2	242.7	242.7	243.6	243.8
Average productivity at city level (f)	157.3	157.2	157.9	157.9	159.2	159.5
Surplus from land consumption at city level (l)	88.0	88.0	87.8	87.8	87.5	87.4
Average commuting costs at city level ($-c$)	-3.00	-2.94	-3.02	-3.00	-3.16	-3.18

Table 2-5: Welfare changes from the application of a workplace parking levy. Monetary values in euros per day

	Welfare change τ_w from 1 to 2					
	$\beta = 0$		$\beta = 0.19$		$\beta = 0.5$	
	Dif.	% Abs. variation	Dif.	% Abs. variation	Dif.	% Abs. variation
Utility per resident ($u = f + l - c$)	-0.10		-0.01		+0.20	
Average productivity at city level (f)	-0.15	73%	-0.03	45%	+0.30	75%
Surplus from land consumption at city level (l)	+0.02	10%	-0.01	10%	-0.08	19%
Average commuting costs at city level ($-c$)	+0.04	17%	+0.03	45%	-0.02	6%

9 Concluding remarks

This chapter studies the effects of workplace parking policies on the urban economy through a stylised analytical model adapted from Brueckner and Franco (2018) and a numerical illustration for the metropolitan area of Barcelona.

First, as Brueckner and Franco (2018), we find that both switching to employee-paid parking and the application of a workplace parking levy mitigate congestion by shifting commuters from road to public transport. This continues to hold when there is a limited shift from underground workplace parking to on-street parking. Second, and here we differ from Brueckner and Franco (2018), we find that a switch to employee-paid parking shifts employment from the suburbs to the city centre and this generates additional agglomeration economies. Third, when parking spillover is limited, the reduced suburbanisation effect of employee-paid parking found in Brueckner and Franco (2018) still holds for dense cities with underground parking facilities. However, a significant parking spillover in residential areas could at least partially offset this effect.

Finally, and most importantly, the numerical application to the case of Barcelona shows the relative importance of the effects of different workplace parking policies. We find that welfare changes are largely dominated by agglomeration effects and to a lesser extent by transport, parking and land use effects.

These findings have policy implications for local authorities considering the implementation of workplace parking policies. A switch to employee-paid parking can be achieved through a cash-out programme complemented by a modification of fiscal legislation that considers employer-paid parking as a taxable fringe benefit. This is found to be a welfare increasing policy for the metropolitan area of Barcelona and the concern that it could induce a loss in agglomeration economies is contradicted by our theoretical and numerical results. The only unintended effect may be the spillover parking on residential areas, which would require ad-hoc regulations.

The application of a workplace parking levy, however, requires some more caution. First, in a context of generalised employer-paid parking, the application of a workplace parking levy may be counterproductive, as it may increase labour costs in the centre with no positive effects on travel behaviour. Therefore, a workplace parking levy should not be seen as a stand-alone policy but as a complement to other policy measures that favour employee-paid parking (i.e. fiscal reform and/or cash-out). Second, we find that the application of a workplace parking levy as a second-best policy to deal with road traffic externalities has to trade-off road external costs with other non-internalised externalities, including agglomeration economies, parking cruising and public transport crowding. Hence, a workplace parking levy is only efficient when the resulting reduction in road externalities are sufficiently high to compensate for unintended effects or when on-street parking, public transport and the labour market are optimally regulated.

Our model remains a toy model with many simplifying assumptions that mainly helps to structure the argumentation and give orders of magnitude. Three types of assumptions are of interest for further work.

First, in our model we consider that the pass-on rate of workplace parking costs (i.e. extent to which employers charge employees for workplace parking costs) is exogenously determined by conditions such as fiscal regime of workplace parking. We treat the pass-on rate as an input of our model that can be directly modified with policy action. An extension of the model could endogenize the decision of firms over how many parking spaces are offered to their employees and the extent to which parking costs are charged to employees. Such an extension would capture the effect of workplace parking policies (e.g. fiscal reform on workplace parking benefits or workplace parking levy) on the supply of workplace parking. The effects of variations in income tax rates could also be captured under this extension.

Second, we use a short cut to model agglomeration economics. We assume homogeneous workers and perfect competition while agglomeration economics builds on imperfect competition, diversity of skills and knowledge. This could lead to differentiated responses of different skills to parking conditions that affect the agglomeration effect.

Third, one could also relax our assumption that transport and parking modes are perfect substitutes Treating them as differentiated goods may lead to smaller absolute changes in the use of transport and parking in our numerical application. Another possible extension would be to relax our assumption on fixed capacity of road and public transport infrastructure. Finally, we note that future research may consider whether earmarking revenues from the workplace parking levy to public transport may alter our results.

Nomenclature

Superscripts

$*$	In equilibrium
FB	First-best optimum
SB	Second-best optimum

Variables

c	Average commuting costs at city level
c_o	Average generalised cost for on-street parking search
c_r	Average generalised cost of road use
c_{sc}	Average commuting costs
c_t	Average generalised cost of public transport use
c_w	Average cost of workplace parking
C_w	Aggregate cost of workplace parking
e_c	Non-land consumption in the centre
e_s	Non-land consumption in the suburbs
f	Average productivity at city level
f_c	Average product in the centre

F_c	Aggregate production in the centre
l	Surplus from land consumption at city level
l_c	Surplus from land consumption in the centre
n_c	Population living and working in the centre
n_r	Road users
n_{sc}	Population living in the suburbs and working in the centre (commuters)
n_{ss}	Population living and working in the suburbs
n_t	Public transport users
p	Generalised price of transport
P_o	On-street parking users
P_w	Workplace parking users
Π_c	Aggregate profit of the firms in the centre
q_c	Land consumption in the centre
q_s	Land consumption in the suburbs
r_c	Land rent for residence in the centre
u	Utility level of residents
v	Utility over land consumption
w_c	Wage in the centre

Parameters

a_o	Area occupied by on-street parking space
α	Utility parameter
β	Pass-on rate of workplace parking costs to employees
c_F	Fuel costs per trip
δ	Elasticity of productivity with respect to employment density
ε_o	On-street parking occupation level threshold
ε_t	Load factor threshold
$\emptyset$	Index of parking access time
ρ	Index of crowding discomfort
k_o	Index of on-street parking capacity
k_r	Index of road capacity
k_t	Index of public transport capacity
$\widetilde{L_h}$	Housing land
$\widetilde{L_p}$	Production land
$\widetilde{r_s}$	Land rent in the suburbs
θ	Index of total factor productivity
s_c	Wage subsidy in the centre
τ_o	On-street parking fee per day
τ_r	Road toll per round trip
τ_t	User fee on public transport per round trip

τ_w	Workplace parking levy per day for employer-provided parking spaces
T_r	Free-flow travel time
T_t	Public transport travel time
σ_o	Daily on-street parking price in payment areas
Ω_o	Number of available free on-street parking spaces
V_T	Value of time
$\widetilde{w_s}$	Wage in the suburbs
$\bar{y}$	Average non-wage income

Appendix A – Proofs of results in the text

First order conditions

$$\frac{\partial L_1}{\partial u} = 1 - \theta_c - \theta_s = 0 \tag{39}$$

$$\frac{\partial L_1}{\partial e_c} = \theta_c - \delta * n_c = 0 \tag{40}$$

$$\frac{\partial L_1}{\partial e_s} = \theta_s - \delta * (n_{sc} + n_{ss}) = 0 \tag{41}$$

$$\frac{\partial L_1}{\partial q_c} = \theta_c * v'(q_c) - \delta * n_c * \widetilde{r_s} - \omega * n_c = 0 \tag{42}$$

$$\frac{\partial L_1}{\partial q_s} = \theta_s * v'(q_s) - \delta * (n_{sc} + n_{ss}) * \widetilde{r_s} = 0 \tag{43}$$

$$\frac{\partial L_1}{\partial n_c} = \delta * F_c'(n_c + n_{sc}) - \delta * e_c - \delta * q_c * \widetilde{r_s} - \lambda - \omega * q_c = 0 \tag{44}$$

$$\frac{\partial L_1}{\partial n_{sc}} = \delta * F_c'(n_c + n_{sc}) - \delta * e_s - \delta * q_s * \widetilde{r_s} - \lambda - \mu = 0 \tag{45}$$

$$\frac{\partial L_1}{\partial n_{ss}} = \delta * \widetilde{w_s} - \delta * e_s - \delta * q_s * \widetilde{r_s} - \lambda = 0 \tag{46}$$

$$\frac{\partial L_1}{\partial n_r} = -\delta * c_r(n_r) - \delta * n_r * c_r'(n_r) - \varphi + \mu = 0 \tag{47}$$

$$\frac{\partial L_1}{\partial n_t} = -\delta * c_t(n_t) - \delta * n_t * c_t'(n_t) + \mu = 0 \tag{48}$$

$$\frac{\partial L_1}{\partial P_w} = -\delta * c_w + \varphi = 0 \tag{49}$$

$$\frac{\partial L_1}{\partial P_o} = -\delta * a_o * \widetilde{r_s} - \delta * c_o(P_o) - \delta * P_o * c_o'(P_o) + \varphi - \omega * a_o = 0 \tag{50}$$

By combining equations (39,40,41) we obtain $\delta = 1$ and $\theta_c = n_c$, $\theta_s = n_{sc} + n_{ss}$. From equation (42), $\omega = v'(q_c) - \widetilde{r_s}$. From equation (46), $\lambda = \widetilde{w_s} - e_s - q_s * \widetilde{r_s}$. From equation (48), $\mu = c_t(n_t) - n_t * c_t'(n_t)$. From equation (49), $\varphi = c_w$. By replacing the results of the parameters into equations (43,44,45,47,50) and rearranging, we obtain equations (5,6,7,8).

Comparative statics results for travel behaviour

In this section we partially differentiate the short-term equilibrium conditions for the transport and parking markets (18,19,20) and $n_r + n_t = n_{sc}$; $n_r = P_w + P_o$ with respect to the parameters of the problem β and τ, and to the number of commuters n_{sc}. Throughout this section, the assumptions of the model $\{\tau_w \geq 0,\ \beta \epsilon [0,1],\ n_{sc} > 0, c_r > 0, c_r' > 0, c_r'' \geq 0, c_t > 0,\ c_t' > 0, c_t'' = 0, c_o > 0,$ $c_o' > 0, c_o'' \geq 0, c_w > 0,\ c_w' = 0\}$ hold.

The **differentiation with respect to β** leads to the following system of equations:

$$\begin{bmatrix} 1 & 0 & -c_t' & 0 & 0 \\ 0 & c_r' & -c_t' & 0 & 0 \\ 0 & 0 & 0 & 0 & -c_o' \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \frac{\partial p}{\partial \beta} \\ \frac{\partial n_r}{\partial \beta} \\ \frac{\partial n_t}{\partial \beta} \\ \frac{\partial P_w}{\partial \beta} \\ \frac{\partial P_o}{\partial \beta} \end{bmatrix} = \begin{bmatrix} 0 \\ -c_w - \tau_w \\ -c_w - \tau_w \\ 0 \\ 0 \end{bmatrix} \tag{51}$$

Solving the system of equations in equation (51) yields:

$$\frac{\partial p}{\partial \beta} = \frac{(c_w + \tau_w) * c_t'}{c_r' + c_t'} > 0 \tag{52}$$

$$\frac{\partial n_r}{\partial \beta} = -\frac{c_w + \tau_w}{c_r' + c_t'} < 0 \tag{53}$$

$$\frac{\partial n_t}{\partial \beta} = \frac{c_w + \tau_w}{c_r' + c_t'} > 0 \tag{54}$$

$$\frac{\partial P_w}{\partial \beta} = -\frac{(c_w + \tau_w) * (c_t' + c_r' + c_o')}{(c_r' + c_t') * c_o'} < 0 \tag{55}$$

$$\frac{\partial P_o}{\partial \beta} = \frac{c_w + \tau_w}{c_o'} > 0 \tag{56}$$

The **differentiation with respect to $\boldsymbol{\tau_w}$** leads to the following system of equations:

$$\begin{bmatrix} 1 & 0 & -c_t' & 0 & 0 \\ 0 & c_r' & -c_t' & 0 & 0 \\ 0 & 0 & 0 & 0 & -c_o' \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \frac{\partial p}{\partial \tau_w} \\ \frac{\partial n_r}{\partial \tau_w} \\ \frac{\partial n_t}{\partial \tau_w} \\ \frac{\partial P_w}{\partial \tau_w} \\ \frac{\partial P_o}{\partial \tau_w} \end{bmatrix} = \begin{bmatrix} 0 \\ -\beta \\ -\beta \\ 0 \\ 0 \end{bmatrix} \tag{57}$$

Solving the system of equations in equation (57) yields:

$$\frac{\partial p}{\partial \tau_w} = \frac{\beta * c_t'}{c_r' + c_t'} > 0 \tag{58}$$

$$\frac{\partial n_r}{\partial \tau_w} = -\frac{\beta}{c_r' + c_t'} < 0 \tag{59}$$

$$\frac{\partial n_t}{\partial \tau_w} = \frac{\beta}{c_r' + c_t'} > 0 \tag{60}$$

$$\frac{\partial P_w}{\partial \tau_w} = -\frac{\beta * (c_t' + c_r' + c_o')}{(c_r' + c_t') * c_o'} < 0 \tag{61}$$

$$\frac{\partial P_o}{\partial \tau_w} = \frac{\beta}{c_o'} > 0 \tag{62}$$

The **differentiation with respect to $\boldsymbol{n_{sc}}$** leads to the following system of equations:

$$\begin{bmatrix} 1 & 0 & -c_t' & 0 & 0 \\ 0 & c_r' & -c_t' & 0 & 0 \\ 0 & 0 & 0 & 0 & -c_o' \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \frac{\partial p}{\partial \tau_w} \\ \frac{\partial n_r}{\partial \tau_w} \\ \frac{\partial n_t}{\partial \tau_w} \\ \frac{\partial P_w}{\partial \tau_w} \\ \frac{\partial P_o}{\partial \tau_w} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \tag{63}$$

