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PUBLIC ECONOMIC POLICIES TO LIMIT CO_2 EMISSIONS FROM CAR USE

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Short abstract of the Thesis

There is a broad range of policy instruments which facilitate reductions in CO_2 emissions within the transport sector. Implementing these tools is legitimate and necessary because of the high contribution to CO_2 emissions to climate change by transportation activities, and more particularly by passenger vehicles (17% in France in 2010). This Thesis questions, throughout three Chapters, the relevance in order to tackle this issue of policy instruments towards targeting passenger vehicles in particular.

The first Chapter is dedicated to an analysis of the supply-side of the automotive system. Its primary focus lies in a consideration of the diversity of industrial actors capable of impacting on a new vehicle's energy performances (*i.e.* car makers, automotive suppliers). The research question consists in investigating whether or not cooperation between these actors leads to the production of vehicles that are less fuel-consuming than were there to be no cooperation. To some extent, the analysis proposed in this Chapter also enables conclusion to be drawn on whether such cooperation could be an alternative to a policy intervention. Results teach us that car makers and automotive suppliers, reacting to the imperatives of supply and demand, do not systematically equip new vehicles with high energy-efficient equipment to optimize fuel consumption. In fact, we demonstrate in this Chapter that the incentive for car maker to use high energy-efficient equipment on vehicles depends on the demand for low fuel-consuming vehicles. When facing relatively weak demand, solely a total cooperation on the vehicle design between the car maker and their suppliers guarantees the production of the least fuel-consuming vehicle. However, whether a manufacturer has an interest in cooperating with other manufacturers is uncertain. This finding justifies the intervention of public decision-makers, including the implementation of *technology push* measures (competitiveness clusters, R&D aids, and so on), and it leads to the conclusion that the cooperation is not a credible substitute for policy intervention. By contrast, when demand for energy-efficient vehicles is relatively high, the least fuel-consuming vehicle is produced, whatever the level of cooperation among producers. In the end, the *market pull* measures (Bonus/Malus, Low Emission Zones, label, and so on) take on their full meaning, at least temporarily, to stimulate demand, and create markets of sufficient size. To evaluate the efficiency of *market pull* measures, an in-depth analysis of the demand-side of the car system is nonetheless necessary.

The second Chapter is dedicated to an analysis of the demand for vehicles and kilometres. We place the emphasis on the interdependency between car choice and car use, and on its impact on the efficiency of car purchase taxes and use taxes. Particular attention is paid to the effects of a purchase tax differentiated according to the level of CO_2 emissions. Implementing such a pricing scheme is shown to translate into an improvement in the fleet's average fuel efficiency, and can thus be accompanied by a rebound effect, namely an increase in the overall distances travelled by car induced by fuel efficiency gains. Interestingly, this rebound effect is actually dependent on gaps in market prices and the unit consumptions of the different vehicles for sale, and it increases with the amount of Malus. This finding implicitly means that a differentiated purchase tax becomes less efficient as the particular tax increases. Implementing a fuel tax, playing on the distances covered by car, could therefore be useful. This second policy intervention could significantly contribute to limiting the rebound effect resulting from the first policy intervention. In a different vein, it is also true that a fuel tax is rather efficient in that this particular pricing tool is alone able to achieve broadly the same reduction as that resulting from policy combining a car usage tax and a Malus scheme. In any case, the reduction in CO_2 emissions should not be the single criterion used by the public decision-makers when they arbitrate among several policy tools. This is particularly true in the transport sector.

The third and last Chapter considers the possibility within the transportation sector of achieving different objectives with a single policy tool. Increases of the households' utility and of automotive sector's profit constitute the other two objectives pursued by public authorities simultaneously with the objective to reduce CO_2 emissions from car use. The analysis shows us that while a fuel tax helps mitigate transport CO_2 emissions, it leads to reduced vehicle usage benefits for households as they will hesitate to consume "useful" kilometres. Conversely, the efficiency in mitigating CO_2 emissions of a Bonus for purchasing low fuel-consuming vehicles is questionable because of the rebound effect discussed above. However, on the one hand, a Bonus helps to offset the households' loss of utility (by decreasing the car purchase cost), whilst increasing the automotive sector's profits (by raising the market prices of 'clean' vehicles and technologies) on the other. In the end, the positive impacts of the Bonus scheme on usage benefits and profits justify its implementation simultaneously with the fuel tax. These two incentive-based mechanisms should be implemented together as their effects on CO_2 emissions are synergistic.

Key-words: CO_2 emissions, passenger vehicles, car makers, automotive suppliers, car purchase and use, transportation public policies, rebound effect.

Court résumé de la Thèse

Il existe un large panel d'instruments de politiques publiques permettant de réduire les émissions de CO_2 du secteur des transports. La mise en place de ces instruments est légitime compte tenu de la contribution du secteur des transports et plus particulièrement des véhicules particuliers aux émissions de CO_2 (17% en France en 2010) et donc au changement climatique. Cette thèse questionne, à travers trois chapitres, la pertinence – au regard de cet enjeu – des instruments de politique publique ciblant les émissions des véhicules particuliers.

Le premier Chapitre est consacré à l'analyse côté offre du marché automobile. Son originalité tient à la prise en compte de l'existence de divers acteurs industriels ayant une influence sur la performance énergétique des nouveaux véhicules (*i.e.* constructeurs automobiles et équipementiers divers). La question de recherche est de déterminer si une coopération entre ces acteurs conduit à la production de véhicules plus économes en carburant qu'en l'absence de coopération. Dans une certaine mesure, l'analyse proposée dans ce Chapitre permet de déterminer si cette coopération est un substitut ou non à l'intervention publique. Les résultats montrent qu'en l'absence d'intervention publique, le libre jeu des constructeurs et équipementiers ne conduit pas toujours à la production du véhicule le plus économe en carburant étant donné les technologies disponibles. Nous mettons en évidence que l'incitation du constructeur à équiper ses véhicules d'équipements performants sur le plan énergétique dépend de la demande de véhicules économes en carburant. Lorsque cette demande est faible, seule une coopération totale entre membres de la filière automobile, en termes de conception du véhicule, garantit la production du véhicule le plus efficient sur le plan énergétique. Toutefois, le fait que chaque producteur ait intérêt à coopérer n'est pas certain. Ce résultat justifie l'intervention des pouvoirs publics telle que la mise en place d'instruments de type « *technology push* » (pôle de compétitivité, aides à la R&D, etc.) ; et amène à la conclusion selon laquelle la coopération entre producteurs n'est pas un substitut crédible à l'intervention publique. En revanche, lorsque la demande de véhicules économes en carburant est plus élevée, le véhicule le plus performant sur le plan énergétique est produit, et ce quel que soit le niveau de coopération entre producteurs. Aussi, l'instauration d'instruments de type « *market pull* » (Bonus/Malus, zone à faibles émissions, label, etc.) est justifiée, ne serait-ce que de manière temporaire pour stimuler la demande, et ainsi créer un marché de taille suffisante. Pour estimer l'efficacité de ces instruments, une analyse plus fine de la demande de véhicule et de kilomètres est toutefois nécessaire.

Le deuxième Chapitre est consacré à l'analyse de la demande de véhicules et de kilomètres. L'accent est mis sur l'interdépendance entre ces deux demandes, et sur son impact sur l'efficacité des taxes à l'achat et à l'usage des véhicules. Un intérêt particulier est porté aux effets d'une taxe à l'achat différenciée en fonction des émissions de CO_2. L'instauration de cet instrument tarifaire se traduit par une amélioration de la performance énergétique moyenne du parc automobile et peut donc s'accompagner d'un effet rebond ; soit une hausse des kilomètres parcourus consécutive à l'amélioration de la performance énergétique. De façon intéressante, lorsque l'effet rebond existe – cela dépend des écarts de prix d'achat et de consommations unitaires des différents véhicules proposés à la vente – celui-ci augmente avec le montant de la taxe à l'achat. Autrement dit, la perte d'efficacité de la taxe différenciée à l'achat, due à l'effet rebond, croit avec le niveau de la taxe. Aussi, l'instauration d'une taxe sur le carburant, en impactant directement les distances parcourues, est intéressante. Elle pourrait permettre de limiter l'effet rebond causé par le premier instrument. Par ailleurs, la capacité d'une taxe sur le carburant (d'un montant raisonnable) à atteindre, seule, la réduction d'émissions permise avec la combinaison d'une taxe sur le carburant et d'un Malus est démontrée. Toutefois, la réduction d'émissions de CO_2 ne doit pas être le seul critère de décision retenu par les décideurs publics lorsqu'ils arbitrent entre plusieurs instruments. Cela est d'autant plus vrai dans le secteur des transports.

La possibilité dans le secteur des transports de servir plusieurs objectifs de politique publique avec un seul instrument est précisément à la base de l'analyse proposée dans le troisième et dernier Chapitre. Précisément, accroitre l'utilité des ménages et le profit de la filière automobile constituent les deux objectifs poursuivis par le décideur public parallèlement à son objectif de réduction des émissions. L'analyse montre qu'instaurer une taxe sur le carburant permet de réduire les émissions de CO_2 mais dégrade dans le même temps les bénéfices retirés de l'usage du véhicule pour les ménages qui vont, du fait de la taxe, parcourir moins de kilomètres. En revanche, l'efficacité du Bonus à réduire les émissions est discutable en raison de l'effet rebond qu'il engendre. Cependant, cet instrument permet une hausse de l'utilité des ménages (en diminuant le coût d'achat du véhicule) et un accroissement du profit de la filière automobile (en augmentant le prix de vente des véhicules économes en carburant). Ces effets justifient d'instaurer simultanément une subvention différenciée à l'achat du véhicule et une taxe sur le carburant. Cette combinaison d'instruments tarifaires semble d'autant plus efficace que ses effets en termes d'émissions de CO_2 sont synergiques.

Mots clés : émissions de CO_2, véhicules particuliers, constructeurs automobiles, équipementiers automobiles, achat et usage du véhicule, politiques publiques de transport, effet rebond.

Contents

General Introduction

"Undesired collective effects may be caused by the sum of rational individual decisions which together result in a pernicious outcome"

(Schelling, 1978)[1]

The high probability of the anthropic origin of climate change – through greenhouse gases (GHG) emissions – has been confirmed by the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2013). Climate change and its related effects (*e.g.* crop failures, sea level rise, water resources stress, flooding, biodiversity losses and so on) are huge negative externalities which will increasingly affect the societies. Yet, externalities are one of the so-called market failures that justify a public intervention. This intervention is all the more necessary given the common understanding that climate change is one of the main global challenges of the 21st century since its impacts are threatening the welfare of human beings.

The reduction of GHG emissions required to meet the objective of keeping below 2°C[2] rise in global temperature (compared to the pre-industrial level) forces the transport sector to move towards new modes of operation and development. Such changes fall within *mitigation* actions, insofar as they tackle the causes of climate change, while *adaptation* actions tackle the impacts of the phenomenon on the societies[3]. In this Thesis, we have chosen to focus on how to mitigate climate change rather than dealing with its *ex post* effects. That said, facing climate change mitigation challenges, it seems instructive to point out that the French Climate Plan launched in 2009 adopts the objective set in the Grenelle 1 Act to cut transport GHG emissions by 20% by 2020, *i.e.* to return to 1990 levels within this period (JORF, 2009).

The transport sector deserves a particular attention since transportation activities contributed to 29% and 24% of the total GHG emissions respectively in France and in the European Union (EU) in 2010 (European Commission, 2013a). Thus, the transport sector is the largest contributor to climate change in France, and the second largest, behind the energy sector, at the

[1] in Crozet and Lopez Ruiz (2013), p294.

[2] Above +2°C, all agree that the effects of global warming would reduce global welfare (Stern, 2006). The ambitious objective of remaining below +2°C was endorsed by the Copenhagen Agreement (COP15, 2009). Dealing with this issue, the IPCC alerts us to the fact that, in 2015, more than two thirds of the 'carbon budget' has already been consumed, when the 'carbon budget' corresponds to the upper limit of CO_2 (about 3,000 billion of tons) that can be emitted since the beginning of the industrial revolution so as to meet the objective of +2°C (as pointed out in de Perthuis and Trotignon, 2015).

[3] The IPCC defines mitigation as "*an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouses gases*", and adaptation as the "*adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*" (IPCC).

European level. What is more, the transport sector is by far the sector that experienced the largest increase of emissions in the EU (+ 34% between 1990 and 2008; EEA, 2011). Among the different transport modes, road transport dominates in terms of emissions. In fact, road transport accounted for 80.2% of transport GHG emissions in France in 2010, and for 72.1% in the EU (European Commission, 2013a). The same year in France, passenger vehicles contributed to 57.4% of road transport CO_2 emissions[4] (CGDD, 2012).

In this Thesis, we thus focus on passenger cars. Our research question is: which policy instruments, targeting the car production, purchase and use decisions, are the most efficient in reducing CO_2 emissions resulting from car use?

Many aspects of the automotive sector have to be taken into account when thinking about a policy intervention, namely:

- the high number of actors in the motor industry (*i.e.* car makers and a myriad of automotive suppliers), in addition to the fact that mobility players are more and more diversified (*e.g.* players involved in the new Information and Communication Technologies sector, or in the energy sector);
- the constant interdependency of the car purchase and use decisions on the demand-side that explains the phenomenon of rebound effect, as we will thoroughly explain later;

and from the perspective of public decision-makers:

- that transport is a derived demand, and generates positive externalities (notably economies of agglomeration) so that it provides wider cross-benefits across other sectors;
- that car use brings into play several negative externalities (pollutions, congestion, noise, lack of safety, etc.) that are interrelated so that tackling a single externality is not possible.

To take those special features of the transportation sector into account, public authorities have actually deployed a wide range of policy instruments which enable to reduce passenger vehicles CO_2 emissions. Firstly, each instrument can target either the demand-side or the supply-side of the low-carbon mobility system's stakeholders. For example, some instruments apply particularly better to some target groups:

[4] CO_2 is the most important greenhouse gas, especially in terms of transportation' emissions. For instance, in France, the total of **GHG** emissions from transportation activities amounted to 133.2 million tons in 2010, when the total of **CO_2** emissions amounted to 127 million tons the same year (CGDD, 2012).

- speed limit measures, Low Emission Zones (LEZ), High-Occupancy Vehicle (HOV) lanes, parking access management, pricing schemes related to vehicle purchase, ownership or use, and so on for road users;
- CO_2 emissions standards, obligation for a minimum biofuel content in fuels and tyre labelling for industrial actors;
- mandatory information reporting on CO_2 emissions from transport services or eco-driving training for transport professionals;
- norms on publicly accessible charging infrastructures for public authorities.

Secondly, instruments are either regulatory constraints (*e.g.* LEZ, HOV, parking restriction) or economic instruments (*e.g.* pricing schemes related to vehicle purchase, ownership or use). In addition to these two kinds of policy tools, public authorities have also developed collaborative initiatives (*e.g.* public procurement, public private partnerships), and informative policies (*e.g.* energy consumption and CO_2 emissions labelling for new passenger cars).

From the above features of the automotive system and the different types of policy instruments, and because of the high contribution to CO_2 emissions made by passenger cars, a wide range of policy instruments targeting passenger vehicle CO_2 emissions as described above have undoubtedly been explored from different perspectives. This Thesis also investigates the policy tools aiming at reducing CO_2 emissions resulting from car use, their type, scope and relevance. More precisely, we attempt to determine which policy intervention is the most efficient in cutting passenger cars CO_2 emissions while considering the car production, purchase and use decisions. The method we propose to address this issue is presented below (cf. 1). The structure of the Thesis will then be developed, and an overview of the key messages of each Chapter will be given (2.).

1. Methodology

In this Thesis, we develop a partial and static equilibrium model of the automotive sector.

This approach has the advantage over the empirical approach of allowing the complementarity of policy tools to be examined in greater depth. This is particularly interesting given the large number of options available to public authorities, and the clear need for action to mitigate CO_2 emissions, with the temptation to combine policy tools so that no potential reduction in emissions is missed. However, policy instruments may interact with each other in several ways (*i.e.* complementarity, additivity, synergy, and substitutability, in May and al., 2006). Investigating whether a policy instrument reinforces or degrades the effects of another one calls for information on the effects of each stand-alone tool and on the impacts of the combination of both tools. This information is not available using an empirical approach in that such an approach only provides information on the effects of the current existing regulation[5]. In this Thesis, the question of the complementarity of different policy tools will be examined, and more particularly the complementarity of pricing schemes relating to both car purchase and car use.

There already exist theoretical works addressing the latter issue. For instance, De Borger (2001) perceives the combination of car use and car purchase taxes as a “two-part tariff”, and examines the way the differences in externalities’[6] and consumers’ characteristics affect the design of the optimal two-part tariff. Because of our focus on a single externality (*i.e.* CO_2 emissions), and because we consider homogenous households (at least in terms of income), it does not make sense to compare our results with those of De Borger (2001). In fact, our contribution is different and looks at the problem from another perspective. We put emphasis on the links between the car purchase and use decisions – namely the two decisions targeted by the policy tools – and on the reason why those links have to be taken into account when designing the optimal regulation.

To this end, we carry out static comparative analyses of a basic model of consumer’s behaviour. More specifically, we jointly address the car purchase decision and the car use, with an indirect-utility-maximising program (see Chapter 2). To be precise, the car purchase decision is: which car to purchase? It differs from the car ownership decision (*i.e.* to own or not a car?) and from the car replacement decision (*i.e.* to replace or not its car?). In this framework, the loss of efficiency of the differentiated purchase tax actually results from the well-known phenomenon of rebound effect, that is to say increases in car use induced by efficiency gains; the latter gains being observed at the aggregate scale because of a new distribution of vehicles in favour of low fuel-consuming vehicles caused by the differentiated purchase tax. In this regard, note that the

[5] A statistical technique used in econometrics to isolate the effects of a single “treatment” is the “Difference in differences” method. It compares the change over time in the dependent variable for the treatment group on the one hand and for a control group on the other hand. Obviously, the choice of the control group is particularly important.

[6] « *Not all types of externalities generate feedback in demand. Congestion and accident risks probably do, especially in the long-run, because they are likely to affect the conditional demand for car use as well as the desirability of owning a car. Pollution, on the other hand, does affect consumer welfare, but it probably does not have any impact on car ownership decisions and on the demand for kilometres* » (De Borger, 2001, p477).

rebound effect is more often studied with empirical studies (a well-known reference is the work of Small and Van Dender (2007)[7]), and generally gains in energy-efficiency are explained by improvements in technologies at the vehicle level, and not at the aggregate scale (that is to say as a result of a new distribution of vehicles more or less fuel-consuming) such as in the present research work.

Then, the fact that we consider a partial equilibrium model means that our model focuses on the demand- and supply-sides of the automotive sector without taking the interactions with the rest of the economy into account. Both sides of the sector are indeed particularly relevant with reference to the ASIF scheme according to which GHG emissions of transport can be tackled through four main levers: transport **A**ctivity, modal **S**hare, the energy **I**ntensity and the carbon intensity of **F**uel (Schipper and al., 2000). In fact, we typically address the issue dealing with distances travelled (*i.e.* 'A' in ASIF) as well as the household's choice of vehicle's energy efficiency (*i.e.* 'I' in ASIF) when studying the demand-side; and we take improvements of vehicle's energy efficiency (*i.e.* 'I' in ASIF) into account when examining the supply-side. At this stage, it is worth noting that we do not consider modal shifts as a way to reduce emissions here since we focus on passenger vehicles. In this regard, note that the downward variation of the fuel intensity of road passenger transport over the last two decades is significantly more pronounced than the upward variation of both the share of road in passenger transport, and that of passenger cars in road passenger transport (EEA, 2011)[8]. Likewise, we do not study the lever 'carbon intensity of fuel'. We will in fact consider vehicles with the same motorisation. This means that substitution effects (for instance those resulting from the implementation of a carbon tax) are not examined here. Besides, leaving aside from our analysis the other sectors is justified by the other two restrictions on our scope, namely our focus on conventional vehicles on the one hand, and our focus on the car-purchasing population on the other hand. Indeed, since we do not attach any importance to electric and alternative fuel vehicles, the need to model the energy sector in details is not as important as for instance in Proost and al. (2009) which examines the impacts of replacing fuel taxes in Belgium by a set of taxes that better take the different external costs of transport into account while considering the possibility os using alternative fuels in conventional engines. In fact, on the supply-side, we put emphasis on the way the action played by a producer affects the behaviour of another producer (with game theory), and we do not go into detail regarding the technological solutions. One of the reasons

[7] Small and Van Dender (2007) estimates the short- and long-run rebound effect for motor vehicles in the USA over the period 1966-2001. On average, the values are respectively 4.5% and 22.2%.

[8] See figure 4.3. Drivers of CO_2 emissions from passenger cars in the EU, 1990-2008.

supporting this choice is that behaviours are as important as technologies in the pursuit of low-carbon mobility, if not more so insofar as the success of more energy-efficient technologies is conditioned by their adoption by downstream producers or final consumers. As regards now the second focus, that is to say the fact that we consider only a part of the whole population, we will argue in Chapter 3 that there is no real reason to include the other sectors of the economy in our model, insofar as the standard assumptions made in general equilibrium models – whereby for instance implementing a new subsidy translates into a new tax on households – do not make sense in our particular framework. Finally, it is worth noting that these two restrictions are evidence on the fact that we do not intend in this Thesis to offer scenarios with the objective of gauging the government's capacity to be on track with international or national commitments in terms of reduction of CO_2 emissions, such as, for example, in Pasaoglu and al. (2012)[9]. Indeed, all vehicles are not taken into account, and a significant part of the population does not enter the scope of our analysis. This is precisely one of the interests of theoretical models, *i.e.* to focus on a limited number of specific phenomena, without the ambition to reflect the complete reality.

Besides, because this Thesis does not aim at drawing scenarios also explains our static framework. Instead, we produce, as already said, a deeper understanding of interacting decisions, and the role of policy tools on them and resulting emissions.

The structure of the Thesis and the main messages formulated all along the different Chapters are further laid out in the next Part.

2. Structure of the Thesis

Three Chapters compose this Thesis. The first Chapter focuses on the supply-side of the automotive system, whilst the second one deals with the demand-side of the system, and the third with the system's equilibrium.

[9] Pasaoglu and al. (2012) reveals that "*under the deployed scenarios, the use of bio-fuel blends, technological learning and the deployment of hybrids, battery electric, plug-in hybrid and fuel cell vehicles can decrease WtW CO_2 emissions in EU-27 passenger road transport by 35–57% (compared to 2010 levels)*" (p 404).

2.1. To what extent is cooperation among producers of the automotive sector a substitute for a policy intervention to ensure the production of the least possible fuel-consuming vehicles?

Focusing on the supply-side, the first Chapter offers a framework of particular relevance to investigate strategies of car makers and automotive suppliers in the pursuit of low-carbon vehicles. More precisely, the diversity of industrial actors capable of playing on a new vehicles' energy performances is at the heart of our concerns in this Chapter.

Indeed, the starting point is that enhancing passenger vehicle energy-performance is considered as a key lever in the fight against CO_2 emissions due to car use (Kobayashi and al., 2009). Yet, different levers can be activated to reduce conventional vehicles' fuel use per kilometre (each one addressing the different restraining forces acting on a vehicle); as a result, the various industrial actors involved can share the efforts required to produce more efficient vehicles. The root of manoeuvre of each industrial actor is thus a key element in the move towards cleaner passenger cars. We focus in this Chapter on the role played by the car makers and the First Tier Suppliers (FTSs), and call upon game theory to better understand who does what. More generally, the research question resides in determining whether cooperation among the different members of the automotive sector results in the production of vehicles that consume less fuel per kilometre as opposed to those produced in the absence of cooperation. To a certain extent, the analysis of this Chapter also helps to decide whether such cooperation is a substitute for a policy intervention to ensure that the cleanest vehicle, given the available technologies, is produced.

Indeed, we investigate the producers' decision to cooperate with other manufacturers on vehicle design in order to create energy efficiency gains, beside the producers' decision in terms of broader energy performance of the technologies or vehicles. More specifically, our model considers one car maker and two suppliers: an engine producer, and a tyre manufacturer. This way, the vehicle's fuel consumption is only a function of the engine's and tyres' energy-performances[10]. What is more, each type of manufacturer is supposed to maximise their profit while producing a given total quantity divided into two different goods that are more or less "clean". That said, we examine first the cases wherein each producer chooses the energy-performance of the vehicles or equipment he produces and the production distribution between

[10] This choice was motivated by the partnership between the French tyre manufacturer Michelin and the Climate Economics Chair which supports this Thesis.

the two vehicles or equipment that maximise his own profit. Then, we investigate the cases wherein there is a cooperation on the vehicle design among two or three producers (in those cases, the producers who cooperate maximise the sum of their profits).

Within a numerical version of the model, we find that car makers and automotive suppliers, reacting to the imperatives of demand and supply, do not systematically equip new vehicles with high energy-efficient equipment to optimize fuel consumption. In fact, the car maker's incentive to use high energy-efficient equipment varies with the final consumers' demand for low fuel-consuming vehicles. When facing a relatively weak demand, the production of the 'cleanest' vehicle will only be achieved through a full cooperation on vehicle design between car makers and their suppliers. However, whether the producers have an individual interest in cooperating with all the other producers is uncertain. By contrast, when the demand for low-fuel consuming is relatively high, the 'cleanest' vehicle is produced regardless of the type of cooperation among producers.

In a context where the impact of CO_2 emissions from car use is so clear, whereas the free functioning of the market does not always result in the production of the least emitting vehicles makes a public intervention legitimate. Two types of public intervention would indeed make sense in this context. On the one hand, when the demand for 'clean' vehicles is low, public decision-makers should encourage the industrial actors to work together. The policy instruments best suited to address these issues are the *technology push* measures (*e.g*. competitiveness clusters, R&D aids, and so on). It is thus worth noting at this stage that the cooperation among the members of the automotive sector does not constitute a credible substitute for a policy intervention. On the other hand, public authorities should encourage more people to purchase 'clean' vehicles; this would promote a scenario where the 'cleanest' vehicle is produced regardless of the players' collaboration strategies. *Market pull* measures can thus be fully leveraged. These are incentive-based mechanisms (*e.g*. Bonus-Malus schemes), command and control levers (*e.g*. