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Using the concept of functional economy to explore the spatial and environmental challenges associated with sustainable mobility

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Abstract

Traffic congestion, parking problems, and air pollution constitute contemporary challenges affecting especially urban areas. These concerns are intertwined and mutually reinforcing ; there is thus a need to address them jointly. Using the concept of functional economy (FE), this thesis attempts to go beyond the traditional compartmentalized approach. More specifically, this study investigates the role of a function-based transportation system, and namely of sharing the uses, in addressing jointly the spatial and environmental issues associated with sustainable mobility. After a short presentation of the concept of FE and its application to transportation (essay 1), we examine the role of sharing the uses in addressing spatial and environmental issues (essay 2). Then, we highlight the mechanisms underlying the rivalry of use affecting parking (essay 3), as well as the impact of local air pollution on labor productivity (essay 4). This thesis allows putting into perspective transportation infrastructure projects or policies through a two-angle analysis of the issues associated with mobility. First, transportation policies are explored from a spatial perspective, with space considered as a scarce resource in open access and whose consumption from transportation modes is subject to a shadow cost and to rivalry. Then, the link between enhanced accessibility and increased local air pollution from transportation is drawn, and the analysis reveals that accounting for environmental impacts leads to more accurate assessments of the expected agglomeration gains.

Keywords : Sustainable mobility, functional economy, rivalry of use, parking, air pollution, agglomeration economies, transportation policies, vehicle sharing, space consumption, optimal resource allocation, spatial issue

« Les enjeux spatiaux et environnementaux liés à la mobilité durable : une approche par l'économie de la fonctionnalité »

Résumé (court)

La congestion automobile, les difficultés de stationnement, et la pollution atmosphérique constituent des enjeux contemporains affectant particulièrement les zones urbaines. Ces enjeux se renforcent mutuellement et appellent des mesures conjointes. Cette thèse propose de dépasser les approches cloisonnées en utilisant le concept d'économie de la fonctionnalité (EF). Plus précisément, cette étude explore le rôle d'un système de transport basé sur la fonction, et notamment sur le partage des usages, dans la résolution des problématiques spatiales et environnementales liées à la mobilité durable. Après avoir présenté le concept d'EF et son application au domaine de la mobilité (article 1), nous explorons le rôle du partage des usages dans la résolution des problématiques spatiales et environnementales (article 2). Nous mettons ensuite en lumière les mécanismes sous-tendant les rivalités d'usage liées au stationnement (article 3), ainsi que l'impact de la pollution atmosphérique locale sur la productivité du travail (article 4). Cette thèse permet de mettre en perspective les projets d'infrastructures ou les politiques de transport par une analyse des problématiques liées à la mobilité sous deux angles distincts. Tout d'abord, les politiques de transport sont explorées en lien avec l'espace pris comme une ressource rare en libre accès et dont la consommation par les modes de transport a un coût implicite et est sujette à rivalité. Ensuite, le lien entre meilleure accessibilité et hausse de la pollution atmosphérique locale est fait et l'analyse montre que la prise en compte des impacts environnementaux conduit à une estimation plus fine des gains d'agglomération attendus.

Mots clés : Mobilité durable, économie de la fonctionnalité, rivalité d'usage, stationnement, pollution atmosphérique, économies d'agglomération, politique de transport, véhicule partagé, consommation d'espace, allocation de ressource, enjeux spatiaux

« Les enjeux spatiaux et environnementaux liés à la mobilité durable : une approche par l'économie de la fonctionnalité »

Résumé (substantiel)

La congestion automobile, les difficultés de stationnement, et les villes polluées par les transports constituent des enjeux contemporains que la science économique tente de s'approprier afin d'apporter des éclairages sur les arbitrages et les mécanismes sous-tendant ces problématiques. Ces phénomènes ont un coût socio-économique dans la mesure où ils limitent la pleine efficacité des capacités de production. Cette thèse explore le rôle des caractéristiques propres à un système de transport basé sur la fonction, et notamment sur le partage des usages, dans la résolution des problématiques spatiales et environnementales liées à la mobilité.

Ces enjeux ne sont pas récents mais ont été exacerbés au cours des dernières années par l'intensification des transports urbains de voyageurs, notamment la hausse du nombre de trajets réalisés et l'allongement des distances parcourues. Il existe une littérature abondante et ancienne sur les externalités négatives liées au transport, en particulier la congestion automobile. Des politiques urbaines de tarification, d'incitation au report modal et même de changement d'organisation spatiale ont été envisagées pour limiter la congestion automobile. Plus récemment, la tarification et la localisation des places de stationnement ont été étudiées, ainsi que les effets de la pollution générée par les transports. Cette dernière thématique a intéressé plusieurs champs scientifiques, des économistes aux climatologues, en passant par les épidémiologistes. Cependant, les enjeux spatiaux (congestion automobile et stationnement) et les enjeux environnementaux (pollution atmosphérique) ont principalement été abordés de façon séparée. Or, cette approche cloisonnée est problématique dans la mesure où enjeux spatiaux et environnementaux sont corrélés. En effet, plus la congestion ou les difficultés de stationnement sont élevées, plus la pollution de l'air générée par les transports est importante. De même, les deux types d'enjeux spatiaux, congestion et stationnement, se renforcent mutuellement.

En parallèle, la prise en compte des impacts environnementaux négatifs d'un produit ou service a été développée par les approches dites de « cycle de vie ». En ce qui concerne les véhicules utilisant de l'énergie, les impacts environnementaux générés par la phase d'usage sont souvent plus importants que ceux générés par la phase de fabrication. Dans une démarche de réduction des impacts environnementaux, la phase d'usage de certains produits ou services doit donc être au centre des considérations. Pour cette raison, la vente de l'usage ou de services autour d'un produit a émergé. Toute une littérature s'est récemment développée en sciences de gestion autour des « produits-services » et de la « servicisation » des biens. Le concept d' « économie de la fonctionnalité » (EF) découle de ces réflexions. L'usage des biens, et donc la fonction, est central dans ce modèle économique et organisationnel. Une approche par l'EF mobilise les concepts d'efficience et de suffisance, au sein d'une démarche plus large de développement durable. Les études existantes montrent un potentiel de réduction des impacts environnementaux des produits et services proposés selon le modèle de l'EF, notamment dans le domaine des transports. Cependant, les problématiques spatiales liées à la mobilité urbaine ne sont pas abordées dans cette littérature.

Cette thèse propose de dépasser les approches cloisonnées des enjeux spatiaux et environnementaux liés à la mobilité en utilisant le concept d'EF. Appliqué à la mobilité, ce concept permet d'aborder ces deux types d'enjeux. Dans une partie introductive, nous mettons en perspective le rôle d'un système de transport basé sur la fonction et le partage des usages dans la prise en compte de ces problématiques. Nous distinguons le partage simultané des usages (type covoiturage) et le partage séquentiel des usages (type véhicules en libre service) dans leurs effets sur les problématiques sus-citées. Ce manuscrit est constitué de quatre articles indépendants.

Après avoir présenté le concept d'EF et son application au domaine des transports urbains de voyageurs (article 1), nous explorons le rôle du partage des usages dans la résolution des problématiques spatiales et environnementales (article 2). Nous mettons ensuite en lumière les mécanismes sous-tendant les rivalités d'usage liées au stationnement (article 3), ainsi que l'impact de la pollution atmosphérique locale sur la productivité du travail (article 4).

L'article 1er explore le concept d'EF, à la fois dans sa théorie et dans sa mise en pratique dans le domaine des transports urbains de voyageurs. Plus précisément, nous proposons une mise en perspective du concept de l'EF par rapport à l'économie dite « standard » et à l'économie des services, ainsi qu'une analyse des caractéristiques propres à ce modèle organisationnel. Les moteurs potentiels d'une transition vers un système de transport basé sur la fonction sont exposés. Dans l'article suivant (article 2), nous nous focalisons sur le rôle du partage des usages (modes de transport partagés) dans la résolution des enjeux spatiaux et environnementaux. Dans un premier temps, nous montrons qu'une entrée par la sphère fonctionnelle permet de prioriser différemment les éléments d'EF constitutifs d'une approche systémique. L'approche systémique est considérée comme le plus haut degré d'intégration du concept avec son environnement. Plus précisément, nous montrons que les modes partagés constituent un élément clé dans la mise en place d'une approche systémique de la mobilité. Dans un second temps, nous analysons l'impact des modes partagés issus de l'EF (covoiturage et véhicules en libre service) sur les problématiques de consommation d'espace. L'approche par les services permet d'aller plus loin. Notre analyse indique que les modes partagés constituent un mode de transport intermédiaire entre modes privés et transports en commun, tant au niveau de la consommation d'espace que des services rendus.

Cette approche des politiques de transport par l'EF nous permet d'explorer les problématiques spatiales liées à la mobilité. Le partage simultané ou séquentiel des usages sur lequel se base l'EF conduit à un nombre plus faible de véhicules en circulation, ce qui réduit l'impact des transports sur l'espace. L'article 3 s'intéresse plus particulièrement aux rivalités d'usage affectant le stationnement en milieu urbain dense. Nous explorons les mécanismes sous-tendant l'allocation de l'espace de stationnement entre agents. L'économie urbaine s'empare généralement des enjeux spatiaux liés au transport, sans prendre en considération la rareté absolue de l'espace. Or, l'espace public dédié au stationnement urbain a toutes les caractéristiques d'une ressource non-renouvelable en libre-accès. Son analyse peut donc s'apparenter au champ de l'économie de l'environnement. Le modèle théorique d'allocation de l'espace entre agents que nous développons nous permet d'identifier et d'expliquer les rivalités d'usage, et met en évidence un coût implicite associé à la contrainte spatiale. Lorsque l'espace est valorisé par les agents, une allocation séquentielle de la ressource « pénalise » les agents « suiveurs » et conduit à une perte de bien-être social. Il y a donc une pression pour accroître le nombre de places de parking, ce qui peut induire une artificialisation des sols. L'intervention des pouvoirs publics est ensuite envisagée afin de réguler l'allocation de cette ressource rare en libre accès et de limiter les rivalités d'usage l'affectant. Nos résultats sont conformes à la littérature sur les ressources non-renouvelables et les ressources en libre accès.

Par ailleurs, une approche des politiques de transport par l'EF nous permet d'explorer également les problématiques environnementales liées à la mobilité. La prise en compte des impacts environnementaux par l'EF peut conduire à l'allongement de la durée de vie des produits, ainsi qu'à la hausse des taux d'utilisation des produits ou services, ce qui réduit les émissions polluantes. L'article 4 s'intéresse plus particulièrement à la pollution atmosphérique et à son impact sur la productivité du travail. Nous étudions l'impact de l'oxyde d'azote (NO_X) – un polluant local principalement issu du transport – sur la productivité des travailleurs. Pour cela, nous considérons la pollution atmosphérique locale comme un déterminant de la productivité du travail et nous l'intégrons dans le cadre théorique mesurant les économies d'agglomération afin d'estimer dans quelle mesure la pollution limite la pleine efficacité des capacités de production. Nous concluons que la prise en compte de la pollution (NO_X) dans l'estimation économétrique des effets d'agglomération permet de « corriger » la sensibilité de la productivité à la densité. Les gains économiques attendus suite à la mise en place d'une nouvelle infrastructure ou politique de transport sont généralement surestimés de plus de 13% lorsque les émissions de NO_X ne sont pas prises en compte. En effet, la mise en place de nouvelles infrastructures et politiques de transport améliore l'accessibilité d'un territoire, ce qui renforce les externalités positives (économies d'agglomération) provenant de la densification d'une zone, mais cela génère également de la pollution supplémentaire du fait des déplacements induits. Or la pollution limite la pleine efficacité des capacités de production.

Ainsi, cette thèse permet de mettre en perspective les projets d'infrastructures de transport ou les nouvelles politiques de transport par une analyse des problématiques liées à la mobilité sous deux angles bien distincts. Tout d'abord, les politiques de transport sont explorées en lien avec l'espace pris comme une ressource rare en libre accès et dont la consommation par les modes de transport a un coût implicite et est sujette à rivalité. Ensuite, le lien entre meilleure accessibilité et hausse de la pollution atmosphérique locale provenant du transport est fait et l'analyse montre que la prise en compte des impacts environnementaux conduit à une estimation plus fine des gains d'agglomération attendus. Notre étude traite à la fois des enjeux environnementaux et spatiaux liés à la mobilité en proposant une approche par l'EF. Les systèmes de transport basés sur la fonction, et notamment sur le partage des usages, permettent une analyse en termes spatial et environnemental des politiques de transport.

Remerciements

Un jour tranquille d'octobre, quelque part dans le Nord de la France, j'ai appareillé sur un trois-mâts carré, pour une destination fascinante... et inconnue. Commencer une thèse, c'est accepter de visiter en chemin des contrées hostiles et essuyer de gros grains, sans vraiment savoir ni à quelle distance ni à quelle latitude se trouve le port d'arrivée. Faire une thèse, c'est partir à l'aventure, pour le meilleur et pour le pire. Je n'avais jamais vraiment navigué avant, mis à part quelques rudiments de catamaran sur l'étang de Leucate, une virée en kayak dans les Calanques de Sormiou et une sortie en barque sur le canal de la Deûle. Je remercie vivement Alain Ayong Le Kama pour m'avoir préparée à la nagivation pendant le mémoire de master, et pour m'avoir accompagnée tout au long de ce périple traversant les mers du globe. Depuis sa tour de contrôle, Alain n'a jamais perdu mon rafiot de vue, il n'a eu de cesse de m'encourager dans les manœuvres difficiles, de m'indiquer le meilleur passage entre les écueils lorsque le brouillard était épais, et de me transmettre ma position lorsque le compas était déréglé. Lors d'une traversée comme celle-ci, l'opérateur de la tour de contrôle est un repère essentiel, un point stable et rassurant avec lequel on communique. Je remercie encore Alain pour m'avoir guidée à travers les brumes, avec confiance et régularité.

Le navire semble être arrivé à bon port. A la fin de ce périple, une équipe de contrôleurs assermentés fait le tour des cales pour vérifier que le bateau n'a pas pris l'eau et que les manœuvres ont été réalisées conformément à l'éthique en vigueur. Les contrôleurs interrogent sur les manœuvres réalisées au cours de l'épopée, pourquoi avoir sorti le foc par grand vent et replié la grand-voile avant d'avoir atteint la terre ferme ? Pourquoi être passé par le détroit de Malacca au lieu du détroit de Torrès ? Je remercie vivement mes deux rapporteurs, Michel Dimou et Mouezz Fodha, ainsi que Christian Du Tertre, le président du jury, et les autres membres du jury, Faiz Gallouj, Moez Kilani et Emmanuel Raoul, pour avoir effectué ces ultimes vérifications nécessaires à un débarquement en toute sécurité.

Cependant, une thèse n'est en rien comparable à une traversée en solitaire. Le port d'attache joue également un rôle crucial, notamment dans la logistique déployée pour le ravitaillement et les escales. Je remercie l'Université de Lille 1 et le Ministère de l'Enseignement Supérieur et de la Recherche pour m'avoir fourni les vivres et l'eau potable tout au long de mon parcours. Je n'aurais sinon probablement pas dépassé la pointe du Raz ! Je souhaiterais également remercier l'école doctorale SESAM et plus particulièrement le laboratoire EQUIPPE et son directeur, *Hubert Jayet, ainsi que le responsable des études doctorales, Stéphane Vigeant, pour m'avoir épaulée tout au long de ce parcours, et m'avoir permis de faire de nombreuses et enrichissantes escales, au cours desquelles j'ai rencontré d'autres navigateurs plus expérimentés et ai pu réviser ma feuille de route. Un grand merci à mon port d'attache pour m'avoir donné l'opportunité de faire escale à plusieurs conférences, workshop et séminaires, et notamment à Saint Pétersbourg, Lyon, et Paris et sa région.*

Le navire a commencé son périple par une mer calme et bleue, puis la brise s'est essoufflée et les voiles sont tombées. Lorsque le vent a fini par se lever, le temps était lourd et les nuages annonciateurs d'orage. La mer s'est agitée et il a fallu de toute urgence calfater la coque et tirer les voiles. Heureusement, j'étais épaulée de toute une équipe de matelots pour m'accompagner et aider aux réparations les plus ardues. Il est vrai qu'aucun matelot n'était vraiment expérimenté et que nous avons appris à naviguer ensemble, contre vents et marées. Mais chacun a sa spécialité et sa spécificité, de l'orientation à la technique, en passant par la navigation de nuit. Merci à tous les matelots de la « Ruche » : David et Hamza perchés sur le grand mât à scruter l'horizon, Léa et Paul à la barre, Clément et Aurélie à la grand-voile, Linjia et Luo sur la dunette, Philippe et Radmila sur le gaillard avant, Rasha et Mehdi se relayant pour la prise de quart, et Fédi, Jérôme, Joseph et Natalia à la manœuvre des cordages. Certains embarquent, d'autres débarquent en cours de route. Merci à Hamza pour avoir régulièrement relu mes feuilles de route. Une petite pensée à Aurélie pour sa ténacité économétrique lorsque nous avions le vent de face. Compagnons de galère, nous avons ramé à l'unisson lorsque le navire s'est retrouvé bloqué dans les Quarantièmes rugissants !

J'ai également eu la chance de faire un bout de chemin avec quelques flibustiers charmants qui écument des sujets liés à l'éthique et au développement durable, sans ménager leurs neurones lors de nos réunions « groupe de travail » : Loraine, Alexandre, Julia et Tereza. Je n'oublie pas non plus les soutiens restés à terre, qui s'enquièrent régulièrement de la trajectoire du bateau et aident à enrouler un cordage ou raccommoder une voile. Merci à mes parents pour leurs relectures... avant le passage à la langue de Shakespeare ! Et une pensée à Marie-Lise pour les soirées débriefing du mercredi soir. Et lors des avis de tempête ou tout simplement pour un moment de repos, il y a encore le Carré, cette petite pièce confortable dans laquelle se réfugier pour se retrouver nez-à-nez avec un matelot un peu particulier qui m'épaule solidement dans cette traversée. Ce co-équipier de vie a une sensationnelle recette pour disperser les doutes : l'optimisme.

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AASQA	Association Agréée de Surveillance de la Qualité de l'Air – French Air Quality Monitoring Association
BSS	Bike-Sharing System
CBD	Central Business District
CCFA	Comité des Constructeurs Français d'Automobiles – French Car Manufacturers Committee
CERTU	Centre d'Etudes sur les Réseaux, les Transports, l'Urbanisme et les constructions publiques – Centre for the Study of Urban Planning, Transportation and Public Facilities
CGDD	Commissariat Général au Développement Durable – French Commission for Sustainable Development
CITEPA	Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique – Interprofessional Technical Centre for Studies on Air Pollution
CO	Carbon monoxide
CO_2	Carbon dioxide
ESCO	Energy Service Company
EU	European Union
IEA	International Energy Agency
INSEE	Institut National de la Statistique et des Etudes Economiques – French National Institute for Statistics and Economic Research

FE	Functional economy
GDP	Gross Domestic Product
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
NO	Nitric oxide
$\mathbf{NO_2}$	Nitrogen dioxide
$\mathbf{NO_X}$	Nitrogen oxide
OECD	Organization of Economic Co-operation and Development
PM	Particulate matter
PSS	Product-Service System
TSC	Time-Space Consumption
US	United States
WHO	World Health Organization
WTSC	Weighted Time-Space Consumption

Introduction

0.1 Cities in movement: Why and how do people move?

This section introduces the concept of mobility and exposes the current trends in mobility. Then, we motivate the need for sustainable mobility patterns.

0.1.1 What is mobility?

Paths are drawn by animals and human beings when they hunt or look for water sources. Archaeologists have noted the existence of networks in all the oldest urban sites (Mesopotamia, Egypt, China) - only very few human settlements in the Indus Valley and in Yemen did not have roads [1] (Paquot, 2009). A city is therefore primarily an organized set of roads, streets and ways. Even nowadays, the very definition of a city involves mobility: in France, a 'urban area' is defined as an agglomeration or urban pole and its suburban area from which at least 40% of the working population commutes to the urban pole or to the surrounding local municipalities (INSEE, 2014). Movement defines cities, both in the statistical and physical sense. Route networks are necessary for the mobility of people. Mobility is however not desirable for itself but for the economic activities it enables. People move from places where they live to places where they work or enjoy leisure activities. Mobility with or without the help of vehicles is a vital function for agents to perform various economic activities. As such, mobility is considered as a derived consumption

1. People used the roofs of houses or indoor passageways to move from one part of the city to another.

(Hägerstrand, 1970; Orfeuil, 2008a; Sasaki and Nishii, 2010).

Several terms can be associated to the movement of people. On the one hand, 'transport' or 'transportation' is a narrower concept designing the system of roads through which people move. Transportation policies are policies related to one or several aspects of the transportation system. One the other hand, 'accessibility' is a much broader - but less consensual - concept. Accessibility relates to "what and how can be reached from a given point in space" (Bertolini et al., 2005) and depends on both the transportation and land use systems. However, accessibility can be achieved through information, and does not necessarily entail the movement of people.

In this thesis, we choose to explore further the concept of mobility, since it constitutes a reasonable and concrete reality between transportation and accessibility. Mobility refers to a physical movement in space. For this reason, the concept of mobility is deeply rooted in the notion of space, one of the main aspects we will focus on thereafter. According to Kaufmann (2002, 2004), the concept of mobility involves the notion of access, but also the notions of skills and appropriation. Access refers to the availability of different travel options and depends on the location of transportation networks, but also on financial and time issues. Skills and appropriation refer to the knowledge the user has of the various transportation modes available, and on its experiences, habits and perceptions to the modes. Mobility patterns then arise from the variety of travel options, individual constraints and preferences, and also from the land use system.

0.1.2 Trends in mobility

Before we investigate the issues related to mobility, let us clarify why and how people move, and what are the trends as regards mobility. Orfeuil (2008a) and CGDD (2010) draw a precise picture of mobility in France, and of its evolution.

Mobility patterns are influenced by many factors, among which are transportation systems and land use patterns, but also economic and socio-cultural features.

On average, 3.2 trips and 23 km per person per day are realized in France. The number of trips has only slightly increased since the 1960s, while the distance covered has gone up by a factor of 5 over the same period. The speed at which people move has also increased steadily: +35% between 1982 and 1994 (Massot et al., 2004). In most developed countries, the main travel mode for both regular and occasional trips is the private car. In France, 65% of trips and 83% of total distances are made by car. Walking trips account for 22% of all trips, and public transportation for 8% - these two modes are on a decreasing trend. The number of trips by car has increased, and car ownership rates went up too. In the European Union (EU), there are 586 vehicles for 1,000 inhabitants. Only 18% of the French households are not motorized. It has been recognized that higher car ownership rates induce more road trips. Despite this evolution, the cost of mobility has been decreasing over time (-6% between 1982 and 1994 according to Massot et al. (2004)) and becomes now stable, with 15.3% of the household budget for mobility, among which 13.2% represents expenditures for private cars or motorized two-wheelers. Similarly, the time budget of households remains stable, with around one hour spent for mobility in France [2]. Why do people move? There are more and more trips for leisure purposes, while commuting trips now only account for a third of all trips in France. However, although their number is decreasing, commuting trips remain crucial when designing transportation policies since they are regular and of structural importance for land use patterns.

Mobility patterns vary among countries, and these differences can be attributed to cultural factors. For instance, Buehler (2011) compares two developed countries

2. This is often called the "Zahavi conjecture", since Zahavi et al. (1980) reveal that on average the time spent for mobility purposes remains constant and varies between 60 and 90 minutes per day depending on the size of the urban area.

with similar car ownership rates, Germany and the United States (US), and concludes that "Americans walk, bike, and use public transport for only 10% of all trips compared to 40% in Germany". This difference may result from disparities in land use patterns, but holds for short trips also, with over 70% of short trips made by walking, cycling and public transportation in Germany against only slightly over 30% in the US.

0.1.3 Towards a 'sustainable' mobility?

Mobility, and especially road mobility, generates various external costs [3]. "External costs of transport are real costs that are not included in the market price of transport and are therefore not born by the user" (Proost, 2011). External costs related to mobility arise from traffic congestion, air pollution, wasted time, public deficit, accidents, noise, rivalry of use for parking, climate change, loss of biodiversity, water pollution, energy security, aesthetic or landscape effects, urban barrier effects, and so forth (Delucchi and McCubbin, 2011; Friedrich and Quinet, 2011). Road transportation is also associated with decreasing densities and urban sprawl, generally linked with economic, social, psychological and environmental costs (see Brueckner (2000) for a detailed analysis of the costs of urban sprawl). Appleyard (1981) reveals that residents of San Francisco living near high volumes of traffic have three times less friends and twice less acquaintances than those living near low volumes of traffic. Furthermore, space allocated to transportation and to settlement in general is sealed, which alters the natural features of the soil and reduces ecosystem services. "Transportation infrastructure can [...] fragment sensitive environmental habitat and thereby disturb and possibly eliminate plants and other (non-human) animals" (Delucchi and McCubbin, 2011). Reduced ecosystem services are also expected from the conversion of natural land to agricultural or urban uses (Tilman et al., 2002). A meta-analysis by Quinet (2004) estimates that external costs from cars

3. See Calthrop and Proost (1998) for a review of externalities in the transportation sector.

amount to 0.093 Euros per passenger-kilometer on average. Negative externalities and use conflicts related to mobility constitute therefore a crucial question since they interfere with the achievement of economic activities.

The negative externalities from mobility are particularly exacerbated in urban areas, where a heavy traffic concentrates on a limited geographic area. The negative effects of local air pollution are therefore made more acute and health risks are more serious due to the large number of people affected. Most of the population lives nowadays in urban areas (77% in France). Moreover, spatial externalities, in particular congestion and rivalry of use for parking, occur primarily in urban areas, since these issues are related to the space required by travel modes. Indeed, a urban area provides a limited surface which is not always able to meet the demand for mobility, notably in peak periods.

The term ‘sustainable mobility’ has emerged in a recent period to favor travel patterns generating less externalities than the current mobility patterns mainly based on road traffic. ‘Sustainable mobility’ has been adopted as an overall objective for European Common Transport Policy in the EU commission white paper on transportation from 1992 (European Commission, 1992) and has been since declined over many strategies. This term is broad and entails many aspects, from environmental costs to social costs, and includes economic costs. In this thesis, ‘sustainable mobility’ refers to strategies or mobility patterns that reduce the spatial and environmental issues we are focusing on, namely congestion, parking and air pollution.

It is worth noting that sustainable mobility usually refers to low-carbon modes, such as public transportation, or to active modes, such as walking and cycling, by opposition to road transportation, which is considered carbon-intensive. Motorized modes are mostly opposed to non-motorized modes. The concept of sustainability is often reduced to lower carbon dioxide (CO_2) emissions. Opposing private modes to shared modes remains uncommon. This categorization allows linking the concept of sustainability to both environmental and spatial issues, the latter being largely overlooked in the transportation literature.

For this reason, this thesis focuses on some externalities that are especially exacerbated in urban areas, namely spatial issues (congestion and parking) and local air pollution. Mobility patterns in general contribute to the aforementioned external costs, but commuting patterns in particular are of structural importance regarding both externalities and land use patterns. Public policies promoting sustainable mobility primarily aim at changing commuting patterns, since these trips are regular and constrained, and are the main source of traffic congestion and rivalry of use for parking spaces (Desjeux et al., 2006).

0.2 Spatial issues related to mobility

The present section explains the spatial issues associated with mobility, and the measures generally implemented to address them. Then, the role of space in mobility is highlighted.

0.2.1 Addressing traffic congestion and rivalry of use for parking

In this subsection, we first detail traffic congestion, then parking issues.

Traffic congestion

Traffic congestion occurs when demand for mobility (e.g., the number of vehicles in traffic) is higher than supply (e.g., road capacity). Congestion issues relate to the demand in road space. It can be caused or made worse by traffic incidents or road work. Yet, in city centers, congestion is often recurring, especially during peak hours, due to the increasing number of vehicles on roads. The congestion caused by an additional trip generates various external costs, "including opportunities forgone due to travel delay, the discomfort of crowding, and the impact of travel-time uncertainty on the reliability of arrival times" (Delucchi and McCubbin, 2011). Congestion represents the largest external cost from transportation (De Palma et al., 2011b). The cost of congestion is discussed in the literature [4] and it is usually admitted that it is the marginal cost that a user imposes on other users (Friedrich and Quinet, 2011). The cost of road congestion is estimated to range from 1 to 2% of Gross Domestic Product (GDP) in Europe (European Commission, 1995, 2007). Other studies focusing on time-delay estimate the costs in the range of 1 to 7 cents per mile (2006 US dollar) for the US (Delucchi and McCubbin, 2011).

Road congestion is a major issue addressed by local authorities. Rietveld and Daniel (2004) show that local authorities have power to influence individual's modal choice through the generalized cost of travel modes, notably with pull and push measures. Pull measures are those "improving the attractiveness of a mode by reducing its generalized cost", while push measures are those "making competitive modes more expensive" (Rietveld and Daniel, 2004). Pull measures generally refer to measures encouraging alternative modes, such as public transportation, cycling and walking, while push measures aim at refraining the use of private cars.

First measures addressing road congestion have aimed to expand road space, such as widening existing roads or building new road infrastructures. However, increased traffic flow leads to induced demand that generates road congestion. Then, local authorities have fostered modal shift to mass transit, bicycles or walking, in particular through increased supply (frequency) and service improvement in public transportation services, or with lower fares, even sometimes free access (De Witte et al., 2006) to public transportation. However, since decreasing the price of fares is not sufficient to raise demand for public transportation, pull measures on non-pecuniary

4. "What constitutes a congestion cost? Is it the cost above the normal travel time, and if so what is 'normal'? Or the total travel time, or the marginal cost?" (Friedrich and Quinet, 2011).

characteristics such as interpersonal transferability and region wide validity (FitzRoy and Smith, 1998), as well as push measures are often combined. Park-and-ride facilities are also measures to encourage commuters to drop their car outside the city center and to use public transportation to reach their final destination. Moreover, cycling and walking facilities have been introduced, such as bicycle lanes or pedestrian zones. Push measures initiated are for instance low speed zones, fuel taxes, congestion tolls (see Santos and Veroef (2011) for a literature review, and De Lara et al. (2008) and De Palma et al. (2011a) for the effects of congestion pricing on the urban form), etc. Finally, measures combine various strategies from low-carbon transportation incentives to restricting demand for private cars (road pricing, parking restrictions), and include city planning and urban design. Bertolini et al. (2005) highlight the importance of integrating transportation and land use planning in supporting sustainable development. Orfeuil (2008b) proposes to consider together jobs and housing construction to avoid long commuting car trips. Staggered school and work hours have also be suggested recently to avoid peak periods (Ljungberg, 2010).

Parking

Parking may be on street or off street. On-street parking is also referred to as curbside parking, while off-street parking designates parking lots or parking structures (Arnott, 2011). Much infrastructure and space is devoted to parking: in the US, there are on average 3 to 6 parking spaces per car, which represents a surface larger than the state of Massachusetts (Arnott, 2011). However, many distortions are associated with parking, among which are the underpricing of both auto travel and on-street parking, the subsidization of off-street parking by employers and shop owners, and minimum parking requirements [5] (Arnott, 2011). Moreover, public parking is generally constrained by political considerations (Arnott, 2011). These

5. “Minimum parking requirements are local regulations, based on planning practice, that specify the minimum amount of parking that must be provided by a land user. They vary by land use, and may be based on the number of employees, number of apartments or hotel rooms, square footage, etc.” (Arnott, 2011). See Litman (2008) for a review and discussion of these standards.

distortions favor the use of private cars.

The demand for parking is derived from the demand for private car travel, which is generally underpriced (Arnott, 2011). More cars on roads induces higher needs for parking spaces and worsens rivalry of use. In densely built-up urban areas, road users compete to park their cars. Conflicts are especially intense for on-street parking, considered as more convenient than off-street parking. Land devoted to transportation in general, and to public parking spaces in particular, can be considered as common resources available to road users in free access (Anderson and De Palma, 2004). Common resources as well as free access resources are prone to conflicts in their allocation. Parking spaces are non excludable but rivalrous: any agent can park her car on public roads, but this prevents another agent to park her car at the same place. Anderson and De Palma (2004) show that equilibrium entails overuse of parking close to the city center, therefore leading to conflicts. Delucchi and Murphy (1998) estimates that the total annualized cost of unpriced parking is at least tens of billions dollars per year in the US.

The expected time to find a parking space "depends on the ratio of the stock of cars cruising for parking to the turnover rate of parking spaces" (Arnott, 2011). Rivalry of use for parking spaces increases road traffic, therefore contributing to road congestion. Therefore, these spatial issues, congestion and parking, are strongly correlated. Parking issues are also related to the demand in road space. For this reason, similar measures are usually implemented for both congestion and parking issues. More specifically, measures to deal with parking concerns are parking restrictions, such as time restriction for parking, pricing policies, and a reduced number of parking spaces available, in particular through *maximum* parking requirements (instead of *minimum*) (Arnott, 2011). Parking fees are generally applied in city centers and the number of spaces decreases in favor of parks, dedicated lanes for buses and/or bicycles, and self-service vehicles. These measures increase the price of urban car travel and thus mitigate the distortions associated with parking.

However, there is very few data on parking throughout the world. This lack of interest for parking is confirmed by the rare literature on the economics of parking, while extensive work has been done on congestion issues. Parking has been considered simply as a fixed cost added to car travel (Arnott, 2011). Most of the work on parking has been carried out by engineers and urban planners to model how much parking spaces are required, how large the fees should be or which time limits are to be applied (see Young (2000) for a literature review). A reason for that may be the critical role space plays in parking concerns. Yet space has long been ignored in economic theory.

0.2.2 The role of space in mobility

"Transport is characterized by certain specific features. The first of these specific characteristics is the role of space. Transport is necessary because activities are spatially separated." (Mc Fadden, 2011). The spatial challenges related to mobility we are focusing on in this thesis, traffic congestion and rivalry of use for parking spaces, are issues related to space, and more precisely to the space 'consumed' by the transportation modes. First, we define space consumption, and explain how it is measured and what are the trends in space consumption. Then, we explore the links between space consumption and both transportation and land use systems. Finally, we expose estimated costs of space consumption and the role of space, taken as an object, in economics. We assume that the spatial issues related to mobility arise due to the fact that the scarce nature of space in urban areas is not taken into account.

Space consumption: definition, measures and trends

Let us first clarify a lexical point about space consumption and land use. The reader may be surprised by the use of the term 'space consumption' throughout this study. Land can be allocated to various uses, from agriculture to mobility, and includes nature (water reserves or carbon stock functions). The term 'land use' generally applies to the surface of land used for a particular function. 'Land use' is a prevailing term in spatial economics. On the contrary, the term 'space consumption' is less common and refers to the consumption of a desirable resource, as in environmental economics. Moreover, 'consumption' refers to an active process and depends on the preferences of agents, contrary to the idea of use, or land used by a function, which is rather passive. In addition, the concept of 'space consumption' is broader than that of 'land use' since the former conveys the idea of a quantity of space consumed, either surface, underground or overground, while the latter only refers to the surface of land (Héran and Ravalet, 2008). For these reasons, we choose the term 'space consumption' to name the use of land by agents or functions.

Before we explore the evolution of space consumption over time, let us describe how space consumption is measured. Space consumption is generally estimated with mapping softwares such as BDCarto or Corine Land Cover. The latter is widespread in land use studies and informs on the biophysical use of land (forest, water surfaces, buildings). A caveat of such softwares is their inability to inform on the functions of land: for instance, a building with housing functions is not distinguished from a building with transportation functions. We must therefore make do with the rough estimates available. In France, the space consumed by transportation infrastructures amounts to 10 to 25% (BDCarto) or to 5 to 25% (Corine Land Cover) of the total space in city centers, but to less than 5% in suburban areas (CERTU, 2007). Similarly, the space consumed by buildings represents between 60 to 80% of the total space in city centers, against less than 5% in suburban areas (CERTU, 2007). As one moves away from the city center, the density of transportation infrastructures in the total space decreases. In dense urban areas, the share of space devoted to transportation purposes is larger than that in suburban areas but benefits proportionally more agents. Therefore, the per capita space consumption is higher in suburban areas than in city centers. This is illustrated by Figure 1 for the Hannover region in Germany. In city centers and in high density areas, per person space dedicated to traffic facilities represents less than a fourth of the total settlement space, while it amounts to a third or more in new settlements on peripheral sites and low density areas (Apel, 2000). The share of space allocated to traffic facilities grows with the increase in settlement space.

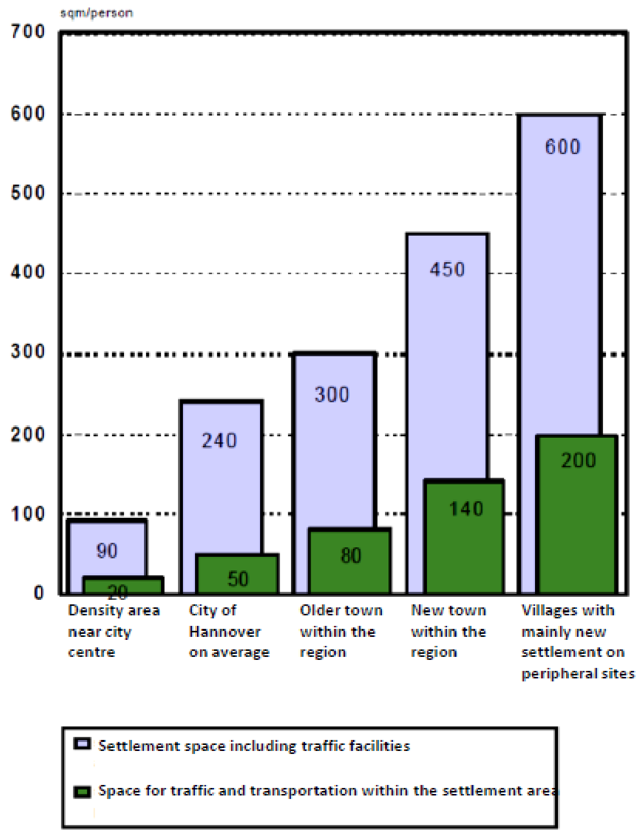


Figure 1: The share of space allocated to mobility within total settlement space in the Hannover region.

Source: Apel, 2000.

Space dedicated to passenger transportation represents 1.2% of the French territory, among which 92% is allocated to private road transportation (CERTU, 1998). The share of artificial space is increasing worldwide, so as the share of artificial space allocated to mobility. Figure 2 shows the share of artificial space for each NUTS 3 area[6] in France in 2006 and the trend towards urbanization since 2000. Areas

6. NUTS stands for Nomenclature of Territorial Units for Statistics.

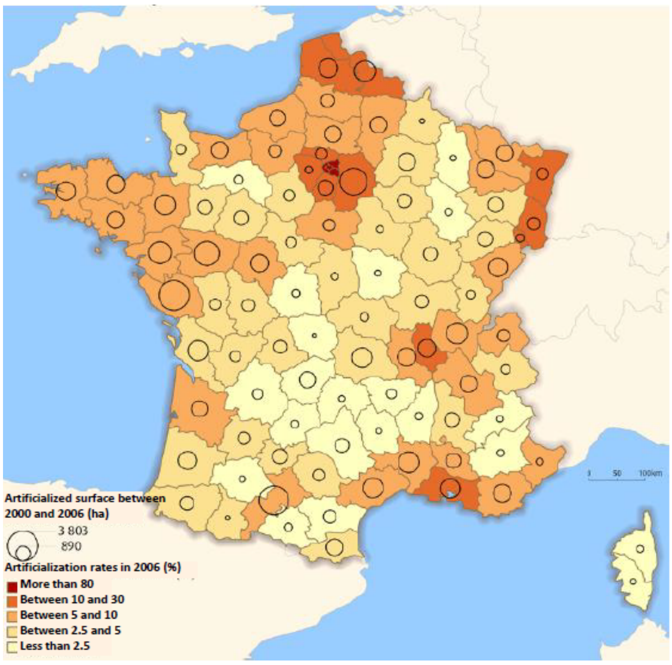


Figure 2: Land artificialization in France, an upward trend.
Source: UE-SOeS, CORINE Land Cover, 2006

with large share of artificial space are predominantly high population density areas. The upward trend of urbanization in France, and in developed countries in general, is driven by various factors that are correlated with one another. First, the total population has increased and additional surfaces of artificial land are required to enlarge existing settlements. Second, urban patterns have changed from compact development to urban sprawl. The organization of cities has turned to separated mono-functional areas. The growth in space results primarily from the development of road facilities that require more per capita space than rail transportation. The change in lifestyles and in both production processes and retail structures has also contributed to the urbanization process (Apel et al., 2001). Third, the per capita housing floor area has been enlarged from on average 15 m^2 in the 1960s to 40 m^2 in 2000 for Germany (Apel, 2000). In France, figures are 31 m^2 and 40 m^2 in 1984 and 2006 respectively (INSEE, 2006). This trend can be explained by the growing number of small households and the individualization of society.

Similarly, factors contributing to the increase of car use are directly associated with increased space consumption. Growth of income, car ownership and demographics effects are also contributing to the increase in car use, in addition to the effect of urban sprawl (Bonnel and Pochet, 2002).

Space: the common denominator of transportation and land use systems

All other things equal, the per capita settlement space follows an increasing trend. In addition, the per capita settlement space increases as we move away from city centers or as density decreases. The growth in housing floor area is also linked to the development of detached houses and thus to suburban developments and urban sprawl. Mangin (2004) reveals that in the last 40 years in France, settlement space has been multiplied by a factor 4 to 5, while density has been halved. The urban structure (functional mix, density, transportation system) influences the total settlement space consumption, and therefore the space consumed by traffic facilities. Large floor area and low densities generate additional land artificialization, but also more car-dependent commuting patterns (the causality is also reversed), which in turn requires large space consumptions. Studies indicate that the metropolitan structure has an influence on commuting patterns (Banister, 1997; Cervero and Kockelman, 1997; Ewing, 1995; Susilo and Maat, 2007) [7]. People living in outer suburbs commute more by cars (Cervero and Landis, 1992; Schwanen et al., 2001; Cervero and Wu, 1998) and require therefore larger settlement surfaces and above all larger surfaces dedicated to mobility. The influence of the land use system as regards car use seems to be larger than that of economic criteria. Joly et al. (2009) investigate the effect on car use of car-ownership (for a given spatial structure) and the effect of the urban structure (localization of activities) (for a given car-ownership) and conclude that the localization effect is stronger than the car-ownership effect.

Several studies try to model the main urban structures and their mobility pat-

7. Counter-studies also exist (see Gordon and Richardson (1997) for instance).

terns. Orfeuil (1994) suggests a typology to classify cities according to the potential of their spatial expansion and to the mix of functions within a city. He distinguishes three main urban dynamics: (1) Californian dynamics, with a large potential of spatial expansion and few zoning initiatives; (2) Rhineland dynamics, with a low potential of spatial expansion and a mix of functions; and (3) Saint-Simonian dynamics, with a large potential of spatial expansion but a strong city center. Besides, Apel (2000) suggests another typology to classify cities according to the per person settlement space and to densities, and also according to the dominant mode of transportation used. In Figure 3, Apel (2000) distinguishes three types of urban structures: (1) the city type "Delft", with high density and the bicycle as main mode of transportation; (2) the city type "Oldenburg", with medium density and both the bicycle and public transportation as main modes of transportation; and (3) the city type "Denver", with low density and the private car as main mode of transportation. It is worth noting that per person settlement space increases as density decreases and as we move from the use of bicycles to private cars. Similarly, the figure reveals that space allocated to traffic facilities increases more than proportionally with settlement space. Both lower density and the use of private car lead to large space consumption. Therefore, this figure illustrates the interrelations between the transportation system, the land use system, and the demand in space.

Estimated costs of space consumption

As mentioned above, space is necessary for achieving vital economic functions. Space allocated to settlement or mobility purposes is nowadays almost entirely artificial, and we have seen that there is an increasing trend towards urbanization. However, space consumption has a cost for society, and especially artificial space consumption.

There are different ways of estimating the cost of space consumption for traffic facilities. First, a direct monetary estimation based on parking pricing assumes

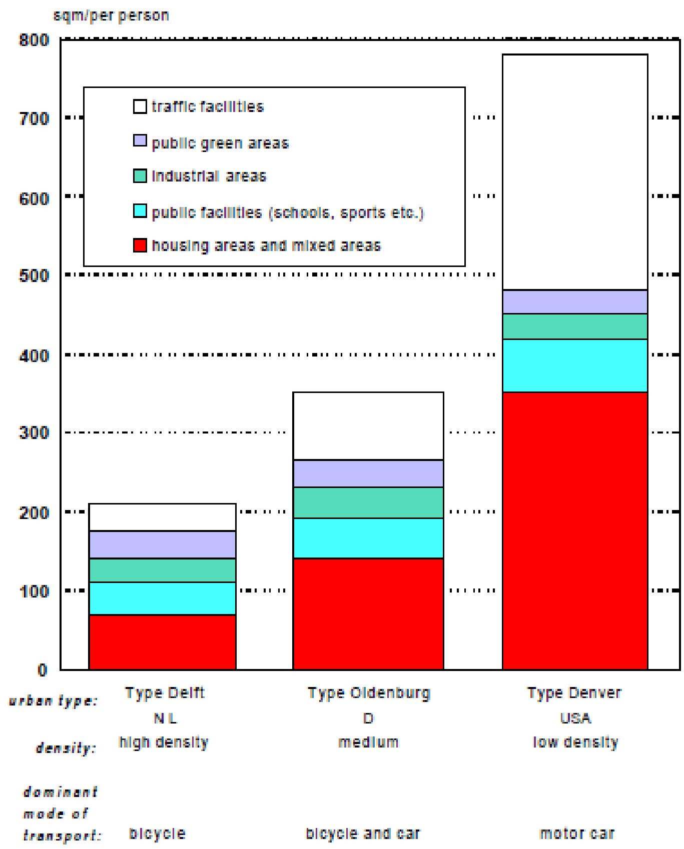


Figure 3: Settlement space by different types of city structures.
Source: Apel, 2000.

that parking fees display the social cost of road space, which is in practice generally not the case since parking pricing pursues other objectives (Commissariat Général du Plan, 2001). Second, an indirect estimation based on the depreciation of investments in new spaces allocated to traffic or parking applies the discounted cost of new surfaces and accounts for their expected duration of use (Commissariat Général du Plan, 2001). Third, Anas et al. (1997) advocate to consider the opportunity cost of the space dedicated to transportation, which is particularly relevant when a change in land use occurs. The opportunity cost corresponds to the value of the forgone best alternative, i.e., the value of a unit of surface allocated to another use. According to the authors, taking into account the opportunity cost of space dedicated to transportation would increase by half the cost of infrastructures. Quantitative assessments of the value of traffic facilities are given by Delucchi and Murphy(1998), Lee (1995) or KPMG (1993). It stands out that local roads in cities are more valued than national roads or highways (Delucchi and Murphy, 1998). Fourth, another approach consists in a hedonic evaluation of space taking into account various benefits resulting from the introduction of the transportation infrastructures, namely an increased accessibility and increased prices of nearby houses. Last but not least, the value of space can be based on the value of the natural soil before the development of infrastructures and buildings. Davis and Heathcote (2007) estimate that almost half (47%) of the value of houses in old city centers can be explained by the value of the natural soil, against 11% for recent developments in peripheral areas.

Overlooking the value of the space dedicated to transportation would result in an excess supply of space-consuming transportation infrastructures at the expense of space-saving transportation infrastructures or of management strategies of existing infrastructures (Woudsma et al., 2006). This is especially true in urban areas since the opportunity cost of space is high and the land value is affected by the accessibility of its localization (Lee, 1992; Vickrey, 1997).

Space, a multifaceted object in economics

Space as an object in economics is a recent idea. The leading works in economic theory do not mention the soil, distances or space; countries are modeled as points (Thisse, 1997). How does it come about that space is a central object in many sciences, and notably in physics, but has been ignored in economics for so long? Thisse (1997) and Combes et al. (2006) suggest that the modern economic theory stems from Anglo-Saxon countries where trade occurred mainly by sea, which was inexpensive compared with trade by road. This would have led Anglo-Saxon economists to overlook space and distances, considered merely as a cost among others, not as a key dimension. On the other hand, the spatial dimension was discussed only in Germany where trade occurred mainly by road (Thisse, 1997; Combes et al., 2006). The seminal work from Von Thünen (1826) on the geographic localization of economic activities has long been ignored by economists before being renewed by Weber (1909), Christaller (1935), and Lösch (1944). They consider space as a critical element in the economic analysis, especially due to the costs incurred by mobility and trade. Standard urban economic models have been developed in the tradition of Alonso, Mills and Muth in the 1960s. Then, the new geography economists following Krugman (1991) have renewed and enlarged geography economics, taking transportation costs and externalities (agglomeration economies) as central features of their theory. Distances and therefore land rents are key elements of urban economics. Space is an object where economic activities locate and its value depends on its localization. Space is generally not regarded as a limited resource and infinite endowments in land are assumed. As such, urban economic theory assumes relative scarcity of land, without considering its absolute scarcity.

However, in agricultural economics, the scarcity of arable land is emphasized, especially in recent studies accounting for growing population pressures. Rising public concerns pertain first to agricultural functions (World Bank, 2011). A crucial question is how to meet an increasing food demand while the productivity of agricultural land is decreasing throughout the world due to poor fertilizer and water management, soil erosion and shortened fallow periods (Oldeman, 1994). The demand for food is expected to increase more than proportionally with the population growth, due to rising incomes and a higher consumption of meat (mainly grain-fed) (Tilman et al., 2002). At the same time, rising demand for urban functions such as housing and transportation is expected to constrain further the provision of ecosystem services (Foley et al., 2005). Land use changes can temporarily help meet growing needs for a particular function, but will soon reach their limits when facing growing needs for various functions. Indeed, the scarcity of land is absolute. This literature focuses primarily on agricultural land, but does not address issues related to its allocation among agents.

If space was not limited in quantity, spatial issues such as traffic congestion and rivalry of use would not occur. But on the short run, there is a fixed number of roads and of parking spaces. As noted by Arnott (2011), the long run treats capacity as variable, while on the short run the capacity of the road and parking lots is fixed. He added that "curbside parking is a scarce economic resource" (Arnott, 2011). For this reason, space allocated to transportation in general and to parking spaces in particular can be considered as a non-renewable resource on the short run. Moreover, rivalry of use arises from the open access of parking spaces. Yet, scarce resources as well as open access resources are dealt with in the field of environmental economics, not in traditional transportation or urban economics. Therefore, it is all the more important to understand the allocation of space for mobility, considered as a scarce resource, since space consumption follows an increasing trend and entails costs.

0.3 Environmental issues related to mobility

In this section, we present some stylized facts about air pollution generated by mobility patterns, and its effects on the environment, the human health and labor productivity. Then, we expose both the sectoral measures applied to reduce air pollution from transportation, and the global measures based on strategies of efficiency and sufficiency.

0.3.1 Air pollution from the transportation sector

Another major issue related to mobility in urban areas is air pollution. The transportation sector is one of the most polluting sector, due to the environmental load (depletion of resources and polluting emissions) from the extraction of the various materials required for the infrastructures, as well as from the use phase. As regards primary energy use, transportation in OECD countries (Organization for Economic Co-operation and Development) is the leading sector in terms of oil resource consumption, with 80% of the resources attributed to road transportation. Oil resource consumption generates polluting emissions, in particular CO_2 emissions. Transportation accounts for 27.5% of total CO_2 emissions in OECD countries (IEA, 2011), and even for 37% in the US (Button, 2011). In France, the transportation sector is the leading sector in terms of Greenhouse Gases (GHG) emissions, especially CO_2. In addition, GHG emissions of the transportation sector are increasing while the other sectors have initiated a decreasing trend.

Transportation releases various pollutants, both global and local. Global pollutants are mainly gases contributing to global warming. Vehicle exhausts release large quantities of CO_2, a GHG which is a leading contributor to climate change. Local air pollutants such as carbon monoxide (CO), nitrogen oxide (NO_X), particulates (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) and aromatic hydrocarbons also arise from transportation. In France, 19% of CO emissions can be attributed to the transportation sector (CITEPA, 2013). NO_X emissions result mainly from transportation due to the exhaust of diesel vehicles. In France, 61% of NO_X emissions are released by transportation [8], among which 93% from road transportation (CITEPA, 2013). It is estimated that 0.08g of NO_X are emitted per passenger-kilometer for a gasoline vehicle with two occupants, against 0.39g and 0.76g for a diesel car with respectively two and one occupant(s) (Roos et al., 1997). However, average per vehicle NO_X releases are to take cautiously since they depend highly on the speed of the vehicle and its weight, as well as on the way of driving and the environment (urban or rural). Local pollutants such as NO_X emissions also contribute to the formation of ozone from the interaction with ultraviolet light. Moreover, the transportation sector releases around 15 to 20% of the total particulates in France (CITEPA, 2013), mainly from vehicle exhausts and the wear of roads, tires and brakes. Let us note

8. In France, more than half of the fleet (61.3%) is made up of diesel vehicles in 2013 (CCFA, 2012).

that among transportation modes, road transportation accounts for the larger share of all the aforementioned emissions (89% in OECD countries) (IEA, 2011).

Air pollution represents the third largest external cost from transportation, after congestion and accidents (De Palma et al., 2011b). Estimates of the external costs of air pollution from transportation "span a very wide range, mainly because of different assumptions regarding [...] the mortality impacts of pollutants, [and] the value of mortality" (Delucchi and McCubbin, 2011). Parry et al. (2007) estimate external costs of air pollution at 1.29 dollar per passenger mile traveled in the US, and Zhang et al. (2004) estimate these costs at 0.87 dollar per passenger mile traveled by urban car.

Let us note that spatial issues strengthen each other but reinforce also the environmental concerns related to mobility. Indeed, air pollution is exacerbated by both road congestion and rivalry of use for parking spaces, since both of these spatial issues result in longer engine running times and therefore higher levels of pollutants. Moreover, very low speeds of vehicles trapped in road congestion result in higher levels of emissions and increased energy use per passenger kilometer (Delucchi and McCubbin, 2011). Finally, "driving in congested conditions increases vehicle wear and tear" (Delucchi and McCubbin, 2011).

0.3.2 The effects of air pollution on the environment, the human health and labor productivity

Both global and local pollutants have significant effects on the environment and the health. However, it is worth noting that the impacts of the pollutants emitted depend not only on the population density, but also on meteorological conditions (wind, temperature and precipitation) and on the chemical composition of the atmosphere.

First, CO_2 emissions mainly affect the environment through climate change, but as a global pollutant it has no direct effect on the human health. Climate change has direct economic effects on countries and people, since they have to adapt to new climate conditions (increase in warmer or colder days, increase in rainy days) and to mitigate the effects, especially violent events such as droughts and storms that cause direct economic losses, through agricultural or infrastructure damages.

Second, CO emissions contribute to the acidification of soils and water, which affects ecosystems. Moreover, CO emissions reduce the oxygen and can be lethal when it is highly concentrated.

Third, particulates reduce visibility, influence climate through the absorption and refraction of light, and contribute to the physical and chemical degradation of materials. In addition, they can suffocate leaves and hinder photosynthesis. Their negative effect on the human health has also been proven. Fine particulates penetrate deep into the lungs and affect the respiratory system, in particular through exacerbated asthma and lung cancer. In addition, fine particulates penetrate into the blood system, therefore inhibiting proper blood flow and increasing risks for heart diseases and strokes (Pope and Dockery, 2006). Particulates may convey toxic, allergen or carcinogenic components such as heavy metals and polycyclic aromatic hydrocarbons. The World Health Organization (WHO) considers that more than 2 million people die prematurely each year due to inhalation of fine particulates. In 2000, the WHO estimated 42,000 prematurely deaths in France due to $PM_{2.5}$ exposure.

Last but not least, NO_X is made of nitric oxide (NO) and nitrogen dioxide (NO_2). NO_2 is highly toxic and penetrates into the lungs, therefore causing respiratory diseases. NO irritates bronchi and diminishes the oxygen power of blood. Latza et al. (2009) provide a review of some experimental and epidemiological studies on NO_2. NO_2 emissions lead to ear, nose and throat infections, otitis media, respiratory infections and in the most extreme cases myocardial infarctions. Ghosh et al. (2012)

demonstrate an association between NO_X and respiratory illnesses (bronchitis and upper airway inflammation) even for levels of NO_X lower than the current European Commission standards, especially among very young children. NO_X emissions also contribute to acid rains damaging the environment. Let us note that local pollutants such as NO_X emissions and particulates primarily impact the human health. As NO_X is mostly released by transportation, this pollutant will be thereafter under particular scrutiny.

It has been widely recognized by epidemiological studies that local pollutants deteriorate the human health, which generates negative economic impacts. On the one hand, people affected by local air pollutants may visit hospitals or their family doctors and consequently they lose work days (Ostro, 1983; Carson et al., 2011; Hanna and Oliva, 2011). For instance, Ostro (1983) demonstrates that a 10% increase in particulate levels generates a 4.4% decrease in work loss days due to hospitalization and diseases. On the other hand, people affected by local air pollutants may not stop working, but their hourly productivity decreases, altering both physical work (Graff Zivin and Neidell, 2012) and cognitive performance (Suglia et al., 2008; Lavy et al., 2012). For instance, Lavy et al. (2012) find a negative relationship between both fine PM and CO emissions and cognitive performance during school tests. Both the extensive and intensive margins of labor are affected. Consequently, local air pollution generates economic losses through the deterioration of human health. Local air pollution limits the full efficiency of production capacities.

0.3.3 Addressing air pollution: from sectoral to global measures

Local authorities regularly warn against pollution peaks in large cities and against their effects on the human health. Measures to reduce air pollution from mobility have long been technical responses (catalytic converters, reduced fuel consumptions) or regulatory measures (e.g., Euro standards for pollution), and are now increasingly directed to road demand management. Transportation policies mainly aim to foster low-carbon or no-carbon modes (mass transit, bicycles, walking) and to restrict the use of private cars through various coercive policies. The second approach is more comprehensive and is expected to lead to structural changes in the modal choices of commuters. The second approach acts at the source of the problem, while the first approach involves rather end-of-pipe measures. Nevertheless, several authors argue that vehicle technology evolution allows reducing air pollution to a larger extent than traffic management (Bouf and Hensher, 2007). They take stock after a year of the implementation of self-service bicycles in Lyon, France, and conclude that "despite the success of the scheme in increasing the use of bicycles, its influence on car use has been miniscule", since car traffic has been reduced by only 4% (Bouf and Hensher, 2007). In addition, Orfeuil (2008b) condemns traffic management measures that are, according to the author, costly and inefficient, compared with vehicle improvements. He claims that the decrease by a third of the air pollution in the French capital is attributable to 26% to vehicle improvements, and to only 6% to traffic management. However, the two types of measures can act as complements rather as substitutes to ensure reduced levels of pollution. On the whole and despite the growth in total vehicle travel, air pollution from transportation has been strongly reduced in the last decades. This is mainly due to a drastic reduction in the emissions per vehicle-kilometer.

Air pollution is a global concern and the transportation sector is not the only contributing sector. Moreover and contrary to the spatial challenges exposed above, air pollution has both local and global effects. Indeed, not only the city dwellers where emissions are released are affected, since emissions move with the wind and may affect other people. In addition, global pollutants have global effects, i.e., they are affecting people all around the world, irrespective of where they have been released from. Global warming is a worldwide issue and public policies primarily aim at reducing the level of CO_2 emissions to mitigate climate change. The climate and energy package in France aims at a 20% reduction of CO_2 emissions by 2020 compared with 1990. Other objectives have been set to developed countries, namely the factor 4 which aims to divide by four GHG emissions by 2050 (Von Weizsäcker et al., 1997). France has committed too to factor 4 (Pope law in 2005 and 'Grenelle de l'Environnement' in 2009), and aims at dividing by four its 1990 GHG emissions by 2050.

Issues related to pollution and energy use are manifold and call up various strategies. The main features of these strategies can be summed up in two words: efficiency and sufficiency (Scott, 2009; Cooper, 2005).

On the one hand, efficiency or eco-efficiency implies increased resource productivity, i.e., the same quantity of inputs will produce more outputs, or less inputs will produce the same level of output. Materials and energy are used in a more productive way. According to the NegaWatt scenario developed in France since 2001, both production and consumption can become more eco-efficient. Technical characteristics of products can be improved, such as the efficiency of car engines or weights leading to reduced energy consumption, and therefore to lower polluting emissions during the use phase. Eco-efficiency has been increasingly accepted by firms and supported by governments (Holliday et al., 2002). Indeed, eco-efficiency can lead to green growth of the economy (Cooper, 2005). However, the rebound effect may offset the environmental gains, or even worsen the environmental load. Issues related to rebound effects are studied more in details in Section 1.4.3. This strategy reduces polluting emissions and energy use in relative terms, but not necessarily in absolute terms. Indeed, resource efficiency is a necessary but not sufficient condition for a sustainable development (Schettkat, 2009).

On the other hand, sufficiency implies a reduction in the throughput of products and services (Cooper, 2005). The number of outputs (products and services) is reduced. For instance, products may be replaced less frequently due to lifespan extension. This strategy may lead to recession and therefore to huge economic losses. However, this strategy allows putting into perspective needs and consumption patterns, what does not allow the efficiency strategy. It also ensures reduced emissions and energy use in absolute terms. Moreover, sufficiency does not necessarily arise from unmet needs and deprivation leading to a lower social welfare; it is a learning process referring to the quality of life: changes occur first in the usage patterns, then in lifestyles and finally in the economic model (Linz, 2004). According to Max-Neef (1995), there is a threshold above which economic growth does not bring an improvement but a deterioration in the quality of life. Arrow et al. (1995) specify that the GDP growth as such is not environmentally damaging, but the structure of growth. Sufficiency can also arise from the re-organization of the economic system. For instance, a reduced number of car trips or of kilometers traveled can stem from the spatial reorganization of economic activities, especially the localization of residential areas and workplaces (Lichtennäher and Pastowski, 1995).

The Wuppertal Institute for Climate, Environment and Energy in Germany has carried out several studies on the strategies driving sustainable development. Some of them use the concepts of efficiency and sufficiency, sometimes adding other concepts to the analysis. Linz (2004) mentions the concept of 'consistency' with the use of technologies consistent with the nature and the ecosystem, close to the concept of 'industrial ecology'. Lichtennäher and Pastowski (1995) and Irrek and Kristof (2008) refer to the concept of 'substitution' from energy-intensive to less energy-intensive consumptions. For instance, the use of public transportation and/or car-sharing could substitute for the use of private car, and renewable resources could substitute for oil resources. These concepts are complements to the two main concepts exposed above.

As illustrated in Figure 4, a combination of both strategies can drive sustainable development (Cooper, 2005; McLaren et al., 1998; Reisch, 2001). They are comple-

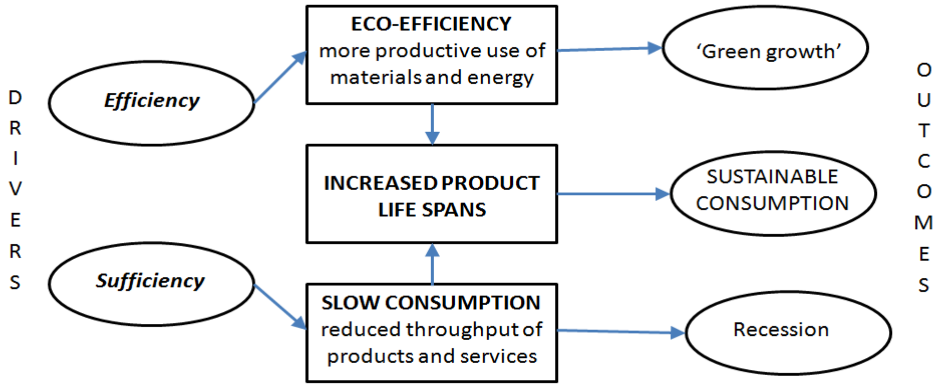


Figure 4: Two complementary strategies for a sustainable consumption.
Source: Cooper, 2005.

mentary in the sense that efficiency limits and may even avoid economic recession, while sufficiency limits and may even avoid rebound effects and the loss of environmental gains. A key concept gathering both strategies and leading to sustainable consumption is product lifespan extension – this concept is detailed thereafter.

0.4 Using the concept of Functional Economy to address jointly the spatial and environmental issues related to mobility

Concurrently, the negative environmental impacts of a product or service have been accounted for by the so called "lifecyle" approaches. The use phase of some products, such as vehicles requiring energy use, generates larger environmental impacts than the manufacturing phase. In a move to reduce environmental impacts, the use phase of some products or services has therefore be under particular scrutiny. For this reason, selling the use of a product, or services associated with a product, have become common practices. A vast literature has recently been flourishing in management sciences around the concept of "product-services" and the "servicization" of goods. The concept of "functional economy" (FE) stems from these thoughts. The use of goods, and thus the function, is central in this economic and organizational model. A function-based approach makes use of both concepts of efficiency and sufficiency, within a broader move towards sustainable development. Existing studies highlight the potential for reduced environmental impacts from products and services offered under the model of FE, especially in the field of transportation.

0.4.1 Servicization of goods and Functional Economy

In the Anglo-Saxon literature, several terms are used to describe the "servicization" of goods (see Van Niel (2007) for a literature review). Stahel (1994) mentions the "utilization-focused service economy", Behrendt et al. (2003) talk about "eco-services", and White et al. (1999) refer to "servicizing" to describe the sale of services associated with products, or the sale of integrated solutions (Brady et al., 2004). Then, the concept of "eco-efficient services" (Hockerts, 1999; Meijkamp, 2000; Brezet et al., 2001) refers to sales of services associated with various kinds of products that remain owned by the producer (Bartolomeo et al., 2003). Finally, the concept of "product-service systems (PSS)" is developed by Mont (2002) [9] and is derived from the work of Manzini (1996) on "product service combinations". PSS are a combination of products and services that aim to satisfy the user's needs through the combined used of products and services. PSS can be either product-oriented, use-oriented or result-oriented. From the PSS are derived the "functional sales" (Lindahl and Ölundh, 2001) that replace the traditional sales of products. Stahel refers to the "functional service economy" (2006) or more generally to the "functional economy" (1997) when he discusses a concept referring to the "servicization" of goods and one of whose main features and aims is the reduction of negative environmental impacts, in particular resource depletion and polluting emissions. For this reason, we choose to focus throughout this thesis on the concept of FE.

9. This concept is usually attributed to Oksana Mont but would have first appeared in a study by Goedkoop et al. (1999).

The FE consists in selling a use function – a solution, seen as a combination of products, services and directions for use – instead of a product. Material goods are regarded as mere instruments providing functions (commuting, communicating).

The concept of FE emerges in the 1980s from the joint work of Walter R. Stahel and Orio Giarini (Giarini, 1980; Giarini and Stahel, 1989) on the performance-based economy, by opposition with a throughput-based economy [10] (Daly, 1992; Ayres and Simonis, 1994). The FE originally aims to dematerialize [11] the economy in order to achieve sustainable economic paths (Stahel, 2006). For this purpose, the economic and organizational model proposes to decouple economic growth from flows of energy and materials. Reduced environmental load, in particular resource depletion and polluting emissions, are clearly stated objectives of a FE. Inputs are optimized through regular maintenance of the products that remain owned by the producer or function provider, as well as through recycling and re-use of materials. Management tools such as lifecycle approaches can help producers and users have an overall cost approach. Moreover, the “logic of access” (Rifkin, 2000) prevails over ownership rights and a particular focus is made on the use value of goods. Let us note that the FE has features of both the product-oriented economy and the service-oriented economy. Further details about the features of a FE will be found in the first essay, in particular in Section 1.2.

0.4.2 The FE: implementing efficiency and sufficiency strategies

We mentioned that two broad strategies to limit polluting emissions and resource depletion are efficiency and sufficiency. A way of making both these strategies

10. In the economic context, throughput refers to “the flow of raw materials and energy from the global ecosystem’s sources of low entropy (mines, wells, fisheries, croplands) through the economy, and back to the global ecosystem’s sinks for high entropy wastes (atmosphere, oceans, dumps)” (Daly and Farley, 2003).

11. To dematerialize means to reduce the volume of materials used (inputs) to meet the needs of agents (output).

concrete would be to introduce a FE. Indeed, the FE has features allowing to reduce polluting emissions and both energy and resource consumption without lowering the service offered. First, the full cost approach gives incentives towards materials and energy savings, as well as towards product lifespan extension. Second, the shift from buying the product to buying services for its use changes consumption patterns towards more sustainability.

A full cost approach

Firms are expected to behave more efficiently in the conception and production process when they are paid by the result (Stahel, 2006; Tukker and Tischner, 2006). They sell solutions or final services, not only the intermediate good providing the final service. For instance, Energy Service Companies (ESCOs) deliver energy solutions (e.g., guaranteeing a comfort temperature of 20°C in houses). Firms have to care about the use phase and the end-of-life of their products or services. For this reason, they get incentives to conceive parts which can easily be repaired, re-used or upgraded. Decision support tools such as lifecycle assessments can help optimize the manufacturing process so as to save inputs. Tukker and Tischner (2006) estimate a reduction by a factor 2 of materials consumed by selling uses instead of goods. Consumers are also expected to behave more efficiently if they are aware of the full cost of products, especially of costs related to its use (Tukker and Tischner, 2006). A full cost approach highlights the cost of providing a unit of service. It is usually admitted that the initial investment of buying a car is then overlooked in the trade-off between the use costs of various transportation options, leading therefore to overuse of road transportation. Furthermore, when the entire product lifecycle is handled by the firm, one can expect that the lifespan of products would be extended. Indeed, profit maximizing companies make rational decisions about product lifetime, which is not always the case for users who may be influenced by non economic variables such as fashion, social norms, prestige. Cooper (2005) shows that only a third of discarded appliances in the UK are "broken beyond repair", while another third are still functional, and the last third can be repaired. However, labor costs for repair work in developed countries are generally high while manufacturing has increasingly relocated to low-cost countries.

Product lifespan in the "standard" economic system has decreased (Kostecki, 1998), mainly due to higher repair costs, but the lifespan of some commodities has also been shortened on purpose (so called "planned obsolescence"). A key feature of the FE leading to reduced environmental load is lifespan extension. The lifetime of resources is extended through the double-loop approach of the FE (see section 1.2.2 for more details). Both loops imply lifespan extension of the product or of the materials embedded in it. The first loop favors re-use of products, repair of damaged products, and technological upgrading of products. It directly extends the lifespan of a product. The second loop favors recycled materials instead of virgin resources, which leads to extended lifespan of materials embedded in the production process. The main advantage of lifespan extension is to reduce the replacement frequency of goods (Van Nes and Cramer, 2006), which avoids emissions and resource consumption from the production process. However, extending the lifespan is not systematically suitable for the environment. Studies about lifespan optimization assess in which situations extending the lifespan of products generates environmental gains, and in which situations it would be better to replace the product by a more efficient one (Van Nes and Cramer, 2006; Kagawa et al., 2008; Nansai et al., 2007). This tradeoff depends on the energy intensity of the initial product and of that of the new one, as well as on when the replacement takes place. Van Nes and Cramer (2006) indicate that it is always environmentally desirable to extend the lifespan of products without any energy involved in their use phase. The number of goods is reduced, and thus the amount of materials and energy required in the production process, as well as the emissions from the manufacturing phase. Hertwich (2005) highlights the importance of the indirect energy consumption embedded in the production phase.

The environmental gain will be exactly equal to the lifespan extension. When the product lifespan increases by 10%, the environmental gain is 10% of the initial impact of the product (Van Nes and Cramer, 2006). This is for instance the case of bicycles that involve energy only during their manufacturing phase. This reasoning also applies for products with energy involved in their use phase but only when the new product involves the same (or higher) energy content in the use phase. In this case, lifespan extension is environmentally beneficial. However, new products are generally more energy-efficient and replacing old energy-intensive products by new energy-efficient products helps save energy. The question of interest is then the time at which the initial product is replaced, or in other words, when does the direct energy saved by the more efficient product during the use phase exceed the indirect energy saved when replacement is refrained. This depends on the energy intensity involved in both manufacturing and use phases. Figure 5 illustrates the environmental effect (E_{gain} for 'environmental gain') of early replacement by a more energy-efficient product. Kagawa et al. (2008) on the Japanese automobile industry reveal that it is environmentally desirable to extend the average vehicle lifespan by one year, rather than buying a new vehicle. But after one year, it becomes environmentally more desirable to replace old vehicles by new ones that are more energy-efficient. In another study, Kagawa et al. (2006) estimate that a one year lifespan extension for vehicles reduces total primary energy requirements by 0.25%. Figures are estimated for the year 1995 and may be out of date, but provide orders of magnitude.

Shifting from a product-oriented to a service-oriented society

The FE implies a shift from a product-oriented to a service-oriented society, which may lead to reduced negative environmental impacts. Environmental gains arise mainly from a reduction in the use of the good or service, rather than from the very nature of the good (service).

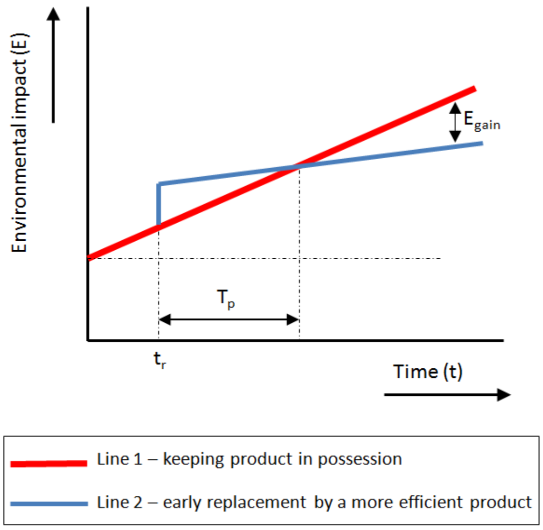


Figure 5: Environmental effect of early replacement by a more energy-efficient product. *Source*: Van Nes and Cramer (2006)

One may think that services have much less environmental impacts associated with them than products. The GHG emission intensity of services (0.5 kg of CO_2 equivalent) is indeed lower than that of other products from the secondary or primary sector (1.0 and 3.0 kg of CO_2 equivalent respectively), even when indirect impacts are accounted for (Suh, 2006). However, offering a trip by car as a service does not involve less energy than the same trip made by a car purchased previously by an agent and not considered as a service in the economy. Services may seem environmentally beneficial when only direct energy content and emissions produced on-site are considered, but the reasoning does not necessary hold when indirect energy and emissions associated with products involved in the service provision are considered. In a study about the US economy, Suh (2006) estimates that each dollar of products or services generates on average 0.83 kg of CO_2 equivalent when direct and indirect impacts are considered. The larger share of the emissions (0.47 kg of CO_2 equivalent) stems from indirect impacts and should therefore be under particular scrutiny in environmental assessments, especially when indirect emissions are imported (carbon leakage) (Scott, 2009).

However, a shift from a product-oriented to a service-oriented society may generate environmental gains due to a reduction in the use. Gains therefore arise from a change in consumer behavior due to a change in the relation the consumer has with the good after it has been servicized. Meijkamp (2000) analyzes empirically car-sharing systems and reports a 44% reduction in the number of cars used by car-sharing members. In addition, a shift from car-ownership to car-sharing results in significant vehicle mileage reduction (Muheim and Inderbitzin, 1992; Baum and Pesch, 1994; Petersen, 1995; Steininger and Novy, 1997). A distinction is to be made between two groups of car users: first, those who had a better access to cars before getting involved in the sharing system, and those who get a better access to cars through the sharing system, mainly for financial reasons. Accessibility to cars is positively correlated with vehicle mileage, and for this reason the former will reduce their mileage, while the latter will increase it. The net effect is estimated to be a reduction in average per person mileage from 42 to 50% (Baum and Pesch, 1994; Petersen, 1995). These examples tend to confirm that rebound effects are limited and that the use of the products or services is reduced, leading therefore to environmental gains.

Nevertheless, a reduction in the number of products or services purchased can lead to economic recession. The economic loss can be significant, especially when environmental gains are not considered to balance this loss. Kagawa et al. (2006) estimate that a one year lifespan extension for vehicles generates a 0.63% reduction in the 1995 Japanese GDP. However, refraining from buying a new car creates income gains for households, compared with the baseline scenario (no lifespan extension). Income gains can be either spent in service consumption, such as in repair of motor vehicles, amusements and health-care, or saved, which stimulates domestic fixed capital formation and polluting activities such as construction (Kagawa et al., 2006). In the first scenario, the net economic effect is positive and a shift from car purchases to service purchases compensates for the economic loss. In the second scenario, however, the GDP still declines. Incentives can be introduced to help consumers change their consumption patterns when they have income gains available due to efficiency or sufficiency strategies. Rebound effects caused by income gains may generate either more or less pollution-intensive growth compared with the baseline scenario. Kagawa et al. (2008) indicate that extending vehicle lifespan for one year still saves energy compared with the baseline scenario, despite the expected rebound effects. Nansai et al. (2007) review various commodities whose final demand is adjustable by households and conclude that reducing the consumption of most commodities engenders environmental gains higher than the forgone economic gains. However, increasing the consumption of a few other commodities would generate higher economic gains than environmental damages. These commodities are usually services with low environmental burden, such as education, financial service and insurance, real estate rental service, house rental, information services, and business and public services.

0.4.3 The FE applied to mobility: implementation and potential

In practice, the FE applied to mobility takes the form of shared use of vehicles. The potential environmental gains from shared use of vehicles are theoretically large since the transportation system is relatively inert and influences the land use system. However, studies reveal that very few vehicle users would be willing to shift from vehicle ownership to vehicle use in the near future.

Two systems of shared vehicles

A function-based transportation system is a transportation system based on the function mobility. The organization of such a transportation system ensures mobility within a given area. In practice, there is no transportation system that is entirely function-based, but only parts of. Applied to the transportation sector, the FE is often implemented through the pooling of vehicles. Indeed, vehicles are costly and bulky, and they remain parked most of the time, which favors a shared use of vehicles. The shared use of vehicles can take two forms, sequential use and simultaneous use of vehicles, and results therefore in two different systems of shared vehicles.

First, the use of a vehicle can be shared sequentially, as in self-service systems. It generally refers to a fleet of vehicles shared sequentially by users. They are usually available in self-service. Vehicles are either bicycles (bike-sharing schemes) or cars. Vehicles are usually provided by a private company, a public authority or a combination of both (public-private partnership). Vehicles are available in several sites of a territory, usually a urban area, and can be rented by a user for a limited period. Bike-sharing schemes are the most popular system and many cities throughout the world have one. The conditions of the service provided differ according to the cities, countries or system's providers. The concept of bike-sharing dates back to the 1960s in Amsterdam (DeMaio, 2009). In France, the first large-scale bike-sharing system has been launched in Lyon in 2005, and two years later a larger one has been introduced in Paris. Let us note that some vehicles shared sequentially are provided by private users to be used within a neighborhood. In this case, the private coordination costs are higher than when the system is provided by a third party.

Second, the use of a vehicle can be shared simultaneously, as in car-sharing systems. It generally refers to a single vehicle shared simultaneously by several users. Vehicles usually belong to private owners who offer a sit in their car against payment. The driver publishes her offer on a dedicated website which acts as an intermediary between drivers and passengers, and which sometimes even delivers payments from passengers to drivers. There are various such websites and a challenge would be to gather them in a unique exchange platform to ensure a better coordination between drivers and passengers. In a less formal way, these services may be organized more regularly within the neighborhood or among colleagues. Sharing vehicles is especially popular in German-speaking countries, such as Germany, Austria and part of Switzerland, but it has been spreading in a recent period in the OECD countries. In all cases, the development of information technologies has helped coordinate users and has enabled the provision of automated mobility services.

Large but beyond reach potential environmental gains

A main issue related to transportation is the relative inertia of this sector. Infrastructures have long lifespan and influence mobility patterns and the level of polluting emissions over decades. This feature can be both a drawback and a potential. The inertia of infrastructures impedes rapid changes in mobility patterns and maintains high-carbon mobility patterns in the future. In addition, transportation infrastructures and mobility patterns are embedded in urban organization and changes may only develop slowly. However, new and low-carbon infrastructures or policies convey a huge potential of energy savings and reduction in polluting emissions for decades. The NegaWatt scenario estimates that the potential for energy savings amounts to 67% for the transportation sector.

Moreover, transportation infrastructures are of structural importance and durably influence residential patterns. Transportation networks play a key role in urban economics, in particular by impacting both the households and firms localization, as well as the density of urban areas, which therefore impacts soil artificialization and the average housing floor area. Large floor area and low densities generate higher levels of polluting emissions from heating and mobility. People living in outer suburbs commute more by cars (Cervero and Landis, 1992; Schwanen et al., 2001; Cervero and Wu, 1998) and drive both longer times and distances (see Ewing (1997) for the US and Naess (2006) for the Copenhagen region), which influences the energy consumption (Newman and Kenworthy, 1989). Housing contributes for 40% of the final energy consumption in France, while the share amounts to 30% for transportation. Together, the housing and transportation sectors require more than two thirds of the total energy consumption. In a move towards reduced polluting emissions, mobility patterns play a critical role since they influence both transportation and land use systems.

The inertia of transportation infrastructures and their influence on residential behavior indicate a significant potential in the reduction of environmental load. Introducing a function-based transportation system such as vehicle sharing or self-service vehicles constitutes a step towards more environmentally sustainable cities. Nevertheless, the shift from car-ownership to car-sharing involves significant changes in user behaviors and depends on various parameters. Prettenthaler and Steininger (1999) explore the potential for car-sharing in Austria, one of the countries where car-sharing is the more widespread. Their findings reveal that the potential depends not only on technical features, but also on the perception users have of cars and of the service they provide. When mileage is considered to be the only service provided, 69% of households would get financial benefits after shifting to car-sharing. But this potential decreases if other services are added cumulatively to the user's perception, such as car availability (22% potential) and prestige (9% potential). Prettenthaler and Steininger's survey also indicates that the immediate attainable potential is as low as 1.5% of households. In addition, Huwer (2004) notes that car-sharing is mostly used on week-ends and vacation days for leisure activities, and therefore not frequently for commuting trips, which are yet of structural importance. Changing household consumption patterns is crucial to achieve sustainable development (Kok et al., 2006). Tukker et al. (2008) admit that the government must set appropriate incentives to encourage change, in particular in order that prices reflect the environmental costs associated with goods and services.

Let us assume that a shift from car-ownership to car-sharing leads to a 50% reduction in the kilometers traveled, roughly equivalent to a 50% reduction in polluting emissions - a strong but illustrative assumption. We also know that around

60% of NO_X emissions arise from transportation. If the whole transportation system becomes function-based (fictional assumption), a 30% reduction in NO_X emissions is to be expected (without taking into account the potential reduction in NO_X emissions from lifespan extension). However, when the immediate 1.5% potential of shift is considered, the reduction in NO_X emissions turns to 0.5%, which would probably have a negligible impact on the human health.

When considering the economic impact of a reduction in CO_2 emissions, let us assume that the average CO_2 emissions per commuter is 0.66 tons of CO_2, and that there are 22,584,611 workers in France (INSEE, 2009). 14,905,843 tons of CO_2 are therefore released by commuting trips each year. A 50% reduction in the volume of polluting emissions will save 7,452,922 tons of CO_2 when every commuter shifts from car-ownership to car-sharing, which is equivalent to more than 238 million Euros saved when assuming a shadow price of 32 Euros per ton of CO_2 (Quinet, 2008). However, when the immediate 1.5% potential of shift is considered, the volume of CO_2 emissions saved turns to 223,588 tons, which is equivalent to slightly more than 7 million Euros saved. These simple illustrations give insights into the economic impacts of the potential reduction in polluting emissions from the shift towards a function-based transportation system.

0.4.4 Which impacts of shared use on mobility issues?

From an environmental perspective, pooling is especially interesting when products have high material or energy content, such as cars. Shared use leads to higher use rates of the goods. On the one hand, cars shared simultaneously allow for a reduction in the number of vehicles, therefore saving resources and avoiding polluting emissions. On the other hand, self-service cars are most often electric cars which do not release CO_2 or NO_X emissions and which cut down PM emissions. Moreover and compared to private vehicles, vehicles shared sequentially allow to maximize the use rate of existing vehicles before more efficient ones are launched in the market.

Compared with private vehicles, shared vehicles allow not only for environmental benefits, but also for enhanced accessibility through reduced spatial concerns. However, the spatial challenges related to urban mobility have not been addressed in this literature. Although they are intertwined, the spatial and environmental concerns related to mobility have been mainly addressed separately. It is interesting to highlight the spatial impacts of shared transportation modes and to reveal how a function-based transportation system, and in particular shared vehicles, allows addressing jointly both spatial and environmental issues related to mobility.

Shared use allows reducing the total number of vehicles on the road in a particular area. More precisely, car-sharing mostly helps reduce both traffic congestion and rivalry of use for parking through higher vehicle occupancy rates. Fewer vehicles are needed to move the same number of users, and therefore fewer vehicles require to park. On the other hand, self-service schemes primarily help reduce rivalry of use for parking spaces. Due to higher use rates, pooled vehicles are parked for a shorter time. Consequently, vehicle-sharing systems mostly help reduce road congestion, while self-service schemes predominantly help reduce rivalry of use for parking spaces.

0.5 Structure of the thesis

In this thesis, we try to go beyond the traditional compartmentalized approach of environmental and spatial issues related to mobility. For this purpose, we explore these challenges using the concept of FE. We reveal that the specific features of the concept, and namely sharing the uses, allow theoretically addressing jointly traffic congestion and rivalry of use for parking spaces, but also air pollution. However, in practice, the potential of shift from vehicle-ownership to vehicle-sharing is extremely low.

There are four independent essays in this thesis. After a short presentation of the concept of FE and its application to urban passenger transportation (essay 1), we examine the role of sharing the uses in addressing spatial and environmental issues (essay 2). Then, we highlight the mechanisms underlying the rivalry of use affecting parking (essay 3), as well as the impact of local air pollution on labor productivity (essay 4).

0.5.1 Essay 1 – Function-based transportation systems: Features, limits and drivers of change

The 1^{st} essay investigates the concept of FE, both theoretically and through its implementation in the field of urban passenger transportation. This article highlights both economic and ecological potentials of function-based transportation systems, and analyzes the conditions required to implement such an economic and organizational model.

First, we propose an overall perspective of the concept of FE relative to the so-called "standard" economy and to the service economy, as well as an analysis of the features specific to this organizational model. The FE is at the crossroad between a product-oriented and a service-oriented economy. Contrary to the linear aspect of the "standard" product-oriented economy, the FE implies a double-loop process which allows extending the lifespan of resources involved in the manufacturing process, and of the final product itself. Then, we propose a clear conceptual distinction between the FE and the service economy. Consumers or users of function-based products or services are active in their consumption, and service providers are also involved in the manufacturing process.

Features peculiar to a FE or to its setting-up are the internalization of costs and, sometimes but not necessarily, the pooling of goods. A full cost approach is made possible due to the internalization of costs throughout the product lifecycle, what fosters firms to organize both maintenance and end-of-life management (recycling) of goods. Moreover, the FE might in practice take the form of shared use of goods. These features allow for environmental gains compared with the standard product-oriented or service-oriented economy. However, several barriers may impede the introduction of function-based models, in particular general barriers as regards both the user and the service supplier sides, or specific barriers such as the rebound effect. Nevertheless, the literature indicates that rebound effects in the transportation sector do not totally negate the expected environmental gains.

Finally, the potential drivers of a transition towards a function-based transportation system are presented. Barriers can be overcome with specific tools (e.g., Life Cycle Assessment (LCA)) evidencing the economic rationality. For this purpose, the State disposes of economic and regulatory tools in order to guide households and firms towards an overall cost approach. Public bodies play a key role in the transition towards a FE. Besides, adopting a systems approach to mobility constitutes an absolute prerequisite for a successful function-based urban passenger transportation system.

0.5.2 Essay 2 – Spatial and environmental issues revisited: Which role for shared transportation modes?

The 2^{nd} essay focuses on the role of sharing the uses (shared transportation modes) in addressing spatial and environmental challenges. The analysis provides guidelines for decision-makers.

First, we explore the mechanisms through which shared modes help reduce road congestion and rivalry of use for parking spaces, as well as air pollution, compared to private modes. On the first hand, simultaneous collective consumption, such as car-sharing, allows saving per car user space both for traffic and parking. This leads to reduced congestion and rivalry of use for parking spaces. On the other hand, sequential collective consumption, such as self-service vehicles, allows saving per vehicle user space for parking spaces. This leads to reduced rivalry of use for parking spaces. A function-based transportation system implementing a combination of these two kinds of collective consumption would therefore affect congestion issues and to a larger extent rivalry of use for parking spaces. In addition, both types of collective consumption help reduce air pollution.

Second, we take existing typologies as a basis and we call into question the interest of considering the functional sphere. However, existing typologies related to FE remain imprecise when considering specific functions. The analysis indicates that a function-based approach allows prioritizing differently the elements of FE that constitute a systems approach. A systems approach is regarded as the highest degree of integration of the FE with its environment. More specifically, we show that when considering the function mobility, shared modes are a key element in implementing a systems approach for mobility. Due to crucial spatial interactions between commuters (traffic congestion and rivalry of use for parking spaces), the satisfaction of individual needs impacts that of collective needs.

Third, we explore the impact of shared modes from the FE (car-sharing and self-service vehicles) on space consumption issues. We highlight the fact that transportation modes do not provide similar services to users. Therefore, gross comparisons in terms of time-space consumptions between modes are oversimplifying. We suggest to put these gross estimations into perspective accounting for additional services provided by transportation modes. Refined measures of time-space consumptions are presented. When the service provided is accounted for, the gap between mass transit and private cars is reduced. More importantly, the results show that shared modes are intermediary transportation modes, between private modes and public transit, both in terms of space consumption and service provided.

Finally, the limits of the present organization for shared modes are mentioned. More precisely, the need for institutionalizing is highlighted for car-sharing, and network expansion required for self-service vehicles.

0.5.3 Essay 3 – How space allocation matters: The role of parking spaces

Using the concept of FE allows us to explore the spatial challenges associated with mobility. Sharing the uses simultaneously or sequentially – a key feature of function-based transportation systems – leads to fewer vehicles on the road, which reduces the consumption of space for mobility purposes. Yet, the consumption of space for settlement and traffic facilities follows an increasing trend, and generates costs for the society. Mobility purposes require space for traffic, and even more for parking.

Space has rarely been integrated in economic models as an influencing factor, and even less as a resource. Urban economics usually takes up spatial challenges linked with transportation, without considering the absolute scarcity of space. Yet public space dedicated to urban parking has the features of a non-renewable resource in open access. It is thus consistent to examine space within the field of environmental economics.

The 3^{rd} essay highlights the importance of considering space as a limited resource in open access, and emphasizes the existence of rivalry of use affecting parking spaces in densely built-up urban areas. We explore the mechanisms underpinning the allocation of parking space among agents. More precisely, we develop a theoretical model of space allocation among agents which allows identifying and explaining rivalry of use, and which reveals the shadow cost associated with the spatial constraint. The shadow cost indicates how much it costs agents to be bounded in their parking space consumption. External costs from space consumption are exacerbated by allocation conflicts among agents that may in some cases result in welfare losses. We draw several allocation scenarios (simultaneous allocation, sequential allocation with and without public intervention), and identify various cases (whether space is valued by agents or not, whether they are constrained in their space consumption).

The findings indicate that when space is valued by agents, a sequential allocation of the resource "penalizes" the "followers" and leads to social welfare losses. Consequently, there are pressures towards more parking spaces, which can induce soil artificialization. The intervention of public authorities is then considered to regulate the allocation of this scarce resource in open access and to curb the rivalry of use affecting it. Public authorities have tools to optimize the allocation of public space among agents. We refer here to public space by virtue of the legal status. The results found are in line with the literature on non-renewable resources and on open access resources.

Being aware of the importance of space for achieving vital economic activities and of the welfare losses generated by the rivalry of use affecting the allocation among agents of space dedicated to mobility, and in particular to parking, we now best understand the need to model the space allocation process and to study the role of public authority.

0.5.4 Essay 4 – Correcting agglomeration economies: How air pollution matters

Besides, using the concept of FE allows us to explore the environmental challenges associated with mobility. Accounting for environmental impacts – a key feature of the FE – may result in extended lifespan of products, as well as in increased use rates of products and services, which leads to reduced polluting emissions. Air pollution is a major concern related to mobility, especially in urban areas where it affects many people. Yet, air pollution impacts negatively not only the environment, but also the human health and labor productivity.

The economic development of regions requires the creation and improvement of transportation infrastructures and policies. The main question of the 4^{th} essay can be summed up by Figure 6. It is widely admitted that new transportation infrastructures or policies enhance accessibility, but the net effect on productivity remains unpredictable when considering also the impact of air pollution. On the one hand, employment is especially favored through enhanced accessibility at the employment area level. Improved accessibility encourages households and firms to locate within the area, and it enlarges the concentration of activities from which agglomeration economies arise, therefore leading to increased productivity. The main idea is that when employment density increases, the productivity of the zone increases. This angle is generally addressed in studies on agglomeration economies. On the other hand, a better accessibility generates more trips and/or longer vehicle mileage, therefore increasing the level of air pollution. As air pollution affects negatively the human health, the productivity is expected to decrease. This angle has however not been treated yet in studies on agglomeration economies, but rather dealt with by epidemiological studies. This essay highlights the importance of accounting for pollution effects when estimating agglomeration economies.

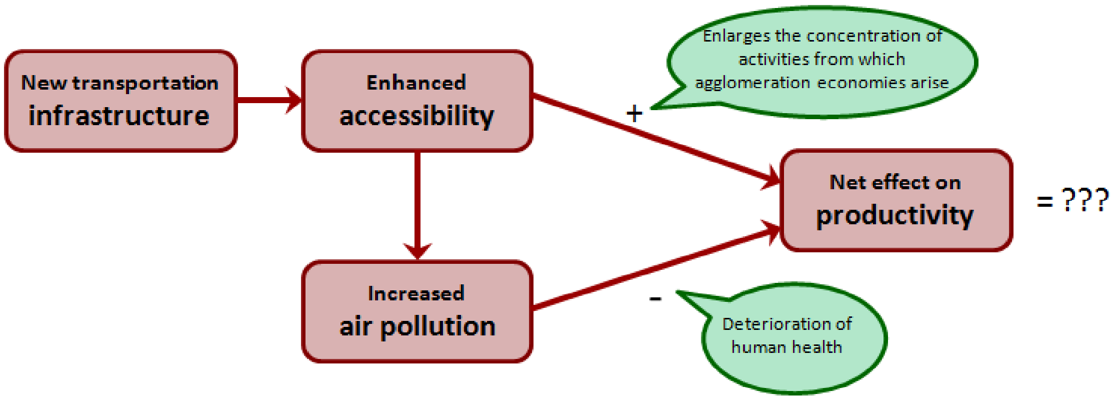


Figure 6: Ambiguous effect of accessibility on productivity

The 4^{th} essay focuses on the effects of NO_X – a local air pollutant released mainly by transportation – on workers' productivity. Indeed, the level of NO_X emissions in an area will be directly impacted by the introduction of a new transportation infrastructure or policy. For this purpose, we consider local air pollution as a determinant of labor productivity and integrate it in the theoretical framework estimating agglomeration economies in order to assess the extent to which pollution limits the full efficiency of production capacities. We conclude that accounting for air pollution (NO_X) in the econometric model of agglomeration economies allows "correcting" the effect of density on productivity. The positive effect of improved accessibility is diminished by the negative effect of air pollution. The economic gains expected from the introduction of a new transportation infrastructure or policy are usually overestimated by more than 13% when NO_X emissions are not taken into account.

This striking result puts into perspective the introduction of some transportation infrastructures or policies, in particular the most polluting ones, based on private road transportation. Strategies supporting mobility should include polluting emissions mitigation and resource use reduction in order to ensure the maximum expected agglomeration gains stemming from the introduction of a new transportation infrastructure or policy. For instance, shared modes constitute a concrete strategy promoting accessibility while limiting the environmental load from mobility. Indeed, introducing new transportation infrastructures and policies improves the accessibility of an area, which enlarges the positive externalities (agglomeration economies) stemming from increased density, but which also generates additional pollution due to induced trips. Yet pollution limits the full efficiency of production capacities.

Therefore, this Ph.D. thesis allows putting into perspective transportation infrastructure projects or new transportation policies through a two-angle analysis of the issues associated with mobility. This study considers both environmental and spatial challenges associated with mobility, using the concept of FE. Function-based transportation systems, and namely sharing the uses, allow analyzing transportation policies from both a spatial and environmental perspective.

Essay 1

Function-based transportation systems: Features, limits and drivers of change

1.1 Introduction

The functional economy (FE) consists in selling a use function instead of a product. Implementing such an economic and organizational system would represent a socio-ecological transition towards sustainable development.

The FE is often discussed in management sciences, with a focus on the possible enhancement of firm competition, organizational changes, and repercussions on the offer and demand sides. Other authors (Bourg, 2003) adopt a political-philosophical approach of the concept, and discuss the organization principles of society while emphasizing necessary changes in values. In this article, we expose the general features of a FE and apply them to transportation issues. This paper highlights the implications of function-based transportation systems, both from an economic and ecological point of view. We investigate the mechanisms through which function-based systems help address both environmental and spatial issues related to transportation, namely air pollution, depletion of natural resources, road congestion and rivalry of use for parking spaces. Function-based transportation systems such as vehicle-sharing systems entail shared use of vehicles, which reduces the number of vehicles in the economy, therefore curtailing pollution from manufacturing phase and both congestion and rivalry of use, and consequently air pollution from the use phase of vehicles. This article analyzes the limits to the spreading of the FE, and explores the drivers of change for function-based transportation systems. More precisely, we highlight the role the State and local transportation authorities play in a systems approach for mobility in urban areas. The original contribution of this article is to explore environmental and spatial issues related to mobility using the concept of FE and to analyze potential drivers of change for comprehensive function-based transportation systems.

The starting point is based on the observation that transportation is a key sector regarding sustainable development and that negative externalities are especially felt in urban areas. Every economic sector (manufacturing industries, residential, agriculture, etc.) follows a decreasing trend in terms of greenhouse gas (GHG) emissions, except the transportation sector. In France, it is the leading sector in terms of GHG emissions, especially carbon dioxide (CO_2), with road transportation accounting for the larger share of emissions (89% in OECD countries) (IEA, 2011). In OECD countries, transportation accounts for 27.5% of total pollution (IEA, 2011). Furthermore, transportation is also the leading sector in terms of energy resource consumption, in particular oil resources, with 80% of resources attributed to road transportation. In addition, materials required for infrastructure building contribute to the depletion of various non renewable resources, as well as abiotic resources (water, soil).

Examples from the literature, in particular the case studies of Michelin and bicycle sharing systems (BSS), support our demonstration. In the tire industry devoted to road freight, Michelin provides since 2002 an integrated service offering: *Michelin Fleet Solution*. The French firm offers road haulers tire management. Tires are a strategic component for fuel consumption [12]. In the urban passenger transportation sector, BSS are the most widespread function-based transportation systems. BSS

12. Tires under-inflated by 10% wear out faster and lead to a 1% increase in fuel consumption.

provide a public access, whether free or not, to bicycles located throughout the city. In 2007, Paris, France, launches its own BSS, Vélib'. With a fleet of 23,000 bicycles and 1,700 stations about every 300 meters in the city-center and inner suburbs, Vélib' is the largest BSS in Europe.

The article is organized as follows. Section 1.2 describes the features of a FE, namely features that distinguish it from the standard economy or the service economy. Section 1.3 examines the mechanisms through which function-based transportation systems help address major environmental and spatial issues, namely depletion of natural resources and climate change, as well as conflicts of use in urban areas. After analyzing the barriers and limits to the FE in section 1.4, the last section highlights the drivers of change for function-based transportation systems, especially economic rationality, the role of the State, and the systems approach.

1.2 The functional economy: features and boundaries

In this section, we define the concept of FE and highlight distinguishing features to set the FE against first the standard economy, and second the service economy.

1.2.1 Emergence of an original economic and organizational model: the FE

In 1980, Giarini suggests to review the notion of economic value (Giarini, 1980), what results in the concept of FE developed by Walter R. Stahel and Orio Giarini from 1986. This concept is also named by Stahel "performance economy" in contrast with an economy based on production throughput [13], or "throughput-based

13. In the economic context, throughput refers to "the flow of raw materials and energy from the global ecosystem's sources of low entropy (mines, wells, fisheries, croplands) through the economy, and back to the global ecosystem's sinks for high entropy wastes (atmosphere, oceans, dumps)"

economy" (Daly, 1992; Ayres and Simonis, 1994). Giarini and Stahel conform to the thinkers of the Club of Rome, clearly aiming at dematerializing the economy in order to achieve sustainable economic paths.

The performance economy has first been developed within the energy sector, in response to the 1970s energy crisis. Energy Service Companies (ESCOs) deliver energy solutions so as to achieve energy savings for their customers. Steinberger et al. (2009) name this output a performance-based energy economy. Economic actors first focused on energy optimization before taking into account materials. At the beginning of the 2000s, the FE has been applied to other economic sectors, and in particular to transportation.

The FE consists in selling a use function – a solution, seen as a combination of products, services and directions for use – instead of a product. Material goods are considered to be mere instruments providing functions (commuting, communicating).

1.2.2 Functional economy and the standard economic model

Following Daly (1992), Walter Stahel (1998) considers the standard economy tantamount to a linear economy symbolized by a river ("river economy") and conveying the idea of flow. Extracted virgin resources constitute the base of product manufacturing. Products are then sold and finally turned into waste after their use. In short, virgin resources rapidly become non-recoverable waste. In such a system, producers take only into account the production process, without further consideration for the use phase and the possible environmental costs and impacts induced. The end-of-life of products does not either fall under the responsibility of producers.

Today's economy is grounded on the existence of ownership rights. In this model, welfare is closely linked to economic growth and thus to the increase in production.

(Daly and Farley, 2003).

An implicit connection exists between material possessions and welfare (Gaglio, 2008). In several industries such as the mobile phone industry and the information technology sector, there is an attempt to increase obsolescence. The so-called "planned obsolescence"[14] aims at an increased replacement rate of products, and consequently at increased sales of new products. Moreover, the industrial revolution and the prevailing economic model developed since are based on the substitution of machines and energy for manpower. Stahel criticizes the fact that 75% of the energy used to manufacture a product is actually allocated to raw material extraction. Only 7% of the materials used to manufacture a product can be found *in fine* in it, 99% of the materials embedded in the product turn into waste after six weeks, and 80% of finished goods give only rise to a single use (Allenby and Richard, 1994). These figures demonstrate the "materialization" of the standard economic system.

Contrary to the standard economic model described above, the FE is referred to as a double-loop economy (cf. Figure 1.1) symbolized by a lake ("lake economy") and conveying the idea of stock stability. The FE is characterized by cycles – a double loop – through which virgin resources go successively before turning into waste. The first loop refers to the extension of the product life span (repair, re-use, reconditioning, and technological upgrading) and the second loop corresponds to the recycling of end-of-life materials that are then reinserted into the production cycle in place of virgin resources. In such a system, producers take into account the use phase of the product, as well as the end-of-life of materials embedded in it; they control the life cycle in its entirety. Consequently, the FE is based on an overall cost approach, also called life cycle cost approach.

The FE aims at substituting manpower for energy and material resources. It also tends to "optimize the use (or function) of goods and services and thus the management of existing wealth (goods, knowledge, and nature)" (Stahel, 2006). The

14. Companies affect deliberately the lifespan of products. They may design products difficult to repair, or encourage consumers to acquire the latest innovations (Buclet, 2005).

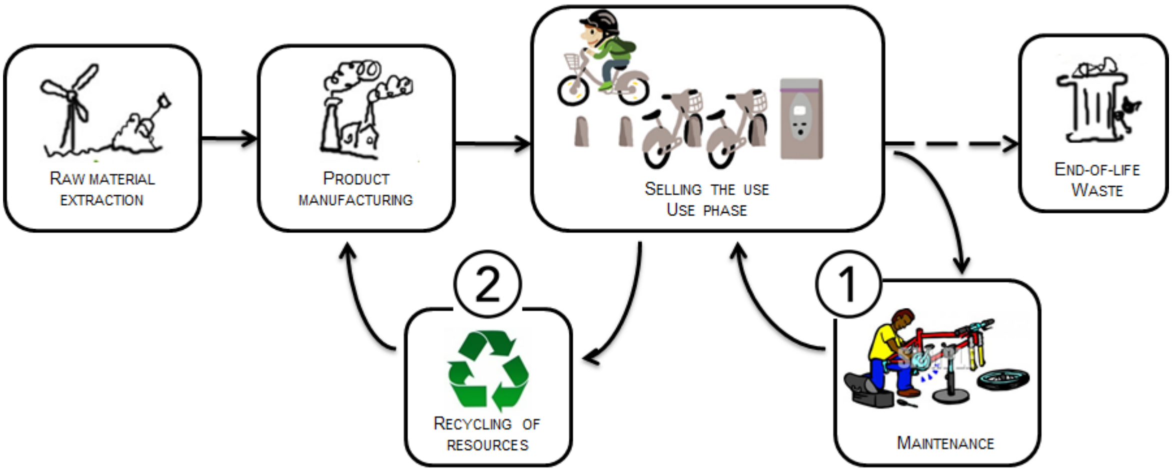


Figure 1.1: The FE as a double-loop economy
Source: adapted from Stahel and Reday-Mulvey (1981)

FE aims at an absolute decoupling between economic growth and flows of materials and energy (Stahel, 2006). Wealth creation is no longer based on the number of units (material goods) manufactured and then sold, but is now based only on the sales of the use of these units. The author states that "the economic objective of the FE is to create the highest possible use value for the longest possible time while consuming as few material resources and energy as possible" (Stahel, 2006). The economic value of goods and services is no longer based on their exchange value, but from now on on their use value[15]. The idea underlying the notion of use value is that the value consumers attach to a commodity lies in the advantages they get from its use, and not in the possession of the commodity in question, therefore challenging traditional ownership rights. This does not mean that ownership of goods disappears, but that ownership rights will be increasingly rarely traded on the market (Rifkin, 2000). Suppliers hold ownership rights, they rent or lease goods, levying access fees or use fees for any use, and possibly also a subscription. Thus, Michelin retains ownership of tires and sells solutions per kilometer traveled: billing depends on the distance traveled, i.e., on the intensity of use. The firm substitutes sales of "units of use"

15. The use value of transportation modes corresponds among other things to the trips enabled by vehicles.

(kilometers traveled) for sales of goods (tires) or services. Lindahl and Ölundh (2001) state that "functional sales" substitute for traditional sales of goods. Similarly, BSS generally offer the use of bicycles for 30 minutes. The "logic of access" (Rifkin, 2000) prevails over ownership rights. In this perspective, material goods (e.g., vehicles) are a means, an *instrument*, for achieving one or more purposes (destination, activity).

Just as markets within the standard economic model, the FE can take various structural forms. Any firm, whether state-owned or private, can operate an area of expertise in accordance with the principles of FE, as Michelin that developed *Michelin Fleet Solution*. The FE can also constitute the base economic and organizational model, as for Elis, now the European leader in rental and maintenance of textile and hygiene articles. Thus, markets within the FE can extend at European (e.g., Michelin, Elis) or world level, but can just as well remain geographically very small, like BSS whose market potential rarely extends beyond the city-center and inner suburbs. Nowadays, this economic and organizational model is still embryonic, and firms may end up as single supplier on the market for this kind of service. One can however expect an increased competition after the FE spreads. Moreover, private service suppliers (e.g., JCDecaux) can join public institutions (e.g., Paris City Hall) in public-private partnerships (as for Vélib'). This market structure enables public bodies to organize function-based public services without bearing the prohibitive initial investment costs. Finally, services are designed either for companies (e.g., Michelin and Elis) or directly for end users (e.g., BSS).

1.2.3 Functional economy and the service economy

The existing literature does not clearly position the FE in relation to the service economy. Giarini and Stahel (1989) define the service economy as an economy in which one does not buy *goods* but *systems* that work. The notion of "system" refers to a combination of products and services, just as the concept of FE. Service-based logic and function-based logic have features in common. Giarini and Stahel oppose a product-oriented economy to a service-oriented economy. Gadrey (2003) makes a distinction between service-oriented logic and product-oriented logic, while Gallouj and Weinstein (1997) adopts an integrative approach and mentions a convergence of goods and services, with both service industrialization and goods servitization. Just as the Service-Dominant logic developed by Vargo and Lusch (2004), Mont's (2002) Product-Service Systems or Lancaster's (1966) characteristics approach, the concept of FE goes beyond the traditional dichotomy between goods and services. The function-based logic suggests a hybrid model, a mix of both product-oriented and service-oriented logics. Besides, Du Tertre (2008) provides a typology in which he defines the FE with respect to the service-oriented model. According to him, the presence of territorial participation distinguishes the FE from the service economy.

Drawing on the hypothesis from the literature, we propose a clear conceptual distinction between service economy and FE. We assume that the FE provides consumers with the use of a product, as well as with related services, that enable them to *produce* their own service, while the service economy directly provides consumers with the service in question. In a FE, users play an active role, they are co-creators of value [16], while in a service economy they are rather passive and need middlemen to consume the service. Thus, the FE borrows from the standard model in that consumers use material goods to create their service, but also from the service-oriented logic since consumers buy only the use of a good, without owning it. In the transportation sector, the service economy offers trips on public transportation or taxi rides – passive users are driven from origin to destination. Conversely, the FE offers the use of BSS (combination of material goods and maintenance services) – active users drive to produce their trip. On the supply side, companies that base their economic model on principles of FE manufacture material goods and sell their use. Thus, Michelin and Vélib' are in charge of manufacturing tires and bicycles, and fix prices depending on the intensity of use. Conversely in the standard eco-

16. As in the *Service-Dominant logic* (Vargo and Lusch, 2004).

nomic model, companies that manufacture goods sell them directly to end users or to rental companies (e.g., Avis rents cars). The latter fixes also prices depending on the intensity of use, but offers rental of the good without manufacturing them. The system is then hybrid but not integrated, which might hinder the ability to take into account the entire product life cycle, and therefore the achievement of environmental objectives, one of the bases of the FE.

Using common examples, Table 1.1 makes a distinction between the three organizational logics developed in the above subsections.

Table 1.1: Defining the FE

Product-oriented logic		Service-oriented logic
Standard economy	Functional economy	Service economy
Purchase of material goods	**Purchase of use functions (combination products + services + advice)**	**Purchase of services**
Purchase of a washing machine	Purchase of a washing machine's use function (e.g., washing) in a launderette	Purchase of laundry services in the dry-cleaners
Purchase of a drill	Purchase of the use of a drill (e.g., for one day)	Purchase of handyman services from a specialized company
Purchase of a vehicle	Purchase of the use of a vehicle (e.g., for 30 min)	Purchase of transportation services from a public transit or taxi company

Drawing on the conceptual distinctions between the FE and other economic and organizational models, we examine in the following section how the features peculiar to a FE or to its setting-up, notably the internalization of costs and pooling of goods, help address major environmental and spatial issues.

1.3 The FE: a response to environmental and spatial issues

The FE reflects a dematerialization strategy, i.e., a reduction in the volume of materials used (inputs) to meet the needs of individuals (output). The intended objective is not only a relative reduction in resource use, i.e., a reduction in resource inputs per product, but also an absolute reduction thus requiring a decrease in the number of goods manufactured. A FE maintains stock (e.g., bicycle fleet management) while optimizing flows (resource use). Tukker and Tischner (2006) estimate a reduction by a factor 2 of materials consumed by selling uses instead of goods. The FE helps slow down resource depletion (materials and energy) and reduce emissions of pollutants through the internalization of costs that favors both maintenance and recycling, as well as through the pooling of goods. Furthermore, pooled vehicles lead to reduced land competition and conflicts of use related to mobility in urban areas.

1.3.1 Internalization of costs: maintenance and recycling

Implementing a function-based approach entails a long-term vision and the internalization of both costs and liabilities. The "Life-Cycle Assessment" (LCA), a method to assess environmental impacts throughout the life cycle, leads to optimized consumption of materials and energy. Firms then consider overall costs, and internalize use costs as well as waste disposal costs in addition to manufacturing costs. Internalizing use costs encourages designing low use cost products that consume less energy, therefore leading to reduced negative environmental impacts compared to traditional business models.

In a FE, producers have an interest in caring for regular maintenance of their products. Indeed, proper maintenance extends the product lifespan and postpones end-of-life management and related waste disposal costs. Maintenance can take the form of repair, re-use of parts, or technological upgrading. A longer product lifespan proves particularly interesting when the manufacturing phase generates more environmental impacts than the use phase, as for bicycles. Contrary to cars, bicycles do not directly release pollutants during their use phase, but require materials and energy when manufactured – according to Shreya Dave from MIT, a bicycle releases on average 240 kg of GHG during manufacturing phase [17]. Energy embedded in the manufacturing phase is called "grey energy". Technicians repair broken Vélib' shared bicycles either on site or in the workshop. Parts of Vélib' bicycles are identical and designed to be easily dismantled, so that they can be used as spare parts. However, repair and maintenance activities described by Stahel in the double loop graph are usually missing in car-sharing systems (Meijkamp, 2000), therefore limiting product durability.

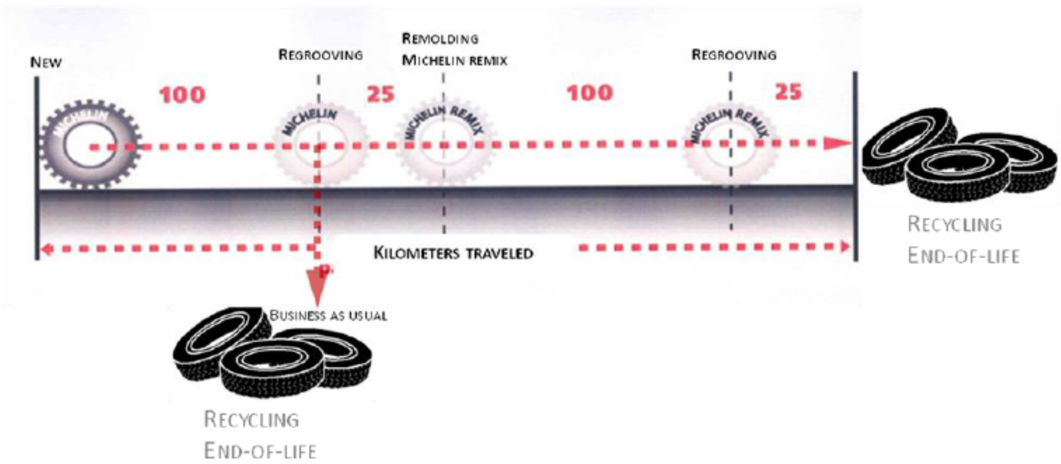


Figure 1.2: The four lives of Michelin tires
Source: adapted from Michelin (2011)

Figure 1.2 reveals that Michelin tire maintenance (inflating, remolding, regular regrooving) makes tires last 2.5 times longer while saving 70 to 75% of raw materials.

17. By way of comparison, 5,500 kg of CO_2 are released to manufacture a one-ton car, and 54 tons of materials are required (IMEDD, 2011).

Waste quantities have been lowered by 36%, and fewer tires are required to provide the same service (20 instead of 64). In addition, professionalizing maintenance drives down flows associated with the use phase (fuel consumption, emissions), in particular when impacts result primarily from the use phase. Tires and cars are examples of goods that generate more impacts during the use phase: White et al. (1999) reveal that cars can consume up to ten times more energy during their use phase than during their manufacturing phase. A study carried out for the *Grenelle de l'environnement* (2008) in France systematically highlights a decrease in material and energy flows during the use phase for function-based experiences.

Furthermore, the circular economy reuses materials and recovers waste, i.e., exploits existing goods as main resources, therefore slowing down resource depletion and limiting waste. Function-based systems usually adopt products designed to optimize their end-of-life recycling. Nevertheless due to the entropic degradation, materials cannot be recycled *ad infinitum*.

1.3.2 Pooling of goods

The FE might in practice take the form of shared use of goods, in particular when goods are barely used by a single individual and when they are bulky. From an environmental perspective, pooling is especially interesting when products have high material or energy content. In urban areas, private passenger vehicles are generally sub-optimally used for mobility functions [18] and could then be pooled in a BSS or car-sharing system. Shared use leads to higher use rates of each one of the goods available. Cabanne (2009) estimates that a shared bicycle in Lyon, France, performs on average five trips a day. In Paris, a Vélib' bicycle operates five to seven trips a day. Therefore, shared bicycles show far higher use rates than private bicycles. Besides, Meijkamp (2000) analyzes empirically car-sharing systems and reports a

18. Household travel surveys carried out in France (CERTU, 2004) reveal that cars stay parked on average 96% of the time, i.e., unused for mobility.

44% reduction in the number of cars used by car-sharing members. However, pooling of goods does not constitute a necessary condition for implementing a function-based system. Indeed, Michelin's tires are not pooled.

Reduced environmental impacts from function-based systems mainly result from a decrease in the number of units manufactured. Dematerialization is made possible by higher use rates of each of the goods available, especially due to maintenance and shared use. Both higher use rates and recycling slow down resource flows in the economy (Scott, 2009) – thus reducing the throughput. This helps curb depletion of natural resources as well as emissions generated by raw material extraction and manufacturing, but also by the use phase of products.

Furthermore as regards mobility, modal shift impacts environmental externalities – this is especially true when a BSS is introduced. Cabanne (2009) estimates that 10% of BSS users would have traveled by car before introduction of the system. Assuming a BSS with a fleet of 23,000 bicycles such as in Paris, 5 trips a day per bicycle, 2 km trips and an average emission rate of 0.066 kg of carbon equivalent per km traveled by private car [19], the emission reduction obtained amounts to more than 5,578 tons of carbon equivalent after introducing a BSS. Given that environmental externalities are valued 5 Euro cents per km traveled by car in urban areas (local pollution, noise, GHG), and given the shadow value of carbon defined in Quinet (2008), the expected environmental benefit resulting from a BSS amounts to nearly 1.4M€ per year.

1.3.3 Spatial issues: road congestion and conflicts of use for parking spaces

Goods in general and private vehicles in particular require space, in a strictly physical sense. Land required by the transportation network has an economic oppor-

19. We account for differences in emission rates for diesel cars and gasoline engines, as well as for their share in the French vehicle fleet.

tunity cost, but also a social cost. Space is a limited and potentially scarce resource, especially in densely built-up urban centers. Land use competition drives land prices up and encourages excessive urban sprawl. Moreover, rivalry of use occurs in urban areas: the same space may be coveted by several uses or by several individuals for similar purposes. Conflicts of use are common in urban transportation, in particular traffic congestion and rivalry of use for parking spaces at peak times. Shared use allows for a reduction in the total number of goods (e.g., vehicles) in the economy, and thus on a particular geographical area, for instance in a city. The FE itself does not directly help to limit spatial competition and conflicts of use, but the way it can be implemented, namely pooling of resources, does. Consequently, a transportation system with pooled vehicles, such as car-sharing systems or BSS, would contribute to optimize the space required by transportation functions in urban areas, thus addressing spatial issues, namely land use competition and the resulting rivalry of use.

Therefore, a function-based transportation system reveals significant potentials in reducing material and energy flows in the economy, as well as in addressing spatial issues in urban areas. Still, general barriers and specific limits can hinder the introduction of function-based systems or reduce the expected environmental benefits.

1.4 Barriers and limits to the FE

This section aims at exposing the general barriers to the introduction of function-based models, as well as specific limits, namely regarding innovation and possible rebound effects. These limits are put into perspective for the transportation sector.

1.4.1 General barriers

The introduction of activities or sectors applying the functional logic may experience a number of barriers, at both macro and microeconomic levels, as well as on the supply side and demand side. One of the main obstacles pointed out in the literature about FE is resistance to change from market players (firms, users, institutions).

On the demand side, i.e., as regards users, psychological barriers might be expected. The loss of ownership rights may seriously hinder users' support towards the system, since in western societies personal fulfillment is partly achieved through product ownership, regarded as a way of expressing social status or personality. Cars are often considered as conveying social status (Belk, 1986). Similarly, users' need of differentiation may be hampered by non customized pooled goods. In addition, possible degradations or dirtiness resulting from shared use may cause inconveniences. Users might no longer feel accountable for the pooled goods they rent, when there is no particular incentive to care for goods they do not own. This would explain the faster degradation of pooled goods. Moreover, reservation conflicts are likely to arise in case of shared goods (HEC, 2008). We can also highlight a risk of heteronomy, i.e., reduced autonomy of users, due to external management of goods, in particular maintenance. The latter can be considered either as a constraint pertaining to ownership or as an individual know-how. For instance, most cyclists can fix a flat tire, and motorists regularly check the tire pressure of their vehicle.

On the offer side, i.e., as regards service suppliers, there is concern about organizational complexity (*Grenelle de l'environnement*, 2008), in particular due to more complex contracts. In addition, function-based systems usually require heavy initial investments, for instance to acquire the vehicle fleet. This may act as a barrier to entry, mainly because investments are not immediately covered, since revenues from rentals are spread over a longer period of time. Nevertheless, this problem can be overcome by charging a subscription at the beginning of the period. Besides, in practice, function-based transportation systems necessitate a certain network density, in the geographical sense. In practical terms, pooled bicycles are to be found on every street corner, close to places for living, working, shopping and leisure. Indeed, people are used to dispose of their private vehicle at any time and might fear additional costs to access pooled vehicles, in particular when stations are located "too far" from the activity location, or in case of temporary unavailability of vehicles (e.g., empty stations) or of parking spaces (e.g., full stations).

Another major barrier to the FE is the expected destabilization in traditional markets, in particular the automobile industry, whose profits and organization are based on the sale of vehicles. Second-hand markets could be highly impacted (Contaldi, 2008). Indeed, vehicles offered in rental systems are maintained in like-new condition, while people predominantly purchase second-hand vehicles. However, the risk seems limited, since function-based systems still represent a niche in the transportation sector, and that the pooling potential first concerns urban areas only. However, firms begin to adapt to the organizational change. For instance, since 2010 Peugeot offers car rental services (function-based logic): "MU by Peugeot".

1.4.2 The FE: a disincentive to innovation?

Product sustainability would hinder innovation due to slower renewal of product ranges. Introducing the FE would therefore amount to give up technical progress. Nevertheless, innovation can lead to more sustainable products –a form of technical progress too. The concept of FE is seen "as a fabulous motor of innovation" (Steinberger et al., 2009) that accelerates the diffusion rate of the most efficient technologies through increased firms profit margins resulting from reduced resource use. The development of technological innovation constitutes however a cost for companies. Manufacturing costs may decrease due to material recycling (though not consistently); they may also increase due to high research and development costs induced ahead. Companies might face difficulties in covering their costs in the short run.

1.4.3 Would rebound effect negate environmental benefits?

Rebound effect – also called take-back effect – refers to the behavioral responses to the introduction of new technologies that increase the efficiency of resource use. More generally, an increase in consumption arises after the limits on the use of a technology have been lowered – those limits can be money or time limits, social or physical limits, limits linked to effort or risk, etc. (Schneider et al., 2001). An increase in consumption then tends to reduce or even negate the beneficial effects expected from a new technology.

Literature on rebound effect focuses on energy consumption, but the theory applies to any natural resource or input. Although consensus emerges on the existence of such rebound effects (Greening et al., 2000), the magnitude and importance of the effects still spark off debates. Direct rebound effect [20] in developed countries ranges from 5 to 40% [21] as regards energy (Greening et al., 2000; Small and Van Dender, 2005). On the contrary, rebound effect would be far more significant in developing and emerging countries, and often larger than 100% due to unmet demand (Roy, 2000). The magnitude of rebound effects depends mainly on the elasticity of demand for goods and services, along with the quantity of energy and resources incorporated in or associated with the goods or services in question. The transportation sector, particularly the automobile, has been particularly studied (Greene et al., 1999; Small and Van Dender, 2005), mainly after technological innovations improving fuel efficiency have been introduced. In this sector, the estimated direct

20. Direct rebound effect appears when improved energy efficiency of a particular energy service results in a decrease in the relative price of the service in question, and consequently leads to an increased consumption of this service. The substitution effect lies behind the direct rebound effect as elasticity of demand is generally negative.

21. This means that 5 to 40% of the potential energy savings expected after the introduction of a technological innovation is lost due to increased consumption.

rebound effect ranges between 10 and 30%, while the indirect rebound effect [22] seems more difficult to estimate and could amount up to 80% (Sorrell and Dimitropoulos, 2007).

In a FE, economic mechanisms can be introduced in order to limit rebound effects and ensure environmental objectives are achieved. A solution consists in maintaining the overall cost associated with the service. Technological upgrading often goes hand in hand with increased capital costs (higher price of equipment [23]), what offsets lower energy costs or lower user costs due to pooling, and reduces the magnitude of the rebound effect, provided consumers entirely bear the cost of equipment. In addition, the possible increase in intangible costs (value of time, costs associated with comfort) would offset the drop in monetary costs. Greater overall cost transparency for users can then be fostered.

To the limits analyzed above must be added possible ethical implications when applying the functional logic to non-produced capital, in particular living natural resources. In the following section, we investigate the drivers of change which could overcome obstacles and limits to the FE and then provide the appropriate conditions to introduce function-based transportation systems.

1.5 Drivers of change: conditions and potentials for a FE

In this section are presented the potential drivers of a transition towards a function-based transportation system.

22. Indirect rebound effect appears when the price of the energy service, relatively lower, induces changes in demand for other goods and services which also require energy during their use phase. The income effect lies behind the indirect rebound effect.

23. For instance, the hybrid car Toyota Prius is more expensive than traditional cars but generates lower fuel consumption per kilometer.

1.5.1 The FE, a rational economic organization

Paradoxically, firms do not implement the FE for sakes of environmental and social sustainability, but by pure economic rationality (Bourg and Buclet, 2005; Stahel, 2006). The LCA is a tool to optimize resource and energy use during the manufacturing process. It has the advantage of dealing with the function of a good or service [24] (e.g., commuting), rather than with the good or service itself (e.g., car or public transportation) – what is fully consistent with the functional logic. Rational strategies may involve seeking competitive advantages, modifying resource management, or creating new markets.

On the user side, pooling costly goods that are barely used (Hirschl et al., 2003) or bulky proves rational. Schrader (1999) reveals that young citizens show less interest in owning goods than in using them. Assuming that consumers first aim at meeting their needs rather than owning goods, then in a FE they buy mobility instead of cars (Popov and DeSimone, 1997; Friend, 1994). The trend depends on sectors and goods, as well as on functions associated with ownership of goods and benefits derived from ownership. As regards transportation, car rental would be all the more accepted as mobility is seen as a "derived" consumption (Orfeuil, 2008a), i.e., "an instrument used only to accomplish another purpose" (Sasaki and Nishii, 2010). Moving from car ownership to car rental or car sharing can be driven by the need to overcome constraints, namely the lack of space in urban areas combined with relatively high land costs. Moreover, the mobility function accounts for 15.3% of households budget in France and represents their second highest outlay (Orfeuil, 2008a). Under certain conditions and provided that the transportation network forms an integrated system, pooled vehicles could reduce monetary costs for mobility and emerge as a credible alternative to private vehicles. Overall costs could be made more transparent to inform users and help them make rational decisions.

24. The functional units, i.e., quantization of a function (e.g., to travel 1 km), make the comparison easier within the different goods and services.

The features exposed above reveal the potential for introducing function-based transportation systems, in particular in urban areas where nuisances and constraints are building-up and emphasize the need for a change in spatial and economic organization. The environmental potential of a FE is all the more significant in the transportation sector as it is the leading sector in terms of CO_2 emissions and oil resource consumption, and as it releases many other local pollutants harmful to the human health such as nitrogen oxides (NO_X) and fine particulates (PM).

1.5.2 The State, a key player

Traditionally, the State plays a key role in building transportation networks. It provides with major road and rail infrastructures, and subsidizes public transportation. In addition, it addresses market failures. In the literature about transportation, overlooked social costs induced by traffic congestion constitute the most widely mentioned market failure. Overlooked social costs resulting from space consumption, as well as the various environmental externalities associated with mobility, also represent market failures that on one side favor road transportation at the expense of rail transportation or cleaner modes (cycling), and on the other side foster private modes at the expense of shared ones. Other market failures from urban economy lead to excessive urban sprawl, and impact the way transportation networks are organized: Brueckner (2000) mentions the failure to account for the social value of open space when converted into urban uses, as well as the failure to account for the whole cost of public infrastructure development. These market failures represent a barrier to the introduction of an efficient, integrated and clean function-based transportation network.

The State can act as the driver of change as it disposes of both regulatory and economic tools (incentives) to address market failures and overcome barriers pertaining to the introduction of a FE. Regulatory and economic tools are complementary: the former are more effective in case of point source emissions, while the latter are applied preferentially to nonpoint source emissions such as passenger transportation in urban areas. Vehicle emission standards (EURO standards) have been introduced; they could be strengthened and enlarged in order to foster the less polluting modes. To encourage firms to move towards a FE, the government could give incentives for recycling and maintenance through more restrictive waste disposal pricing. In addition, the State could foster the pooling of private goods (discount on purchase, tax deduction) and organize the pooling in legal terms (institutional structure, contractual framework). The government has actively participated in the introduction of most BSS through public-private partnerships. As prices are set depending on the intensity of use, function-based transportation systems help users take into account costs associated with the use phase in a more transparent and systematic way. Environmental externalities generated by transportation can be monetized and incorporated in the use cost of services. However, households are less used to think in the long term or on the basis of overall costs than firms. Private individuals lack knowledge of real costs and may value non economic dimensions (e.g., symbolic or emotional values). For that reason, the FE has primarily occurred in B2B markets. Economic incentives could guide households towards greater consideration for overall costs, in particular use costs, in the long run. Therefore, public intervention has tools to assist the transition from the current economic model to a FE.

1.5.3 Towards a systems approach to mobility

Jaccard et al. (1997) show that the magnitude of energy savings achieved depends on the infrastructure lifespan, as well as on the "level" considered (cf. Figure 1.3). First, at the product level, environmental impacts can be easily and quickly reduced with the help of new technologies, mainly through vehicle improvement (lower fuel consumption, catalytic converters). These so-called end-of-pipe corrective measures aim at managing negative environmental externalities at the end of the process, generally using technical devices. This leads to individual management of impacts, mostly downstream and in a restorative way. This approach often proves efficient in the short run [25], but inadequate in a longer run. Then, at the intermediate level, manufacturing processes (e.g., recycling) and transportation modes (e.g., incentives for modal shift to cleaner modes) generate reduction in resource consumption. The literature however informs on the difficulties related to modal shift when the spatial organization of urban systems remains unchanged. Hence, changes occurring at the systems level give rise to larger energy savings in the long term. Regarding urban mobility, mixed land uses producing shorter trips, as well as the way the transportation network is organized, are key elements for an integrated, efficient and clean mobility. Introducing a function-based transportation system falls within the systemic level and reveals a high potential for ecological efficiency.

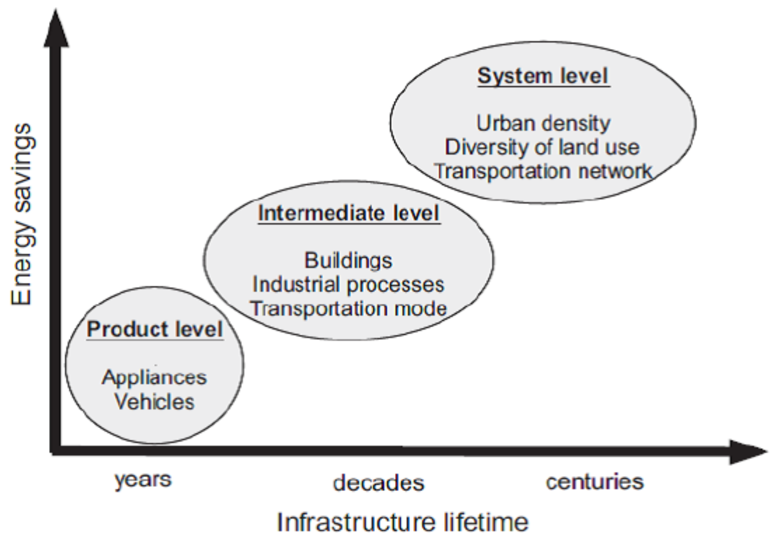


Figure 1.3: Relationship between energy savings and infrastructure lifetime
Source: Jaccard et al. (1997)

Function-based mobility services become economically – and ecologically – ra-

25. According to some authors (Bouf and Hensher, 2007; Orfeuil, 2008b), successive regulations for air pollution (EURO standards) and technological innovations has lowered air pollution in a much larger extent than traffic management (disincentives to cars in city centers) or urban planning. However, only the environmental impacts resulting from vehicle use are considered; emissions from the manufacturing phase are ignored.

tional only if the transportation network and the spatial organization constitute an integrated system. Developing adequate alternatives to private car ownership implies a more comprehensive urban policy integrating transportation and town planning. BSS and car-sharing systems are not meant to be the only passenger transportation modes in use in urban areas, but can complement the existing public transportation network. Boisier and Sabourin (2010) reveal that Vélib' constitutes an alternative to conventional transportation modes although not the main mode for users. Pooled vehicles produce cleaner multi-modal trips when they are used to join public transit stations located on the outskirts. Additional services could also be developed to address specific or occasional needs, such as long term car rental for family leisure trips (holidays, weekends), and on-demand transportation (parents with young children, elderly or disabled people). The interconnected mobility services would form an integrated system accessible to all users.

1.6 Concluding remarks

Objectives and features peculiar to the FE show the way towards sustainable development, in particular in the urban passenger transportation sector. Internalization of costs throughout the product life cycle fosters firms to organize both maintenance and end-of-life management (recycling) of goods. Optimizing the various phases of the product life cycle, and eventually pooling goods, in particular vehicles, contribute to cut down material and energy flows in the economy, therefore slowing down local air pollution, climate change and resource depletion. Introducing such an economic and organizational model may face barriers. The latter can however be overcome with specific tools (e.g., LCA) evidencing the economic rationality and the State disposes of economic and regulatory tools in order to guide households and firms towards an overall cost approach. Public bodies play a key role in the transition towards a FE. Besides, adopting a systems approach to mobility constitutes an absolute prerequisite for a successful function-based urban passenger transportation system. From the perspective of "sustainable cities", several authors (including Bertolini et al., 2005) emphasize the need for comprehensive land use planning policies integrated with transportation policies.

Future research directions include further investigations of the link between FE and spatial economy, in particular cause and effect relationships and their scope. In addition, the FE spurs reflection on measures of wealth and productivity, and by extension of social welfare. The functional logic identifies the "units of service" a product or service provides (e.g., number of passenger-kilometers, in Saari et al. (2007)); they can then be compared with resource consumption throughout the life cycle. Benefits from cleaner modes such as walking, cycling [26], or pooled vehicles would therefore be highlighted.

26. Bouwman and Moll (2002) apply the life cycle approach to transportation and conclude that cycling is the most beneficial transportation means for travel distances up to 5 kms, while a combination between cycling and public transit is to be favored for longer trips.

Essay 2

Spatial and environmental issues revisited: Which role for shared transportation modes?

2.1 Introduction

Spatial and environmental issues related to mobility are exacerbated in urban areas. Road congestion, rivalry of use for parking spaces and air pollution are major issues regularly at the heart of local transportation policies. These issues have been addressed mainly separately. However, a function-based transportation system has the features to help address both spatial and environmental issues, when collective consumption (shared transportation modes) is considered. The study reveals that shared modes are key components of a comprehensive and efficient transportation system.

Such a transportation system is based on the concept of functional economy (FE), an organizational model that has been increasingly widespread in a recent period. In a narrow sense, the FE consists in selling a use function - a solution, seen as a combination of products, services and directions for use - instead of a product. Material goods are considered to be mere instruments providing functions (commuting, communicating). The concept of FE emerges in the 1980s from the joint work of Walter R. Stahel and Orio Giarini (Giarini, 1980; Giarini and Stahel, 1989) on the performance-based economy, in contrast with a throughput-based economy [27] (Daly, 1992; Ayres and Simonis, 1994). Through the decoupling of economic growth from flows of energy and materials, the FE originally aims to dematerialize [28] the economy in order to achieve sustainable economic paths (Stahel, 2006). Reduced impacts on the environment (resource depletion, pollution emissions) are at the heart of this concept. Optimizing the inputs implies maintenance, recycling and re-use of materials. For this purpose, function providers often consider the whole products' life cycle and have an overall cost approach. Moreover, the "logic of access"(Rifkin, 2000) prevails over ownership rights and a particular focus is made on the use value of goods.

Several theoretical studies try to disentangle the abundance of business initiatives and marketing innovations flourishing under the label FE (Buclet, 2014; Van Niel, 2014). Some novelties are pure sales strategies, such as offering associated services or products in addition to the core product, while others can be seen as breakthrough innovations. In the latter case, the function addressed is reconsidered, sometimes through a systems approach. A systems approach encompasses all the agents and elements related to or impacted by the function (users and providers, products and services, the environment and territory, etc.).

A systems approach is especially relevant for mobility, since this function generates both spatial and environmental issues, namely road congestion and rivalry of use for parking spaces, as well as air pollution. Crucial interactions occur between commuters. Every commuter impacts the accessibility of a territory through three simultaneous distortions: congestion and air pollution, which are negative externalities, and parking spaces, which generates rivalry of use. Goods in general and

27. In the economic context, the throughput refers to "the flow of raw materials and energy from the global ecosystem's sources of low entropy (mines, wells, fisheries, croplands) through the economy, and back to the global ecosystem's sinks for high entropy wastes (atmosphere, oceans, dumps)" (Daly and Farley, 2003).

28. To dematerialize means to reduce the volume of materials used (inputs) to meet the needs of agents (output).

vehicles in particular require space, in a strictly physical sense. Space scarcity may be felt in densely built-up city centers. Public space devoted to transportation can be considered as a common good available in free access and therefore subject to conflict in its allocation. Although they are strongly correlated, these issues are usually dealt with separately in the literature. An interesting approach consists in discussing both issues in a single framework. A comprehensive approach of the transportation system is therefore required.

Road congestion is a major issue addressed by local authorities. In city centers, congestion is often recurring, especially during peak hours. More cars on roads also induces higher needs for parking spaces and worsens rivalry of use. In densely built-up urban areas, road users compete to park their cars. Conflicts are especially intense for on-street parking. Although fees may be required, on-street public parking spaces can be considered as available in free access, or open access. Indeed, public parking spaces are usually underpriced and this distortion leads to an overuse of parking space (Arnott, 2011). Rivalry of use for parking spaces increases road traffic, therefore contributing to road congestion.

Another major issue related to transportation in urban areas is air pollution. Transportation, and in particular road traffic, generates various air pollutants. Air pollution is exacerbated by both road congestion and rivalry of use for parking spaces, which results in longer engine running times. Moreover, very low speeds of vehicles trapped in road congestion result in higher levels of emissions. Vehicle exhausts release large quantities of carbon dioxide (CO_2), a greenhouse gas (GHG) which is a leading contributor to climate change. Local air pollutants such as carbon monoxide (CO), nitrogen oxide (NO_X) and particulates (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) also arise from transportation. They have significant effects on the environment (acid rain, contribution to ozone pollution and to climate change) and the health (asthma, lung cancer, heart diseases and strokes).

Road traffic, and especially private cars, contributes to a large extent to the spatial and environmental issues mentioned above. However, private cars remain the leading transportation mode for commuting trips[29]. Policies fostering a modal shift from private cars to mass transit or to bicycles have often had mitigated results. Indeed, it is generally assumed that alternative transportation modes offer similar services, namely origin-to-destination trips. Furthermore, shared modes are usually overlooked by policies as a credible alternative to private modes and as a solution to address spatial and environmental issues related to mobility.

In this article, we focus on shared modes, namely vehicle-sharing and self-service vehicles. The contribution is threefold. First, we explore the mechanisms through which shared modes help reduce road congestion and rivalry of use for parking spaces, as well as air pollution, compared to private modes. Second, we show the limits of the existing typologies of a FE. The analysis indicates that due to their generalist nature they remain imprecise when considering specific functions. More specifically, we summarize the existing typologies into a unique model applied to a particular function, mobility, and highlight the role collective consumption plays in a systems approach. We show that a systems approach addressing mobility issues implies a peculiar business model, namely pooling of vehicles. Indeed, commuters are interrelated. The mode by which one commutes, as well as the direction, influence the others' mobility through congestion and rivalry of use for parking spaces. Collective needs are impacted by individual needs. When collective needs related to mobility are explored, the whole transportation system has to be taken into account. These findings first reveal the need to classify function-based innovations according to their functional sphere. The function is at the heart of the FE. Third, we highlight the fact that transportation modes do not provide similar services to users. Therefore, gross comparisons in terms of time-space consumptions between modes are oversimplifying. We suggest to put these gross estimations into perspec-

29. Except in some large cities, such as in Paris where mass transit is the leading mode.

tive accounting for additional services provided by transportation modes. Refined measures of time-space consumptions are presented. When the service provided is accounted for, the gap between mass transit and private cars is reduced. More importantly, the results show that car-sharing and self-service cars constitute relevant alternatives to private cars in terms of time-space consumption per unit of service provided.

The analysis provides guidelines for decision-makers since it clearly indicates orders of magnitude for time-space consumptions from various transportation modes. In addition, the adaptive model developed helps service providers or local authorities to implement a systems approach when addressing mobility issues. The model clearly indicates the elements to be included for an efficient transportation system. Furthermore, we mention the limits of the present organization for shared modes. More precisely, the need for institutionalizing car-sharing is highlighted, and network expansion required for self-service vehicles.

The article is organized as follows. Section 2.2 investigates the mechanisms through which shared modes help reduce both spatial and environmental issues. Section 2.3 briefly presents the various typologies related to the FE, before drawing a non-linear model and adapting it to the function mobility. Then, in Section 2.4 the concept of time-space consumption from transportation modes is explored and gross estimations of time-space consumption are refined accounting for the service provided. Section 2.5 provides guidance for transportation policy-makers, and section 2.6 concludes.

2.2 Exploring a specific function: mobility

The FE can take the form of shared use of goods, in particular when goods are barely used by a single agent and when they are bulky (Hirschl et al., 2003). Two different systems of shared vehicles can be distinguished. First, vehicle-sharing systems, such as car-sharing, generally refer to a single vehicle shared simultaneously by several users. Second, self-service systems, such as bike-sharing schemes in urban areas, refer to a fleet of vehicles shared sequentially. Shared use allows reducing the total number of vehicles in the economy, and thus in a particular area. More precisely, car-sharing mostly helps reduce traffic congestion through higher vehicle occupancy rates. Fewer vehicles are needed to move the same number of users. On the other hand, self-service schemes primarily help reduce rivalry of use for parking spaces. Due to higher use rates, pooled vehicles are parked for a shorter time. Vehicle-sharing systems mostly help reduce road congestion, while self-service schemes predominantly help reduce rivalry of use for parking spaces. Yet, road congestion and conflicts for parking spaces are strongly correlated to each other. The more cars on road, the more cars need to park at the end of their trip. Similarly, the more cars trying to park, the more congestion on roads. In summary, shared vehicles can reduce congestion and rivalry of use, compared with private vehicles. Compared with private vehicles, shared vehicles allow not only for enhanced accessibility, but also for environmental benefits.

From an environmental perspective, pooling is especially interesting when products have high material or energy content. In urban areas, private vehicles are sub-optimally used for mobility [30] and could then be pooled. Shared use leads to higher use rates of the goods. The use rate of vehicles can be considered from an intensive or an extensive perspective. From an extensive perspective, vehicles shared sequentially would not necessarily generate environmental gains. Indeed, if the lifespan of the good depends on its use, ten vehicles used over ten years by ten agents would be equivalent to one shared vehicle used ten times more by the ten agents but replaced every year. However, this is environmentally equivalent only when one considers that goods are discarded at the end of their lives, when they are

30. Household travel surveys carried out in France (CERTU, 2004) reveal that cars are parked on average 96% of the time, i.e., unused for mobility.

broken. Literature on consumption patterns highlights that goods are often thrown away because there exists new and more desirable goods on the market, not because they are unusable (Cooper, 2005). In this case, the second situation is more desirable, since it will maximize the use rate before the next innovation. In addition, those two situations are equivalent only when the vehicle use does not entail energy consumption, or when energy consumption remains stable or increases over time. Nevertheless, current trend indicates improved energy efficiency of vehicles over time. In this case, the second situation is more desirable, since it will allow to save energy. From an intensive perspective, vehicles (mainly cars) shared simultaneously allow for a reduction in the number of vehicles in the economy, since it does not damage the vehicle to carry three commuters instead of one. In addition, vehicles offered in self-service schemes are generally less polluting than private vehicles. Self-service cars are most often electric cars which do not release CO_2 or NO_X emissions and which cut down PM emissions.

Cabanne (2009) estimates that a shared bicycle in Lyon, France, performs on average five trips a day. Therefore, shared bicycles show far higher use rates than private bicycles. Moreover, Meijkamp (2000) analyzes empirically car-sharing systems and reports a 44% reduction in the number of cars used by car-sharing members. Reduced environmental impacts arise primarily from a decrease in the number of units manufactured. This is made possible not only by maintenance and re-use, which are central features of a FE, but also mainly by shared use. Both higher use rates and recycling slow down resource flows in the economy (Scott, 2009), as well as emissions generated by raw material extraction and manufacturing. In addition, a change in the relation the consumer has with the good after it has been servicized may lead to a reduction in its use. Studies about car-sharing systems in German-speaking countries indicate that the vehicle mileage can decrease by up to 50% (Muheim and Inderbitzin, 1992; Baum and Pesch, 1994; Petersen, 1995; Steininger and Novy, 1997), therefore leading to reduced emissions from the use of cars. It is worth noting that accounting for environmental impacts is central to the FE (Stahel, 2006).

2.3 The role of collective consumption in a systems approach for mobility

In this section, we call into question the interest of considering the functional sphere.

2.3.1 Existing typologies for the FE

The most widespread and long-established typology related to function-based models has been drawn by Hockerts (1999) and taken up by Mont (2002). It includes three categories of Product-Service Systems (PSS). First, product-oriented PSS provide additional services to the product sold. Second, use-oriented PSS offer the use of a product, not the product itself. Third, result-oriented PSS guarantee the satisfaction of needs, irrespective of the services and goods entailed. The classification refers to the aim or "orientation" of the innovation.

Differences among function-based innovations arise also from their business model. Van Niel (2014) distinguishes models relying on collective consumption, such as pooled or shared goods, from sales of use functions (leasing and functional sales) and from performance-based contracts (energy or facilities management, least-cost provision). Such a typology highlights various implementation strategies of a FE. The classification adopted is clear and allows for the inclusion of many innovations, from a narrow to a large definition of FE.

Du Tertre (2008) positions the FE against other organizational and economic models, namely clean industry, industrial ecology, and service economy with users' involvement. The features for a FE are both a service-based logic with intangible technology and a local involment on the territory considered. In a pyramid-shaped typology, Buclet (2014) classifies innovations from a narrow vision to the broadest and ideal definition of the concept. The first category is the narrowest one and consists in selling the use of a good instead of the good itself. The next categories include of a broader scope of the function, innovations in the use or in the materials providing the function (e.g., multimodal materials). The last two categories entail innovations that meet agents' needs at the scale of a specific territory (defined according to the function) and designed involving users. Such a systems approach and stakeholders' involvement constitute the ideal form of a FE.

The typologies presented above have a general form. This constitutes both an asset and a drawback. General classifications allow for sorting innovations irrespective of the functions considered, but may lack precision when a specific function is investigated. Yet, the function is at the heart of the FE. In this section, we highlight the key role pooled vehicles play in a systems approach for mobility.

2.3.2 The adaptive model

In this subsection, we propose a theoretical model to classify function-based innovations according to their degree of integration towards a systems approach. Elements are derived from existing typologies. The structure of the model is partly based on the typology proposed by Buclet (2014). Each innovation ranges from low to high integration degree with the system. The scope of the function can be restricted to the activity itself, for example the use of shared bicycles requires the provision of bicycles. Extending the scope of the function, shared bicycles can be organized in a network around the city, with bike lanes connecting stations. In a systems approach, the bike-sharing system is also connected with the other transportation modes, for instance through integrated ticketing and multimodal incentives (information boards, bicycles parking spaces near stations or the possibility to take bicycles on train or bus).

The distinctive feature of the model drawn in Figure 2.1 is to show how it can adapt to the function considered. More precisely, the need for collective consumption to account for collective needs is highlighted for the function mobility.

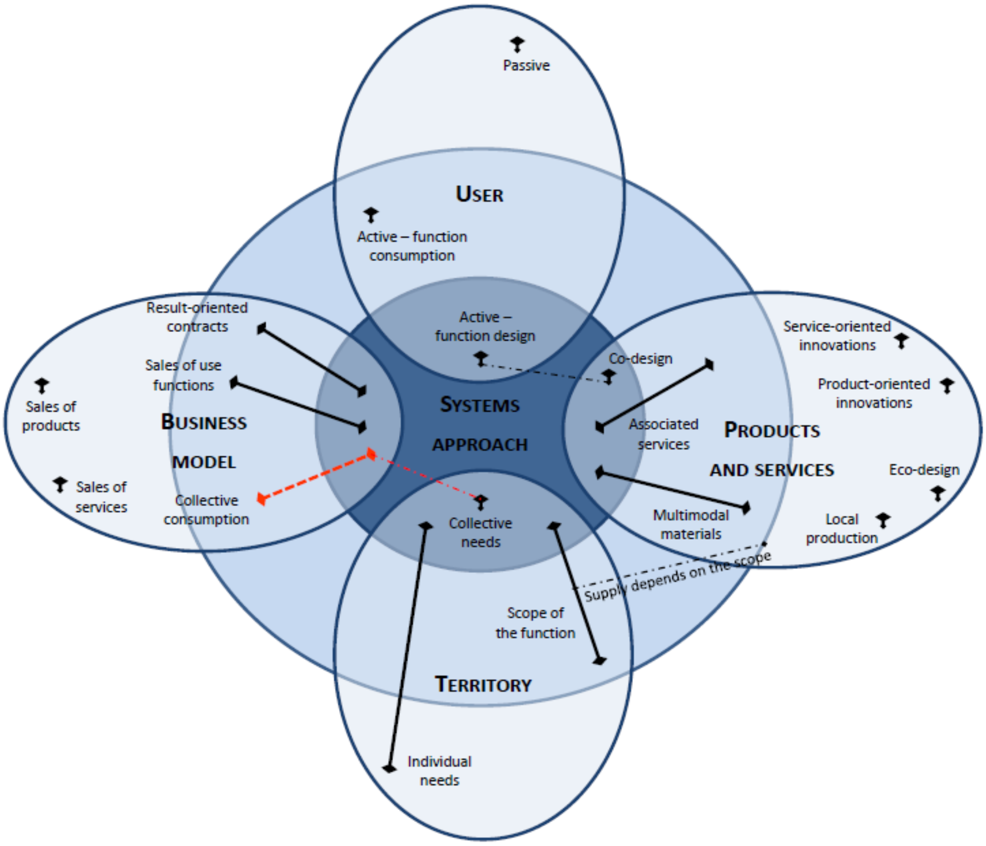


Figure 2.1: The role of collective consumption in a systems approach addressing mobility issues.

The model consists of a series of concentric circles. The inside circle is the systems approach and constitutes the heart of an efficient FE. The intermediate circle is made up of elements forming a FE, though less integrated with the system. The outside circle includes innovations that may constitute elements of a FE, but whose very nature does not characterize a FE.

The model comprises four pillars. The first pillar relates to the user's involvement in the function (see Drut (2013) for more details). In pure service-oriented offers, such as public transportation, users play a passive role - they are taken from origin to destination. Users play an active role when consuming the function, and also when designing the function. Users traveling with shared vehicles are not consistently *taken* from origin to destination by a third party, they can move themselves actively, as in self-service transportation systems and sometimes in car-sharing. In addition, they can participate to the design of the function through meetings with local authorities or evaluation forms. Involving users in the design of functions implies a systems approach.

The second pillar relates to products and services for the provision of the function. Service or product-oriented innovations are sometimes claimed to belong to the FE, as well as eco-design or local production. However, they may only aim to increase sales, enhance the firm's reputation or lower the environmental burden. On the contrary, offering services associated with the original service or product (e.g., information on vehicle availability), or offering multi-modal materials (e.g., long *vs* short run rentals, a basket or large trunk) constitutes function-based innovations. Co-design is directly linked with the user's involvement and entails a systems approach. Users have a field practice of the activity and specific requirements.

The third pillar relates to the functional scope of the activity. Innovations that address not only individual needs, but also collective needs result in a systems approach. Similarly, the scope of the function can range from a restricted sense (bike-sharing system) to a broader sense (mobility in the urban area). The broader the functional scope, the more integrated the function into a systems approach.

The fourth pillar relates to the business model and is adapted from Van Niel (2014). Standard sales of products or services do not define a FE. Sales of use functions (e.g., leasing of vehicles, selling a 30 minute use of bicycles), result-oriented contracts (e.g., least cost trip between origin and destination) may lead to an integrated transportation system, yet not consistently. One of the contributions of this paper is to demonstrate that when mobility is considered, collective consumption (car-sharing, self-service systems) becomes a prerequisite for a systems approach, while not consistently for other functions. In the case of mobility, the adaptive nature of the model is illustrated with the element "collective consumption".

Pooling of goods is not a prerequisite for any efficient systems approach. Nevertheless, addressing mobility issues through a systems approach requires collective consumption. Due to the interactions between commuters and the spatial and environmental issues related to mobility, accessibility must be addressed taking into account each user and the transportation system as a whole. It is not sufficient to address individual needs with individual offers. A systems approach requires to consider collective needs, not only individual ones. Therefore, the function considered must be central to the debate.

2.4 The role of shared modes in the space allocated to mobility

Road congestion and rivalry of use are issues related to the space required by transportation modes. Section 2.2 emphasizes that shared modes reduce the per-person space consumption required for a trip. This section gives measures of the space required per person per trip for various transportation modes. Gross time-space consumptions are indicated, before we account for the service provided by the different transportation modes to refine time-space consumption estimates.

2.4.1 Gross time-space consumption estimates

Generally, a trip generates two types of space consumption: a consumption associated with the movement of individuals or vehicles (traffic), and a consumption related to the parking of vehicles. Let us call the former a dynamic consumption and the latter a static consumption (after Marchand (1977)). The two types of space consumption can be aggregated when expressed in a common unit, namely "time-space consumption" ($m^2.h$) which combines surfaces (m^2) and duration of the consumption (h) (Marchand, 1993).

On the one hand, there is a consensus on the calculation method used to assess static space consumption. Both the vehicle's dimensions and the type of parking infrastructure (off-street or on-street parking) are considered. On the other hand, several methods have been used to measure dynamic space consumption (CERTU, 2007). Road capacity measures give estimates of the necessary road width required for a given flow of vehicles, according to transportation modes. This oversimplified measure of space consumption ignores the speed of vehicles and the duration of road occupancy. The speed of vehicles impacts the flow of transportation infrastructures, the distance between vehicles [31], the road occupancy time and the width of rights-of-ways [32]. The underlying idea is that higher speeds enable to cover a given distance in a shorter period of time, therefore consuming less time-space than slower vehicles. Time-space consumption depends therefore highly on the speed of vehicles. Moreover, higher speeds increase the road capacity. However, as the distance between vehicles increases more than proportionately with the speed, dynamic space consumption rises with the speed. In addition, higher speeds require larger right-of-ways, in particular for unguided modes such as cars. According to the capacity-speed curves by Cohen (2006), a speed of around 60 to 90 kmph allows for maximal road capacity. The length of vehicles is also accounted for in dynamic space consumption, despite its negligible impact.

The method developed by Marchand (1993) entails both static (parking) and dynamic (traffic) space consumptions, and accounts for the speed of vehicles. Both

31. Distance between vehicles corresponds to the stopping distance, i.e., both the reaction distance and the braking distance.

32. Right-of-ways are lateral safety distances on both sides of vehicles and roads, sometimes combined with median strips or emergency lanes.

time-space consumptions are expressed in m^2.h and given by, respectively (Marchand, 1993):

$$TSC_i^{parking} = \frac{1}{n_i} \left(S_i * h_i \right)$$

and

$$TSC_i^{traffic} = \frac{1}{n_i} \left(l_i * d_i \left(V_i \right) * \frac{L}{V_i} \right)$$

or

$$TSC_i^{traffic} = \frac{1}{n_i} \left(\frac{l_i * L}{Q_i \left(V_i \right)} \right) * 1000$$

with TSC_i the time-space consumption of transportation mode i, n_i the occupancy rate of transportation mode i, S_i the surface in square meters required to park transportation mode i, h_i the length of stay (parking) in hours for the transportation mode i, l_i the road width where transportation mode i moves, d_i the distance between vehicles of transportation mode i which depends on their speed V_i and can be summarized by $Q_i \left(V_i \right)$ the road capacity where transportation mode i moves, L the length of the trip in kilometers, and 1000 to obtain m^2 instead of km^2.

Marchand (1993) gives estimates of time-space consumptions for several transportation modes (car, two-wheeler, bus, subway and walking) and several trip purposes (work, shopping and leisure). Parking length varies strongly according to trip purposes, from 9 hours for work trips to 1.5 hours for shopping trips. Table 2.3 in appendix summarizes the results from Marchand. For a 10 kilometer return commuting trip, time-space consumptions per person range from 90 m^2.h for cars to 1 m^2.h for subway and include 2 m^2.h for walking, 21 m^2.h for two-wheelers and 3 to 12 m^2.h for buses. These estimates reveal that car commuters consume up to 90 times more time-space than subway commuters. Results are striking and claim for increasing use of mass transit to reduce congestion and parking issues in cities.

Nevertheless, these results can be considered as gross estimates. First, the underlying assumptions are strong and sometimes unclear (see Table 2.4 and Table

2.5 in Appendix). Second, transportation modes are compared without accounting for their generalized costs and the utility they provide to users. Transportation modes cannot be compared so simply since they do not provide similar services to commuters and have different generalized costs. Commuters make the final decision about transportation modes, and for this reason the determinants of mode choice should be explored. The service provided by a transportation mode, as well as its generalized cost, are leading determinants of mode choice. In the next subsection, we refine time-space consumptions accounting for the service provided by the mode and including other transportation modes, namely shared modes, in the analysis.

2.4.2 Accounting for the service provided

Gross estimates from Marchand (1993) rely on the oversimplified assumption that the only service provided by transportation modes is the origin-to-destination trip. In this section, we assume that transportation modes do not provide similar services to commuters and neither have similar generalized costs. Accounting only for gross time-space consumption of transportation modes allows to meet collective needs, while ignoring individual needs. For this reason, time-space saving modes such as mass transit may remain empty despite regular incentives from local authorities. Users choose the cheapest transportation mode from which they derive a given level of utility (Hicksian utility function). Therefore, their choice depends on the services provided by the mode, on its generalized cost and on the level of utility desired. The optimization program of a representative user according to transportation mode j can be written as follows:

$$\min_{t_{ij},x} E\left(t_{ij},x\right) = \sum_{i=1}^{n} p_{ij} t_{ij} + p_x x \tag{2.1}$$

$$s.t. \begin{cases} U_j\left(t_{ij},x\right) = \alpha \ln\left(T + \sum_{i=1}^{n} \beta_i t_{ij}\right) + \ln x \\ U_j \geq U_0 \end{cases}$$

Let E be the expenditure the user wants to minimize. She buys two goods: transportation services with mode j, which corresponds to $i = 1, ..., n$ services that are inseparable from the given mode, t_{ij}, at price p_{ij} (it corresponds to the generalized cost of the mode), and a composite good x at price p_x. The representative user wants to reach a level of utility, noted U_j, equal to or greater than U_0. The utility function is the sum of the utility derived from transportation and from composite good. The user has a preference α for transportation compared to composite good. Transportation with mode j provides the core service T or origin-to-destination trip, and additional services $t_1, ..., t_n$ provided by the mode j, and to which the user attaches a weigh β_i. What is interesting is to find what are the optimal combinations in terms of transportation modes, and how they vary, when the given level of utility U_0 varies, or when the price associated with a particular service $p_{1j}, ..., p_{nj}$ varies. It is worth noting the importance of the weight associated to a service. According to users, the relative importance of services varies, which affects their level of utility.

The aim is not only to find which transportation mode is the more likely to reduce spatial issues theoretically, but also to assess which modes would be practically operated by users. To give an illustration of the impact of the service provided and generalized cost on the final choice of users, let us take a simple but concrete example that considers the service provided by transportation modes only - not the generalized cost.

The utility derived by commuters results from several services, not only from the origin-to-destination trip. Prettenthaler and Steininger (1999) explore additional services provided by private cars, compared with shared ones, and mention the comfort, the immediate availability, and the prestige (symbolic function). Bouladon (1974) highlights the private space provided by private cars: “The automobile fulfills a basic need, that of being alone, in a private space”. In this study, we include additional services such as carrying heavy loads, driving people with reduced mobility (children, the elderly or those without a driving license), avoiding road congestion, making physical efforts or not, providing symbolic functions, offering private space for discussion, covering more than 5 kilometers, being available immediately, etc. Other services could be added to the list. We attribute weights to these services and aggregate them to the core service, namely the origin-to-destination trip. Let us arbitrarily set 1 for the core service and 0.2 for each additional service provided by a given transportation mode [33]. Note that physical efforts can be viewed either as a positive or as a negative attribute. In the latter case, the weight -0.2 is applied. The list of services and weights is provided in Table 2.1. The weights for each service associated with a given transportation mode are then aggregated and the time-space consumption of the mode is weighted by this value. This allows us to get time-space consumptions per person and *per unit of service provided.* Therefore, previous gross estimates are put into perspective. Furthermore, we add transportation modes not previously considered by Marchand, in particular private bicycles and shared modes (car-sharing, self-service schemes for cars and bicycles, taxis).

Table 2.1: Services provided by transportation modes

Service provided	Weight
Origin-to-destination trip	1
Carrying heavy loads	0.2
Driving people	0.2
Avoiding road congestion	0.2
Physical efforts (positive)	0.2
Physical efforts (negative)	-0.2
Symbolic functions	0.2
Private space for discussion	0.2
Covering distances > 5 km	0.2
Immediate availability	0.2

Table 2.2 summarizes the various transportation modes and the aggregated weights derived from the services they provide. Time-space consumption per unit

33. Different weights could be set according to the importance of the service considered. However, we prefer to limit the arbitrary nature of the weight setting and set similar weights for all services.

of service provided extends and refines the work from Marchand (1993).

Table 2.2: Time-space consumption (TSC) per person for a 10 km return commuting trip

Transportation modes		Use rate	W	TSC			WTSC
				Dyn.	Stat.	Total	Total
Private modes	Cars	1.1	2.2	20.5	81.8	102.3	46.5
	Motorized two-wheelers	1	1.6	7.5	13.5	21	13.1
	Bicycles	1	1.2	3.8	6.8	10.6	8.8
			1.6	3.8	6.8	10.6	6.6
Shared modes	Car-sharing	2.5	1.2	9	36	45	37.5
	Self-service cars	1 (5/day)	2	22.5	16.4	38.9	19.5
	Taxis	1.1 (5/day)	1.8	20.5	14.9	35.4	19.7
	Self-service bicycles	1 (5/day)	1.2	3.8	1.4	5.2	4.3
			1.6	3.8	1.4	5.2	3.3
Mass transit	Bus with dedicated lanes	1,500/h/day	1.4	12	0	12	8.6
	Bus without dedicated lanes	1,500/h/day	1.2	3	0	3	2.5
	Subway	10,000/h/day	1.4	3	0	3	2.1
Other	Walking	1	1.2	2	0	2	1.7
			1.6	2	0	2	1.3

Note: W: Aggregated Weight; WTSC: Weighted Time-Space Consumption; Dyn.: Dynamic; Stat.: Static

Private cars are defined as cars owned and used by a private user. Car occupancy rate for commuting trips is about 1.1 [34]. Therefore, both static and dynamic space consumptions are first weighted by the occupancy rate, and then by the aggregated weights associated with this transportation mode. Private cars rank highest in terms of service provided. In addition to the origin-to-destination trip, private cars can be used to carry heavy loads, to drive people and to cover long distances, they provide symbolic functions (mainly social status through the type of vehicle owned, and self-expression through customization) and private space for discussion. Moreover, private cars are available immediately, since they are owned by a single agent and generally parked close to residences.

34. Occupancy rates for all transportation modes are given for France.

Two different systems of shared cars can be distinguished: car-sharing and self-service cars. Car-sharing occupancy rate is logically much higher than that of private cars. In a high-hypothesis case, let us assume that shared cars move on average 2.5 people. Therefore, both static and dynamic space consumptions are weighted by 2.5 and thus reduced compared to private cars. In addition to the origin-to-destination trip, car-sharing allows to cover distances greater than 5 kilometers. In some countries, such as the United States, High Occupancy Toll lanes allow shared cars to avoid congestion [35]. Self-service cars allow not only to cover long distances, but also to carry heavy loads, to drive people, and they provide private space for discussion and possibly symbolic functions (Prettenthaler and Steininger, 2009). Their occupancy rate is assumed to be lower than that of private cars: 1 people per trip. However, while cars shared simultaneously stay parked between outward and return trips, cars shared sequentially can perform up to 5 trips a day (high-hypothesis case). Therefore, while dynamic space consumption of self-service cars is divided by 1, their static space consumption is divided by 5.

Taxis provide functions similar to those offered by self-service cars. The difference is that they do not provide private space for discussion, but they allow to avoid road congestion through dedicated lanes. Commuting trips generally occur during peak hours and avoiding congestion leads to precious time savings. Taxi occupancy rate is assumed to be similar to that of private vehicles when the driver is not accounted for.

Private motorized two-wheelers allow to cover distances greater than 5 kilometers, and are immediately available to the user. Moreover, they may help avoid congestion in urban areas. Symbolic functions are usually not associated with motorized two-wheelers. Their occupancy rate is estimated to 1.

35. They are lanes where tolls are applied on low-occupancy vehicles but free for high occupancy vehicles (2 or more occupants) (Santos and Veroef, 2011). However, we do not consider this service for shared vehicles in our analysis.

Private bicycles allow to avoid congestion through dedicated lanes and are available immediately. Symbolic functions are usually not associated with private bicycles. Furthermore, they require physical efforts to move from origin to destination, which can be viewed either as a positive (health benefits) or a negative (tiredness, perspiration, weather-sensitivity, need for suitable clothes) feature. Bicycle occupancy rate is 1.

Shared bicycles are usually part of a self-service scheme. They have the same characteristics as private bicycles, except the fact that they are not immediately available to the user. In addition, they may provide symbolic functions, in particular expressing environmental awareness of users. Their occupancy rate is 1, but they perform on average 5 trips a day.

Buses are of 2 types: buses on non-exclusive lanes and buses on exclusive lanes (30 vehicles per hour). They allow covering more than 5 kilometers. In addition, dedicated lanes help avoid congestion. Bus occupancy rate amounts to 50 (high-hypothesis case rather suitable to large urban areas). Moreover, it is assumed that mass transit vehicles are constantly moving, especially during peak hours. When they park, they park outside city centers, where rivalry of use does not occur. Static time-space consumption for buses is therefore zero.

A subway has characteristics similar to buses with dedicated lanes, except its occupancy rate which is estimated to be much higher: 10,000 commuters per hour (hypothesis for large cities).

Walking allows to avoid congestion during peak hours, and is immediately available. Walking requires physical efforts, considered either positively or negatively.

Although the estimates from Marchand are subject to many criticisms, we use them as a basis to introduce the notion of service provided by transportation modes.

Figures should be treated cautiously; the order of magnitude is far more informative in this analysis.

The underlying idea is that mass transit occupies far less time-space than private vehicles and notably than cars. Gross estimates reveal that private cars used for commuting trips require up to 90 times more space than the subway. However, we emphasize that mass transit provides far less services to users than private cars. For instance, the weight associated with the service provided by the subway is 1.4, against 2.2 for private cars. Weighted time-space consumptions remain in favor of mass transit, but the relation decreases from 1 to 90 to 1 to 22 when assumptions are modified and the service provided by the mode accounted for. This order of magnitude shows that the additional time-space consumption of private cars is not fully offset by the additional services they provide. Therefore, they remain time-space consuming modes.

Due to their intermediate position between mass transit and private modes, one may expect better results from shared modes. Indeed, self-service cars provide almost as many services as private cars, while they strongly reduce per person time-space consumption. However, effects from car-sharing are not so significant. Time-space consumption from self-service cars is divided by more than 2 compared with private cars, while that of car-sharing is divided only by 1.2. This is due to the fact that cars require high static time-space consumption for parking which can be reduced only when increasing the use rate of vehicles.

Let us also note that private bicycles perform worse than most mass transit, even when bicycles provide more services. Shared bicycles allow to reduce the time-space consumed compared with private bicycles, but still perform worse than most mass transit. Only buses with dedicated lanes require more time-space than either shared or private bicycles (when physical effort is viewed negatively). Furthermore, it is worth noting that private bicycles perform better than self-service cars. Shared cars' use rate should increase exponentially so that self-service cars rank higher than bicycles - which is practically impossible. The first results allow us to make policy recommendations to help local transportation authorities address spatial and environmental issues related to mobility.

2.5 Policy implications

Spatial issues related to mobility can be approached by the time-space consumption required by transportation modes. In this sense, policy makers favor transportation modes that are less time-space consuming. Mass transit has long been considered as the only solution to road congestion and rivalry of use for parking spaces. Gross estimates reveal the very low time-space consumption of mass transit compared to other modes. Moreover, mass transit is generally far less expensive than private cars. Hence, one can wonder why private cars remain dominating, even for commuting trips. In this article, we show that other needs and functions are overlooked. For instance, mass transit does not allow to carry heavy load, to drive a relative, to enjoy private space for discussion or to be available immediately. The need for these additional functions may explain the mitigated success of mass transit.

For this reason, shared vehicles constitute a credible alternative to private vehicles. They provide additional functions to mass transit and allow to save time-space compared to private vehicles. However, car-sharing and self-service cars are relatively new transportation infrastructures and they have many caveats. First, the institutional framework governing car-sharing remains confused. Car-sharing is most often based on private initiatives from neighbors or offered to non-neighbors for occasional trips, mainly inter-urban trips. It entails costly coordination costs that may discourage users to join car-sharing groups. Coordination platforms are set up on the Internet to bring car drivers and car passengers together. Lack of institutionalization contributes to confine car-sharing to sporadic uses. Car-sharing could be better regulated, with the help of a legal framework giving guarantees to both drivers and passengers. Coordination platforms could be encouraged to be comprehensive and flexible. Second, self-service cars have been introduced in some large cities. They remain however too sparse to constitute flexible alternatives to private car users. Moreover, the outskirts and many places in the countryside have potential to host self-service car stations. The network could be enlarged and incentives given to private car users to quit their cars and use shared cars. Third, using shared modes would discourage some users to buy private cars if their needs can be fully met with shared cars. Hence, complementary offers could be developed, such as family car rentals for several days or weeks at attractive prices. The car rental market is generally disconnected from the transportation providers within a city. In addition, the relatively high prices discourage from regular uses, since then buying a car remains cost saving. Therefore, regular car rental for long period is currently not competitive with private cars. Incentives to integrate car rental with other transportation services could be introduced to build a comprehensive and efficient transportation system in which shared modes are a key component.

Transportation policies fostering the use of taxis are uncommon but could be reconsidered in light of the time-space consumed per service provided. Taxis are shared modes rather similar to self-service cars, in terms of service provided and time-space consumed. However in countries with high labor costs, the monetary cost of taxis remains higher than that of other shared modes, due to the need of a driver.

Furthermore, the size of the city and its transportation infrastructure are major elements to account for when discussing local transportation policy. Results from Table 2.2 indicate that subway commuters need less time-space than either private of self-service bicycles. Nevertheless, subways and similar light-rail mass transit are implemented in large cities only. Medium-sized cities would rather have buses with dedicated lanes. In this case, results show that private bicycles (when physical effort is viewed positively) and to a larger extent shared bicycles perform better than mass transit in terms of time-space consumption. This is especially true because buses occupancy rate falls in medium-sized cities, leading buses to perform worse than in larger cities. Consequently, shared bicycles seem to represent a rational compromise to address spatial issues in medium-sized cities.

Environmental issues related to transportation can also be approached by time-space consumption. Traditionally, policy makers encourage low-carbon modes such as mass transit, as well as active modes (walking and cycling) in order to reduce air pollution resulting from transportation. Mass transit releases far less air pollutants than private cars (for instance, rail transport releases 0.0026 kg of CO_2 equivalent per kilometer against 0.07 for a private gasoline vehicle (ADEME, 2006)). Walking and cycling do not release any air pollutant during their use phase. Nevertheless, mass transit has been criticized for its lack of flexibility and limited functions provided to users. Walking and cycling require physical efforts which can be considered negatively by users. In addition, mass transit vehicles and bicycles necessitate materials during the manufacturing phase. Producing vehicles contributes to pollution and resource depletion. On the contrary, shared modes help reduce the number of vehicles in the economy and therefore the number of vehicles manufactured. This is particularly interesting for bicycles whose environmental impact can be fully attributed to the manufacturing phase. In addition, time-space saving transportation modes such as mass transit, shared modes and walking are also low polluting modes. For these reason, shared bicycles could be favored by local transportation authorities rather than private bicycles, especially as the service they provide is similar.

2.6 Concluding remarks

Due to their general form, existing typologies related to the FE remain imprecise when considering specific functions. Adaptive models could be built for each function and elements explored in light of the function addressed. As regards mobility issues, collective consumption constitutes a key feature for an efficient transportation system. Indeed, the satisfaction of individual needs impacts that of collective needs due to traffic congestion and rivalry of use for parking spaces. The model can serve as a decision-making tool since it clearly indicates the elements that constitutes a systems approach for mobility, i.e., practically an efficient transportation system. Collective consumption in mobility refers to shared modes such as taxis, car-sharing and self-service cars or bicycles. Though their key role for a enhanced mobility, they are often overlooked in transportation policies. The analysis conducted in this article explores their role in mitigating both spatial and environmental issues. This study helps service providers or local authorities to consider the impact of shared modes on time-space consumption and related spatial issues. The analysis clearly indicates that shared cars help reduce road congestion, rivalry of use and air pollution compared to private cars, while providing additional functions to users compared to mass transit. Indeed, shared modes are intermediate modes between time-space consuming modes such as private cars and time-space saving modes such as mass transit. Moreover, shared low-carbon modes, such as self-service bicycles, have the potential to reduce simultaneously both spatial (congestion and rivalry of use) and environmental (air pollution) issues in medium-sized city. Both vehicle-sharing and self-service vehicles constitute credible alternatives to private cars when investigating time-space consumptions per unit of service provided. Shared modes contribute to address spatial and environmental issues related to mobility and could be favored as a leading component of a comprehensive transportation system. As such, this study provides guidance for policy-makers.

The main caveat of this article lies in the assumption of a modal shift from private vehicles to shared ones. One may object that the modal shift occurs from public transportation to shared vehicles. In the later case, congestion and rivalry of use for parking spaces would be instead worsened, and environmental impacts due to energy and material consumption would be worsened too. Proper economic incentives can be introduced to favor a modal shift from private to shared vehicles, so as to ensure both environmental gains and a reduction in spatial issues related to mobility. In addition, interaction and coordination costs related to the use of shared goods are expected to be significant and should therefore be assessed. Similarly, the faster degradation of shared goods arises from the careless use of the shared goods compared with that of private goods and can generate financial and environmental losses. A more comprehensive analysis from the whole transportation system of a city could be carried out to explore opposite effects with respect to energy consumption and spatial issues.

2.7 Appendix

Table 2.3 presents the gross estimates from Marchand (1993) related to the time-space consumptions per person in m^2.h for a 10 km return commuting trip with different transportation modes. Table 2.4 and Table 2.5 present the underlying assumptions for Marchand's dynamic and static time-space consumption estimates, respectively. Finally, Table 2.6 presents the services provided by each transportation mode.

Table 2.3: Time-space consumption per person for a 10 km return commuting trip

Transportation modes	Time-space consumption		
	Dynamic	Static	Total
Cars (1.25 people/vehicle)	18	72	90
Two-wheelers	7.5	13.5	21
Bus with dedicated lanes	12	0	12
Bus without dedicated lanes	3	0	3
Subway	1	0	1
Walking	2	0	2

Source: Marchand (1993)

Table 2.4: Assumptions for Marchand's dynamic TSC estimations

Transportation modes	Distance d_i (m)	Width l_i (m)	Speed V_i (kmph)	Occupancy rate n_i (people/veh)	Road capacity Q_i (veh/h)	Trip length L (km)	Dynamic TSC (m^2.h)
Cars	15	2.7	18	1.25	1200	10	18
Two-wheelers	6	1.5	12	1	2000	10	7.5
Bus with dedicated lanes	500	3	25	50	30	10	12
Bus without dedicated lanes	50	3	15	50	200	10	3
Subway	500	3	25	600	50	10	1
Walking	1.4	0.7	5	1	3571	10	2

Note: TSC: Time-Space Consumption; veh: vehicle
Source: Derived from Héran and Ravalet (2008)

Table 2.5: Assumptions for Marchand's static TSC estimations

Transportation modes	Surface S_i (m^2)	Stay duration h_i (h)	Occupancy rate n_i (people/veh)	Static TSC (m^2.h)
Cars	10	9	1.25	72
Two-wheelers	1.5	9	1	13.5
Bus with dedicated lanes	N.A.	0	50	0
Bus without dedicated lanes	N.A.	0	50	0
Subway	N.A.	0	600	0
Walking	N.A.	0	1	0

Note: TSC: Time-Space Consumption; veh: vehicle; N.A.: Not Available
Source: Derived from Marchand (1993) and Héran and Ravalet (2008)

Table 2.6: Services provided by transportation modes

	Origin-to-destination trip	Carrying heavy loads	Driving people	Avoiding road congestion	Physical efforts	Symbolic functions	Private space for discussion	Covering distances > 5 km	Immediate availability
Private cars	✓	✓	✓			✓	✓	✓	✓
Private motorized two-wheelers	✓			✓				✓	✓
Private bicycles	✓			✓	✓				✓
Car-sharing	✓							✓	
Self-service cars	✓	✓	✓			✓	✓	✓	
Taxis	✓	✓	✓	✓				✓	
Self-service bicycles	✓			✓	✓	✓			
Bus with dedicated lanes	✓			✓				✓	
Bus without dedicated lanes	✓							✓	
Subway	✓			✓				✓	
Walking	✓			✓	✓				✓

Essay 3

How space allocation matters: The case of parking spaces

3.1 Introduction

Common resources are prone to conflicts in their allocation. Competition among agents and uses arises when resource scarcity is real or felt. In densely built-up urban areas, road users compete to park their cars. Conflicts for park spaces are especially intense for on-street parking, considered as more convenient than off-street parking. Parking policies are at the heart of local urban plans. They take various forms, from paid-parking schemes throughout the city to the creation of large parking lots located next to public transportation facilities on the outskirts. Besides being a sensitive political issue challenging each local election, rivalry of use for park spaces generates various negative impacts. Road users looking for a space drive around longer and therefore increase road congestion and polluting emissions. Moreover, the time they loose in this search is a cost for them and for the society as a whole. Finally, some agents might be unable to find a park space in the city center and see their welfare decrease sharply.

Parking policies are generally treated from an urban economics perspective. In this sense, land is considered as heterogeneous in terms of natural endowments, climate or accessibility (Ricardo, 1817; Von Thünen, 1826). Relative scarcity of space is highlighted through the concept of land rents. Locations close to the central business district (CBD) display higher land rents since the CBD is assumed to be the attractive center where jobs concentrate. Issues related to workers and firms localization are core questions of urban economics. Distances, and especially commuting distances, constitute a key parameter in the analysis. Standard urban economic models in the tradition of Alonso, Muth and Mills assume relative scarcity of land, without taking into account the absolute scarcity of space. Their models imply infinite endowments in land.

Studies related to the various functions the Earth provides reveal the finite nature of the resource land. Worries arise from the finite nature of Earth combined with the expected growth in demand for these functions (Meyfroidt et al., 2010; Godfray et al., 2010; Wirsenius et al., 2010). Needs for food, housing or environment increase with the population. The accounting approach of Lambin and Meyfroidt (2011) summarizes estimations on the topic and provides an explicit insight of absolute land scarcity. Growing needs for agricultural uses (food, raw materials, energy) have become a public concern (World Bank, 2011). Projections for demands in urban uses (housing, transportation) are also on a rising trend, due to changes in demographics, revenues and consumption patterns (Döös, 2002; Alig et al., 2004; Seto et al., 2010). Rising urban land compete with agricultural functions and more importantly with natural functions (ecosystem services, biodiversity) which are often overlooked though their crucial role (Turner et al., 2007). Despite potential land use changes among functions, the scarcity of land is absolute.

In this study, we focus on artificial urban land, and especially public parking spaces. With intertemporal or long run perspectives, parking space can be considered as a renewable resource. The stock of parking spaces is not fixed, and can be increased or decreased through land use changes. However, in the short run, land allocated to parking spaces is fixed. As noted by Arnott (2011), the long run treats capacity as variable, while on the short run the capacity of the road and parking lots is fixed. He added that "curbside parking is a scarce economic resource" (Arnott, 2011). In this sense, we consider parking space as a non-renewable resource. Renewable and non-renewable resources have similar features. Any resource is potentially renewable on the (very) long run, and any renewable resource is exhaustible if the exploitation rate is higher than the regeneration rate. The time horizon and the exploitation pattern allow for a distinction between non-renewable and renewable resources. Moreover, a feature that distinguishes artificial space from other non-renewable resources is its propensity to be consumed without depletion or damage. For this reason, theory of resource allocation at time t can be properly applied to space. This article deals with the spatial management of an exhaustible resource at time t. As far as we know, the spatial perspective of resource allocation is not directly treated in environmental economics. The literature on both non-renewable and renewable resources mainly deals with intertemporal issues. Space is usually not the subject of environmental economics, while it is a core concept of geographical and urban economics. However, urban economics rather focus on location issues without explicitly considering the scarcity of space.

Environmental economics provide an abundant literature on several issues related to natural resources. A major concern is the allocation over time of non-renewable resources (Dasgupta and Heal [chapter 6 and 12], 1979; Conrad and Clark [chapter 3], 1987; Solow, 1974). A seminal work from Harold Hotelling (1931) highlights the concept of scarcity rent [36], a positive rent that results from the scarce nature of the resource. The Hotelling rule states that the price of the resource, and thus the scarcity rent, must grow at the rate of interest on the optimal extraction path. This simple model has then been improved by introducing heterogeneity in the resource (Solow and Wan, 1976), uncertainty about the stock of the resource (Kemp and Long, 1979; Gilbert, 1979), or imperfect information in contracts (Gaudet et al., 1995; Osmundsen, 1998). The notion of scarcity is thoroughly explored, and scarcity indices are debated in the literature (Pindyck, 1978; Halvorsen and Smith,

36. Also called Hotelling rent

1984). The above mentioned issues partly apply to renewable resources. Fish stock management is probably the most prolific topic (Dasgupta and Heal [chapter 5], 1979; Conrad and Clark [chapter 2], 1987; Clark, 1990; Hannesson, 1993). Gordon (1954) and Schaefer (1957) developed fisheries management models in which they estimate the maximum sustainable yield taking into account the regeneration rate of the resource. A spatial dimension appears in the spatial management of resources, which is mainly addressed through fishing site choice (Wilen, 2000). Contrary to fossil fuels and minerals, renewable resources such as fish or forests are generally not privately owned and issues related to the management of common property resources or free access to the resource are raised. Hardin (1968) investigates the issue of free access in his famous "Tragedy of the Commons". Contrary to a frequent confusion, conflicts do not arise from the nature of common goods, but from the rules (or absence of rules) governing their access. The different types of property regimes range from open access regimes (e.g., fishery resources in international waters) to private property regimes, and include State property and common property regimes (Seabright, 1993). Various policies can be implemented to overcome the overexploitation of free access resources. Besides taxes, quotas are frequently used in fisheries to limit the quantity of resource extracted.

Following Anderson and De Palma (2004), we define public park spaces as common resources, at the crossroads of private and public goods. Like private goods, park spaces are rivalrous; but like public goods, they are non excludable. Any agent can park her car on public roads, but this prevents another agent to park her car at the same place. After we study the nature of this particular good, let us analyze the regime of access to public park spaces. Although fees must be required for the use of the good, park spaces can be considered as available on free access, also called open access. Indeed, public parking spaces are usually underpriced and this distortion leads to an overuse of parking space (Arnott, 2011). For this reason, use conflicts among agents occur, especially when population and activity density is high. Anderson and De Palma (2004) show that equilibrium entails overuse of parking close to the city center, therefore leading to conflicts. By definition, these particular externalities are not taken into account in the cost born by agents, what leads consumption to stumble over the spatial constraint. The economic scarcity results from the gap between desired and available goods, i.e., between offer and demand. Although scarcity has an absolute nature, this concept is generally considered as relative, since people's desires may change, as well as the way they meet their needs (substitutes) (Baumgärtner et al., 2006). Considering park spaces, people face local scarcity, not global scarcity. Indeed, parking needs are localized, and the resource (park lots) is local too.

This article investigates the mechanisms underpinning space allocation. In the context of parking spaces, it is not too strong an assumption to define space as a homogeneous commodity. We particularly highlight the role the shadow cost associated with a scarce resource plays in allocation mechanisms. The shadow cost indicates how much it costs agents to be bounded in their parking space consumption. We show that overlooking the shadow cost of the spatial constraint when space is allocated sequentially induces pressures towards more parking spaces and drives down the social welfare.

The results we find confirm the standard conclusions of the literature on non-renewable and open access resources. Park spaces are non-renewable resources and the allocation model highlights the scarcity rent resulting from the limited nature of the resource. Moreover, the whole resource is to be consumed by agents when there is a shadow cost stemming from the spatial constraint. Exploring intertemporal allocation of non-renewable resources, Hotelling (1931) concludes that at the end of the world, the resource has been exhausted. On the other hand, park spaces are available in free access. Following the literature on open access resources such as fish stock, the analysis we conduct shows that space consumption generates use conflicts and a lower social welfare. Although the model developed thereafter is original, the results are in line with the literature on non-renewable and open access resources. Our contribution consists in analyzing a particular resource, space, and to explore allocation mechanisms on a spatial perspective. While studies on fisheries exhibit overexploitation of the resource, we demonstrate mis-consumption of park spaces. The distinctive feature of this paper consists in considering space as a non-renewable resource, without considering distances and questions of urban economics.

Through a static micro-based allocation model, we investigate three situations (S): simultaneous allocation (S1), sequential allocation without public intervention (S2), and sequential allocation with public intervention (S3). Under each situation, four possible cases (C) are identified: whether a shadow cost is associated with the spatial constraint or not, and whether exogenous features constrain space consumption or not. Exploring space allocation process allows us to compare the utility and social welfare achieved under each situation. Simultaneous allocation of parking spaces (S1) leads to an equilibrium providing the highest social welfare possible. Nevertheless, commodities prone to externalities and conflicts of use experience market failures. When competition is high, parking spaces are indeed allocated sequentially (S2). In this case, the order of access to the resource is a key element. Results show that the social welfare is lower than in a perfectly competitive market. Therefore, public authority can intervene (S3) to guarantee optimal welfare. We then draw the multiple equilibria obtained after regulatory measures are introduced (S3). The model estimates the optimal space consumption rates to be set under the various cases identified. We compare specifically the low-competition case (C1) with the high-competition case (C2). When there is no shadow cost associated with the spatial constraint (C1), our findings reveal that the various situations (S1, S2, S3) are equivalent. However, when a shadow cost is associated with the spatial constraint, a sequential allocation without public intervention (S2) results in a lower social welfare than expected with other situations (S1, S3).

The paper is organized as follows. The next section introduces the model developed for the three situations (S1, S2, S3) presented above. Section 3.3 presents the main results in terms of space consumption, utility and social welfare. Section 3.4 draws the social welfare analysis and investigates the space consumption rates to be set by the public authority. Section 3.5 concludes.

3.2 The model

We consider an economy with two commodities: parking spaces, also called "space" (s), and a composite good (x). Space is allocated among a continuum of N agents, simplified to 2 agents without loss of generality[37]. Any agent $k = i, j$ aims to maximize her own utility expressed by the following utility function: $u_k(s, x) = \alpha_k \ln s_k + \ln x_k$. Agents draw their utility from the consumption of both commodities (s_k, x_k). Utility is supposed to increase with space consumption. Moreover, we assume that both commodities are necessary. Consequently, we use logarithmic utility functions, since they satisfy the Inada conditions $(s_k, x_k > 0)$. Any agent has a relative preference α_k for parking spaces compared to composite good, with $\alpha_k > 0$. Preferences depend on the quality of space, not on prices.

We suppose that any agent faces two constraints: a budget constraint and a spatial constraint. The budget constraint is assumed to be saturated, so that $R_k = p_s s_k + p_x x_k$. Let R_k be the income of agent k. A price p_s applies to any agent for the consumption of a unit of space. Similarly, a price p_x is set for a unit of composite good. As in standard fisheries models, revenues and prices are set exogenously. Consumers are price-takers and compete with one another. The spatial constraint means that space consumption is limited by the total quantity of space available in the economy, noted $\overline{S}$, so that $s_k \leq \overline{S}$. The sum of the quantities consumed by agents cannot exceed the total space available, so that $\sum_{k=1}^{n} s_k \leq \bar{S}$ for n agents. The

37. In a more realistic approach, the agents we are bringing into play in the model must be considered as categories of agents, with each category entailing several agents.

spatial constraint introduces interdependent relationships between agents. Indeed, space consumptions are interrelated and generate rivalry of use. Furthermore, a particular agent cannot consume the whole space. It is assumed that agents need a minimum quantity of space, so that $s_k \geq \underline{s} > 0$, with $\underline{s}$ a norm or a right for agents. We suppose that anyone can afford this minimum quantity, $R_k > p_s\underline{s}$, and that the remaining revenue left for composite good is positive, $\widetilde{R}_k > 0$. Finally, the model considers that the total space available is equal to or larger than the sum of minimal quantities for each agent, so that $\bar{S} \geq \sum_{k=1}^{n} \underline{s}$ in case of n agents. In addition, we assume a fixed share x of public parking space in the city. The urban area is assumed to be surrounded by natural space.

The allocation process is described first for homogeneous agents, taken as a benchmark, and then for heterogeneous agents. Homogeneous agents are defined with identical revenues ($R_i = R_j$) and preferences ($u_i(s,x) = u_j(s,x)$ with $\alpha_i = \alpha_j$). On the contrary, heterogeneous agents are defined with different revenues ($Ri \neq Rj$) and preferences ($u_i(s,x) \neq u_j(s,x)$ with $\alpha_i \neq \alpha_j$).

Agents can have either strong or low relative preferences for parking spaces. If both agents have low relative preferences for space, each agent consumes only a small share of the total space. As the resource is not fully consumed, there is no use competition and hence no need for regulation. On the other hand, if both agents have strong relative preferences for parking spaces, conflicts of use arise.

We develop simple theoretical utility maximization models for three situations (S): simultaneous space allocation (S1), sequential space allocation without public intervention (S2), and sequential space allocation with public intervention (S3). Under each situation, four possible cases (C) are identified[38]: whether a shadow cost is associated with the spatial constraint on quantities or not[39], and whether

38. Under S1 and S3, the four cases appear (C1, C2, C1' and C2'), while under S2, only C1 and C2 appear since one of the two spatial constraints is dropped.

39. For the sake of simplicity, we distinguish cases for which there is a shadow cost associated with

Table 3.1: Four cases emerge under each situation

	No shadow cost $\mu_k = 0$ thus $s_i + s_j \leq \bar{S}$	Shadow cost $\mu_k > 0$ thus $s_i + s_j = \bar{S}$
Unconstrained space consumption $\gamma_k = 0$ thus $s_k \geq \underline{s}$	**CASE 1** Low competition	**CASE 2** High competition
Constrained space consumption $\gamma_k > 0$ thus $s_k = \underline{s}$	**CASE 1'**	**CASE 2'**

exogenous features constrain space consumption or not. Exogenous features are social or cultural norms about the minimum space requirement, or demographical features constraining the space consumed by each agent. We note μ_k the shadow cost associated with the spatial constraint on quantities. Let γ_k be the marginal cost derived from the consumption of the minimum quantity. Table 3.1 describes the cases. In Case 1 (C1), no shadow cost is associated with the spatial constraint on quantities and its consumption is not constrained by exogenous features. In Case 1' (C1'), no shadow cost is associated with the spatial constraint on quantities but its consumption is constrained by exogenous features. In Case 2 (C2), a shadow cost is associated with the spatial constraint on quantities and its consumption is not constrained by exogenous features. In Case 2' (C2), a shadow cost is associated with the spatial constraint on quantities but its consumption is constrained by exogenous features. Thereafter, we are especially interested in the comparison between Case 1

the spatial constraint on quantities, from cases for which there is no such shadow cost. However, it would be more thorough to mention that a shadow cost is associated with every cases, but that it may be positive ('shadow cost') or equal to zero ('no shadow cost'). Therefore, when we mention that there is a shadow cost, the reader should understand that there is a *positive* shadow cost. Similarly, when we mention that there is no shadow cost, the reader should understand that there is *no positive* shadow cost, so the shadow cost is equal to zero.

and Case 2. In Case 1, competition for parking spaces is relatively low and space may not be wholly consumed, while in Case 2, competition is relatively high, and the whole space is consumed. Competition arises when a shadow cost is associated with the spatial constraint on quantities.

3.2.1 Simultaneous space allocation (S1)

First, we build a utility maximization model for the situation of simultaneous space allocation (S1). Competing for parking spaces, agents adjust their consumption levels simultaneously to reach equilibrium, as in a perfectly competitive market economy. The utility maximization model of any agent $k = i, j$ is as follows:

$$\max_{s_k, x_k} u_k (s, x) = \alpha_k \ln s_k + \ln x_k \tag{3.1}$$

$$s.t. \begin{cases} R_k = p_s s_k + p_x x_k \\ s_i + s_j \leq \bar{S} \\ s_k \geq \underline{s} \end{cases}$$

We use the Karush-Kuhn-Tucker method to solve the above maximization model:

$$L (s_k, x_k, \lambda_k, \mu_k, \gamma_k) = \alpha_k \ln s_k + \ln x_k + \lambda_k (R_k - p_s s_k - p_x x_k) + \mu_k \left(\bar{S} - s_i - s_j\right) + \gamma_k (s_k - \underline{s}) \tag{3.2}$$

with λ_k the marginal value of revenue for any agent k. Any agent is constrained by (1) her budget, (2) the total quantity of space available in the economy, and (3) a minimum amount of space she has to consume.

For any agent k, the first-order conditions are:

$$\begin{cases} \frac{\partial L}{\partial s_k} = \frac{\alpha_k}{s_k} - \lambda_k p_s - \mu_k + \gamma_k = 0 \\ \frac{\partial L}{\partial x_k} = \frac{1}{x_k} - \lambda_k p_x = 0 \\ \frac{\partial L}{\partial \lambda_k} = R_k - p_s s_k - p_x x_k = 0 \\ \mu_k \left(\bar{S} - s_i - s_j\right) = 0 \\ \mu_k \geq 0 \\ \bar{S} - s_i - s_j \geq 0 \\ \gamma_k \left(s_k - \underline{s}\right) = 0 \\ \gamma_k \geq 0 \\ s_k - \underline{s} \geq 0 \end{cases} \tag{3.3}$$

Solving the program 3.1, we find the following space consumptions: $s_k = \left(\frac{\alpha_k}{1+\alpha_k}\right)\left(\frac{R_k}{p_s}\right) \geq \underline{s}$ in C1, and $s_k = \underline{s}$ in C1' for both homogeneous and heterogeneous agents, as well as $s_k = \left(\frac{\bar{S}}{2}\right) \geq \underline{s}$ in C2 and $s_k = \left(\frac{\bar{S}}{2}\right) = \underline{s}$ in C2' for homogeneous agents, and $s_i = \bar{S} - s_j$ and $s_j = \bar{S} - s_i$ for heterogeneous agents given that $s_k \geq \underline{s}$ in C2 and $s_k = \underline{s}$ in C2'.

3.2.2 Sequential space allocation without public intervention (S2)

Second, we build a utility maximization model for the situation of sequential space allocation without public intervention (S2). Agents access the market sequentially. Some categories of agents may access parking spaces first and therefore limit the amount left to others. We assume that agent i maximizes her utility first. Her spatial constraint is defined by the whole space available minus the minimum quantity to be consumed by the other agent, so that $s_i \leq \overline{S} - \underline{s}$. As agent i disposes of almost the whole space, we suppose that she is able to consume the minimal quantity required. Hence, we remove the second spatial constraint, $s_k \geq \underline{s}$. The space left after the first agent's consumption is then $\overline{S}' = \overline{S} - s_i$ to be shared among the other agents. The utility maximization model of agent i is as follows:

$$\max_{s_i, x_i} u_i\left(s, x\right) = \alpha_i \ln s_i + \ln x_i \tag{3.4}$$

$$s.t. \begin{cases} R_i = p_s s_i + p_x x_i \\ s_i \leq \bar{S} - \underline{s} \end{cases}$$

given that $s_k \geq \underline{s}$, we get

$$L\left(s_i, x_i, \lambda_i, \mu_i\right) = \alpha_i \ln s_i + \ln x_i + \lambda_i \left(R_i - p_s s_i - p_x x_i\right) + \mu_i \left(\bar{S} - \underline{s} - s_i\right) \tag{3.5}$$

Agent j maximizes her utility in second position. By analogy, we obtain the utility maximization model of agent j. The spatial constraint turns to $s_j \leq \bar{S}'$.

Solving the program 3.4, we find the following space consumptions:
$s_k = \left(\frac{\alpha_k}{1+\alpha_k}\right)\left(\frac{R_k}{p_s}\right) \geq \underline{s}$ in C1, and $s_i = \bar{S} - \underline{s}$ and $s_j = \underline{s}$ in C2 for both homogeneous and heterogeneous agents.

3.2.3 Sequential space allocation with public intervention (S3)

Third, we build a utility maximization model for the situation of sequential space allocation with public intervention (S3). Agents access the market sequentially, but the public authority intervenes to set space consumption rates. The aim is to protect agents accessing parking spaces in second position. The space consumption rate is noted τ for agent i, and $(1-\tau)$ for agent j, with $0 < \tau < 1$. It represents a maximum threshold as regards space consumption. The space consumption of agent i (agent j) cannot exceed a certain share of the total space, so that $s_i \leq \tau \overline{S}$ ($s_j \leq (1-\tau)\overline{S}$). Space consumption rates are supposed to be set according to agents' relative preferences for parking spaces and their income. Agent i maximizes her utility first. The utility maximization model of agent i is as follows:

$$\max_{s_i, x_i} u_i (s, x) = \alpha_i \ln s_i + \ln x_i \tag{3.6}$$

$$s.t. \begin{cases} R_i = p_s s_i + p_x x_i \\ s_i \leq \tau \bar{S} \\ s_i \geq \underline{s} \end{cases}$$

we get

$$L (s_i, x_i, \lambda_i, \mu_i, \gamma_i) = \alpha_i \ln s_i + \ln x_i + \lambda_i (R_i - p_s s_i - p_x x_i) + \mu_i \left(\tau \bar{S} - s_i\right) + \gamma_i (s_i - \underline{s}) \tag{3.7}$$

By analogy, we obtain the utility maximization model of agent j. The spatial constraints turn to $s_j \leq (1 - \tau) \bar{S}$ and $s_j \geq \underline{s}$.

Solving the program 3.6, we find the following space consumptions: $s_k = \left(\frac{\alpha_k}{1+\alpha_k}\right) \left(\frac{R_k}{p_s}\right) \geq \underline{s}$ in C1, and $s_k = \underline{s}$ in C1' for both homogeneous and heterogeneous agents, as well as $s_i = \tau \bar{S}$ and $s_j = (1 - \tau) \bar{S}$ for homogeneous and heterogeneous agents, given that $s_i = s_j \geq \underline{s}$ in C2 and $s_i = s_j = \underline{s}$ in C2'. Section 3.4 presents the social welfare analysis using τ; its functional form is specified thereafter. Before drawing the social welfare analysis, let us analyze the results.

3.3 Results

Results are presented situation by situation (S1, S2, S3), then case by case (C1, C2) [40].

40. When discussing the results, we focus on C1 and C2 only, since in these cases only agents can choose their space consumption to be larger than the minimum space requirement. Indeed, in C1' and C2', space consumption is constrained by exogenous features such as social/cultural norms or demographical pressures and agents have no other choice but to consume the minimal quantity of space. The tradeoffs resulting from these cases are interesting under particular conditions and

3.3.1 Situation-by-situation results (S1, S2, S3)

Each situation allows for a comparison between the indirect utilities achieved by both agents. The indirect utility is derived from the optimal consumption of both goods, so that $V_k\left(R_k, p_s, p_x, \bar{S}, \underline{s}, \alpha_k\right) = u_k\left(s^*, x^*\right)$ for any agent k. Under each situation, different cases are possible and results may differ according to the case considered. Hence, within a given situation, comparison is made between cases. We then give a measure of the social welfare obtained under the situation analyzed. The utilitarian form of social welfare is expressed as $W = \eta V_i + \varphi V_j$, with equal weights given to the utilities of the two agents. We define the social welfare as the aggregation of the indirect utilities of all agents constituting the society, so that $W = \sum_{k=1}^{n} V_n$ for n agents. In our model, we have two agents, agent i and agent j.

Simultaneous space allocation (S1)

Results found for any agent k under simultaneous space allocation (S1) are summarized in Table 3.2 (homogeneous agents) and Table 3.3 (heterogeneous agents), Appendix A, Section 3.6.1. Under simultaneous allocation, we note $V_k^{Sim(l)}$ the indirect utilities whatever the case $l = 1, 2, 1', 2'$. They are detailed in Table 3.4 (homogeneous agents) and Table 3.5 (heterogeneous agents), Appendix A, Section 3.6.1. When agents are homogeneous, we find that indirect utilities are equivalent whatever the case considered: $V_i^{Sim(l)} = V_j^{Sim(l)}$, with $s_i = s_j$. Agents have equal space consumption. When agents are heterogeneous, we get $V_i^{Sim(l)} \gtrless V_j^{Sim(l)}$, with $s_i \gtrless s_j$. Space consumption differs between agents [41], according to their relative preferences for parking spaces and their income. No agent is clearly better off than the other. We denote by $W^{Sim(l)}$ the social welfare under simultaneous space allocation, so

raise concerns different from those in which we are interested in this article. These particular cases could be investigated further in future research. Detailed results for C1' and C2' are yet provided in appendices.

41. A particular case appears when the difference in the relative preferences for parking spaces is exactly compensated by an inverse difference in income, leading to $s_i = s_j$ even for heterogeneous agents. Although quite unlikely, it is not to be excluded.

that $W^{Sim(l)} = V_i^{Sim(l)} + V_j^{Sim(l)}$.

Lemma 1 - *Under simultaneous space allocation, no agent is clearly better off than the other, whatever the case considered (C1 and C2).*

Sequential space allocation without public intervention (S2)

Results found for any agent k under sequential space allocation without public intervention (S2) are summarized in Table 3.6 (homogeneous and heterogeneous agents), Appendix B, Section 3.6.2. Under sequential allocation, we note $V_k^{Seq(l)}$ the indirect utilities whatever the case $l = 1, 2, 1', 2'$. They are detailed in Table 3.7 (homogeneous and heterogeneous agents), Appendix B, Section 3.6.2. When agents are homogeneous, their indirect utilities are equivalent in Case 1: $V_i^{Seq(1)} = V_j^{Seq(1)}$ with $s_i = s_j$. However in Case 2, the agent maximizing her utility first (here, agent i) clearly gets a higher utility [42] than the other agent (here, agent j): $V_i^{Seq(2)} > V_j^{Seq(2)}$ with $s_i > s_j$. When agents are heterogeneous, in Case 1 we get $V_i^{Seq(1)} \gtrless V_j^{Seq(1)}$ with $s_i \gtrless s_j$. Space consumption differs between agents, according to their relative preferences for parking spaces and their income. No agent is clearly better off than the other. However in Case 2, all other things being equal, the agent maximizing her utility first (here, agent i) clearly gets a higher utility than the other agent (here, agent j): $V_i^{Seq(2)} > V_j^{Seq(2)}$ with $s_i > s_j$. This interpretation may not hold if agent i has lower relative preferences for parking spaces, and a lower income than agent j. We note $W^{Seq(l)}$ the social welfare under sequential space allocation without public intervention, so that $W^{Seq(l)} = V_i^{Seq(l)} + V_j^{Seq(l)}$.

Lemma 2a - *Under sequential space allocation without public intervention and when no shadow cost is associated with the spatial constraint on quantities (C1), no agent is clearly better off than the other.*

Lemma 2b - *Under sequential space allocation without public intervention and*

42. This finding holds only when $(\overline{S} - \underline{s}) > \underline{s}$, i.e., when $\overline{S} > 2\underline{s}$ for an economy with 2 agents.

when a shadow cost is associated with the spatial constraint on quantities (C2), agent j is clearly worse off than agent i.

Sequential space allocation with public intervention (S3)

Results found for any agent k under sequential space allocation with public intervention (S3) are summarized in Table 3.8 (homogeneous and heterogeneous agents), Appendix C, Section 3.6.3. Under sequential allocation with public intervention, we note $V_k^{SeqPI(l)}$ the indirect utilities whatever the case $l = 1, 2, 1', 2'$. They are detailed in Table 3.9 (homogeneous and heterogeneous agents), Appendix C, Section 3.6.3. When agents are homogeneous, we expect the respective rates of space consumption τ and $(1-\tau)$ to be equal, so that $\tau = (1-\tau) = 0.5$. Consequently, their indirect utilities are equivalent whatever the case: $V_i^{SeqPI(l)} = V_j^{SeqPI(l)}$ with $s_i = s_j$. When agents are heterogeneous, we get $V_i^{SeqPI(l)} \gtrless V_j^{SeqPI(l)}$ with $s_i \gtrless s_j$. The public authority regulation limits the quantity of space agent i can acquire. Space consumption differs between agents, according to the rates set. Since space consumption rates are supposed to be set according to agents' relative preferences for parking spaces and their income, no agent is clearly better off than the other. We note $W^{SeqPI(l)}$ the social welfare under sequential space allocation with public intervention, so that $W^{SeqPI(l)} = V_i^{SeqPI(l)} + V_j^{SeqPI(l)}$.

Lemma 3 - *Under sequential space allocation with public intervention, no agent is clearly better off than the other, whatever the case considered (C1 and C2).*

3.3.2 Case-by-case results (C1, C2)

Each case is explored in terms of space consumption, indirect utilities and social welfare. Similarly, for each case several situations can occur. Hence, within a given case, comparison is made between situations. We discuss first results for homogeneous agents, then for heterogeneous agents.

Low competition case (C1)

In Case 1, there is no shadow cost associated with the spatial constraint on quantities ($\mu_k = 0$). Provided that the total quantity of space available, $\overline{S}$, is not constrained by exogenous features such as demography or sociology ($\gamma_k = 0$), agents are able, if desired, to obtain a quantity of space larger than the minimal quantity, so that $s_k \geq \underline{s}$. In this case, the space available may not be fully consumed, so that $s_i + s_j \leq \overline{S}$. Therefore, competition for parking spaces is relatively low. Case 1 is consistent with low relative preferences for parking spaces.

The optimal space consumption of agent k is given by $s_k = \left(\frac{\alpha_k}{1+\alpha_k}\right)\left(\frac{R_k}{p_s}\right)$ under all three situations (S1, S2, S3) and for homogeneous as well as heterogeneous agents. Space consumption depends on agents' relative preferences for parking spaces, as well as on their income and the price of the resource. All things being equal, the higher the relative preferences for parking spaces, the larger the quantity of space consumed, and the smaller the quantity of composite good consumed.

In Case 1, the indirect utilities present a similar structure whatever the situation analyzed:
$V_k^{(1)} = V_k^{Sim(1)} = V_k^{Seq(1)} = V_k^{SeqPI(1)} = \alpha_k \left[\ln\left(\frac{\alpha_k}{1+\alpha_k}\right) + \ln\left(\frac{R_k}{p_s}\right)\right] + \left[\ln\left(\frac{1}{1+\alpha_k}\right) + \ln\left(\frac{R_k}{p_x}\right)\right]$.
Homogeneous agents achieve identical utilities, so that $V_i^{(1)} = V_j^{(1)}$ with $V_i^{Sim(1)} = V_i^{Seq(1)} = V_i^{SeqPI(1)}$ and $V_j^{Sim(1)} = V_j^{Seq(1)} = V_j^{SeqPI(1)}$. When agents are heterogeneous, they obtain different utilities depending on their relative preferences for parking spaces and respective incomes, so that $V_i^{(1)} \gtrless V_j^{(1)}$ with $V_i^{Sim(1)} = V_i^{Seq(1)} = V_i^{SeqPI(1)}$ and $V_j^{Sim(1)} = V_j^{Seq(1)} = V_j^{SeqPI(1)}$. No agent is clearly better off the other. Likewise, the social welfare is similar whatever the situation considered. It is

expressed as follows:

$$\begin{aligned}
W^{Sim(1)} &= W^{Seq(1)} = W^{SeqPI(1)} \\
&= V_i^{(1)} + V_j^{(1)} \\
&= \left\{ \alpha_i \left[\ln\left(\frac{\alpha_i}{1+\alpha_i}\right) + \ln\left(\frac{R_i}{p_s}\right)\right] + \left[\ln\left(\frac{1}{1+\alpha_i}\right) + \ln\left(\frac{R_i}{p_x}\right)\right]\right\} \\
&+ \left\{ \alpha_j \left[\ln\left(\frac{\alpha_j}{1+\alpha_j}\right) + \ln\left(\frac{R_j}{p_s}\right)\right] + \left[\ln\left(\frac{1}{1+\alpha_j}\right) + \ln\left(\frac{R_j}{p_x}\right)\right]\right\}
\end{aligned} \tag{3.8}$$

Consequently, when no shadow cost is associated with the spatial constraint on quantities (C1), the various situations (S1, S2, S3) are equivalent. Agents are therefore indifferent between the three situations.

Proposition 1 - *When no shadow cost is associated with the spatial constraint on quantities (C1), the various situations (S1, S2, S3) are equivalent.*

High competition case (C2)

In Case 2, a shadow cost is associated with the spatial constraint on quantities ($\mu_k > 0$). Provided that the total quantity of space available, $\overline{S}$, is not constrained by exogenous features such as demography or sociology ($\gamma_k = 0$), agents are able, and desire, to obtain a quantity of space larger than the minimal quantity, so that $s_k \geq \underline{s}$. As a shadow cost is associated with the spatial constraint, Case 2 is consistent with high relative preferences for parking spaces. Agents compete against one another to get the largest quantity of space possible, within their budget and spatial constraints. Competition for parking spaces is relatively high. Therefore, the space available is fully consumed, so that $s_i + s_j = \overline{S}$.

The optimal space consumptions vary according to the situation considered. Under simultaneous space allocation (S1), the optimal space consumptions are given by $s_k = \left(\frac{\bar{S}}{2}\right)$ for homogeneous individuals, and by $s_i = \bar{S} - s_j$ and $s_j = \bar{S} - s_i$, for heterogeneous individuals. The total space available is shared between agents, either equally (homogeneous agents) or not (heterogeneous agents). Under sequential space allocation without public intervention (S2), the optimal space consumptions are $s_i = \bar{S} - \underline{s}$ and $s_j = \underline{s}$ for both homogeneous and heterogeneous individuals when agent i accesses parking spaces first. Agent i obtains the maximum quantity of the space available in the economy (i.e., the whole space minus the minimum quantity required for the other agent). Agent j is then not able to get anything but the minimum quantity. Under sequential space allocation with public intervention (S3), the optimal space consumptions are $s_i = \tau \bar{S}$ and $s_j = (1-\tau)\bar{S}$ for both homogeneous and heterogeneous individuals when agent i accesses parking spaces first. For homogeneous agents, the optimal rates of space consumption is $\tau = (1-\tau) = 0.5$. For heterogeneous agents, the optimal rates of space consumption differ, with $0 < \tau < 1$. Since the rates set by the public authority are based on agents' relative preferences, space consumption depends on agents' preferences.

In Case 2, the indirect utilities vary according to the situation analyzed. Under simultaneous space allocation (S1), homogeneous agents achieve a level of utility given by $V_k^{Sim(2)} = \alpha_k \left[\ln \bar{S} - \ln 2\right] + \left[\ln \widetilde{R}_k - \ln p_x\right]$, with $V_i^{Sim(2)} = V_j^{Sim(2)}$. The indirect utility for heterogeneous agents is $V_i^{Sim(2)} = \alpha_i \left[\ln\left(\bar{S} - s_j\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]$ and $V_j^{Sim(2)} = \alpha_j \left[\ln\left(\bar{S} - s_i\right)\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]$, with $V_i^{Sim(2)} \gtreqless V_j^{Sim(2)}$. No agent is clearly better off than the other. Under sequential space allocation without public intervention (S2), for both homogeneous and heterogeneous agents we have $V_i^{Seq(2)} = \alpha_i \left[\ln\left(\bar{S} - \underline{s}\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]$ and $V_j^{Seq(2)} = \alpha_j \left[\ln \underline{s}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]$, with $V_i^{Seq(2)} \neq V_j^{Seq(2)}$. All other things being equal, agent i is better off than agent j, so $V_i^{Seq(2)} > V_j^{Seq(2)}$. Under sequential resource allocation with public intervention (S3), we obtain $V_i^{SeqPI(2)} = \alpha_i \left[\ln \tau + \ln \bar{S}\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]$ and $V_j^{SeqPI(2)} = \alpha_j \left[\ln(1-\tau) + \ln \bar{S}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]$, with $V_i^{SeqPI(2)} = V_j^{SeqPI(2)}$ for homogeneous agents and $V_i^{SeqPI(2)} \gtreqless V_j^{SeqPI(2)}$ for heteregeneous agents. No agent is clearly better off than the other. Comparative statics related to the shadow cost associated with the spatial constraint on quantities are presented in Appendix D, Section 3.6.4.

The social welfare differs according to the situation considered. Under S2, agent j has no other choice but to consume only the minimum quantity of space. The agent maximizing her utility in second position is clearly worse off. We prove that her low utility level cannot be fully compensated by the high utility level of agent j. Therefore and all other things being equal, the social welfare achieved under S2 is lower than that expected under the other situations (S1, S3), for both homogeneous and heterogeneous agents. We have $W^{Seq(2)} < W^{Sim(2)}$ and $W^{Seq(2)} < W^{SeqPI(2)}$, so that:

$$\begin{aligned} V_i^{Seq(2)} + V_j^{Seq(2)} &< V_i^{Sim(2)} + V_j^{Sim(2)} \Leftrightarrow \\ &\left\{\alpha_i \left[\ln\left(\bar{S} - \underline{s}\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]\right\} + \left\{\alpha_j \left[\ln \underline{s}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]\right\} \\ &< \left\{\alpha_i \left[\ln \bar{S} - \ln 2\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]\right\} + \left\{\alpha_j \left[\ln \bar{S} - \ln 2\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]\right\} \end{aligned} \tag{3.9}$$

and

$$\begin{aligned} V_i^{Seq(2)} + V_j^{Seq(2)} &< V_i^{SeqPI(2)} + V_j^{SeqPI(2)} \Leftrightarrow \\ &\left\{\alpha_i \left[\ln\left(\bar{S} - \underline{s}\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]\right\} + \left\{\alpha_j \left[\ln \underline{s}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]\right\} \\ &< \left\{\alpha_i \left[\ln \tau + \ln \bar{S}\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]\right\} + \left\{\alpha_j \left[\ln(1-\tau) + \ln \bar{S}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]\right\} \end{aligned} \tag{3.10}$$

with $W^{Sim(2)} = W^{SeqPI(2)}$ when τ is optimally set. Consequently, when there is a shadow cost associated with the spatial constraint, a sequential allocation without public intervention (S2) results in a lower social welfare. The various situations (S1, S2, S3) are not equivalent in terms of social welfare achieved. Neither are they equivalent for the agents. Agent i prefers S2 ($V_i^{Seq(2)} > V_i^{Sim(2)}$ and $V_i^{Seq(2)} > V_i^{SeqPI(2)}$), while agent j goes for S1 or S3 ($V_j^{Sim(2)} > V_j^{Seq(2)}$ and $V_j^{SeqPI(2)} > V_j^{Seq(2)}$).

Proposition 2 - *When a shadow cost is associated with the spatial constraint, a* *sequential allocation without public intervention (S2) results in a lower social welfare.*

3.4 Social welfare analysis

Given the limited but necessary nature of space, a shadow cost is likely to be associated with the spatial constraint. Case 2 is therefore the most plausible case. Moreover, we assume that the society wants to move towards the highest welfare achievable. Since open access resources are prone to market failures, simultaneous allocation of space is unlikely to happen. A sequential allocation would rather take place. Without any public intervention, a sequential allocation results in a lower social welfare than that expected under simultaneous allocation. A public authority can intervene to guarantee optimal welfare to society. Its role is to set a space consumption rate τ that is optimal to ensure optimal social welfare. The public authority sets a space consumption rate τ that maximizes the social welfare:

$$\max_{\tau} W^{SeqPI(2)} = \alpha_i \left[\ln \tau + \ln \bar{S}\right] + \left[\ln \widetilde{R}_i - \ln p_x\right] + \alpha_j \left[\ln (1-\tau) + \ln \bar{S}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right] \tag{3.11}$$

The F.O.C. are:

$$\frac{\partial W^{SeqPI(2)}}{\partial \tau} = 0 \Leftrightarrow W^{SeqPI(2)\prime} = \left(\frac{\alpha_i}{\tau}\right) - \left(\frac{p_s \bar{S}}{R_i - p_s \tau \bar{S}}\right) - \left(\frac{\alpha_j}{(1-\tau)}\right) + \left(\frac{p_s \bar{S}}{R_j - p_s (1-\tau) \bar{S}}\right) = 0 \tag{3.12}$$

which can be split up into two subfunctions as follows:

$$\left(\frac{\alpha_i}{\tau}\right) - \left(\frac{\alpha_j}{(1-\tau)}\right) = \left(\frac{p_s \bar{S}}{R_i - p_s \tau \bar{S}}\right) - \left(\frac{p_s \bar{S}}{R_j - p_s (1-\tau) \bar{S}}\right) \tag{3.13}$$

with

$$g(\tau) = \left(\frac{\alpha_i}{\tau}\right) - \left(\frac{\alpha_j}{(1-\tau)}\right) \qquad (3.14)$$
$$f(\tau) = \left(\frac{p_s\bar{S}}{R_i - p_s\tau\bar{S}}\right) - \left(\frac{p_s\bar{S}}{R_j - p_s(1-\tau)\bar{S}}\right)$$

We find:

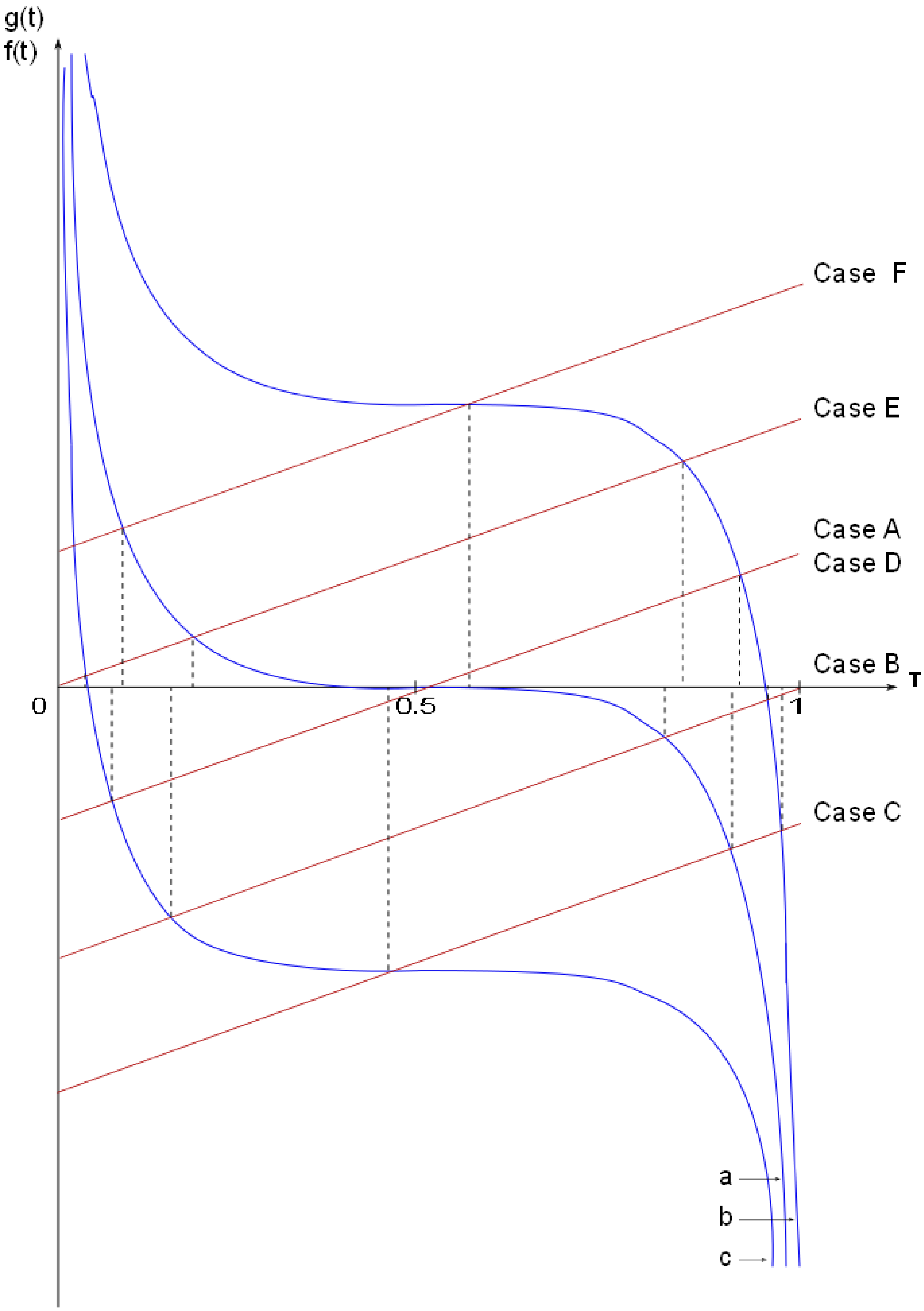
$$g'(\tau) = -\frac{\alpha_i}{\tau^2} - \frac{\alpha_j}{(1-\tau)^2} < 0 \qquad (3.15)$$
$$f'(\tau) = \left(\frac{p_s\bar{S}}{R_i - p_s\tau\bar{S}}\right)^2 + \left(\frac{p_s\bar{S}}{R_j - p_s(1-\tau)\bar{S}}\right)^2 > 0$$

$g(\tau)$ is a decreasing function, with $\lim_{\tau\to 0}(\tau) = +\infty$, $\lim_{\tau\to 1}(\tau) = -\infty$ and $g(\tau) = 0$ when $\tau = \left(\frac{\alpha_i}{\alpha_i+\alpha_j}\right)$. Since $g''(\tau) = 0$ when $\tau = (1-\tau) = 0.5$, there exists an inflection point so that $g(0.5) = 0$ when $\alpha_i = \alpha_j$ (a), $g(0.5) > 0$ when $\alpha_i > \alpha_j$ (b), and $g(0.5) < 0$ when $\alpha_i < \alpha_j$ (c).

$f(\tau)$ is an increasing function, whose limits vary according to various cases:

- Case A: R_i is slightly larger than R_j
  $R_j + p_s\bar{S} > R_i > R_j$, with $\lim_{\tau\to 0}(\tau) < 0$ and $\lim_{\tau\to 1}(\tau) > 0$
- Case B: R_i is larger than R_j
  $R_j + p_s\bar{S} = R_i > R_j$, with $\lim_{\tau\to 0}(\tau) < 0$ and $\lim_{\tau\to 1}(\tau) = 0$
- Case C: R_i is strongly larger than R_j
  $R_i > R_j + p_s\bar{S}$, with $\lim_{\tau\to 0}(\tau) < 0$ and $\lim_{\tau\to 1}(\tau) < 0$
- Case D: R_i is slightly smaller than R_j
  $R_j > R_i > R_j - p_s\bar{S}$, with $\lim_{\tau\to 0}(\tau) < 0$ and $\lim_{\tau\to 1}(\tau) > 0$
- Case E: R_i is smaller than R_j
  $R_j > R_i = R_j - p_s\bar{S}$, with $\lim_{\tau\to 0}(\tau) = 0$ and $\lim_{\tau\to 1}(\tau) > 0$
- Case F: R_i is strongly smaller than R_j

Figure 3.1: Optimal space allocation rates



$R_i < R_j - p_s\bar{S}$, with $\lim_{\tau\to 0}(\tau) > 0$ and $\lim_{\tau\to 1}(\tau) > 0$

Case A is close to Case D. For clarity purposes, they are merged in the following graph.

The optimal rates τ^* obtained under the various cases considered above are illustrated in Figure 3.1. We expect $\tau = (1-\tau) = 0.5$ for homogeneous agents, and $\tau \neq (1-\tau)$ for heterogeneous agents. The lower income inequalities (as in Case A or D), the closer to 0.5 the rate is. All other things being equal, the higher the income or the relative preferences for parking spaces, the larger the space consumption rate. When the higher-incomer displays higher relative preferences for parking spaces than the lower-incomer, then τ^* moves away from 0.5. However, if the higher-incomer displays lower relative preferences for parking spaces than the lower-incomer, then τ^* moves closer to 0.5.

Furthermore, the relation between the social welfare and the price of space (p_s), or the total quantity of space available ($\overline{S}$), is consistent with the intuition. Indeed, it is equivalent to reduce the price of space along with an increase in the total quantity, and to increase the price of space while reducing the total quantity available. Increasing p_s or $\bar{S}$ moves $f(\tau)$ upwards when $R_i > R_j$ (the slope of the function increases), which means that τ^* decreases, or downwards when $R_i < R_j$ (the slope of the function increases too), which means that τ^* increases. Therefore, all other things being equal, increasing the price of space or the quantity available brings τ^* closer to 0.5. The resource is then shared more equally in order to maintain the highest social welfare possible.

3.5 Concluding remarks

This article explores the basic mechanisms underpinning space allocation. We especially highlight the role the shadow cost plays in the allocation process. We demonstrate that space consumption and utility obtained by homogeneous and heterogeneous agents vary according to the allocation process. The social welfare differs too. We show that under sequential resource allocation and when a shadow cost is associated with the spatial constraint, the social welfare is lower than expected under other situations. Market failures arise and lead to a pressure towards the creation of additional parking spaces. New parking spaces will be created through land use changes, thus limiting other uses. Moreover, when natural uses are turned into urban uses (so called phenomenon of "land artificialization"), environmental externalities are generated, in particular irreversibility of land use changes, loss of biodiversity, ecosystem fragmentation and lower resilience.

We highlight the fact that the creation of additional parking spaces can be overcome with appropriate public intervention. It is a question of first recognizing and then internalizing the shadow cost associated with the spatial constraint. The model aims to investigate the optimal space consumption rates to be set in order to prevent pressures towards more parking spaces. The optimal space consumption rate proves straightforward for homogeneous agents, with space shared equally. When agents are heterogeneous, the optimal rate depends on the relative size of the preferences for parking spaces and of the respective incomes of agents.

One of the main limits of this article relates to the structure of the model. Indeed, a one-period model does not allow us to observe the effective creation of additional parking spaces. However, we can assume that the public authority regulates the creation of artificial surfaces. Even when it does not directly intervene in the allocation process, it can set a maximum quantity ρ to be turned into parking spaces in case of pressure towards more parking uses. In this case, in period 2, the total parking space to be allocated among agents would be $\overline{S} + \rho$. Moreover, two mechanisms can alter the absolute scarcity over time and are not accounted for in the present analysis: the extensive margin and the intensive margin. The former mechanism, the extensive margin, means that land use changes allow for the creation of additional park spaces (urban sprawl). The latter mechanism, the intensive margin, means that more needs would be met with a finite stock of park spaces (urban densification).

Another limit relates to the choice of the resource: parking space. Optimization regards parking space as a homogeneous resource. Yet though the apparent homogeneity of parking spaces, space can also be considered as heterogeneous. Urban lands may face different topographical constraints, infrastructure endowments or accessibility (Saiz, 2010). Agents' preferences would vary according to the type of space (horizontal vs. vertical[43]), its localization, existing amenities (urban or environmental) on the space or nearby, etc. A research perspective is to take into account the heterogeneity of space through a multi-amenity approach.

Finally, following the emission trading scheme conceived by Coase (1960) and elaborated by Dales (1968) for water resources, our model could be enriched with the creation of a market scheme of space consumption rights for parking. The trading scheme would substitute for the introduction of a space consumption rate set exogenously by the public authority. It would allow agents with low preferences for parking spaces to exchange part of the space they could acquire with agents having higher preferences for parking spaces but who were not able to get as much space as desired. According to Hannesson (2004), individual transferable quotas are a first best regulatory regime for open access resources.

43. Vertical space, such as multi-floor parking facilities, and horizontal space, such as on-street parking.

3.6 Appendices

3.6.1 Appendix A: Simultaneous space allocation (S1)

Results and indirect utilities found in Case 1 and Case 1' under simultaneous space allocation are identical for homogeneous and heterogeneous agents. The only difference to keep in mind is that $\alpha_i = \alpha_j$ and $R_i = R_j$ for homogeneous agents, while $\alpha_i \neq \alpha_j$ and $R_i \neq R_j$ for heterogeneous agents. Table 3.3 and Table 3.5 only include the results and indirect utilities that differ.

Let us check the conditions under which μ_k is strictly positive.

$\mu_k = \left(\frac{\alpha_k}{\left(\frac{1}{2}\right)\bar{S}}\right) - \left(\frac{p_s}{\tilde{R}_k}\right) > 0$

$\mu_k = \left(\frac{\alpha_k}{\left(\frac{1}{2}\right)\bar{S}}\right) - \left(\frac{p_s}{R_k - \left(\frac{1}{2}\right)p_s\bar{S}}\right) > 0$

$R_k > \left(\frac{1+\alpha_k}{\alpha_k}\right)\left(\frac{1}{2}p_s\bar{S}\right)$

Given that $\left(\frac{1+\alpha_k}{\alpha_k}\right) > 0$ since $\alpha_k > 0$, $\mu_k > 0$ if and only if $R_k > \frac{1}{2}p_s\bar{S}$, which is true when $\tilde{R}_k > 0$. This result can easily be generalized to the other situations studied thereafter.

3.6.2 Appendix B: Sequential space allocation without public intervention (S2)

The results found in Case 1 under sequential space allocation are identical to those found in Case 1 under simultaneous allocation.

3.6.3 Appendix C: Sequential space allocation with public intervention (S3)

The results found in Case 1 under sequential space allocation with public intervention are identical to those found in Case 1 under the two previous situations. The results found in Case 1' are identical to those found in Case 1' under simultaneous allocation.

3.6.4 Appendix D: Analyzing the shadow cost

We characterize the evolution of the shadow cost associated with the spatial constraint, μ_k, towards other variables (relative preferences for the resource α_k, and incomes R_k). Let us consider $\mu_i = \left(\frac{\alpha_i}{\tau\bar{S}}\right) - \left(\frac{p_s}{R_i - p_s\tau\bar{S}}\right)$ and $\mu_j = \left(\frac{\alpha_j}{(1-\tau)\bar{S}}\right) - \left(\frac{p_s}{R_j - p_s(1-\tau)\bar{S}}\right)$. Four different situations are identified.

- If $\alpha_i < \alpha_j$ and $R_i < R_j$, then $\left(\frac{\alpha_i}{\tau\bar{S}}\right) < \left(\frac{\alpha_j}{(1-\tau)\bar{S}}\right)$ and $\left(\frac{p_s}{R_i - p_s\tau\bar{S}}\right) > \left(\frac{p_s}{R_j - p_s(1-\tau)\bar{S}}\right)$, so that $\mu_i < \mu_j$.
- If $\alpha_i < \alpha_j$ and $R_i > R_j$, then $\left(\frac{\alpha_i}{\tau\bar{S}}\right) < \left(\frac{\alpha_j}{(1-\tau)\bar{S}}\right)$ and $\left(\frac{p_s}{R_i - p_s\tau\bar{S}}\right) < \left(\frac{p_s}{R_j - p_s(1-\tau)\bar{S}}\right)$, so that the situation is undefined.
- If $\alpha_i > \alpha_j$ and $R_i < R_j$, then $\left(\frac{\alpha_i}{\tau\bar{S}}\right) > \left(\frac{\alpha_j}{(1-\tau)\bar{S}}\right)$ and $\left(\frac{p_s}{R_i - p_s\tau\bar{S}}\right) > \left(\frac{p_s}{R_j - p_s(1-\tau)\bar{S}}\right)$, so that the situation is undefined.
- If $\alpha_i > \alpha_j$ and $R_i > R_j$, then $\left(\frac{\alpha_i}{\tau\bar{S}}\right) > \left(\frac{\alpha_j}{(1-\tau)\bar{S}}\right)$ and $\left(\frac{p_s}{R_i - p_s\tau\bar{S}}\right) < \left(\frac{p_s}{R_j - p_s(1-\tau)\bar{S}}\right)$, so that $\mu_i > \mu_j$.

Consequently, if agent i has relatively higher preferences for parking spaces α_i than her budget is low compared to agent j, then $\mu_i > \mu_j$. High preferences for parking spaces, as well as a high income, make the shadow cost grow. The relation between μ_i and μ_j depends on the relative size of preferences and incomes between agents.

Table 3.2: Results for homogeneous agents under simultaneous space allocation

	s_k	x_k	λ_k	μ_k	γ_k
Case 1	$s_k = \left(\frac{\alpha_k}{1+\alpha_k}\right)\left(\frac{R_k}{p_s}\right)$ given that $s_k \geq \underline{s}$ thus $\left(\frac{\alpha_k}{1+\alpha_k}\right)\left(\frac{R_k}{p_s}\right) \geq \underline{s}$	$x_k = \left(\frac{1}{1+\alpha_k}\right)\left(\frac{R_k}{p_x}\right)$	$\lambda_k = \left(\frac{1+\alpha_k}{R_k}\right)$	$\mu_k = 0$	$\gamma_k = 0$
Case 1' with $\widetilde{R}_k = R_k - p_s\underline{s}$	$s_k = \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_k = 0$	$\gamma_k = \left(\frac{p_s}{\widetilde{R}_k}\right) - \left(\frac{\alpha_k}{\underline{s}}\right)$
Case 2 with $\widetilde{R}_k = R_k - \left(\frac{1}{2}\right)p_s\bar{S}$	$s_k = \left(\frac{\bar{S}}{2}\right)$ given that $s_k \geq \underline{s}$ thus $\left(\frac{\bar{S}}{2}\right) \geq \underline{s}$ or $\bar{S} \geq 2\underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_k = \left(\frac{\alpha_k}{\left(\frac{1}{2}\right)\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_k}\right)$	$\gamma_k = 0$
Case 2' with $\widetilde{R}_k = R_k - \left(\frac{1}{2}\right)p_s\bar{S}$ $= R_k - p_s\underline{s}$	$s_k = \left(\frac{\bar{S}}{2}\right)$ given that $s_k = \underline{s}$ thus $\left(\frac{\bar{S}}{2}\right) = \underline{s}$ or $\bar{S} = 2\underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_k = \left(\frac{\alpha_k}{\left(\frac{1}{2}\right)\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_k}\right) + \gamma_k$ $\mu_k = \left(\frac{\alpha_k}{\underline{s}}\right) - \left(\frac{p_s}{\widetilde{R}_k}\right) + \gamma_k$	$\gamma_k = \left(\frac{p_s}{\widetilde{R}_k}\right) - \left(\frac{\alpha_k}{\left(\frac{1}{2}\right)\bar{S}}\right) + \mu_k$ $\gamma_k = \left(\frac{p_s}{\widetilde{R}_k}\right) - \left(\frac{\alpha_k}{\underline{s}}\right) + \mu_k$

Table 3.3: Results for heterogeneous agents under simultaneous space allocation

	s_k	x_k	λ_k	μ_k	γ_k
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - s_j\right)$ $\widetilde{R}_j = R_j - p_s\left(\bar{S} - s_i\right)$	$s_i = \bar{S} - s_j$ $s_j = \bar{S} - s_i$ given that $s_k \geq \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_i = \left(\frac{\alpha_i}{\bar{S} - s_j}\right) - \left(\frac{p_s}{\widetilde{R}_i}\right)$ $\mu_j = \left(\frac{\alpha_j}{\bar{S} - s_i}\right) - \left(\frac{p_s}{\widetilde{R}_j}\right)$	$\gamma_k = 0$
Case 2' with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - s_j\right)$ $\widetilde{R}_j = R_j - p_s\left(\bar{S} - s_i\right)$ $\widetilde{R}_k = R_k - p_s\underline{s}$	$s_i = \bar{S} - s_j$ $s_j = \bar{S} - s_i$ given that $s_k = \underline{s}$ thus $s_i = s_j = \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_i = \left(\frac{\alpha_i}{\bar{S} - s_j}\right) - \left(\frac{p_s}{\widetilde{R}_i}\right) + \gamma_i$ $\mu_j = \left(\frac{\alpha_j}{\bar{S} - s_i}\right) - \left(\frac{p_s}{\widetilde{R}_j}\right) + \gamma_j$ $\mu_k = \left(\frac{\alpha_k}{\underline{s}}\right) - \left(\frac{p_s}{\widetilde{R}_k}\right) + \gamma_k$	$\gamma_i = \left(\frac{p_s}{\widetilde{R}_i}\right) - \left(\frac{\alpha_i}{\bar{S} - s_j}\right) + \mu_i$ $\gamma_j = \left(\frac{p_s}{\widetilde{R}_j}\right) - \left(\frac{\alpha_j}{\bar{S} - s_i}\right) + \mu_j$ $\gamma_k = \left(\frac{p_s}{\widetilde{R}_k}\right) - \left(\frac{\alpha_k}{\underline{s}}\right) + \mu_k$

Table 3.4: Indirect utilities for homogeneous agents under simultaneous space allocation

	Indirect utilities $V_k^{Sim(l)}\left(R_k, p_s, p_x, \bar{S}, \underline{s}, \alpha_k\right)$
Case 1	$V_k^{Sim(1)} = \alpha_k \left[\ln\left(\frac{\alpha_k}{1+\alpha_k}\right) + \ln\left(\frac{R_k}{p_s}\right)\right] + \left[\ln\left(\frac{1}{1+\alpha_k}\right) + \ln\left(\frac{R_k}{p_x}\right)\right]$
Case 1' with $\widetilde{R}_k = R_k - p_s\underline{s}$	$V_k^{Sim(2)} = \alpha_k \left[\ln \underline{s}\right] + \left[\ln \widetilde{R}_k - \ln p_x\right]$
Case 2 with $\widetilde{R}_k = R_k - \left(\frac{1}{2}\right) p_s\bar{S}$	$V_k^{Sim(3)} = \alpha_k \left[\ln \bar{S} - \ln 2\right] + \left[\ln \widetilde{R}_k - \ln p_x\right]$
Case 2' with $\widetilde{R}_k = R_k - \left(\frac{1}{2}\right) p_s\bar{S} = R_k - p_s\underline{s}$	$V_k^{Sim(4)} = V_k^{Sim(2)}$

NB: The terms $\ln\left(\frac{\alpha_k}{1+\alpha_k}\right)$ and $\ln\left(\frac{1}{1+\alpha_k}\right)$ might be negative. However, the comparison between indirect utilities would not be impacted.

Table 3.5: Indirect utilities for heterogeneous agents under simultaneous space allocation

	Indirect utilities $V_k^{Sim(l)}\left(R_k, p_s, p_x, \bar{S}, \underline{s}, \alpha_k\right)$
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - s_j\right)$ $\widetilde{R}_j = R_j - p_s\left(\bar{S} - s_i\right)$	$V_i^{Sim(3)} = \alpha_i\left[\ln\left(\bar{S} - s_j\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]$ $V_j^{Sim(3)} = \alpha_j\left[\ln\left(\bar{S} - s_i\right)\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]$
Case 2' with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - s_j\right)$ $\widetilde{R}_j = R_j - p_s\left(\bar{S} - s_i\right)$ $\widetilde{R}_k = R_k - p_s\underline{s}$	$V_k^{Sim(4)} = V_k^{Sim(2)}$

Table 3.6: Results for homogeneous and heterogeneous agents under sequential space allocation without public intervention

	s_k	x_k	λ_k	μ_k
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - \underline{s}\right)$ $\widetilde{R}_j = R_j - p_s\underline{s}$	$s_i = \bar{S} - \underline{s}$ $s_j = \underline{s}$ Therefore $\bar{S}' = \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_i = \left(\frac{\alpha_i}{\bar{S} - \underline{s}}\right) - \left(\frac{p_s}{\widetilde{R}_i}\right)$ $\mu_j = \left(\frac{\alpha_j}{\underline{s}}\right) - \left(\frac{p_s}{\widetilde{R}_j}\right)$

Table 3.7: Indirect utilities for homogeneous and heterogeneous agents under sequential space allocation without public intervention

	Indirect utilities $V_k^{Seq(l)}\left(R_k, p_s, p_x, \bar{S}, \underline{s}, \alpha_k\right)$
Case 1	$V_k^{Seq(1)} = V_k^{Sim(1)}$
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\bar{S} - \underline{s}\right)$ $\widetilde{R}_j = R_j - p_s\underline{s}$	$V_i^{Seq(3)} = \alpha_i\left[\ln\left(\bar{S} - \underline{s}\right)\right] + \left[\ln \widetilde{R}_i - \ln p_x\right]$ $V_j^{Seq(2)} = \alpha_j\left[\ln \underline{s}\right] + \left[\ln \widetilde{R}_j - \ln p_x\right]$

Table 3.8: Results for homogeneous and heterogeneous agents under sequential space allocation with public intervention

	s_k	x_k	λ_k	μ_k	γ_k
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\tau\bar{S}\right)$ $\widetilde{R}_j = R_j - p_s\left(1-\tau\right)\bar{S}$	$s_i = \tau\bar{S}$ $s_j = \left(1-\tau\right)\bar{S}$ given that $s_i, s_j \geq \underline{s}$ thus $\tau\bar{S}, \left(1-\tau\right)\bar{S} \geq \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_i = \left(\frac{\alpha_i}{\tau\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_i}\right)$ $\mu_j = \left(\frac{\alpha_j}{\left(1-\tau\right)\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_j}\right)$	$\gamma_k = 0$
Case 2' with $\widetilde{R}_i = R_i - p_s\left(\tau\bar{S}\right)$ $\widetilde{R}_j = R_j - p_s\left(1-\tau\right)\bar{S}$ $\widetilde{R}_k = R_k - p_s\underline{s}$	$s_i = \tau\bar{S}$ $s_j = \left(1-\tau\right)\bar{S}$ given that $s_i = s_j = \underline{s}$ thus $\tau\bar{S} = \left(1-\tau\right)\bar{S} = \underline{s}$	$x_k = \left(\frac{\widetilde{R}_k}{p_x}\right)$	$\lambda_k = \left(\frac{1}{\widetilde{R}_k}\right)$	$\mu_i = \left(\frac{\alpha_i}{\tau\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_i}\right) + \gamma_i$ $\mu_j = \left(\frac{\alpha_j}{\left(1-\tau\right)\bar{S}}\right) - \left(\frac{p_s}{\widetilde{R}_j}\right) + \gamma_i$ $\mu_k = \left(\frac{\alpha_k}{\underline{s}}\right) - \left(\frac{p_s}{\widetilde{R}_k}\right) + \gamma_k$	$\gamma_i = \left(\frac{p_s}{\widetilde{R}_i}\right) - \left(\frac{\alpha_i}{\tau\bar{S}}\right) + \mu_i$ $\gamma_j = \left(\frac{p_s}{\widetilde{R}_j}\right) - \left(\frac{\alpha_j}{\left(1-\tau\right)\bar{S}}\right) + \mu_j$ $\gamma_k = \left(\frac{p_s}{\widetilde{R}_k}\right) - \left(\frac{\alpha_k}{\underline{s}}\right) + \mu_k$

Table 3.9: Indirect utilities for homogeneous and heterogeneous agents under sequential space allocation with public intervention

	Indirect utilities $V_k^{SeqPI(l)}\left(R_k, p_s, p_x, \bar{S}, \underline{s}, \tau, \alpha_k\right)$
Case 1	$V_k^{SeqPI(1)} = V_k^{Seq(1)} = V_k^{Sim(1)}$
Case 1' with $\widetilde{R}_k = R_k - p_s\underline{s}$	$V_k^{SeqPI(2)} = V_k^{Sim(2)}$
Case 2 with $\widetilde{R}_i = R_i - p_s\left(\tau\bar{S}\right)$ $\widetilde{R}_j = R_j - p_s\left(1-\tau\right)\bar{S}$	$V_i^{SeqPI(3)} = \alpha_i\left[\ln\tau + \ln\bar{S}\right] + \left[\ln\widetilde{R}_i - \ln p_x\right]$ $V_j^{SeqPI(3)} = \alpha_j\left[\ln\left(1-\tau\right) + \ln\bar{S}\right] + \left[\ln\widetilde{R}_j - \ln p_x\right]$
Case 2' with $\widetilde{R}_i = R_i - p_s\left(\tau\bar{S}\right)$ $\widetilde{R}_j = R_j - p_s\left(1-\tau\right)\bar{S}$ $\widetilde{R}_k = R_k - p_s\underline{s}$	$V_k^{SeqPI(4)} = V_k^{SeqPI(3)} = V_k^{Sim(4)}$

Essay 4

Correcting agglomeration economies: How air pollution matters

This chapter has been co-written with Aurélie Mahieux (EQUIPPE, Université Lille 1).

4.1 Introduction

Agglomeration economies play a key role in urban economics. The very existence of cities or of any concentration of activities can only be explained in the light of increasing returns in production activities, provided that we rule out the role played by the attributes of physical geography (Fujita and Thisse, 2002). Agglomeration economies are positive externalities derived from the spatial concentration of economic activity (firms and households) that affects the productivity of firms. They are increasing external returns to scale with respect to the size or density of population or employment.

Studies generally estimate the agglomeration effects and support that agglomeration positively impacts labor productivity. Concentration of economic activity was first defined by the size of the population or employment, then with measures of density. Ciccone and Hall (1996) are the first to propose a framework investigating the effects of employment density on labor productivity. In more recent years, new geography economists such as Combes et al. (2008, 2011) have enhanced the basic framework by adding new elements such as market potential, land area, firms specialization and economic diversity.

Other authors (Graham, 2007; Rice et al., 2006) focus on the effects of a new transportation infrastructure on labor productivity. They conclude that a new infrastructure has a positive effect on accessibility, thus enlarging the opportunities offered to workers and leading to increased labor productivity. Nevertheless, none of the above mentioned studies takes into account the environmental impact generated by an increased accessibility, namely commuting. Yet, enhanced accessibility increases air pollution, in particular nitrogen oxide (NO_X) emissions which primarily result from transportation. Epidemiological studies show that atmospheric pollution has a negative and significant impact on human health (see e.g., Currie et al. (2009a, 2009b)). The deterioration of health implies both lower labor supply (Ostro, 1983; Hanna and Oliva, 2011; Carson et al., 2011) and lower labor productivity (Lavy et al., 2012; Graff Zivin and Neidell, 2012).

This article aims at correcting estimations of agglomeration economies by accounting for air pollution resulting from commuting. We add air pollution variables in the general framework studying agglomeration economies. More specifically, we explore the impact of NO_X emissions on productivity. NO_X emissions originate mainly from diesel vehicle exhaust. The objective of the present paper is to show that pollution has to be included in the estimations of agglomeration effects. The results obtained confirm a negative and significant impact of air pollution on productivity.

We use aggregate data for the year 2009 for the 304 French metropolitan employment areas. The employment area level constitutes the relevant spatial unit for transportation projects and policies, as well as for studies related to the labor market

(Combes and Lafourcade, 2012). However, very few studies are conducted on such a fine geographic level. In this article, we combine standard data concerning the main determinants of agglomeration economies, such as employment and wages, as well as data on emissions for one air pollution variable, NO_X. Data are disaggregated at the industry level into five sectors and then these data are pooled.

First, we estimate the effects on labor productivity per worker of employment density, accessibility measured as a market potential *à la* Harris (1954), surface area, economic diversity, and sectoral specialization. In line with the literature, the results show an increase in productivity of 0.03% for a 1% increase in employment density. Second, we introduce the variable measuring air pollution: NO_X emissions. In our specification, we use NO_X emissions as a proxy for atmospheric pollution. In line with epidemiological studies, we find that air pollution negatively impacts labor productivity. A 1% increase in the level of NO_X emissions leads to almost 0.1% decrease in productivity. Third, we compare the models with and without air pollution. When pollution is accounted for, the positive effect of employment density on productivity is reduced. Finally, we focus on an illustrative case to show the magnitude of the reduction of agglomeration economies when local air pollution is considered. When NO_X emissions are included in the model, the productivity gains of agglomeration are reduced by more than 13%.

Agglomeration economies are often enhanced by new transportation policies or infrastructures that improve accessibility and contribute to the densification of the area. However, improved accessibility induces traffic and therefore pollution emissions. So far as we know, the impact of air pollution on productivity is never addressed in specifications estimating agglomeration effects. In a sustainable development context, these results shed a new light for the assessment of transportation projects such as tramways or Bus with a High Level of Service. This study allows putting into perspective the agglomeration benefits resulting from the implementation of a new transportation infrastructure or policy.

The paper is organized as follows. Section 4.2 provides a brief review of the literature on agglomeration economies. Section 4.3 presents the data and descriptive statistics. Section 4.4 estimates the general econometric model and addresses common endogeneity issues. In Section 4.5, we introduce the environmental variable and present the adjusted results. In Section 4.6, we compare both specifications and develop the illustrative case. In Section 4.7, we draw conclusions.

4.2 Literature review on agglomeration economies

4.2.1 Sources and classification of agglomeration economies

Already long ago, Marshall (1890) set the assumption that geographic concentration of activities generates productivity gains. Duranton and Puga (2004) explore the theoretical microeconomic foundations of agglomeration economies. They emphasize three distinct mechanisms leading to agglomeration economies: learning, matching, and sharing. First, learning effects or technological spillovers relate to the generation, the diffusion, and the accumulation of knowledge. The process of learning occurs at small spatial scales, since it requires close interactions and physical proximity. Therefore, dense areas make a higher degree of specialization possible (Ciccone and Hall, 1996). Second, large and dense labor markets allow for better employees/employers matching with lower search costs. Third, large and dense markets lower access costs to both customers and suppliers of intermediate goods and services, even when transportation costs are low (Krugman, 1991). Moreover, this last mechanism allows for the sharing of local public goods and of any other indivisible facilities, as well as the sharing of risks.

A further distinction can be made between "localization economies" and "urbanization economies" (Krugman, 1991; Rosenthal and Strange, 2004), though their sources are similar. Localization economies, also called within-industry externalities or Marshall-Arrow-Romer effects, imply increasing returns to scale that are external to the firm but internal to the industry (e.g., technological spillovers, intermediate inputs sharing, labor market matching). Urbanization economies, also called between-industry externalities or Jacobs externalities (after Jacobs (1969)), refer to agglomeration benefits that are external to the firm or the industry but internal to the city (e.g., local public goods sharing, input-output sharing). In this work, we do not aim at estimating these two kinds of effects separately. Indeed and as stated by Graham (2007), "an aggregate estimate of density externalities is sufficient to demonstrate the relationship between agglomeration, productivity, and transport investment".

The creation and growth of cities result from two opposing forces: agglomeration (centripetal forces) and dispersion (centrifugal forces) (Krugman, 1991; Fujita and Thisse, 2002). It is usually agreed that agglomeration effects follow a bell-shaped curve (Henderson, 1974; Fujita et al., 1999). Agglomeration economies first exceed diseconomies up to a certain threshold, and lead to concentration of activities. Thereafter concentration of activities leads to congestion and pollution issues, rising land rents, higher labor costs, crime and socio-economic polarization, which constitutes costs for society, and hence a dispersion force. In the literature, these two effects are rarely identified separately.

4.2.2 Magnitude of agglomeration effects

Several literature reviews are available on this topic (see e.g., Rosenthal and Strange (2004); Puga (2010); Melo et al. (2009)). Although they are drawn on different methodologies and on countries (mainly the US and Europe) of various size and industry-structure, all the studies support evidence that agglomeration economies positively impact labor productivity. Depending on the measure applied, elasticity coefficients for productivity usually range from 0.03 to 0.08 (Rosenthal and Strange, 2004). This means that a 1% increase in either density or city size results in a 0.03 to 0.08% increase in labor productivity. Ciccone and Hall (1996) find that doubling employment density raises the average labor productivity by 6%, and that more than half of the variance in output per worker across US states can be explained by differences in employment density. Ciccone (2002) finds similar results (4.5-5%) for five European countries. Combes et al. (2008, 2011), using the same measure, estimate an elasticity of productivity of about 0.08 on French departments, and of 0.06 on French employment areas with aggregate data, along with an estimate of 0.03-0.04 on French employment areas with individual data. Rice et al. (2006) stress on the fact that studies based on individual data show smaller coefficient values.

4.2.3 The impact of transport

Other authors focus on the effects of a new transportation infrastructure on labor productivity and employment growth. First, "by driving down travel costs, extra roads increase the attractiveness of a city, which brings new residents" and therefore increases employment (Duranton and Turner, 2012). Duranton and Turner (2012) find that a 10% increase in a city's stock of highways causes a 1.5% increase in its employment. Furthermore, assumption is made that new or improved transportation infrastructures enhance accessibility, which in turn enlarges the concentration of activities from which agglomeration economies arise (Gibbons and Overman, 2009). Venables (2007) explores the theoretical foundations behind the effects of transportation infrastructures on productivity. He concludes that better accessibility leads to increased productivity. In an empirical study, Rice et al. (2006) and then Matas et al. (2013) confirm this finding and evidence a 1.2% increase in productivity when travel times are reduced by 10%. However, there is evidence of a steep decrease of agglomeration economies with distance (Rice et al., 2006; Graham et al., 2009; Matas et al., 2013). Therefore, a new transportation infrastructure mainly benefits to the surrounding area.

Agglomeration economies are additional benefits that are more and more accounted for in transportation project appraisals as "wider economic benefits" (Vickerman, 2007; DfT, 2005; Victoria Department of Transport, 2012). Additional benefits can be substantial, as reveals the 25% increase in benefits for the London CrossRail project [44] (DfT, 2005). Nevertheless, none of the above mentioned studies takes into account the environmental impact generated by an increased accessibility, namely commuting. Correcting the assessment of agglomeration economies brings new perspectives on transportation project appraisals and allows for a better allocation of public funds.

4.3 Data and descriptive statistics

"A fine level of geographical details" is required to obtain accurate estimates (Ciccone, 2002). For this purpose, we choose to draw our analysis at the employment area level. So far, very few studies have investigated the effects of agglomeration at the employment area level (see Combes et al. (2008, 2010)). Most studies use larger spatial units, such as NUTS 3 areas [45] (Ciccone, 2002; Rice et al., 2006; and Combes et al., 2011). French employment areas were defined in 1983 and modified several times thereafter (1994, 1999 and 2010). They are smaller than NUTS 3 areas (French "Departments"), but larger than LAU 1 areas [46] (French "Cantons"). Furthermore and contrary to NUTS or LAU areas, their borders are defined by commuting patterns rather than being administratively stated. It is admitted that at least 75% of the labor force lives and works within the same employment area. Most employment areas correspond to a metropolitan area or to a city and its catchment area (see Figure 4.3 in Appendix A, Section 4.8.1). Thus, analyzing the effects of transportation infrastructure on employment areas seems all the more relevant, since employment areas are built on commuting trips. Moreover,

44. The CrossRail project in London is an underground east-west rail link connecting existing rail networks on each side of the city (DfT, 2005).
45. NUTS stands for Nomenclature of Territorial Units for Statistics.
46. LAU stands for Local Administrative Unit.

small spatial units such as employment areas constitute the appropriate spatial level for studying productivity issues since it has been demonstrated that agglomeration effects decrease rapidly with distance and mainly arise within 80 km.

In 2010, Metropolitan France includes 304 employment areas. We use cross-sectional data for the year 2009, which are aggregated at the employment area level. We combine data from General Census of Population with data on employment and wages for the year 2009. All data are derived from INSEE (French Institute of Statistics and Economic Studies). They are disaggregated at the industry level into five sectors (agriculture, manufacturing, construction, trade and services, public administration), and then pooled. The database is a two-dimension panel: employment area and industry. It consists of 1,520 observations. We use workplace-based data on wages [47] to approximate labor productivity. To obtain employment densities, we use data on the number of jobs [48] divided by the surface areas. Surface areas are in square kilometers. The variable 'specialization' is constructed with the employment share of each sector in total area. The measure ranges from 0 when nobody works in a specific sector to 1 when the total employment of the area is concentrated in this sector. We use as a measure of diversity the inverse of Herfindhal Index, applying data on sectoral employment. The measure equals 1 when jobs are concentrated in one sector, 5 when they are perfectly divided into the 5 sectors considered. The market potential of a zone is the sum of the opportunities derived from all the other zones while considering the distance between this zone and all the other ones. An opportunity is defined as the employment density of a particular zone divided by the distance from this zone to another zone. Since French employment areas are built on commuting patterns, it can be assumed that employment centers are usually located at the centroid of the area. Since it constitutes a more accurate measure of accessibility than Euclidean distance, we compute real road network distances with

47. File "Rémunérations" from INSEE.
48. File "Postes" from INSEE.

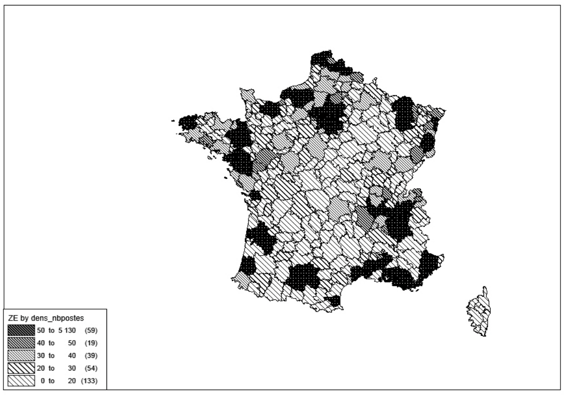


Figure 4.1: Employment density in French employment areas

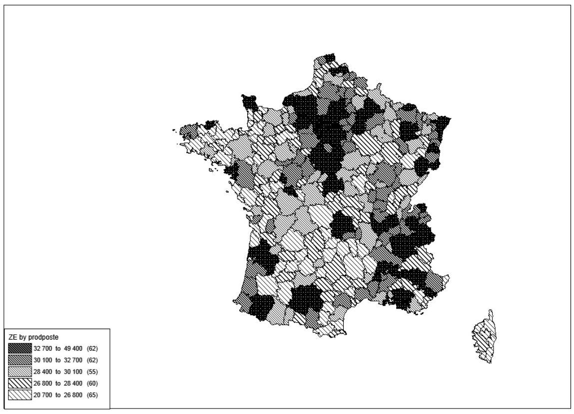


Figure 4.2: Worker productivity in French employment areas

a Geographical Information System [49] to build the market potential variable.

Table 4.1: Summary statistics

Variables	Obs.	Mean	Std. Dev.	Min	Max
Productivity	1,520	24,869.65	4,454.30	11,988.95	49,399.54
Density	1,520	65.66	315.16	2.48	5,124.87
Area	1,520	1,796.87	1,390.35	119.40	8,752.00
Specialization	1,520	0.20	0.15	0.0002	0.64
Diversity	1,520	3.23	0.33	2.09	4.29
Market Potential	1,520	83.67	57.51	25.22	480.53

Figure 4.1 and Figure 4.2 show that the highest employment density areas correspond to the most productive areas. These figures illustrate the underlying intuition behind agglomeration economies: labor productivity is likely to be correlated with employment density.

49. Distances are computed using calcdist-280.mbx tool on MapInfo. With this software, we compute distances between the centroids of each French employment areas.

4.4 The standard model

This section estimates the net effect of employment density on labor productivity per worker. We develop the general framework for French employment areas and control for common endogeneity issues.

4.4.1 The general framework

The basic framework has recently been enhanced by additional explanatory variables measuring urbanization economies, such as accessibility measured as a market potential, surface area, and economic diversity. Sectoral specialization is often added to identify localization economies. Variables used in the general econometric specification are described below.

Common variables used in the literature

In the literature, we observe two main approaches measuring labor productivity. First, productivity can be estimated with the help of a production function using data on value added, since agglomeration economies lead to increased total factor productivity (Rosenthal and Strange, 2004). Second, wage equations are commonly in use to approximate productivity, assuming that at the competitive equilibrium workers receive wages equal to their marginal labor productivity. Rice et al. (2006) show the existence of a strong correlation (0.76) between these two kinds of productivity variables, namely gross value added per employee per hour worked and average hourly earnings. Moreover, the authors stress the fact that for small areas measuring productivity with gross value added may be biased by the spatial allocation of non-wage incomes.

Various measures of concentration are found. Some authors focus on employment, population or industry size (Sveikauskas, 1975; Segal, 1976; Henderson, 1986) or working age population size (Rice et al., 2006), while others apply measures of density. Ciccone and Hall (1996) define density as 'the intensity of labor, human, and physical capital relative to physical space'. They are the first to propose a framework investigating the effects of employment density on labor productivity. Density is a continuous variable that is far less sensitive to the geographic boundaries used than measures of size.

When people and goods are mobile, employment areas are interconnected by migration and trade flows. These interactions have an influence on labor productivity (Head and Mayer, 2004, 2006). In the literature, two families of accessibility measures are in use: effective density and market potential (Matas et al., 2013). The effective density, as applied by Graham (2007) and Matas et al. (2013), is a comprehensive measure of both the accessibility to activity concentration within a specific area and from this area to the other areas. The market potential, derived from Harris (1954) and applied by Combes et al. (2008, 2011), measures only the accessibility to activity concentration of a particular area to the other areas [50]. For this reason, in any specification the market potential has to be used jointly with a measure of the size or density for each area. It is worth noting that changes in transportation infrastructure or policy modify the market potential of a particular area since the relative proximities of activity are altered.

The surface of employment areas is added in order to distinguish density effects from pure scale effects. Indeed, surfaces vary significantly between areas and can impact density effects. Moreover, it is common to introduce a diversity index to capture the local distribution of jobs between the various economic sectors, as well as a measure of sectoral specialization to indicate the within-industry concentration.

50. A limit of the market potential measure is that accessibility to foreign countries is not accounted for. This may bias coefficient estimates of border areas.

Formalizing the standard model

Following Combes et al. (2008, 2011), this article uses the employment density as a measure of concentration, and the average wage per worker as dependent variable. As prescribed by Moretti (2004), we use nominal wages. In this article, we use the market potential variable, since it best allows for discriminating between the effect of density and the effect of accessibility. Finally, we add other common variables, namely the surface of employment areas, a diversity index and a measure of sectoral specialization.

The general specification is the following:

$$\ln prod_{zs} = \alpha + \beta \ln dens_z + \rho \ln MP_z + \delta \ln area_z + \eta \ln \mathrm{div}_z + \theta \ln spe_{zs} + \gamma_s + \varepsilon_{zs},$$

where $prod_{zs}$ is the average labor productivity per worker for sector s in zone z, $dens_z$ the employment density in zone z, MP_z the market potential of zone z, $area_z$ the surface of employment area z, div_z a measure of the economic diversity of zone z, spe_{zs} the average sectoral specialization of zone z, γ_s the industry fixed effects, and ε_{zs} the error term. All variables are measured at the employment area level. In line with the recent literature, we use logs of the variables. The coefficient estimates are then interpreted as elasticities with respect to the different variables.

Table 4.2 shows the correlation between all variables. As expected, the variable 'productivity' is clearly and positively correlated with the variable 'density'. Table 4.2 also indicates that the specialization of the area is a factor contributing to higher productivity. In addition, results reveal that 'density' and 'accessibility' are strongly correlated. 'Specialization', 'density' and 'market potential' seem to have a positive correlation with labor productivity. Employment area surface and diversity are negatively correlated with labor productivity.

Table 4.3 presents estimation results for robust Ordinary Least Squares (OLS)

Table 4.2: Correlation matrix

Variables	ln *prod*	ln *dens*	ln *area*	ln *spe*	ln *div*	ln *MP*
ln *prod*	1.0000					
ln *dens*	0.3401	1.0000				
ln *area*	-0.0146	-0.3192	1.0000			
ln *spe*	0.3505	-0.0962	0.0268	1.0000		
ln *div*	-0.2181	-0.4059	-0.0078	0.1176	1.0000	
ln *MP*	0.2089	0.4244	-0.3144	-0.0452	-0.0435	1.0000

in the general framework. Variables are introduced successively according to the importance of their correlation with productivity. In line with the literature, we find an elasticity of productivity with respect to density of 0.05. All estimated variables are significant at the 1% level. Market potential is positive and highly significant too. Its magnitude is comparable to that of density. Both specialization of a zone and its surface impact positively on labor productivity. As found by Combes et al. (2008), the coefficient for economic diversity is negative.

4.4.2 Controlling for endogeneity issues

Endogeneity issues are then controlled with instruments commonly in use in the literature. Unbiased results are finally presented.

Common instruments used in the literature

The OLS method assumes that the explanatory variables are uncorrelated with the error term. Otherwise, coefficient estimates are biased. However, two potential sources of endogeneity are identified in standard econometric specifications related to agglomeration economies: simultaneity bias and omitted variable bias. Simultaneity bias, also called reverse causality, arises when either firms or workers migrate to locations with high productivity, leading therefore to higher densities. Graham et al. (2010) analyze the direction of causality between productivity and agglomeration.

Table 4.3: Estimation results for robust Ordinary Least Squares (OLS)

Variables	OLS1	OLS2	OLS3	OLS4	OLS5
ln *spe*	0.0448***	0.0495***	0.0495***	0.0496***	0.0509***
	(0.004)	*(0.004)*	*(0.004)*	*(0.004)*	*(0.003)*
ln *dens*		0.0638***	0.0580***	0.0629***	0.0517***
		(0.004)	*(0.005)*	*(0.005)*	*(0.005)*
ln *MP*			0.0286**	0.0385***	0.0447***
			(0.009)	*(0.009)*	*(0.009)*
ln *area*				0.0294***	0.0254***
				(0.005)	*(0.005)*
ln *div*					-0.2166***
					(0.048)
N	1,520	1,520	1,520	1,520	1,520
R^2	0.123	0.264	0.269	0.283	0.298

Note: Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

They find substantial evidence of reverse causality, in particular for localization economies. This bias would lead to a 20% overestimation of agglomeration economies (Combes and Lafourcade, 2012; Combes et al., 2008, 2011). Omitted variable bias, or unobserved heterogeneity, is particular features impacting productivity but which are not explicitly accounted for in the specification. For instance, the industry mix of a zone or specific geographic characteristics (e.g., climate or relief) may impact productivity (Combes et al., 2010). Factor endowments such as public goods or natural resources play as well a role in determining productivity levels. The level of education of workers is also a leading determinant for wages (Ciccone and Hall, 1996; Combes et al., 2011). Agglomeration effects can be either over or underestimated when variables are omitted.

Combes and Lafourcade (2012) provide a literature review of the solutions usually implemented to correct these biases. The most common approach to deal with the simultaneity bias is to use long lags on population size or population density as instrumental variables (Ciccone and Hall, 1996; Rice et al., 2006; Combes et al., 2008, 2010, 2011). The underlying assumption is that previous patterns of population concentration are correlated with current population or employment densities (the endogenous variable), but are independent from current labor productivity.

Furthermore, firm selection issues may also lead to biased agglomeration effects. Firm selection refers to the fact that large and dense markets are more competitive and hence exclude less productive firms. Therefore, higher productivity in larger or denser areas is the result of a selection process, where only the more productive firms survived. However, Combes et al. (2012) reveal that firm selection is not an important bias for agglomeration economies estimates.

Instrumenting endogenous variables in the standard model

Since both density and market potential are likely to be endogenous, we instrument both variables. We first instrument employment density using NUTS 3 population densities from 1866 and 1891. We then instrument market potential using NUTS 3 population density from 1866 over inter-zones distances as a measure. Then, unobservable heterogeneity can be controlled for by introducing fixed effects (Glaeser and Maré, 2001). In this study, we use industry fixed effects to control for sectoral heterogeneity.

Table 4.4 shows the results of various estimations of standard agglomeration economies. Introducing industry fixed-effects slightly modifies the coefficients. Moreover, industry fixed-effects raise the R^2 significantly. Instrumenting potentially endogenous variables leads to a slight decrease in the density coefficient, from 0.050 to 0.027. The results are in line with the literature when education is not accounted for [51]. We also observe that the magnitude and significance of market potential decrease after addressing endogeneity issues.

51. As highlighted in Combes et al. (2011), introducing the human capital decreases significantly the magnitude of density effects for recent periods. Ciccone and Hall (1996) and Combes and

Table 4.4: Standard agglomeration economies: results for various estimation methods

Variables	OLS5	OLS6	IV1	IV2
ln *dens*	0.0517***	0.0504***	0.0271***	0.0272***
	(0.005)	*(0.004)*	*(0.007)*	*(0.007)*
ln *MP*	0.0447***	0.0435***	0.0555***	0.0554***
	(0.009)	*(0.007)*	*(0.008)*	*(0.008)*
ln *area*	0.0254***	0.0257***	0.0182***	0.0182***
	(0.005)	*(0.004)*	*(0.004)*	*(0.004)*
ln *div*	-0.2166***	-0.1895***	-0.2715***	-0.2711***
	(0.048)	*(0.042)*	*(0.044)*	*(0.044)*
ln *spe*	0.0509***	0.0290**	0.0249*	0.0249*
	(0.003)	*(0.010)*	*(0.010)*	*(0.010)*
Industry fixed-effects	No	Yes	Yes	Yes
N	1,520	1,520	1,520	1,520
R^2	0.298	0.592	-	-
Cragg-Donald F-stat	-	-	383.224	383.224
Kleibergen-Paap Statistic	-	-	300.934	300.934
Hansen J-Stat	-	-	0.002	0.002
Chi-sq P-value	-	-	0.9631	0.9631
Endogeneity C-stat	-	-	32.327	32.327
Chi-sq P-value	-	-	0.000	0.000

Note: OLS5: No fixed-effects; OLS6: Industry fixed-effects; IV1: Generalized Method of Moments (GMM); IV2: Two Step Least Squares (2SLS); IV1 and IV2: we use log of NUTS 3 population density from 1866 and 1891 to instrument the variable 'ln *dens*'. Variable 'ln *MP*' is instrumented by the log of the market potential with population density from 1866. Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The Stock and Yogo critical values for the Cragg-Donald F-Statistic are 13.43 for 10% maximum IV bias. The endogeneity C-stat confirms that instrumentation is needed for density and market potential. According to the Cragg-Donald F-stat and Kleibergen-Paap statistic, instruments are not weak. The Hansen J-stat shows

Lafourcade (2012) also warn against the existence of a sorting effect. Highly-skilled workers tend to concentrate in densely populated areas, and they get accordingly higher wages. Variables related to workers' education must be added to the specification in order to control for heterogeneity of skills among workers. However as this paper aims at correcting 'standard' estimates of agglomeration economies with pollution features, we prefer to keep the specification as standard as possible.

that the set of instruments is exogenous.

Finally, given the spatial nature of the study, we check the spatial autocorrelation by computing the Moran's Index. For this purpose, we build a rook weights matrix, i.e., a contiguity-based matrix in which contiguity is defined by shared boarders. The p-value for the Moran's I statistic (0.53) indicates that we cannot reject the null hypothesis of no spatial autocorrelation. Therefore, there is no need to use spatial econometric models.

4.5 The extended model: including NO_X emissions

First, we expose the effect of local air pollution, and especially NO_X, on the human health and on labor productivity. Then, we develop the extended specification where a pollution variable (NO_X emissions) is added to the standard framework of agglomeration economies.

4.5.1 The effect of pollution on health and productivity

The link between pollution and health has first been assessed through epidemiological studies on mortality rates. For instance, Lave and Seskin (1970) measure the long-term effects of sulfur oxides and particulates on mortality rates. Then, studies have been carried out on the effects of pollution on morbidity, focusing on variations in labor supply. Ostro (1983) demonstrates that a 10% increase in particulate levels generates a 4.4% decrease in work loss days. Carson et al. (2011) evidence a 8% decrease in household labor supply in Bangladesh due to arsenic exposure. Hanna and Oliva (2011) show that a 1% increase in sulfur dioxide results in a 0.61% decrease in the hours worked in Mexico City. These studies generally use hospital outcomes such as length of stay, emergency room visits, or work loss days to measure the impact of several pollutants on health. However, air pollution may affect not only the extensive margin, but also the intensive margin, that is labor productivity. Graff Zivin and Neidell (2012) first demonstrate the impact of ozone pollution on the productivity of agricultural workers in California. Ozone pollution diminishes lung functioning and negatively impacts productivity in physical work, even when the labor supply remains unchanged. Suglia et al. (2008) show that children living near higher levels of fine particulates perform worse on cognitive tests. Similarly, Lavy et al. (2012) find a negative relationship between both fine particulate matter and carbon monoxide and cognitive performance during school tests. They show that altered cognitive performance results in mis-ranking of students. This may result in inefficient allocation of workers across occupations, and negatively affect labor productivity, especially for intellectual work. In this sense, environmental protection is considered as an investment in human capital sustaining labor productivity and therefore economic growth (Graff Zivin and Neidell, 2012).

In this study, we focus on nitrogen oxide (NO_X). Nitrogen oxide (NO_X) is made of nitric oxide (NO) and nitrogen dioxide (NO_2). NO_2 is highly toxic and penetrates into the lungs, therefore causing respiratory diseases. NO irritates bronchi and diminishes the oxygen power of blood. NO_X emissions result mainly from transport (61%, among which 93% from road transport) due to the exhaust of diesel vehicles. Latza et al. (2009) provide a review of some experimental and epidemiological studies. NO_2 emissions lead to ear, nose and throat infections, otitis media, respiratory infections and in the most extreme cases myocardial infarctions. In addition, Ghosh et al. (2012) demonstrate an association between NO_X and respiratory illnesses (bronchitis and upper airway inflammation) even for levels of NO_X lower than the current European Commission standards, especially among very young children.

Although NO_X emissions are on a decreasing trend (-45% in France over the period 1990-2011) (CITEPA, 2013), their actual level remains harmful for health. Furthermore, this pollutant affects the environment. NO_X are among air pollutants causing acid rains. They also contribute to ozone pollution and to climate change. Although environmental effects are not accounted for in our specification, they are relevant and could be integrated in future analysis.

4.5.2 The extended specification

First estimations of the extended specification are presented, before we control for endogeneity issues and present unbiased results.

First estimations

In this article, we use data on NO_X emissions for the year 2009 at the NUTS 2 level (French "regions"). Emissions are obtained from each regional AASQA (Association Agréée de Surveillance de la Qualité de l'Air, which is the French regional association for air quality monitoring). The year 2009 is the only available dataset for NO_X emissions. Since the specification is defined at an aggregated level, we apply emissions that are an aggregated measure of concentrations recorded at each particular monitoring station. We are aware of the fact that air quality affecting human health is best approximated by concentration levels of pollutants. The relation between concentrations and emissions is complex. For a given level of emissions, concentrations vary depending on meteorological and physical factors such as wind, temperature, humidity, precipitation, topography and height of buildings. In order to partly avoid such bias, we use spatial units which are much larger than employment areas. Indeed, larger units would better account for wind effects. We obtained pollution data for 21 of the 22 French regions. The following results are therefore drawn on a slightly smaller number of observations than the standard model presented above. We have now 1,485 observations for 297 employment areas.

The extended specification is based on the general framework presented in Section 4.4.1 and includes the pollution variable for a zone z, noted '$poll_z$':

$$\ln prod_{zs} = \alpha + \beta \ln dens_z + \rho \ln MP_z + \delta \ln area_z + \eta \ln \mathrm{div}_z + \theta \ln spe_{zs} + \lambda \ln poll_z + \gamma_s + \varepsilon_{zs}$$

We test the impact of NO_X emissions per worker on labor productivity. We integrate the air pollution variable in the general model. Since Lavy et al. (2012) find that pollution has a non-linear impact on productivity, we use the logarithmic form.

Table 4.5 represents the correlation matrix between all the variables of the general framework and the NO_X emissions variable. Since correlations between standard agglomeration economies variables are quite similar, complete correlation matrix is not presented in this section. As expected, the correlation matrix shows that NO_X is negatively correlated with labor productivity.

Table 4.5: Correlation matrix for NO_X emissions

Variables	ln NO_X
ln *prod*	-0.2316
ln *dens*	-0.3255
ln *area*	0.2491
ln *spe*	0.0581
ln *div*	0.2686
ln *MP*	-0.3568
ln NO_X	1.0000

Table 4.6 presents the effect of NO_X emissions on labor productivity. NO_X emissions by worker have a negative and significant effect at the 1% level on labor productivity. The results show that a 1% increase in NO_X emissions lowers labor productivity by almost 0.07%. Table 4.6 also indicates that the positive effect of density on productivity is reduced when the variable is instrumented, while the

positive effect of accessibility is strengthened. The coefficients of the other variables only slightly differ after instrumentation.

Table 4.6: The effect of air pollution on productivity

	OLS1	OLS2	IV1	IV2
ln *dens*	0.0526***	0.0514***	0.0265***	0.0265***
	(0.005)	*(0.004)*	*(0.007)*	*(0.007)*
ln *MP*	0.0374***	0.0365***	0.0452***	0.0452***
	(0.009)	*(0.006)*	*(0.007)*	*(0.007)*
ln *area*	0.0328***	0.0329***	0.0242***	0.0241***
	(0.005)	*(0.004)*	*(0.004)*	*(0.004)*
ln *div*	-0.1456**	-0.1229**	-0.2137***	-0.2131***
	(0.051)	*(0.044)*	*(0.047)*	*(0.047)*
ln *spe*	0.0515***	0.0323**	0.0279**	0.0279**
	(0.003)	*(0.010)*	*(0.010)*	*(0.010)*
ln NO_X	-0.0602***	-0.0595***	-0.0655***	-0.0654***
	(0.012)	*(0.008)*	*(0.008)*	*(0.008)*
Industry fixed-effects	No	Yes	Yes	Yes
N	1,485	1,485	1,485	1,485
R^2	0.318	0.617	-	-
Cragg-Donald F-stat	-	-	359.202	359.202
Kleibergen-Paap Statistic	-	-	300.707	300.707
Hansen J-stat	-	-	0.006	0.006
Chi-sq P-value	-	-	0.9378	0.9378
Endogeneity C-stat	-	-	32.266	32.266
Chi-sq P-value	-	-	0.0000	0.0000

Note: OLS1: No fixed-effects; OLS2: Industry fixed-effects; IV1: Generalized Method of Moments (GMM); IV2: Two Step Least Squares (2SLS); IV1 and IV2: we use log of NUTS 3 population density from 1866 and 1891 to instrument the variable 'ln *dens*'. Variable 'ln *MP*' is instrumented by the log of the market potential with population density from 1866. The Stock and Yogo critical values for the Cragg-Donald F-Statistic are 13.43 for 10% maximum IV bias. As remarked in section 4.4.2, instrumentation is needed because of endogeneity problems. Besides, the set of instruments is not weak and is exogenous. Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Controlling for endogeneity issues

We are aware of the potential endogeneity bias affecting the pollution variable (reverse causality). On the one hand, the literature introduced in Section 4.5.1 highlights the causal link between pollution and productivity: pollution impacts negatively on labor productivity. On the other hand, productive regions are likely to pollute more. Therefore, the causal link between pollution and productivity may be reversed.

Previous results constitute first estimations of the effect of air pollution on productivity. They could be enhanced with instrumental variables, such as car ownership rates. We expect NO_X emissions to be positively correlated with car ownership rates. Generally, high levels of car ownership rates mean higher car availability, and therefore more trips carried out by car, resulting in higher levels of air pollution. In addition, car ownership rates may also be correlated with productivity, since higher wages facilitate access to cars. Nevertheless, car ownership patterns change rapidly overtime, and we expect lagged car ownership rates not to be correlated with present wages. We use car ownership rates from 1999 as instrument for pollution emissions.

Table 4.7 presents results for the extended specification when the endogeneity of the pollution variable is controlled. The results slightly differ from the first estimations. The density coefficient is reduced from 0.0265 to 0.0253, which indicates that the positive effect of density on productivity is lowered when the endogeneity of the pollution variable is controlled. In addition, the NO_X emissions coefficient decreases from -0.0655 to -0.1031, which indicates a stronger negative effect of pollution on productivity. The impact of air pollution on labor productivity remains negative and highly significant, with a 1% increase in air pollution leading to a 0.1% decrease in productivity. According to the standard tests on instrumented variables, the set of instruments used is valid.

In addition, we test the interaction between NO_X emissions and density. The interaction term (-0.0186) is negative and significant at the 5% level (see Table 4.9 in Appendix B, Section 4.8.2), which is in line with the results of the literature on local air pollutants. Consequently, NO_X emissions negatively impact the effect of density on productivity. The denser an area, the more polluted it is, and the more acute health problems will be. Indeed, health problems directly impact workers' productivity, as demonstrated in the literature.

4.6 How air pollution reduces agglomeration gains

This section draws a comparison between the two econometric models and estimates the extent to which expected agglomeration gains are reduced when air pollution is accounted for in agglomeration economies estimates.

4.6.1 Comparing the two econometric models

Agglomeration gains are revealed by the elasticity of productivity with respect to density. Estimating the magnitude of the correction of the agglomeration economies requires the comparison between the density coefficients of both models, namely the standard model and the extended model. For this purpose, identical samples are needed. Table 4.8 presents the results of the standard model on the same sample as the extended model presented in Table 4.7.

When pollution is accounted for, the density coefficient decreases from 0.0287 to 0.0253, which clearly highlights a reduction in the positive effect of density on productivity. A 1% increase in density now leads to a 0.025% increase in labor productivity, instead of the standard 0.029% increase in productivity. Agglomeration economies are therefore reduced when pollution is introduced in the model.

Table 4.7: The effect of air pollution on productivity after controlling for endogeneity biases

	IV1	IV3
ln *dens*	0.0265***	0.0253***
	(0.007)	*(0.007)*
ln *MP*	0.0452***	0.0373***
	(0.007)	*(0.009)*
ln *area*	0.0242***	0.0266***
	(0.004)	*(0.004)*
ln *div*	-0.2137***	-0.1881***
	(0.047)	*(0.047)*
ln *spe*	0.0279**	0.0285**
	(0.010)	*(0.010)*
ln NO_X	-0.0655***	-0.1031***
	(0.008)	*(0.021)*
Industry fixed-effects	Yes	Yes
N	1,485	1,485
Cragg-Donald F-stat	359.202	81.291
Kleibergen-Paap Statistic	300.707	51.135
Hansen J-stat	0.006	0.116
Chi-sq P-value	0.9378	0.7334
Endogeneity C-stat	32.266	32.878
Chi-sq P-value	0.0000	0.0000

Note: IV1: Generalized Method of Moments (GMM); IV3: Generalized Method of Moments (GMM); IV1 and IV3: we use log of NUTS 3 population density from 1866 and 1891 to instrument the variable 'ln *dens*'. Variable 'ln *MP*' is instrumented by the log of the market potential with population density from 1866; IV3: we use log of car ownership rates from 1999 at the employment area level to instrument the pollution variable, NO_X. The Endogeneity C-Stat indicates that instrumentation is needed. Besides, the set of instruments is not weak and is exogenous. Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 4.8: Comparison between the standard and the extended specification

	IV3	IV4
ln *dens*	0.0253***	0.0287***
	(0.007)	*(0.007)*
ln *MP*	0.0373***	0.0589***
	(0.009)	*(0.007)*
ln *area*	0.0266***	0.0200***
	(0.004)	*(0.004)*
ln *div*	-0.1881***	-0.2572***
	(0.047)	*(0.047)*
ln *spe*	0.0285**	0.0268*
	(0.010)	*(0.011)*
ln NO_X	-0.1031***	-
	(0.021)	
Industry fixed-effects	Yes	Yes
N	1,485	1,485
Cragg-Donald F-stat	81.291	361.373
Kleibergen-Paap Statistic	51.135	302.372
Hansen J-stat	0.116	0.141
Chi-sq P-value	0.7334	0.7071
Endogeneity C-stat	32.878	29.103
Chi-sq P-value	0.0000	0.0000

Note: IV3: Generalized Method of Moments (GMM) for the extended specification; IV4: Generalized Method of Moments (GMM) for the standard specification; IV3 and IV4: we use log of NUTS 3 population density from 1866 and 1891 to instrument the variable 'ln *dens*'. Variable 'ln *MP*' is instrumented by the log of the market potential with population density from 1866; IV3: we use log of car ownership rates from 1999 at the employment area level to instrument the pollution variable, NO_X. The Endogeneity C-Stat indicates that instrumentation is needed. Besides, the set of instruments is not weak and is exogenous. Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4.6.2 Estimating the reduction in agglomeration gains: the illustrative case

For the illustrative case, let us assume a representative employment area of 700 square kilometers with a GDP of 5 billion euros and 70,000 workers. We assume the introduction a new structural transportation infrastructure such as a Bus with High Level of Service (BHLS). The infrastructure is expected to create 1,000 new jobs in the employment area. These hypothesis are totally fictional. The aim of the illustrative case is to provide rough estimates of the reduction in agglomeration economies and to monetarize this loss of wealth.

Due to the implementation of the new transportation infrastructure, the density of the employment area increases by 1.4%. The productivity differential with respect to density is 0.0399% when air pollution is ignored, against 0.0352% when pollution is accounted for. This results in a productivity gain of 28.5 and 25.14 euros per worker, respectively. The agglomeration gains from the 71,000 final workers amount to 2,023,500 euros when pollution is ignored, against 1,784,940 euros when pollution is considered. Therefore, accounting for air pollution reduces the expected agglomeration gains by 13.4%. A 1% increase in NO_X emissions reduces the productivity by 0.1%, which corresponds to an economic loss of 238,560 euros for the given level of GDP. The GDP growth expected with the implementation of the new transportation infrastructure is 0.04% when pollution is ignored, against 0.036% when pollution is taken into account. To conclude, considering the aforementioned assumptions, such an infrastructure is expected to generate negligible wealth creation, and an even more negligible one when pollution is accounted for.
This illustrative case allows putting into perspective the expected wealth creation resulting from the implementation of a new transportation infrastructure or policy.

4.7 Concluding remarks

This article enlarges the general framework that studies determinants of agglomeration economies by exploring the impact of air pollution on worker productivity. It confirms that pollution has a negative and significant impact on productivity. The results obtained show that taking into account air pollution in agglomeration economies estimations reduces their magnitude by more than 13%. Empirically, the main contribution of this paper is to include a pollution variable in the standard specification of agglomeration economies. The result indicates that air pollution is an omitted variable in standard econometric models estimating agglomeration economies and reduces expected gains. Even if agglomeration economies are substantial when implementing a new transport infrastructure or policy, a part of them should be corrected by the negative environmental impact from the trips induced by improved accessibility. This paper explicits the general intuition that pollution is harmful to health and that health problems affect negatively labor productivity. It is usually admitted that new transportation infrastructures or policies enhance accessibility and therefore productivity. However, improved accessibility induces new trips which generate increased air pollution. This result provides guidance for policy makers. For this reason, low-carbon transportation infrastructures or policies should be favored to ensure the lowest reduction in the expected agglomeration gains due to air pollution (e.g., car-sharing policies, bike-sharing systems). In addition, policies supporting mobility can be set, such as commuting costs subsidized by firms or mobility learning for young and disadvantaged population.

The results presented are obtained for a specific air pollutant, NO_X. Only direct effects are accounted for. It is usually admitted that pollution has cumulative effects on productivity and health. Further work would consist in introducing cumulative effects of air pollution to strengthen our results. In addition, other pollutants can be added to better reproduce air quality and to generalize our findings. Further work could use individual data over several years to control for heterogeneity of workers, in particular with the inclusion of human capital variables such as education. These data would confirm that the results we find are not due to the particular year we use. Moreover, we could investigate the link between the contribution of human capital to agglomeration economies and its variations following the inclusion of pollution.

4.8 Appendices

4.8.1 Appendix A: French employment areas

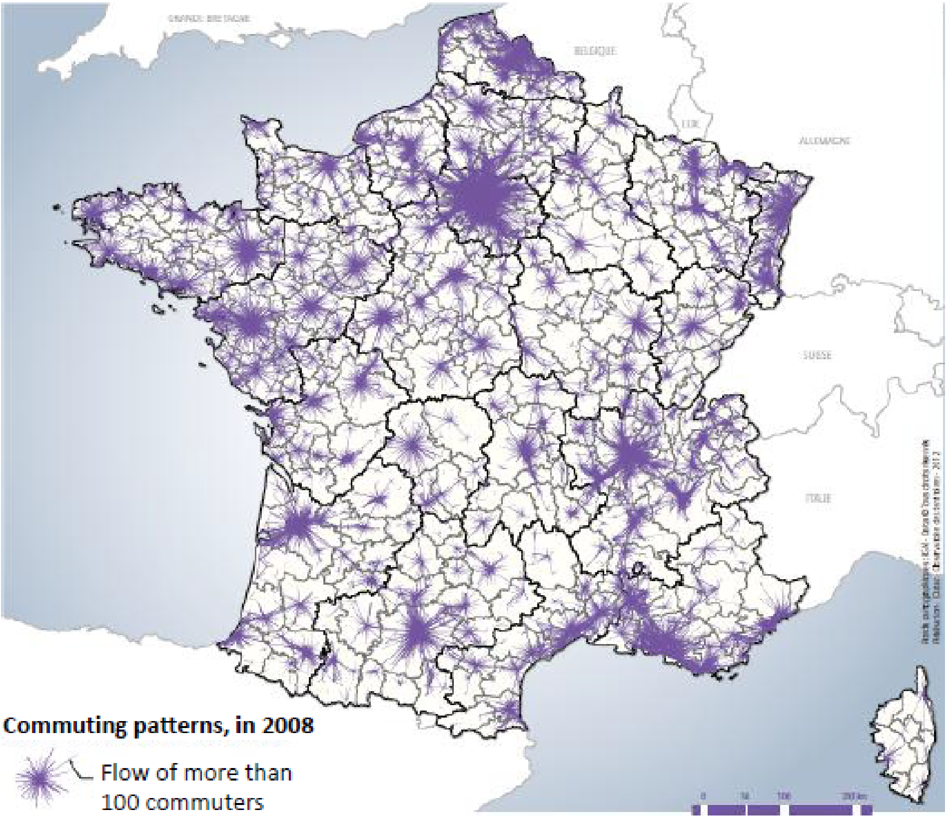


Figure 4.3: Commuting patterns define French employment areas.
Source: INSEE, 2010

4.8.2 Appendix B: Interaction coefficient

Only the interaction term is of interest, while the other coefficients are not directly interpretable.

Table 4.9: Interaction coefficient

	IV5
inter	-0.0186*
	(0.008)
ln NO_X	0.0105
	(0.031)
ln *dens*	-0.0010
	(0.025)
ln *MP*	0.0290***
	(0.008)
ln *area*	0.0330***
	(0.004)
ln *div*	-0.0776
	(0.044)
ln *spe*	0.0375***
	(0.010)
Industry fixed-effects	Yes
N	1,485

Note: IV5: Generalized Method of Moments (GMM); we use log of NUTS 3 population density from 1866 and 1891 to instrument the variable 'ln *dens*'. Variable 'ln *MP*' is instrumented by the log of the market potential with population density from 1866; we use log of car ownership rates from 1999 at the employment area level to instrument the pollution variable, NO_X. Robust standard errors in brackets. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Conclusion

This thesis attempts to go beyond the traditional compartmentalized approach addressing spatial issues on one side, and environmental issues on the other side. When they are related to mobility, these concerns are intertwined and mutually reinforcing, and for this reason there is a need to address them jointly. The concept of functional economy (FE) applied to mobility allows analyzing jointly both traffic congestion and rivalry of use for parking, as well as air pollution.

The 1^{st} essay investigates the concept of FE, both theoretically and through its implementation in the field of urban passenger transportation. This article highlights both economic and ecological potentials of function-based transportation systems, and analyzes the conditions required to set up such an economic and organizational model.

The 2^{nd} essay focuses on the role of sharing the uses (shared transportation modes) in addressing spatial and environmental challenges. After exploring briefly the mechanisms through which shared modes impact road congestion and rivalry of use for parking places, as well as air pollution, we conclude that due to the crucial spatial interactions occurring between commuters, shared modes constitute a key element enhancing mobility. More specifically, we show that shared modes are intermediary transportation modes, between private modes and public transit, both in terms of space consumption and service provided.

The 3^{rd} essay highlights the importance of considering space as a limited resource in open access, and emphasizes the existence of rivalry of use affecting parking places in densely built-up urban areas. The model developed features the mechanisms underlying the allocation of parking places among agents and reveals the shadow cost associated with the spatial constraint. We conclude that when space is valued by agents, some situations lead to social welfare losses.

The 4^{th} essay focuses on the effects of a local air pollutant released mainly by transportation – NO_X – on workers' productivity. For this purpose, we integrate NO_X emissions in the theoretical framework estimating agglomeration economies in order to assess the extent to which pollution limits the full efficiency of production capacities. We conclude that accounting for air pollution (NO_X) reduces by more than 13% the economic gains expected from the introduction of a new transportation infrastructure or policy.

Hence, this Ph.D. thesis allows putting into perspective transportation infrastructure projects or new transportation policies through a two-angle analysis of the challenges related to sustainable mobility. First, transportation policies are explored from a spatial perspective, with space considered as a scarce resource in open access and whose consumption from transportation modes is subject to a shadow cost and to rivalry. Then, the link between enhanced accessibility and increased local air pollution from transportation is drawn, and the analysis reveals that accounting for environmental impacts leads to more accurate assessments of the expected agglomeration gains. This study examines both environmental and spatial concerns associated with sustainable mobility, using the concept of FE. Function-based transportation systems, and in particular sharing the uses, allow exploring transportation policies from both a spatial and environmental perspective. This thesis reveals that under particular hypothesis, function-based transportation systems can favor the full efficiency of production capacities.

When discussing sustainable mobility, the leading criterion is most often polluting emissions released by the transportation modes. The use of space rarely appears as a criterion for sustainability (see Bouwman and Moll (2002) for an exception).

This thesis provides a better understanding of the role of space in sustainable mobility patterns.

This study confirms the relevance of a comprehensive approach to mobility. Consistency between transportation policies, urban planning policies and environmental policies is required to drive sustainable mobility (Bertolini et al., 2005). Furthermore, this thesis allows investigating the impact of shared transportation modes on current mobility concerns, and in particular on the spatial and environmental issues. Yet so far, there are very few studies on shared modes.

For this reason, much remains to be done in the scientific field, and in particular in economics. Future research includes further investigations in behavioral economics and environmental economics, as well as in transportation economics and spatial economics.

First, both behavioral and transportation economics can explore the determinants of a modal shift from private to shared modes. The impacts of various measures (push and pull) on the modal choice require further investigation as regards shared modes, especially to avoid inefficient and costly measures, or a decrease in mobility. Moreover, the conditions of acceptance for both users and service providers can be analyzed, in particular the interaction and coordination costs related to the use and introduction of shared modes. Multi-modal combinations between transportation modes, such as between mass transit and shared bicycle, can be favored through coordinated transportation authorities. For instance, many German public transportation companies are already in cooperation with car-sharing structures (Huwer, 2004).

Second, environmental economics have tools to explore further the implication of considering space, and specifically the space devoted to mobility, as a scarce resource in open access. The role of public authorities in the regulation of space consumption requires further analysis, notably the quotas and exchange markets that could be implemented to limit welfare losses. Furthermore and compared with private modes, shared modes require less space per unit of service provided. This allows for reduced spatial concerns, but potentially also for changing land use patterns from mobility uses to alternative uses. Promoting uses based on non-economic values, such as the existence value or the option value, could be examined.

Last but not least, spatial economics can reasonably give insights into the relationships between shared modes and the organization of land use patterns, notably residential patterns and workplaces. The effect of considering the absolute scarcity of space on the traditional spatial economics, and especially on the relative scarcity of space (land rents and distances), can be further investigated.

Mobility patterns are usually grounded in collective decisions (e.g., family constraints) that may be irreversible (e.g., residential localization choices), or in public decisions related to urban planning (e.g., localization of commercial and working centers). Mobility is a broad concept and driving sustainable mobility would involve both multidisciplinary and cross-disciplinary research.

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