Solving the system of equations in equation (63) yields:

$$\frac{\partial p}{\partial n_{sc}} = \frac{c_r' * c_t'}{c_r' + c_t'} > 0 \tag{64}$$

$$\frac{\partial n_r}{\partial n_{sc}} = \frac{c_t'}{c_r' + c_t'} > 0 \tag{65}$$

$$\frac{\partial n_t}{\partial n_{sc}} = \frac{c_r'}{c_r' + c_t'} > 0 \tag{66}$$

$$\frac{\partial P_w}{\partial n_{sc}} = \frac{c_t'}{c_r' + c_t'} > 0 \tag{67}$$

$$\frac{\partial P_o}{\partial n_{sc}} = 0 \tag{68}$$

The **differentiation with respect to $\boldsymbol{n_{sc}}$ and $\boldsymbol{\beta}$** leads to the following system of equations:

$$\begin{bmatrix} 1 & 0 & -c_t' & 0 & 0 \\ 0 & c_r' & -c_t' & 0 & 0 \\ 0 & 0 & 0 & 0 & -c_o' \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \frac{\partial^2 p}{\partial n_{sc} \partial \beta} \\ \frac{\partial^2 n_r}{\partial n_{sc} \partial \beta} \\ \frac{\partial^2 n_t}{\partial n_{sc} \partial \beta} \\ \frac{\partial^2 P_w}{\partial n_{sc} \partial \beta} \\ \frac{\partial^2 P_o}{\partial n_{sc} \partial \beta} \end{bmatrix} = \begin{bmatrix} c_t'' * \frac{\partial n_t}{\partial n_{sc}} * \frac{\partial n_t}{\partial \beta} \\ c_t'' * \frac{\partial n_t}{\partial n_{sc}} * \frac{\partial n_t}{\partial \beta} - c_r'' * \frac{\partial n_r}{\partial n_{sc}} * \frac{\partial n_r}{\partial \beta} \\ c_o'' * \frac{\partial P_o}{\partial n_{sc}} * \frac{\partial P_o}{\partial \beta} \\ 0 \\ 0 \end{bmatrix} \tag{69}$$

Solving the system of equations in equation (69) and replacing with equations (52-56,64-68) yields:

$$\frac{\partial^2 p}{\partial n_{sc} \partial \beta} = -\frac{(c_w + \tau_w) * \left(c_t'^2 + c_r''\right)}{(c_r' + c_t')^3} < 0 \tag{70}$$

The **differentiation with respect to $\boldsymbol{n_{sc}}$ and $\boldsymbol{\tau_w}$** leads to the following system of equations:

$$\begin{bmatrix} 1 & 0 & -c_t' & 0 & 0 \\ 0 & c_r' & -c_t' & 0 & 0 \\ 0 & 0 & 0 & 0 & -c_o' \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \frac{\partial^2 p}{\partial n_{sc} \partial \tau_w} \\ \frac{\partial^2 n_r}{\partial n_{sc} \partial \tau_w} \\ \frac{\partial^2 n_t}{\partial n_{sc} \partial \tau_w} \\ \frac{\partial^2 P_w}{\partial n_{sc} \partial \tau_w} \\ \frac{\partial^2 P_o}{\partial n_{sc} \partial \tau_w} \end{bmatrix} = \begin{bmatrix} c_t'' * \frac{\partial n_t}{\partial n_{sc}} * \frac{\partial n_t}{\partial \tau_w} \\ c_t'' * \frac{\partial n_t}{\partial n_{sc}} * \frac{\partial n_t}{\partial \tau_w} - c_r'' * \frac{\partial n_r}{\partial n_{sc}} * \frac{\partial n_r}{\partial \tau_w} \\ c_o'' * \frac{\partial P_o}{\partial n_{sc}} * \frac{\partial P_o}{\partial \tau_w} \\ 0 \\ 0 \end{bmatrix} \tag{71}$$

Solving the system of equations in equation (71) and replacing with equations (58-62,64-68) yields:

$$\frac{\partial^2 p}{\partial n_{sc} \partial \tau_w} = -\frac{\beta * \left(c_t'^2 + c_r''\right)}{(c_r' + c_t')^3} < 0 \tag{72}$$

Proof of proposition 1

The sign of $\frac{dn_{sc}}{d\beta}$ will determine the effect of a switch to employee-paid parking on the employment in the city centre and, consequently, on agglomeration economies. By applying the comparative statics principle to the profit maximising condition (17), $sign\left(\frac{dn_{sc}}{d\beta}\right)$ is equal to $sign\left(\frac{\partial^2 \Pi_c}{\partial n_{sc}\partial\beta}\right)$. The latter is obtained by differentiating equation (17) with respect to β:

$$\frac{\partial^2 \Pi_c}{\partial n_{sc}\partial\beta} = -\frac{\partial p}{\partial\beta} + (c_w + \tau_w) * \frac{\partial P_w^*}{\partial n_{sc}} - \frac{\partial^2 p}{\partial n_{sc}\partial\beta} * (n_c + n_{sc}) - (1-\beta) * \frac{\partial^2 P_w^*}{\partial n_{sc}\partial\beta} \tag{73}$$

By applying equations (52,67), it can be easily seen that the first order terms in equation (73) $-\frac{\partial p}{\partial\beta} + (c_w + \tau_w) * \frac{\partial P_w^*}{\partial n_{sc}}$ cancel out. This is because in a switch to employee-paid parking, employers compensate savings in parking costs with increased wages for all employees in a revenue neutral way. In a full switch to employee-paid parking $\beta = 1$, the term $(1-\beta) * \frac{\partial^2 P_w^*}{\partial n_{sc}\partial\beta}$ is also zero. Then, $sign\left(\frac{\partial^2 \Pi_c}{\partial n_{sc}\partial\beta}\right)$ entirely depends on $\frac{\partial^2 p}{\partial n_{sc}\partial\beta}$, which according to equation (70) is negative. Therefore, we conclude $\frac{\partial n_{sc}}{\partial\beta} > 0$ (proposition 1a).

Similarly, to analyse the effects of a workplace parking levy on employment in the city centre $\frac{\partial n_{sc}}{\partial\tau_w}$ we ought to look at $sign\left(\frac{\partial^2 \Pi_c}{\partial n_{sc}\partial\tau_w}\right)$, which is obtained by differentiating equation (17) with respect to τ_w:

$$\begin{aligned}\frac{\partial^2 \Pi_c}{\partial n_{sc}\partial\tau_w} = -\frac{\partial p}{\partial\tau_w} + (1-\beta) * \frac{\partial P_w^*}{\partial n_{sc}} - \frac{\partial^2 p}{\partial n_{sc}\partial\tau_w} * (n_c + n_{sc}) - (1-\beta) \\ * (mc_w + \tau_w) * \frac{\partial^2 P_w^*}{\partial n_{sc}\partial\tau_w}\end{aligned} \tag{74}$$

In this case, by applying equations (58,67), we see that the first order terms in equation (74) do not cancel out but add to $-\frac{\partial P_w^*}{\partial n_{sc}}$. This means that, if we only focus on first-order effects, a workplace parking levy has a net negative effect on the marginal profit of an extra commuter. However, this effect is offset by the term $-\frac{\partial^2 p}{\partial n_{sc} \partial \tau_w} * (n_c + n_{sc})$, which is overall positive as per equation (72). Therefore, $sign\left(\frac{\partial n_{sc}}{\partial \tau_w}\right)$ can either be positive or negative depending on the specific context (proposition 1b). As per equation (72), $\frac{\partial^2 p}{\partial n_{sc} \partial \tau_w}$ is proportional to β, which means that when β is higher, it is more likely that an increase in the workplace parking levy (τ_w) leads to more commuters (n_{sc}).

Comparative statics results for central residence

We totally differentiate the residential equilibrium condition (24) with respect to β and rearrange terms, which leads to the following expression:

$$\frac{dn_c}{d\beta} = -\frac{\frac{\partial p}{\partial n_{sc}} * \frac{dn_{sc}}{d\beta} + \frac{\partial p}{\partial \beta} + a_o * \frac{\partial P_o}{\partial \beta} * v''\left(\frac{L_h - P_o^* a_o}{n_c}\right) * \left(\frac{L_h - P_o a_o}{n_c^2}\right)}{v''\left(\frac{L_h - P_o^* a_o}{n_c}\right) * \frac{(L_h - P_o^* a_o)^2}{n_c^3}} \qquad (75)$$

Under the assumptions of the model the following conditions hold: $\frac{\partial p}{\partial n_{sc}} > 0$ as per equation (64), $\frac{\partial p}{\partial \beta} > 0$ as per equation (52), $\frac{dn_{sc}}{d\beta} > 0$ as per Proposition 1 and $v''(q) < 0 \; \forall q$ by definition. With this, when the spillover effect is negligible ($a_o \to 0$), it is straightforward to see that $\frac{dn_c}{d\beta} > 0$. Otherwise, no general conclusions can be drawn on the effect of employee-paid parking on residential location.

Proof of proposition 2

The optimisation of the Lagrangian in equation (31) in terms of n_{sc} and τ_w leads to the following first order conditions:

$$\begin{aligned}\frac{\partial L_2}{\partial n_{sc}} = {} & F_c{}' - \widetilde{w_s} - p - n_{sc} * \frac{\partial p}{\partial n_{sc}} - a_o * \widetilde{r_c} * \frac{\partial P_o^*}{\partial n_{sc}} + \tau_w * \frac{\partial P_w^*}{\partial n_{sc}} + \widetilde{\tau_r} * \frac{\partial n_r^*}{\partial n_{sc}} + \widetilde{\tau_t} \\ & * \frac{\partial n_t^*}{\partial n_{sc}} + \widetilde{\tau_o} * \frac{\partial P_w^*}{\partial n_{sc}} + \lambda * \left(f_c' - \frac{\partial^2 p}{\partial n_{sc}^2} * (\widetilde{n_c} + n_{sc}) - 2 * \frac{\partial p}{\partial n_{sc}} \right) = 0\end{aligned} \tag{76}$$

$$\begin{aligned}\frac{\partial L_2}{\partial \tau_w} = {} & -n_{sc} * \frac{\partial p}{\partial \tau_w} - a_o * \widetilde{r_c} * \frac{\partial P_o^*}{\partial \tau_w} + \tau_w * \frac{\partial P_w^*}{\partial \tau_w} + \widetilde{\tau_r} * \frac{\partial n_r^*}{\partial \tau_w} + \widetilde{\tau_t} * \frac{\partial n_t^*}{\partial \tau_w} + \widetilde{\tau_o} * \frac{\partial P_w^*}{\partial \tau_w} \\ & + \lambda * \left(- \frac{\partial^2 p}{\partial n_{sc} \partial \tau_w} * (\widetilde{n_c} + n_{sc}) - \frac{\partial p}{\partial \tau_w} \right) = 0\end{aligned} \tag{77}$$

Adding equation (76) multiplied by $\frac{dn_{sc}}{d\tau_w}$ and equation (77), and applying the first-order condition of firms (22) we eliminate λ. Then rearranging yields:

$$\begin{aligned}& \left(F_c' - f_c + \frac{\partial p}{\partial n_{sc}} * (\widetilde{n_c} + n_{sc}) - \widetilde{s_c} \right) * \frac{dn_{sc}}{d\tau_w} - n_{sc} * \frac{dp}{d\tau_w} + \tau_w * \frac{dP_w^*}{d\tau_w} + (\widetilde{\tau_o} - a_o * \widetilde{r_c}) \\ & * \frac{dP_o^*}{d\tau_w} + \widetilde{\tau_r} * \frac{dn_r^*}{d\tau_w} + \widetilde{\tau_t} * \frac{dn_t^*}{d\tau_w} + P_w^*\end{aligned} \tag{78}$$

The term $n_{sc} * \frac{dp}{d\tau_w}$ can be developed as follows:

$$\begin{aligned} n_{sc} * \frac{dp}{d\tau_w} &= (n_r + n_t) * \left(c_r' * \frac{dn_r}{d\tau_w} + 1 \right) \\ &= c_r' * n_r * \frac{dn_r}{d\tau_w} + (c_r' * \frac{dn_r}{d\tau_w} + 1) * n_t + P_w^* + P_o^* \\ &= c_r' * n_r * \frac{dn_r}{d\tau_w} + c_t' * n_t * \frac{dn_t}{d\tau_w} + P_w^* + c_o' * P_o^* * \frac{dP_o}{d\tau_w}\end{aligned} \tag{79}$$

Replacing equation (79) into equation (78) and considering the definition of first-best instruments yields to equation (31) in Proposition 2.

Appendix B – Numerical application: Data, calibration and sensitivity analysis

Calibration method and data

The calibration process starts with the calibration of the equations (18,19) which govern the equilibrium of the transport and parking market. With the functional forms adopted in Table 2-1, these can be expressed as:

$$\begin{aligned} 2 * \left[c_F + V_T * T_r * \left(1 + \left(\frac{n_r}{k_r}\right)^4\right)\right] + \tau_r + \beta * (c_w + \tau_w) + \emptyset \\ = 2 * T_t * \left(V_T + \rho * \left(\frac{n_t}{k_t} - \varepsilon_t\right)\right) + \tau_t \end{aligned} \tag{80}$$

$$\beta * (c_w + \tau_w) = \frac{V_T * (P_o - \varepsilon_o)}{k_o} + \tau_o + \sigma_o * \left(\frac{P_o - \Omega_o}{P_o}\right) \tag{81}$$

The unknown parameters $\emptyset$ and ε_o are calibrated by applying values described in Table 2-6 to equations (80, 81) and solving the resulting system of equations.

Once the transport and parking equilibrium equations are calibrated, we calculate p following Eq. (20) and numerically approximate $\left.\frac{\partial p}{\partial n_{sc}}\right|_{n_{sc}=180555} \approx \left.\frac{\Delta p}{\Delta n_{sc}}\right|_{n_{sc}=180555}$ and $\left.\frac{\partial P_w}{\partial n_{sc}}\right|_{P_w=46005} \approx \left.\frac{\Delta P_w}{\Delta n_{sc}}\right|_{P_w=46005}$ This results in $p = 17.3079$, $\left.\frac{\partial p}{\partial n_{sc}}\right|_{n_{sc}=180,555} = 4.2721 * 10^{-5}$ and $\left.\frac{\partial P_w}{\partial n_{sc}}\right|_{P_w=46005} = 0.2165$.

Considering the average gross wage in the city centre w_c in Table 2-6, we obtain the average productivity f_c by applying equation (23) and the wage in the suburbs w_s with equation (21). We proceed to calibrate the functional form assumed for the average productivity in Table 2-1 ($f_c(n_{sc}, n_c) = \theta * (n_{sc} + n_c)^{\delta}$) and obtain the total index of productivity θ for the assumed elasticity of productivity in Table 2-6.

Finally, we calibrate equations (24, 25), which determine the equilibrium for the number of residents in the centre and the suburbs and the associated land use allocation. By applying the functional forms in Table 2-1, these can be expressed as:

$$p + \alpha * \log\left(\frac{L_h - P_o\, a_o}{n_c}\right)\left(\frac{L_h - P_o\, a_o}{n_c}\right) - \frac{\alpha * n_c}{L_h - P_o\, a_o} * \left(\frac{L_h - P_o\, a_o}{n_c}\right) = \alpha * \log\left(\frac{\alpha}{r_s}\right) - \alpha \tag{82}$$

$$r_c = \frac{\alpha * n_c}{L_h - P_o\, a_o} \tag{83}$$

The unknown parameters α and r_s are calibrated by applying the values of variables and parameters in Table 2-6 to equations (82, 83) and solving the resulting system of equations.

The calibrated parameters are presented in Table 2-7.

Table 2-6: Data for the calibration of the numerical illustration

Nomenclature	Description	Value	Data source
Variables			
n_c	Population with both residence and workplace in the centre	507,980	Enquesta de mobilitat obligada 2011 (Survey on commuting trips), Institut d'Estadística de Catalunya
n_{sc}	Population with residence in the suburbs and workplace in the centre	180,555	Enquesta de mobilitat obligada 2011 (Survey on commuting trips), Institut d'Estadística de Catalunya
n_{ss}	Population with both residence and workplace in the suburbs	288,921	Enquesta de mobilitat obligada 2011 (Survey on commuting

Nomenclature	Description	Value	Data source
			trips), Institut d'Estadística de Catalunya
n_r	Number of road users	88,472	Based on 49% share of trips by car (with respect to total motorised trips) from Enquesta de mobilitat quotidiana 2016 (Survey on commuting trips), Autoritat del Transport Metropolità
n_t	Number of public transport users	92,083	Based on 51% share of trips by public transport (with respect to total motorised trips) from Enquesta de mobilitat quotidiana 2016 (Survey on commuting trips), Autoritat del Transport Metropolità
P_w	Number of workplace parking users	46,005	Based on 51% share of workplace parkers (with respect to total road journeys) from Enquesta de mobilitat quotidiana 2016 (Survey on commuting trips), Autoritat del Transport Metropolità
P_o	Number of on-street parking users	22,118	Based on 22% share of on-street parkers (with respect to total road journeys) from Enquesta de mobilitat quotidiana 2016 (Survey on commuting trips),

Nomenclature	Description	Value	Data source
			Autoritat del Transport Metropolità
Generic parameters from literature			
ρ	Index of crowding discomfort	6	Tirachini et al. (2013)
ε_t	Load factor threshold	0.6	Tirachini et al. (2013)
δ	Elasticity of productivity with respect to employment density	0.045	Ciccone (2002)
Specific parameters for the case of Barcelona			
c_F	Fuel costs per trip (€)	1.26	Based on fuel costs per km from DGIMT (2015) of 0.074 €/km and average distance of 17 km estimated with Google maps (average distance from centres of AMB municipalities to the centre of Barcelona weighted by population)
V_T	Value of time (€/hour)	11	DGIMT (2015)
T_r	Free-flow travel time by car (hours)	0.38	Google maps, average travel time (off-peak) from centres of AMB municipalities to the centre of Barcelona weighted by population
k_r	Index of road capacity	104,316	Based on average increased travel time per car user at peak hours of 12 min from RACC (2016), La congestió als corredors viaris d'accés a la ciutat de Barcelona

Nomenclature	Description	Value	Data source
T_t	Public transport travel time (hours)	0.66	Based on average travel time of 40 min estimated with Google maps (average travel time from centres of AMB municipalities to the centre of Barcelona weighted by population)
k_t	Index of public transport capacity	146,711	Assumed current load factor threshold $\left({}^{n_t}/_{k_t}\right)$ of 0.6
c_w	Average cost of workplace parking (€/day)	4.5	Assumed, based on typical rates for working journey passes in off-street parking spaces in Barcelona
k_o	Index of on-street parking capacity	91,531	Based on marginal external cruising cost $\left({}^{V_T}/_{k_o}\right)$ of 5% of the hourly wage as per Inci et al. (2017)
σ_o	Daily on-street parking price in payment areas	12	Assumed, based on average hourly fee in Zones C and D (1.5 €/hour) multiplied by 8 hours (working journey)
a_o	Space per on-street parking space (m2)	20	Assumed based on anecdotal evidence
τ_o	Global on-street parking fee	0	Assumed that no minimum on-street parking fee at city level as there are still a few unregulated spaces
Ω_o	Number of available free on-street parking spaces	22,118	Assumed that available free on-street parking spaces are fully occupied
w_c	Average annual gross wage in the centre (€/day)	141.76	Based on average annual wage of 28,383€ from the Departament d'Estadística i Difusió de Dades. Ajuntament de Barcelona (2018 average) and assumed 200 working days per year
r_c	Rental price centre (€/m^2/day)	0.67	Based on rental price per m^2 and month of 13.4 €/m^2/month from the Departament d'Estadística i Difusió de Dades. Ajuntament de Barcelona (2018 average) and assumed 20 days per month
L_h	Residential land (m^2)	20,952,532	Based on Superfície dels locals cadastrals 2014, Ajuntament de Barcelona

Nomenclature	Description	Value	Data source
Policy instruments			
τ_r	Road toll per round trip (€/trip)	0	Assumed, no city-wide congestion charge applied
τ_t	Public transport fee per round trip (€/trip)	2.42	Based on a weighted average of prices for multiticket travel cards (T-10) in AMB municipalities (tariff zones 1 and 2)
τ_w	Workplace parking levy per day for employer-provided parking spaces (€/day)	0	Assumed, no workplace parking levy applied
β	Pass-through rate of workplace parking costs	0.19	Assumed that the pass-through rate is equal to the aggregated share of employee-paid parking
s_c	Wage subsidy in the centre	0	Assumed, no wage subsidy applied

Table 2-7: Calibrated parameters for the numerical illustration

Parameter	Description	Value
$\emptyset$	Index of parking access time	1.14
ε_o	Occupation level threshold	5516
w_s	Average daily gross wage in the suburbs (€/day)	124.5
θ	Index of total factor productivity	93.92
α	Utility parameter	27.05
r_s	Suburbs land rent (€/m^2/day)	0.3534

Sensitivity analysis

Table 2-8 and Table 2-9 present the sensitivity test for a lower elasticity of productivity with respect to employment density, which captures agglomeration effects. This shows that the relative magnitude of agglomeration effects holds for a lower value of the elasticity of production.

Table 2-8: Effects of a switch to employee-paid parking for $\boldsymbol{\delta = 0.02}$.instead of $\boldsymbol{\delta = 0.045}$ Monetary values in euros per day. Baseline equilibrium for $\boldsymbol{\beta = 0.19}$

	Pass-on rate (β)			
	0	0.19	0.5	1
Transport and parking effects				
Road transport share (%)	52%	49%	45%	38%
Used on-street parking spaces ($* 10^3$) (P_o)	15.0	22.1	24.4	28.9
Average commuting costs (c_{sc})	16.7	16.5	16.3	16.5
Agglomeration effects				
Number of commuters ($* 10^3$) (n_{sc})	176.5	180.6	187.4	202.9
Average productivity in the centre (f_c)	171.9	172.0	172.1	172.3
Land use effects				
Number of residents in the centre ($* 10^3$) (n_c)	504.8	507.9	518.4	539.8
Surplus from land consumption in the centre (l_c)	85.7	85.5	85.1	84.5

Table 2-9: Welfare effects of a switch to employee-paid parking for $\boldsymbol{\delta} = \mathbf{0.02}$.instead of $\boldsymbol{\delta} = \mathbf{0.045}$ Monetary values in euros per day. Baseline equilibrium for $\boldsymbol{\beta} = \mathbf{0.19}$

	Pass-on rate (β)				Welfare change β from 0.19 to 1	
	0	0.19	0.5	1	Dif.	% Abs. variation
Utility per resident ($u = f + l - c$)	242.5	242.7	243.3	244.4	+1.8	
Average productivity at city level (f)	157.6	157.9	158.8	160.8	+2.8	72%
Surplus from land consumption at city level (l)	87.9	87.8	87.6	87.1	-0.7	18%
Average commuting costs at city level ($-c$)	-3.02	-3.05	-3.13	-3.43	-0.4	10%

Chapter 3 Environmental rail charges in Europe

1 Introduction

Since the approval of the European Directive 91/440/ECC, the separation of the infrastructure management (non-competitive part) from the railway operation (competitive part) has been compulsory, at least in accounting terms. This division requires the introduction of rail access charges for the use of the infrastructure. The European Directive 2001/14/EC (European Parliament and Council of the European Union, 2001) and its subsequent recast Directive 2012/34/EC (European Parliament and Council of the European Union, 2012a) determine that these charges must be transparent and non-discriminatory and that they should be based on 'costs directly incurred as a result of operating the train service'. This means that railways should be priced according to short-run marginal costs and, as a consequence, the efficient use of the infrastructure and the elimination of market access barriers are prioritised over financial stability and long-run incentives.[27]

Directive 2001/14/EC also states that the external costs of environmental impacts, accidents, and congestion may be introduced into rail access charges, following the Pigouvian principle of equating charges to marginal social costs (Pigou, 1920). This defines the legal framework to introduce environmental rail charges and agrees with the European policy objective of reaching a full internalisation of external costs across all transport modes (European Commission, 1995, 1998).

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[27] For a further discussion about the short-run marginal cost pricing principle applied to railways, see e.g. Nash (2005).

However, in the case of railways, a simple but rather vague ‘second-best’ principle holds in the current legislation: external costs charging should not result in an increase of the overall revenue accruing to the infrastructure manager unless a comparable pricing scheme for external costs is applied to competing modes. According to this, only bonus or *feebate* internalisation schemes may be valid for railways, particularly when road congestion is significant. Nevertheless, optimal second-best environmental rail charges should consider the cross-elasticity of demand between modes (Arnott and Yan, 2000; Rouwendal and Verhoef, 2004).

Other difficulties appear when implementing Pigouvian environmental charges. Despite multiple European-wide studies on the subject,[28] the socio-economic valuation of transport-related environmental costs still shows a significant level of uncertainty and an insufficient level of disaggregation. Moreover, studies have mainly focused on road transport external costs whilst much less research has been conducted in the case of railways.

On top of that, the essential issue of how to transfer external costs to a realistic pricing system with an optimal degree of pricing complexity is still unsolved (Nash and Matthews, 2005). Another difficulty is that the context of imperfect competition in the railway market requires taking into account the market power of rail operators when defining an environmental charging system (Meunier and Quinet, 2012). Finally, the regulatory, operational, and financial rigidities in this market imply complex decisions on how to allocate abatement efforts among the different stakeholders in a cost-effective and equitable way.

All these difficulties need to be addressed by setting adequate deviations from the first-best benchmark that take into account the particularities of the rail market. Due to these practical problems and to the lack of specificity in the related legislation, just a few European railways administrations (Germany,

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[28] See, for instance, Bickel, Friedrich, Link, Stewart, and Nash (2006); INFRAS and IWW (2000); Nunes and Travisi (2007); Ricardo-AEA, DIW econ, and CAU (2014).

Switzerland, The Netherlands, Finland, Sweden, and the Czech Republic) have introduced environmental rail charges. This chapter reviews the European experience on the subject and assesses the performance of the case studies in terms of an analytical framework. Based on this, it identifies best practices, possible improvements, and future lines of research.

The chapter is structured as follows. Section 2 presents an analysis framework that goes through the second-best issues that need to be addressed when defining environmental rail charges. This leads to the definition of the four basic analysis dimensions. In Sections 3 and 4, this is applied to critically analyse the effectiveness of current noise and pollution rail charges and the technologies being used in railways for the abatement of environmental impacts. Finally, general conclusions are drawn in Section 5.

2 Analytical framework

Is well-known that the first-best solution relies on unrealistic assumptions such as the possibility of implementing a practical pricing instrument able to differentiate prices in such a way that every individual user faces exactly the caused marginal external costs. Besides, whenever there are inefficiencies (market power, unpriced externalities or distortionary taxes) in the rail market itself or in related markets, charges should deviate from the first-best solution.[29]

Furthermore, a basic result of environmental economics is that the crucial condition for a cost-effective environmental policy is that marginal abatement costs are equated across all pollutant sources (Baumol and Oates, 1988). This goal will be achieved when effective incentives are provided to all the agents with capacity for abatement. In consequence, although our study is focused on

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[29] See the Chapter 1: Introduction for a complete description.

charges to rail operators, the abatement possibilities of the upstream agents should also be considered.

All these issues are examined hereafter.

2.1 Allocation of abatement efforts

Environmental damages can be reduced in two ways: by reducing the damage per travel unit using an abatement technology or by decreasing the amount of travel that generates the externality. In general, the choice of the abatement technology depends mostly on the upstream agents (for example, vehicle manufactures or energy producers, in this case) whereas final consumers (rail operators and users, in this case) decide their quantity of travel.

In the case of noise and air pollution, it is generally more effective to introduce abatement technologies than to adapt travel use (Proost, 2011). Indeed, the reduction of 'polluting travel' often is not a real option, as service regulations clearly limit the margin of manoeuvre of operators to adapt their transport supply. For passenger trains, public service contracts often fix frequencies and schedules while freight trains have severe path allocations restrictions because priority is given to passenger services. For example, even if the freight rail operator would be bound to pay a higher noise charge for night trains, it may not be possible to reschedule his train paths due to capacity constraints.

With regards to abatement technologies, it must be noted that the application of environmental charges requires a clear conceptual framework. If they are only applied to rail operators it will be difficult for them to transfer these costs upstream in the short-term and provide incentives to upstream agents to introduce abatement technologies. In this line, with the aim of ensuring minimum environmental standards, the European Union, applies regulations in terms of noise and air pollution emission ceilings to rolling stock.

A common practice to promote the abatement technology in current environmental pricing schemes for railways is to subsidise completely or partially abatement costs derived from regulation compliance through mileage-based bonus to rail operators. This is a practical approach to achieving specific objectives because it fosters improved abatement technology in most services and avoids appraising environmental costs. However, this policy generally increases the level of subsidy in railways, which may lead to inefficient market distortions (see Section 2.5). Furthermore, the final abatement outcome will be sub-optimal as emissions ceilings enforce abatement measures homogeneously regardless of their cost-efficiency in each particular case.

It should be noted that, in any case, the wider the scope of the targeted abatement measures (abatement technology or reduction of amount of travel), the more cost-efficient the final outcome will be (Parry et al., 2014).[30] Indeed, the optimal outcome will be a particular combination of abatement technologies and changes in travel use involving multiple stakeholders.[31] As for rail operators, the range of considered abatement possibilities should be expanded by further differentiating rail charges according to the magnitude of the environmental impact, i.e. the marginal environmental cost. In this way, operators will deliver more efficient abatement choices for each particular case based on their margin for manoeuvre and the costs involved.

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[30] The total marginal abatement cost curve envelopes the marginal abatement cost curves of each particular measure (the minimum among all of them). Thus, a wider range of abatement possibilities will generally lead to a lower total marginal abatement cost.

[31] The optimal combination of both will be reached when technology abatement is performed up to the point where marginal costs of environmental damages equate marginal abatement costs and final users trade-off their marginal benefit (consumer surplus) with the marginal social cost of travel given the optimal technology abatement (Proost and Van Dender, 2012). If the emission charge is levied on the producer, the optimal output both in terms of abatement technology and consumption will be reached as the producer will transfer the increased price downstream (Proost, 2011).

2.2 Uncertainty in the environmental appraisal

A proper appraisal of the environmental damages of the transport system is necessary to differentiate charges in an efficient way. In practice, this requires a suitable methodology and the collection of ad hoc data.[32]

It must be stressed that there is still a significant level of uncertainty in the estimation of the environmental costs of transport, particularly for railways. The impacts of transport air pollution have been the subject of many studies and, in general, can be determined with reasonable precision with state-of-the-art methodologies. Obtaining the economic costs of these impacts through the application of existing reference values is, however, a complex exercise subject to many caveats.

The case of noise is even more difficult to handle due to the non-linearity of the effects of noise emissions (a logarithmic scale is used[33]) and the difficulties in valuing noise annoyance. In spite of recent contributions (Andersson and Ögren, 2013; Bristow et al., 2014), a consensus on the values of the marginal costs of rail noise may not be reached soon.

Nevertheless, even if these cost estimates are relatively imprecise, the interest of differentiating charges according to them seems obvious, because the social welfare gains derived from any internalisation scheme are rather insensitive to errors in estimating marginal environmental costs (Rabl et al., 2005).

2.3 Degree of differentiation and administrative costs

A charging scheme based on differentiation requires an adequate monitoring and enforcement system to ensure that charges are correctly applied. This will

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[32] A bottom-up approach is recommended for pricing purposes because it allows a differentiation of marginal environmental costs (CE Delft et al., 2008).

[33] The sound pressure level (SPL) of noise is measured in decibels (dB) in the following way: $L_p(dB) = 10 \cdot log_{10}\left(\frac{p}{p_o}\right)^2$ where p is the sound pressure and p_o is the reference sound pressure ($2 \cdot 10^{-5}$ Pa).

generate administrative costs (both implementation and transaction costs), which inevitably increase with the amount of differentiation and the number of agents in the market. Fortunately, in the case of railways, the number of stakeholders is limited, so administrative costs might be reasonable.

Besides cost, another factor working against increasing the number and the sophistication of charges is that people and organisations become less sensitive with higher levels of pricing complexity due to psychological constraints (DIFFERENT, 2008).

Operators and users' behaviour are expected to be closer to the socially optimal behaviour with further differentiation, as market signals become more precise and include a wider range of abatement possibilities. There is, therefore, a clear trade-off in the degree of differentiation between potential efficiency gains and simplicity that has to be carefully taken into consideration when defining an internalisation scheme.

2.4 Market power

The rail market is generally dominated by monopolistic or oligopolistic operators. In these cases, a second-best charging scheme has to trade-off two sources of misallocation: the distortion due to the externalities and the monopolistic underproduction. This means that the market power of rail operators should be taken into account to avoid an excessive decrease in the transport supply when applying environmental charges. Barnett (1980) first solved the problem and concluded that optimal charges on monopolistic polluters fall short of marginal external costs in an amount which is inversely proportional to the market elasticity.[34]

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[34] For an updated and comprehensive review on the issue see Requate (2005) and for other insights see e.g. Meunier & Quinet (2009, 2012).

2.5 Intermodal competition

An environmental charging system for railways will most likely have impacts on the price of final users and therefore affect, in a way, the modal split. In turn, changes in demand will have effects on the quantity of 'polluting travel' across different transport modes.

As already mentioned, European policy promotes the harmonisation of taxes and charges across all transport modes in terms of an equivalent level of internalisation. In the case of railways, legislation states that only bonus or feebate programmes are allowed if other modes are not charged for their external costs.

This framework implicitly assumes a perfect substitutability in demand between transport modes. In terms of economic efficiency, however, intermodal cross-price elasticities of demand should be considered when defining an environmental charging scheme. The two-mode problem with fixed capacities (Arnott and Yan, 2000) defines a basic second-best pricing scheme for one mode (rail, in this case) when an imperfect substitute (road, for example) is underpriced. This implies that the environmental charge in railways should be lower than the marginal external cost to offset the underpriced externality in road transport while still addressing the deadweight loss in the rail market. The optimal difference with respect to the marginal external cost is positively related to the substitutability between the two modes.

Beuthe, Jourquin, & Urbain (2014) report a cross-elasticity of road freight demand (in ton.km) to rail total costs of 0.11. For short-distance passenger transport, cross-elasticities of car travel (in number of trips) with respect to transit costs are around 0.15 and 0.3 in the long-run (Litman, 2004), whereas for long-distance trips the cross-elasticity of car use (in travelled distance) with respect to rail fares is 0.05 according to Börjesson (2014). Given these low cross-elasticities of demand, it is clear that rail and road, in both freight and passenger transport, have to be considered as imperfect substitutes when setting an internalisation policy.[35]

Railways and other subsidised public transport modes are often supported on the grounds that subsidies allow lower fares and, as a consequence, a reduction of road use and its related externalities. One may argue that this policy should be refined to take into account the particular cross-elasticities of demand, but also two other arguments that might justify railway subsidies, particularly in urban areas (Parry and Small, 2009; Proost and Dender, 2008). First, economies of scale in the addition of users' and operators' costs imply marginal social costs lower than average costs, and, second, railway transport is often seen as a public service ensuring basic accessibility that could not be provided by other modes with less capacity. This public service requires, in general, public funding both for investment and operation. Therefore, it is not straightforward to extract which part of the subsidy is related to unpriced externalities.

Any optimisation of the public support to rail must deal, on the other hand, with the extent to which road transport internalises its external costs. This is a complex issue. In Europe, fuel taxes generate a great amount of public revenues that compensate for a substantial proportion of the total (social) costs of road transport. But they are not ideal for the attainment of environmental objectives. Parry & Small (2005) find that fuel taxes cause greater shifts in decisions related to fuel economy (car typology, driving behaviour, etc.) than in amount of veh-km produced and so they are not properly addressing distance-related externalities (e.g. congestion). In consequence, where congestion is significant and no specific charges are applied, road transport would still be clearly underpriced or, at least, not optimally priced. Regarding the air pollution and noise externalities, fuel taxes have a moderate correlation with

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[35] Rail and air competition is generally limited to High-Speed Rail (HSR) and it is not included in this study. For different approaches on this issue see e.g. (Albalate et al., 2015; Sánchez-Borràs et al., 2010).

them and, thus, none of them will be properly internalised if no specific charges are put in place.

2.6 Analysis dimensions

The former considerations can be summarised in four basic dimensions that may be used to analyse any proposal of environmental differentiation of charges for rail transport (Table 3-1). This analysis framework will be used in the following sections to review charges currently implemented in Europe.

Table 3-1: Four basic dimensions for the analysis of an environmental charging scheme for rail transport

Dimension	Description
Charging approach	Describes whether the charging scheme is based on the assessment of environmental costs or aims to cover the costs of the required abatement to comply with environmental regulations
Allocation of abatement efforts	Describes the scope and the targeted abatement measures of the charging scheme with the aim of assessing the cost-effectiveness in the allocation of abatement efforts
Degree of differentiation	Analyses the differentiation variables and the charging units used in the pricing scheme in terms of the incentives they provide and the implementation and transaction costs they imply

Dimension	Description
Intermodal approach	Analyses how the internalisation scheme deals with impacts on demand across transport modes. For this, the level of bonus or malus of charges is compared to the level of internalisation in competing modes with emphasis on the substitutability between modes

3 Differentiated rail access charges for noise

3.1 Main abatement options and regulation

Noise is widely recognised as the greatest environmental impact caused by rail (UIC, 2010), at least in Europe where most of the busiest network is electrified. Noise abatement proposals have focused on freight wagons as they are considered to be the main source of rail noise nuisances, in part because they often take place at night. Less attention has been paid to the aerodynamic noise of passenger trains at high speeds (over 200 km/h), as it is mainly produced during the day and in low population density areas. The level of noise impact and the related public concern varies strongly, however, among Member States within the EU, as it mainly depends on rail freight traffic volumes and population density.

European institutions have dealt with the rail noise problem through the Environmental Noise Directive (END) and the Noise Technical Specifications for Interoperability (TSI). The former requires Member States to publish noise maps and action plans, and the latter establishes the limit values of the noise level for new and renewed rolling stock.

Rolling noise, due to the irregular contact between wheel and rail, is the main rail noise source. Cast iron brake blocks, widely used in old freight wagons, significantly increase wheel roughness. The noise they produce can be reduced by up to 10 dB when they are retrofitted with new composite brake blocks (UIC, 2010). In recent years, the rail sector has developed two types of composite brake blocks: K-blocks and LL-blocks. K-blocks require an important adjustment of the braking system whilst LL-blocks, need minimal adaptation and are usually preferred because their overall retrofitting costs are much lower. However, it should be noted that the use of composite brake blocks causes an increase in maintenance costs in both cases.

Studies show that acting at the source by retrofitting cast iron brake blocks is the most cost-effective noise abatement measure as it benefits the whole train path (KCW et al., 2009). Other noise abatement methods such as noise barriers, which are commonly used, have a similar noise reduction potential but their effect is local (UIC, 2010).

The biggest obstacle to retrofitting is that wagon owners have no economic incentive for it, since replacement involves both an investment and an increase in the operational cost. Therefore, public intervention is necessary to reduce the noise impact of freight wagons equipped with cast iron brake blocks.

Given that EU countries have a common environmental policy, such intervention has been implemented through Regulation 2015/429 (European Commission (EC), 2015), which sets out the modalities to be followed for the application of the noise-differentiated rail charges mentioned in Directive 2012/34/CE. The purpose of the regulation is to define a common pricing framework to incentivise the retrofitting of freight wagons by allowing the reimbursement of relevant costs linked with the installation of composite brake blocks. According to this regulation, infrastructure managers shall introduce bonus per axis·km for railway undertakings using retrofitted wagons and/or complying with TSI noise emission ceilings. A bonus per silent train[36] is also recommended. To compensate this, a malus may be introduced for noisy trains, taking into account the noise sensitivity of the area affected, but the total sum of the maluses revenues in the system should not be higher than the sum of the bonuses. The implemented scheme shall apply before the end of 2021.

3.2 The European experience

Despite the fact that European policy promotes the introduction of noise-differentiated track access charges, only three countries (Germany, Netherlands, and Switzerland) are already applying them (Table 3-2). These countries are possibly the most affected by rail noise as they have important rail freight traffic in dense (or sensitive) areas.

All three charging systems fit into Regulation 2015/429 and are bonus-based time-limited programmes that promote the retrofitting of cast iron brake blocks in freight wagons. However, they show some minor differences.

In Germany, besides the bonuses for retrofitted wagons, a malus is applied to “noisy trains” (20% or more of noisy wagons), adding 1–2% of the total rail charge to partly finance the bonuses. The German case is also particular in that bonuses are shared by rail operators and wagon owners.

The Swiss railway system has the longest tradition of implementing rail noise abatement policies. The State has directly subsidised the retrofitting of freight wagons since 2000. Additionally, in order to cover additional operating costs and to extend the incentives to foreign rail freight traffic, noise-differentiated rail access charges have also been implemented. Unlike the other systems, the Swiss programme is unlimited in terms of the amount of bonus that can be obtained per wagon.

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[36] According to the Implementing Regulation, a “silent train” should be composed of at least 90% of wagons complying with TSI noise norms.

In the case of the Netherlands, besides the temporal bonus per retrofitted wagon, an extra bonus is awarded to “silent trains” (fewer than two wagons not retrofitted).

Table 3-2: Main characteristics of current rail noise charging systems implemented in Europe

	Germany	**The Netherlands**	**Switzerland**
Type of system (bonus, bonus/malus, malus)	Bonus/malus	Bonus	Bonus
Bonus level	0.01 €/axis ·km	0.04–0.05 €/wagon ·km	0.008–0.025 €/axis ·km (2)
Malus level	1–2% total access charge	-	-
Maximum bonus per wagon	1668 € (1)	4800 €	Unlimited
Maximum bonus duration	8 years	4 years	Unlimited
Eligible traffic	Retrofitted freight wagons	Retrofitted freight and passenger wagons	Retrofitted freight wagons

	Germany	**The Netherlands**	**Switzerland**
Differentiation level	Silent/non-silent trains	Silent/non-silent trains	Wheel diameter and brake system
Control system	Audited self-declaration	Audited self-declaration	Audited self-declaration
Covered costs	Retrofitting	Retrofitting and additional operation costs	Additional operation costs (2)
Charged/Awarded agents	Rail operator and wagon owner(3)	Rail operator	Rail operator

(1) Four-axis wagon hypothesis.

(2) Retrofitting costs are covered through direct subsidies.

(3) Bonuses are split at 50% each.

Source: Network Statements of Rail Infrastructure Managers (DB Netze, 2015; ProRail, 2015; SBB AG, 2015)

3.3 Analysis of the case studies

The current noise-differentiated rail charges of the three countries are analysed according to the dimensions described in Table 3-1.

3.3.1 Charging approach.

As discussed above, current noise-differentiated track access charges are time-limited incentive programmes that support the required renewal or retrofitting of wagons to comply with TSI noise emission ceilings. The incentives (mostly bonuses) are set on the basis of abatement costs and have no direct relation with the actual reduction in externalities. This approach complies with the

European legislation on the subject. The difficulties in appraising noise impacts justify the adoption of this practical approach. However, if incentives are not differentiated according to the magnitude of the avoided impact, there is a risk of obtaining a flat abatement regardless of the saved noise damage in each particular case. Further research on the estimation of rail noise marginal costs is required for a practical and efficient incentives system.

3.3.2 Allocation of abatement efforts

The scope of current noise charges is limited to freight wagons and the only targeted abatement measure is the retrofitting with cast iron brake blocks, considered the most cost-efficient noise reduction measure. However, incentives to rail operators to apply other technologies or adapt their operation to reduce noise during the most sensitive areas and time periods should also be considered in order to allow more flexible decisions by rail operators.

The pricing system must take into account that rail operators have to transfer these incentives upstream when they do not use their own wagons. They may belong to other transport or logistics operators, be leased from specialised leasing companies, or be rented from wagon owners. In this sense, the German scheme constitutes the best practice among the analysed cases in that incentives are split between rail operators and wagon owners.

3.3.3 Degree of differentiation

Due to the logarithmic scale of noise perception, adding a noisy wagon in a silent train generates a high impact. Adding it to a noisy train has a modest effect that actually decreases with the number of noisy wagons in the train. As a consequence, a linear bonus per wagon·km or axis·km will not adequately reflect the magnitude of the avoided impact. Instead, incentives should reflect the logarithmic nature of noise. A simple but effective way of moving to this direction is to differentiate “silent trains” from the rest. This would incentivise the use of silent train sets rather than the distribution of silent wagons in train sets. This differentiation is made in Germany and the Netherlands for trains that include few noisy wagons. This could be improved by a special treatment of completely silent trains as it would make a bigger difference in terms of reduced noise impact. A logarithmic formulation of charges according to the number of noisy wagons would entail even higher efficiency gains, but it would require modest transaction costs and a calculation method that is easy to understand by rail operators.

Furthermore, none of the current noise charging schemes is differentiated by location (or route) and day period. It would be relatively easy to do so given that this information is already included in the rail traffic activity statement and thus provide the correct incentives to operators without generating additional transaction costs.

3.3.4 Intermodal approach

Current noise pricing schemes subsidise retrofitting through mileage-based bonuses. In Germany, also maluses are placed for noisy trains but the overall variation in revenue accruing to the infrastructure manager is negative in any case. This subsidy is commonly justified on the grounds that the already low competitiveness margin of freight rail transport should not be damaged by the increased costs deriving from noise regulation compliance, given that no specific noise charges are applied to road transport in Europe. The argument is rather poor given that road and rail freight transportation show quite a low substitutability (see section 2.5). Both modes are usually complementary as trucks are used for the last mile of rail freight services. Therefore, pure bonuses for the abatement of rail noise should not be applied by default. Instead, the overall level of noise surcharges levied to rail operators should probably be increased if cross-elasticity of demand is sufficiently low.

4 Differentiated rail access charges for air pollution

4.1 Main abatement options and regulation

About 80% of rail traffic volume in Europe uses electricity as its energy source (CleanER-D, 2014), which means that most trains practically do not emit air pollutants where they run.[37] Instead, emissions are produced at power stations and depend on the electricity generation mix and on the net energy consumption of the rail operation.

Regenerative brakes provide a wide range of possibilities for optimising total consumption of electricity by trains. Recovered energy can be used by the auxiliary systems of the train and by other trains running in the same track circuit. If there is energy left, it can be fed back into the network in the case of two-way substations or be stored in on-board or external storage systems. When this does not happen, the unused energy is converted into heat in the rheostats. Following García and Martín (2008), the energy presently lost in the rheostats is still significant. The lack of economic incentives to feed power back into the network and to reduce consumption explain this energy waste.

Another possibility of reducing energy consumption is adopting eco-driving strategies. Operators can apply speed profiles that achieve optimal energy consumption for a given travel time (López-López et al., 2014).

The remaining 20% of EU rail traffic volume using diesel engines produces local emissions and is responsible for 1–2% of the particulate emissions (PM_{10}) and 1–3% of the emissions of nitrogen oxides (NO_x) generated by transport in Europe (CER and UIC, 2009).

The European Commission, through the Non-Road Mobile Machinery Directive (European Parliament and Council of the European Union, 2012b), defines

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[37] Dust and other direct emissions can be deemed negligible, with the possible exception of underground stations.

pollutant emission limits for new or renewed diesel locomotives and railcars. In 2012, Stage IIIB of the Directive came into effect, entailing a 50% reduction in NO_x limits and a 90% reduction in PM_{10} limits compared with the previous Stage IIIA.

Compliance with Stage IIIA has been achieved with just engine-based emission reduction measures. However, to meet Stage IIIB limits, exhaust gas after-treatment measures are required. The use of after-treatment technologies in the railway sector has been very limited until now, but according to the CleanER-D project trials, adequate technology is available to comply with Stage IIIB restrictions (CleanER-D, 2014). One of the main technological constraints of abating pollutants is the trade-off between NO_x emissions and fuel consumption, which makes it difficult to reduce NO_x and particulates emissions at the same time (Zavada et al., 2011).

It is obvious, in any case, that an air-pollution-differentiated rail access charge would promote electrification or, at least, the renewal of diesel engines, bring new technology to the market and incentivise energy efficiency in the sector.

4.2 The European experience

The definition of air-pollution-differentiated rail access charges is, however, still at an early stage. Unlike the case of noise, European policy does not explicitly promote their introduction. The lack of a legal framework for standardising their implementation, and even of recommendations on what to do, explain the wide spectrum of air-pollution-related charges currently implemented.

Four countries in Europe (Sweden, Switzerland, Finland, and the Czech Republic) apply surcharges to diesel rolling stock in relation to its air pollution impacts (Table 3-3).

In Sweden, charges are applied as a function of the self-declared fuel consumption whereas in the other countries they are based on gross tonne ·km. Moreover, the Swedish case provides a higher level of differentiation, with charges depending on the type of engine and vehicle (locomotive or railcar) and reduced charges on engines that meet the EU standard for Stage IIIA or Stage IIIB. The schemes implemented in the other countries have a lower level of complexity. Only in the Czech Republic are charges set according to compliance with European standards of air pollution emissions.

Another difference is that in Switzerland and the Czech Republic surcharges are only applied to diesel vehicles running on electrified lines whereas in Sweden and Finland all diesel vehicles are included in the charging scope.

Only the Swedish and Swiss Network Statements explicitly assert that charge levels are set according to the external cost estimates of air pollution. No information has been found on how charge levels have been set in the rest of the cases.

Table 3-3: Main characteristics of current rail air pollution charging systems implemented in Europe

	Czech Republic	**Finland**	**Sweden**	**Switzerland**
Type of system (bonus, bonus/malus, malus)	Malus	Malus	Malus	Malus
Bonus level	-	-	-	-

	Czech Republic	**Finland**	**Sweden**	**Switzerland**
Malus level	1–1.075 factor applied to infrastructure charge per gross tonne·km	0.0005 €/gross tonne·km	0.06–0.12 €/fuel litre 0.07–0.14 €/fuel m^3	0.0025 €/gross tonne·km
Eligible traffic	Diesel trains running on electrified lines	Diesel freight trains	Diesel trains	Diesel trains running on electrified lines
Differentiation level	Compliance with emission ceilings	None	Type of engine, locomotive/ rail car, emission class	None
Control system	Audited self-declaration	Audited self-declaration	Audited self-declaration	Audited self-declaration
Covered costs	n/d	n/d	External air pollution costs	External air pollution costs

	Czech Republic	Finland	Sweden	Switzerland
Charged/Awarded agents	Rail operator	Rail operator	Rail operator	Rail operator

Source: Network Statements of Rail Infrastructure Managers (Liikennevirasto, 2015; SBB AG, 2015; SZDC, 2015; Trafikverket, 2015)

4.3 Analysis of case studies

The current air pollution-differentiated rail charges are analysed following the dimensions described in Table 3-1.

4.3.1 Charging approach

Sweden and Switzerland rely on appraisals of air pollution impacts to set their emission surcharges. Although no information is provided in the Network Statements on the appraisal methodology, one may expect that their estimates of air pollution costs are consistent and reliable.

In Finland and the Czech Republic, air-pollution-differentiated rail charges are not explicitly set according to the evaluation of impacts, nor are they defined based on the abatement costs of particular measures. As a consequence, the adopted charging approach is rather unclear, but it is most likely an *ad hoc* surcharge based on the particular requirements of the respective domestic rail markets.

4.3.2 Allocation of abatement efforts

All the air-pollution-differentiated rail charges currently implemented exclude electric-powered vehicles. In this case, the producer (combustion plants) can abate unit air pollution whereas the consumer (rail operator) can only reduce its electricity consumption.

Therefore, to tackle emissions in a cost-effective way in electrified lines, emission charges (or other environmental policies) must be applied to electricity producers as they can transfer prices downstream. On the other hand, infrastructure managers should apply electricity charges to rail operators linked to their net consumption, even introducing incentives for reduced unit consumption (i.e. related to consumption per gross tonne km), and thus promote energy recovery and efficiency. When these lines are used by diesel vehicles, specific charges should be applied to them. In this case, rail operators may opt between switching to electrical vehicles or updating their diesel rolling stock.

In non-electrified lines, to reduce air pollution the infrastructure manager may electrify the line or the rail operator reduce unit emissions and/or the quantity of travel. This case is complex because the infrastructure manager is involved in the abatement of air pollution and, at the same time, is the one applying the environmental charges. A cost-benefit analysis could easily determine the convenience of electrifying the line, which is usually only justified when there is a substantial traffic flow. Then, charges to trains running on non-electrified lines should only be applied when reducing the amount of travel and/or introducing abatement technologies in diesel vehicles is more cost-effective than electrifying the line. Based on this, one may think that countries applying air pollution charges on non-electrified lines (Finland and Sweden) implicitly assume that electrifying their lines is not cost-effective whereas Switzerland and the Czech Republic consider the contrary.

4.3.3 Degree of differentiation

In Switzerland and Finland, air pollution charges on gross tonne·km are applied to diesel vehicles without regard to their performance on air pollution emissions. Administrative costs will be very low as no extra information is needed to apply this charge, but at the cost of only targeting abatement measures related to switching to electric vehicles and reducing the quantity of travel.

Instead, Sweden, with its differentiated charges, incentivises rail operators to buy less polluting diesel rolling stock. Charges are also applied per unit of consumed fuel (litres or cubic metres), providing very clear incentives to increase fuel efficiency. However, a certain degree of voluntary commitment by rail operators is required as the control system is based on self-declaration. If this were not the case, the applied degree of differentiation might imply high administrative costs.

4.3.4 Intermodal approach

In the currently implemented schemes, air pollution charges are clearly defined as a malus, that is, a surcharge to account for the impact of diesel vehicles emissions. Unlike the case of noise, road air pollution is partially internalised in some countries through road infrastructure access charges (tolls or vignettes).

On Swedish roads, the time-based Eurovignette system for heavy goods vehicles (above 12 tonnes) that differentiates the EURO class of the vehicle is applied. In Switzerland and the Czech Republic, a distance-based system for freight vehicles (above 3.5 tonnes) is implemented, which also differentiates according to the emission class. Therefore, where road charges incentivise the use of less pollutant road vehicles and given the low cross-elasticity of road freight demand with respect to rail tariffs, surcharges to rail operators based on the cost of generated air pollution appear as efficient and convenient.

The case for charging passenger diesel trains is more delicate. Present tolls or vignettes for automobiles do not differentiate the emission class of the vehicles (Booz & Company, 2012) and existing fuel taxes do not provide adequate incentive for the abatement of all air pollutants.[38] Therefore, especially in urban environments where air pollution impacts are higher and

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[38] The fuel consumption is closely linked to CO_2 emissions, but NO_x, $PM_{2.5}$ and SO_x are more dependent on the fuel type and engine type. Thus, fuel taxes should at least be differentiated according to the fuel type to provide a more adequate incentive for the abatement of all air pollution emissions (TML et al., 2012).

substitutability between modes is more likely, air pollution charges on railways should be lower than the full marginal external cost.

Given that the internalisation criteria used for road transport in the various European countries are quite diverse and are applied differently for passenger and heavy goods vehicles, the definition of air pollution-differentiated rail charges for passenger and freight trains should be adapted to the particular context.

5 Conclusions

This chapter has firstly discussed second-best issues about the implementation of environmentally differentiated rail charges, from which four basic analysis dimensions have been defined: charging approach, allocation of abatement efforts, degree of differentiation, and intermodal approach. According to this analytical framework, the few environmental charging schemes already implemented in Europe have been assessed. It can be concluded that:

(1) European rail policy promotes the introduction of an environmental dimension in rail access charges and abatement measures are readily available to reduce noise and air pollution impacts. Notwithstanding, environmental rail charges are still at an early stage in Europe due to difficulties in their practical implementation.

(2) The four dimensions of analysis considered (charging approach, allocation of abatement efforts, degree of differentiation, and intermodal approach) have demonstrated to be useful in providing a qualitative assessment of environmental internalisation schemes applied to railways and in identifying best practices and improvements.

(3) The uncertainty linked to the valuation of the environmental costs generated by railways entails an important difficulty in transferring them into efficient and practical pricing schemes. State-of-the-art estimates of air pollution costs are more reliable than those for noise. For this reason,

whereas current air-pollution-differentiated charges are mostly based on marginal environmental costs, noise charges are defined as time-limited bonuses to compensate for abatement costs. In any case, a more efficient methodology should be applied to differentiate charges according to the assessment of environmental impacts.

(4) Although the study is focused on environmental charges to rail operators, the abatement possibilities of upstream agents (e.g. vehicle manufactures or energy producers) have to be considered to seek for a cost-efficient combination of abatement efforts. According to this, different pricing scopes may be envisaged. In electric-powered trains, air pollution charges should be levied on producers as rail operators can only decide on the quantity of energy consumption. Instead, for air pollution generated by diesel vehicles and noise impacts, where rail operators have a wider range of abatement possibilities, environmentally differentiated charges may be allocated to rail operators or shared with upstream agents. Finally, when the infrastructure manager plays a role in the overall environmental abatement, a previous cost-benefit analysis is convenient to determine the pricing scope based on the cost-effectiveness of respective abatement efforts.

(5) The trade-off in the level of charging differentiation requires a comparison of efficiency gains and the costs of additional differentiation. In this sense, it has been found that currently implemented environmental rail charges could introduce further pricing differentiation to provide more precise signals to the market without increasing transaction costs. In some cases, however, further differentiation requires a certain degree of voluntary commitment by rail operators to make the system feasible.

(6) The vague principle of allowing only bonuses or *feebates* for railways if other modes are not internalising their environmental impacts assumes implicitly a perfect substitutability between modes. However, current estimates of cross-elasticities of demand contradict this assumption. Therefore, the level of surcharges can be increased, in general, up to a value

close to the full marginal external cost. The only exception would be urban passenger rail transport, for which the level of surcharges should be very moderate.

Further research is required to improve the performance of environmental rail charges. In particular, the most relevant research topics are the appraisal of environmental costs of railways, the estimation of administrative and other costs of differentiating charges, the modelling of rail operators' response in the face of environmental charges, and the determination of detailed elasticities and cross-elasticities of demand in the railway market. This would provide the tools to quantitatively assess the performance of environmental rail charges.

Chapter 4 Road pricing reform in Catalonia

1 Introduction

Road pricing is widely acknowledged as a suited instrument to deal with traffic congestion and finance roads. The European policy on transport pricing, under the principles of 'user-pays' and 'polluter-pays', promotes the introduction of user charges that internalise the infrastructure and external costs across all transport modes. In the case of roads, the Eurovignette Directive sets a common framework for road charges applied to heavy goods vehicles (HGV). Either time-based or distance-based charges can be applied in motorways such that the infrastructure and environmental costs caused by HGV are recovered.

The *momentum* of the Directive has led to an evolution, in Europe, from a road funding system basically based on the public budget towards the introduction of several road user charges that can partially finance the system. Examples of distance-based road charges for HGV can be found in Switzerland (Balmer, 2005), Austria, Germany (Broaddus and Gertz, 2008), Czech Republic, Slovak Republic, Belgium, and in other European countries. These systems are based on either DSRC or GPS technology to monitor the travelled distance. In turn, many HGV tolls are complemented with time-based user charges (*vignettes*) for passenger cars (Booz&Co, 2010). The main purposes of these systems are the funding of the road system and the limitation of the transit traffic. The implemented models have different proportions of self-financing. For example, in Switzerland the whole road network is completely self-funded through a combination of road charges and earmarked fuel taxes. Instead, in countries like Austria or Germany, only motorways are self-funded through road charges.

In other countries, including France, Italy and Spain (Vassallo et al., 2012), private tolls are implemented in many sections of the motorway network, whilst in other countries (e.g. United Kingdom, Denmark), vehicles only pay tolls in a few special sections of fixed links, tunnels, and bridges.

On the other hand, the emergence of electric vehicles represents a challenge for road funding systems, heavily dependent on fuel taxes. The U.S. has been considering a Vehicle Miles Travelled (VMT) fee as a long-run alternative to fuel taxes. Four states charge a weight-distance tax (WDT) to HGV (Conway and Walton, 2009) and several pilot tests have been performed for passenger vehicles using GPS technology (Hanley and Kuhl, 2011).

In this context, Catalonia is debating the implementation of a new road pricing model. Currently, in Catalonia, the users of 44% (in km) of the motorway network pay tolls to the private concessionaires who manage them. Ever since the first toll road was inaugurated in 1970, most of the network development has been funded using the private concession model. More recently, a shadow toll approach has been adopted for new constructions to reduce the burden on road users. The rest of the road network is publicly owned and financed by the public budget of the different government levels in charge.

Four main reasons call for a review of the present model of road pricing and financing. First, the lack of coherence and equity in the application of tolls both within the region and compared to other parts of across Spain has generated opposition to the model. Second, the system does not fully traffic congestion and air pollution in metropolitan areas. Third, the public budget for road maintenance and construction is severely constrained by public deficit restrictions, whilst compelled by shadow tolls payment obligations. Fourth, most existing toll roads contracts will expire in the next few years and road taxes collection is diminishing, so a resetting of the model becomes timely.

An improved road pricing model should thus simultaneously pursue three main objectives: providing sufficient funds for the maintenance and construction of roads, introducing incentives for the appropriate management of congestion and environmental impacts, and ensuring spatial equity (i.e. coherent prices across different links/regions) over the Catalan road network to make it acceptable. Matching these three objectives will involve multiple trade-offs.

This chapter proposes a new road pricing model that seeks a correct balance between the defined objectives. The analysis is based on the determination of the revenues-costs matrix disaggregated by type of vehicle and road class.

2 Literature review

Our problem has been tackled in the literature in many ways. According to Ferrari (2002), tolls on the road network may be imposed for two main reasons: diminishing network congestion and recovering investment and operation costs. These two approaches are characteristic, in general, of the urban and interurban network, respectively, and will lead, in principle, to divergent charging strategies. In this chapter, following Ferrari's terminology, *congestion tolls* will refer to charges explicitly designed to manage traffic congestion whereas *road tolls* will refer to charges with the ultimate objective of completely or partially funding roads.

By far, congestion tolls have been the issue receiving more attention among academics. From the Pigouvian benchmark, several extensions have been developed considering: traffic dynamics (Arnott et al., 1993), unknown demand function (Zhou et al., 2015), macroscopic theories of traffic (Daganzo and Lehe, 2015), unpriced alternatives (Verhoef et al., 1996), users' heterogeneity (Small and Yan, 2001), and interaction with other taxes (Mandell and Proost, 2016; Parry and Bento, 2001). Indeed, while the fundamentals of congestion tolls are rather well established, second-best settings need to be evaluated case-by-case according to the local conditions (Parry, 2009).

Mohring and Harwitz (1962) linked, in a way, congestion and road tolls by proving that, under certain technical conditions (neutral scale economies in road construction and congestion technology), the revenues from optimal congestion pricing would self-finance the optimal capacity provision. Then, under these conditions, capacity should only be expanded if toll revenues per unit of capacity are higher than unit capital costs of capacity provision (Verhoef and Rouwendal, 2004). However, this self-financing principle only holds and can be an adequate policy guide whenever congestion exists. Since road capacity is not fully divisible, uncongested roads (e.g. roads in rural areas or providing basic accessibility) may have spare capacity, which cannot be adjusted to demand. This means that this spare capacity will have to be funded otherwise.

Ferrari (2002) focuses on road tolls in non-urban networks and analyses the optimal allocation of road costs between public financing and user charges. Public financing causes an *excess burden* but, on the other hand, user charges will involve administrative costs and re-routing problems. Then, by optimizing this trade-off, it is concluded that optimal tolls are independent of road fixed costs but increase with the willingness to pay for road use and the opportunity costs of public funds. Furthermore, from a pure policy view, one can discuss the earmarking of taxes to roads. The trade-off here is between road financing sustainability (improved asset management) and fiscal (and so political) flexibility (Gwilliam and Shalizi, 1999).

Regarding the case of private toll roads, Yang and Meng (2000) set a methodology to calculate the effect of toll levels and capacity choices on the private profitability and the social welfare for a Build-Operate-Transfer (BOT) scheme. This leads to the definition of a feasibility region for both private operators (positive private profitability) and public bodies (positive social welfare). Other authors (e.g. (de Palma and Lindsey, 2000)) point out that the final outcome of the concession will be strongly determined by the competition with other road links with different ownership regimes.

These theoretical road pricing models set a long-run horizon. However, in terms of real policy making, the implementation path from the status quo to the long-run model may be even more relevant than the long-run model itself (Rouwendal and Verhoef, 2006). Generally, the main constraint for each implementation step is the acceptability of road users and society in general. The key factors for toll acceptance are: a transparent use of toll revenues within the road sector (Schuitema and Steg, 2008), ensuring the privacy of users, and the perception of equity (Agrawal et al., 2016). In particular, the spatial equity principle applied to road pricing will imply that differences in the generalized cost of travel (including tolls) between different OD pairs should be modest (Yang and Zhang, 2002).

Furthermore, the practical implementation of a road pricing scheme will require a technology to monitor road use, communicate billing data and enforce the payment (Noordegraaf et al., 2008). A complete review of the state-of-the-art technologies for road pricing purposes can be found in (de Palma and Lindsey, 2011). Indeed, the decision on the most appropriate technology should take into account the trade-off between the efficiency gains linked to an increased level of differentiation and the transaction costs generated by more differentiation.

3 Revenues-costs matrix

A road pricing model may pursue funding and/or mobility objectives. The former are related to the self-financing capacity of the whole road system, while the latter focus on the internalisation of external costs.

In order to determine the self-financing capacity of the system, one should calculate, on the one hand, the revenues stemming from tolls and taxes linked to road transport and, on the other, the total costs derived from the provision of road infrastructure.

The revenues-costs matrix can simultaneously assess the self-financing capacity of the overall road system and its degree of internalisation. It identifies the revenues from taxes on road transport and from tolls obtained from interurban road use. Some of these revenues will directly finance the system (e.g. tolls) while others will do it indirectly through the public budget (e.g. fuel taxes). The basic selection criterion used in the matrix formulation is whether the revenues are linked or not to costs caused by interurban road use. On the costs side, both the infrastructure (construction, maintenance and operation) and the external costs are included. In the case of external costs, only inter-sectorial costs are considered (i.e. external costs transferred outside the road sector). Congestion and most accident costs are considered to be intra-sectorial, as they are essentially borne by road users.

Under these premises and the relevant data on revenues and costs it is possible to build the matrix, disaggregated by type of vehicle (passenger cars or heavy goods vehicles) and by class of road (motorways or second-class roads) so it can become a useful tool to diagnose the current state of costs allocation in the road system and to provide estimates of the eventual impacts of the implementation of different charging systems.

3.1 Calculation of total revenues and costs

The revenues-costs matrix should reflect a consistent view of the situation. Therefore, while revenues and external costs are presented as annual data (in 2014) as they are mostly stable, infrastructure, operation and maintenance and financing costs are calculated as a mean value of the expenditure in previous years because they tend to show high variability. This criterion is based on the Eurovignette Directive, which indicates that construction and financial costs should be calculated as the yearly average of the last 30 years (1984-2014) whereas maintenance costs as the average of the last 10 years (2004-2014).

The costs of infrastructure are considered as full financial costs of the road system, and include, therefore, related VAT (value added tax) and corporate taxes linked to private financing. For consistency, VAT is also included in tolls and fuel taxes. External costs are calculated based on currently used socioeconomic values, following a top-down approach.

As the scope of the study is the interurban road system in Catalonia, the scope of the revenues and costs of the matrix fits the physical borders of its territory. When required, aggregated data are interpolated for specific market segments according to the respective traffic volumes. Table 4-1 summarises the calculation methodology and data sources.

Table 4-1: Calculation methodology for total revenues and costs of the Catalan road system

Revenues	Private tolls	Total annual revenues from road tolls in Catalonia in 2014 as reported by the concession companies. VAT included.
	Fuel taxes	Total annual revenues from transport fuel taxes in Catalonia in 2014 as reported by the Spanish Tax Agency. The VAT rate applied on top of the fuel tax is included. The interurban component has been computed taking the corresponding traffic proportion.
	Vehicle taxes	Total annual revenues from taxes on the purchase of passenger cars (HGV are exempt) in Catalonia in 2014 as reported by the Spanish Tax Agency. The interurban

		component has been computed taking the corresponding traffic proportion. Municipal taxes are not included.
Infrastructure costs	Construction costs	Annual investment in the construction of new roads or in rehabilitation/improvement of existing ones. Yearly average for the 1984-2014 period. VAT included. Reported by public bodies and private concession companies and converted to real prices (base year 2014).
	Maintenance and operation costs	Costs of annual ordinary and extraordinary road maintenance. Operation costs of the tolling system are also included. Yearly average for the 2004-2014 period. VAT included. Reported by the public bodies and by private concession companies and converted to real prices (base year 2014).
	Financial costs	Financial annual costs linked to road investments as reported by both public bodies and private concession companies and converted to real prices (base year 2014). Yearly average for the 1984-2014 period.
	Profits of private concessions before taxes	Annual profits before taxes reported by the private concession companies and converted to real prices (base year 2014). Yearly average for the 1984-2014 period.
External costs	Air pollution and climate change	Average total annual emissions of $PM_{2.5}$, NO_x, NMVOC, SO_2 and CO_2 are calculated based on traffic volumes and EMEP/EEA (Samaras and Ntziachristos, 2010) and then multiplied by the

		unit socioeconomic values included in the Handbook on external costs of transport (Ricardo-AEA et al., 2014).
	Noise	Averaged total annual noise impacts of road use are provided in noise maps of the Spanish Ministry of Agriculture and Environment. Noise levels are multiplied by exposed population and unit socioeconomic values included in the Handbook on external costs of transport (Ricardo-AEA et al., 2014).
	Accidents	Annual data on fatalities and injuries caused by road accidents are provided by the Catalan Traffic Agency. These are multiplied by the socioeconomic values included in the Handbook on external costs of transport (Ricardo-AEA et al., 2014). Only direct and indirect economic costs are included. The value of safety per se is not included because it is deemed intra-sectorial.

3.2 Disaggregation of revenues and costs

As previously mentioned, revenues and costs are disaggregated by type of vehicle (passenger car or heavy goods vehicle) and by class of road (motorway or second-class road). The disaggregation is performed through equivalence factors for each category (Table 4-2). The following formula (1) is applied:

$$C_{IJ} = \frac{C}{\sum_i \sum_j F_i \cdot X_i \cdot G_j \cdot X_j} \cdot F_I \cdot X_I \cdot G_J \cdot X_J \qquad (1)$$

where

C_{IJ} = cost of type of vehicle (I) and class of road (J);

C = total cost;

X_i = dimension of equivalence (e.g. veh.km) for the category (i) of type of vehicle;

X_j = dimension of equivalence (e.g. veh.km) for the category (j) of class of road;

F_i = factor of equivalence for the category (i) of type of vehicle; and

G_j = factor of equivalence for the category (j) of class of road.

The equivalence factors by vehicle type F_i related to infrastructure costs have been obtained from the observation of detailed costs provided by roads managers and by applying the cost-occasioned approach (Balducci and Stowers, 2008). For instance, the allocation of construction costs between passenger cars and HGV has been done by assigning the full costs of pavement construction to HGV and splitting the rest of costs (clearing, earthwork, drainage, etc.) in proportion to traffic volumes in passenger car equivalents. A similar criterion has been followed to allocate operation and maintenance costs. Pavement works are fully assigned to HGV while the rest of costs (monitoring, surveillance, cleaning, road signs, tolling system, etc.) are split in proportion to equivalent traffic flow rates. It is thus assumed that pavement damage is exclusively due to HGV. As such pavement damage is rapidly increasing with axle weight (see e.g. Table 13 in (FHWA, 2000)), car-produced pavement deterioration can be deemed negligible.

The equivalence factors by class of road G_j are based on the observed average cost per kilometre for motorways and secondary roads in Catalonia.

Regarding the allocation of external costs, the factors of equivalence have been computed as a ratio between the respective marginal costs included in the Handbook on external costs of transport (Ricardo-AEA et al., 2014), for both the type of vehicle and the class of road.

Table 4-2: Equivalence factors

	Type of vehicle F_i			Class of road G_j		
	Unit	Passenger car	Heavy goods vehicle	Unit	Motorways	Second-class roads
Private tolls	veh.km	1.0	2.4	-	1.0	0.0
Fuel taxes	veh.km	1.0	2.8	veh.km	1.0	1.0
Vehicle taxes	veh.km	1.0	0.0	veh.km	1.0	1.0
Construction costs	veh.km	1.0	5.3	km	2.0	1.0
Maintenance and operation costs	veh.km	1.0	6.2	km	3.0	1.0
Financial costs	veh.km	1.0	5.3	km	2.0	1.0
Profits of private concessions before taxes	veh.km	1.0	5.3	-	1.0	0.0
Pollution	veh.km	1.0	4.1	veh.km	1.0	0.9
Climate change	veh.km	1.0	2.4	veh.km	1.0	0.9
Noise	veh.km	1.0	3.0	veh.km	1.0	2.5
Accidents	veh.km	1.0	4.0	veh.km	1.0	2.0

3.3 Results

The resulting revenues-costs matrix is shown in Table 4-3. Revenues from tolls and taxes clearly cover road construction, operation and maintenance costs and generate an annual financial surplus of €570 million (without considering external costs). However, if external costs are included, the resulting deficit is €109 million. The conclusion reached is that, in Catalonia, the social costs of road transport are not fully paid by the direct revenues generated by road users.

Moreover, the disaggregated balances show that the allocation of revenues and costs among road users is not so well balanced. In terms of type of vehicle, there is a clear cross-funding from passenger cars to HGV. While cars produce a net surplus of €206 million, HGV do not even cover their infrastructure costs. Regarding the class of road, the surplus generated in motorways clearly offsets the deficit in second-class roads. This result is explained by the great differences in traffic intensity between both road classes.

The situation, including the global balance, may change if road concession contracts terminating in the next years entail the elimination of user-paid tolls. In 2022, when most of the currently tolled network may have been handed back to public bodies, toll revenues would be reduced from the current €881 million to €242 million with a clearly negative net balance for the system, unless tolls are somehow maintained. The situation could be even worse for the financial balance if other revenues diminish, for instance following a reduction in fuel consumption due to the progressive electrification of the vehicles fleet.

Table 4-3: Resulting revenues-costs matrix in 2014. Units in million € (2014). In brackets data for 2022 if tolls are abolished

		Total	**By type of vehicle**		**By class of road**	
			Passenger cars	**Heavy goods vehicles**	**Motorways**	**Second class roads**
Revenues	Private tolls	881 (242)	672	209	881	0
	Fuel taxes	1246	941	305	718	529
	Vehicle taxes	55	55	0	32	24

		Total	By type of vehicle		By class of road	
			Passenger cars	**Heavy goods vehicles**	**Motorways**	**Second class roads**
Inf. costs	Construction costs	708	438	269	208	499
	Maintenance and operation costs	497	288	209	244	253
	Financial costs	123	76	47	118	6
	Profits of private concessions before taxes	284	176	108	284	0
External costs	Air pollution	334	227	108	202	132
	Climate change	211	164	46	125	86
	Noise	14	10	4	5	9
	Accidents	120	82	38	49	72
Financial result (revenues –infrastructure costs)		570 (-69)	689	-119	776	-206
Total net result (revenues – infrastructure costs – external costs)		-109 (-748)	206	-315	395	-504

4 The proposed road pricing model

The policy approach adopted for the new road pricing model for Catalonia aims at improving both the financial sustainability and the efficiency in road use while ensuring that the road network guarantees some spatial equity across the country. It implies addressing the increasing deficit, if tolls are discontinued, and the observed misallocation of costs among road users.

To define the conceptual framework of the model, four basic issues need to be addressed: the scope of the pricing scheme, the cost coverage, the level of distance differentiation, and the use of revenues from externalities pricing. Regarding the scope, this model aims at integrating the whole interurban network in a single pricing scheme and, thus, all vehicle types and all classes of roads are included. On the subject of use of revenues, they should be allocated to the road sector, or at least to the transport sector, to prevent the caused externalities. The second and third issues are analysed in detail hereafter.

4.1 Total or partial cost coverage?

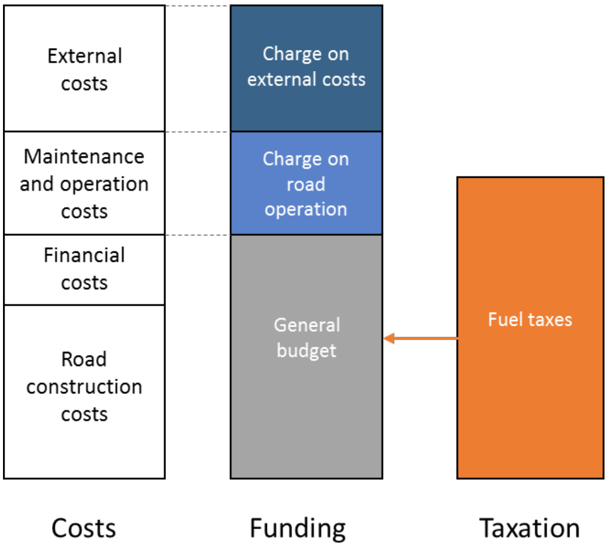
The basic question here is which costs should be directly covered by user charges and which ones should be financed by the public budget (indirectly covered by road taxes or not). The matter is related to the above-mentioned trade-off (see the literature review section) in the level of revenues earmarking between road financing sustainability and overall fiscal flexibility and to the previous taxation.

In road transport, fuel taxes (and other vehicle taxes) imply a substantial burden on road users. Thus, if fuel taxes remain unchanged, applying road user charges that fully cover road costs would not be appropriate in terms of equity as road users would have to pay a price for road use higher than the generated cost. In this case, the second-best optimal is a mix of fuel and distance-based charges (Parry, 2008). Fuel taxes in Catalonia are currently 0.47 €/litre for petrol and 0.38 €/litre for diesel and are allocated to the general budget. For the purpose of this study, fuel taxation is assumed to remain unchanged. This means that, to cover the total social road costs, user charges are needed to complement fuel taxes.

Fuel taxes do not adequately address distance-based externalities (Parry and Small, 2005). Therefore, costs that depend on road use such as maintenance, operation and external costs should be covered by appropriate user charges. On the other hand, fixed costs of road construction and financing, which basically depend on political decisions, could be funded by the public budget. This would ensure the budgetary flexibility in road investment decisions. Furthermore, fuel taxes indirectly cover these fixed costs and so the model is coherent. In 2014, fuel taxes revenues from interurban road transport were €1,246 million while annual fixed costs (construction plus financial costs) of the interurban road network amounted to €1,115 million.

Then, the proposed road pricing model is focused on road system operation rather than on network development, which is left for the general budget. Road charges will be designed to correctly allocate the costs of maintenance, operation and externalities within the complete interurban road network (Figure 4-1).

Figure 4-1: Schematic representation of the proposed road pricing model



Until now congestion costs have not been considered because they have been treated as an intra-sectorial externality in the revenues-costs matrix. However, individual charges should include a time-differentiated (basically distinguishing peak and off-peak periods) congestion fee in urban and metropolitan areas where congestion persists. The marginal cost of congestion should be a reference value for charges but, given the complexity of the network, in practice, time-differentiated charges dealing with urban congestion can be set iteratively to meet defined targets of level of service as it is done in the Singaporean ERP system (Olszewski and Xie, 2005). This issue falls outside the scope of this study, which is focused on interurban roads, but it seems obvious than an urban pricing scheme could be complementary and take advantage of existing synergies in technology and operation with the proposed network-wide road pricing model.

4.2 Distance-based or time-based?

The defined road charges on maintenance, operation and external costs can be implemented for a range of levels of differentiation. It is particularly important to decide, in the first place, whether they are differentiated by travelled distance or by duration of road use, because the incentives to road users will diverge. Distance-based charges will clearly constraint road use whereas time-based lump-sum charges (known as *vignettes* in Europe) will mostly affect vehicle ownership decisions, especially when the charge covers a large time period.

A distance-based road charge will be appropriate in motorways for three main reasons. First, users have a higher willingness to pay in exchange for their time savings and the increased driving comfort. Second, normally urban motorways have congestion problems, then, pricing could be used to manage road use demand. Third, the higher demand diminishes the unit costs of operating a distance-based charging scheme.

If the arguments above are applied in the other way around, it can be deduced that time-based lump-sum charges will be more appropriate for second-class roads. In this case, road links do not normally have a transport alternative and the provision of accessibility becomes clearly more important than the management of mobility. Thus, by applying time-based charges in second-class roads, spatial equity is ensured.

According to this, a two-part tariff is proposed. The fixed charge would be paid by road users yearly (or in shorter periods of time for foreigners and occasional users) per vehicle for the right to access the whole road network and it will be designed to cover the maintenance, operation and external costs of second-class roads. On the other hand, a variable charge would be paid by road users per unit of distance driven in motorways and would be meant to finance the maintenance, operation and external costs of motorways.

In terms of the previous study of social costs of the interurban road system and of available data on total traffic volume and stock of vehicles, the tariffs of the defined road pricing model can be computed. They are shown below (congestion charge is not included):

Passenger cars: 31 €/year + 0,026 €/km in motorways;

Heavy goods vehicles: 988 €/year + 0,076 €/km in motorways.

5 Implementation path

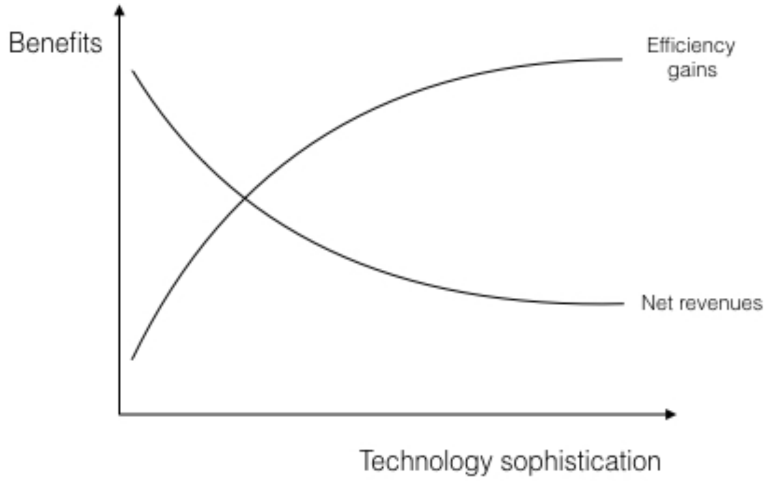
The previous conceptual model defines a horizon in the mid-term but a transition process is required. The implementation path from the *status quo* to the proposed road pricing model will be affected by the technology feasibility and several constraints or barriers. It can be seen as a succession of second-best pricing models adapted to these time-varying boundary conditions (Rouwendal and Verhoef, 2006).

Technologies to monitor and manage a road pricing scheme are rapidly evolving. Indeed, this is the reason why more sophisticated schemes have been implemented in the last decades in both interurban and urban contexts. The

GPS-based system for the German motorway network or the Singaporean system relying on DSRC communications are examples of state-of-the-art technologies for road pricing purposes.

There is a basic trade-off in the technology choice. On the one hand, a more sophisticated technology would, in general, enable a higher degree of differentiation of charges. This will better correlate costs to charges and lead to efficiency gains in terms of overall costs reduction. On the other hand, a more sophisticated technology would most likely imply higher implementation and operation costs that could reduce the net revenues generated from the charging scheme, and may be difficult to assimilate by users and thus reduce the pursued behavioural changes (Figure 4-2). This trade-off is time-varying with the technology evolution and the particular budgetary constraints.

Figure 4-2: Scheme of the trade-off in the technology choice



It can therefore be argued that, in this case, the funding and mobility objectives of the road pricing system are not necessarily aligned. If only the funding of the system matters, the technology sophistication should be set to the minimum in order to maximize the net revenues. Instead, if only mobility objectives are considered, the level of sophistication should be set at the point where net welfare gains are maximised. A balanced approach, as is the case of this study, will seek an in-between solution. Moreover, a distinction should be made between costs. Charges on maintenance and operation costs should provide a minimum amount of net revenues to fund them, while in the case of externalities pricing, the provision of adequate incentive is more effective than the collection of revenues.

The implementation path will also face several constraints. Most likely, public acceptability will be the main concern when trying to implement a road pricing system. This is highly related to each particular context. In the case of Catalonia, the perception of lack of spatial equity has been a main driver of public opposition to tolls.

This leaves basically two alternative implementation paths: a transition without private tolls and a transition through private tolls. Two feasible implementation paths are shown in Table 4-4.

Table 4-4: Alternative implementation paths. *Note: PPP (public-private partnership), PC (passenger cars), HGV (heavy duty vehicles)*

	Class of road	**Type of Vehicle**	**Main differentiation variables**	**Technology**	**Organisation**
Current state	Motorways	PC	Mileage	Toll with barriers	PPP
		HGV	Mileage, weight	Toll with barriers	PPP
	2nd class	PC	-	-	Public
		HGV	-	-	Public

		Class of road	Type of Vehicle	Main differentiation variables	Technology	Organisation
Alternative A: Without private tolls	Middle phase	Motor-ways	PC	Duration of use, emissions	Vignette sticker/ANPR	Public
			HGV	Mileage, emissions, weight	DSRC/GPS	Public/PPP
		2nd class	PC	Duration of use, emissions	Vignette sticker	Public
			HGV	Duration of use, emissions, weight	Vignette sticker/GPS	Public/PPP
	Final phase	Motor-ways	PC	Mileage, emissions, time of day	DSRC/GPS	Public/PPP
			HGV	Mileage, emissions, time of day, weight	DSRC/GPS	Public/PPP
		2nd class	PC	Duration of use, emissions	Vignette sticker/GPS	Public/PPP
			HGV	Duration of use, emissions, weight	Vignette sticker/GPS	Public/PPP
Alternative B: Through private tolls	Middle phase	Motor-ways	PC	Mileage	Toll with barriers	PPP
			HGV	Mileage, emissions, weight	DSRC/GPS	PPP

	Class of road	Type of Vehicle	Main differentiation variables	Technology	Organisation
	2nd class	PC	-	-	Public
		HGV	Duration of use, emissions, weight	Vignette sticker/GPS	PPP
Final phase	Motor-ways	PC	Mileage, emissions, time of day	DSRC/GPS	PPP
		HGV	Mileage, emissions, time of day, weight	DSRC/GPS	PPP
	2nd class	PC	Duration of use, emissions	Vignette sticker/GPS	PPP
		HGV	Duration of use, emissions, weight	Vignette sticker/GPS	PPP

6 Conclusions

The development of information and communication technologies has enabled the implementation of more refined road pricing schemes worldwide. Nowadays it is realistic to think of network-wide road pricing models improving, at the same time, the financial sustainability and the abatement of externalities. Nevertheless, both objectives are divergent on many occasions and several trade-offs emerge when designing a road pricing solution. On top of this, spatial equity becomes an important requirement for the acceptability of comprehensive pricing schemes and, thus, it should also be considered as a policy goal.

In Catalonia, motorways have been traditionally funded by private tolls, even though shadow tolls have been used in recent developments. The actual model is often perceived as unequal in terms of spatial equity. Furthermore, the performed study on revenues and costs allocation reveals that the system will become clearly under-financed when actual private tolls contracts will expire. It also detects a misallocation of costs among road users.

To address these issues an upgraded road pricing model is proposed. The scheme is focused on costs derived from the road use while capital costs are left for general budget financing. Then, the road price improves the financial sustainability of road operation and the internalisation of externalities, while ensuring a budget and political flexibility in the decision-making of road development. In terms of equity, the scheme is consistent because road charges together with fuel taxes cover the full social costs of road transport.

On the other hand, motorways and second-class roads have different requirements and have to be treated differently. To integrate the whole road network in a single pricing scheme, a two-part tariff is proposed. The fixed part covers the costs of second-class roads and its payment provides the right to access the whole network. Users travelling on motorways would pay an extra charge per unit of distance designed to cover the costs of the motorway network.

The implementation of the road pricing model would require a transition path basically conditioned by the technological feasibility and other constraints such as public acceptability and the rights of present concession holders. As the trade-off between efficiency gains and generated net revenues is still changing quickly with technology, a step-by-step approach should better adapt the system needs to the evolution of technology. This is why distance-based charges are initially implemented for heavy goods vehicles. Lastly, two alternative implementation paths are drawn, which show the compatibility of the proposed pricing model with different schemes based on public-private partnerships.

Chapter 5 Conclusions and policy implications

This thesis comprises three essays on specific second-best pricing issues in different contexts to gain insight on the design and implementation of practical pricing schemes for transport infrastructure. These essays reflect the diversity of methods and disciplines falling under this area of knowledge. This intends to show different approaches whereby policy making in the field of transport pricing can be enriched with concepts and tools taken from second-best pricing theory.

Chapter 2 studies the application of workplace parking policies in the metropolitan area of Barcelona and how these interact with other distortions in the urban economy such as traffic congestion, agglomeration economies and urban sprawl. This essay contributes to the existing literature by focusing on underground parking facilities, typical in dense cities, and by capturing crowding effects in public transport and parking spillover.

The findings from this essay have policy implications for local authorities considering the implementation of workplace parking policies. It shows the welfare gains from a switch to employee-paid parking by means of agglomeration effects and to a lesser extent by urban sprawl and transport effects. This contradicts a general concern by which a switch to employee-paid parking would damage the economic activity of city centres. In this sense, promoting a switch to employee-paid parking should be considered by local authorities as an effective policy in metropolitan areas with traffic congestion issues and significant agglomeration effects. This can be achieved by a combination of a cash-out programme whereby employers are required to offer a wage compensation to employees *in lieu* of the parking benefits and/or a fiscal reform that considers employer-paid parking as a taxable fringe benefit. Our research has not considered how these two measures could affect the parking supply decision of firms nor the legal implications of these measures. Further research following on these aspects would contribute to making a stronger case for local authorities to promote a switch to employee-paid parking.

Public authorities tend to favour the application of a workplace parking levy as a mechanism to raise funds for public transport, following the example of Nottingham in the UK and some Australian cities. However, the results of our research regarding the implementation of a workplace parking levy are more nuanced. These suggest that a workplace parking levy may lead to welfare losses if employers bear the costs of the levy and do not pass them on to their employees. It follows that a workplace parking levy should be carefully assessed and should not be seen as a stand-alone policy but as a complement to other policy measures that favour employee-paid parking.

Chapter 3 studies the application of environmental rail charges in Europe based on an analytical framework with four dimensions: charging approach, allocation of abatement efforts, degree of differentiation and intermodal approach.

Findings from this analysis have some policy implications that can be extrapolated to other cases where pricing schemes aim to promote environmental measures among transport options that already have an environmental benefit compared to others. The main conclusion for public authorities is that such pricing schemes should be tailored to the specific context based on a comprehensive analysis of demand substitutability between transport modes, the system governance and the abatement opportunities for transport operators and upstream agents.

Chapter 4 assesses a road pricing reform in Catalonia which aims to balance financial and demand management policy objectives along with public acceptability conditions, such as spatial equity.

Whilst this analysis is used to define a specific road pricing model and implementation path for interurban roads in Catalonia, some general policy implications can be extracted for authorities facing similar issues. The proposed revenue and costs matrix can be used to conduct a diagnosis on the allocation of costs across road users and road classes. In addition, our proposed two-part tariff model could be adapted by road authorities with a similar road class hierarchy where there is a political goal to establish a network-wide pricing model. Finally, our implementation path shows the compatibility of a network-wide road pricing model with existing or future public-private partnerships.

Overall, this thesis demonstrates the applicability of a wide range of elements from second-best pricing theory to the design and implementation of specific pricing schemes for transport infrastructure. Since second-best issues are context-dependent by definition, a natural continuation of this research would be to study similar second-best transport pricing issues in other contexts and potentially through complementary approaches. This would enhance our understanding of complex trade-offs associated with the implementation of transport pricing schemes and further contribute to reducing the gap between academic discussion and practical decision making in this area.

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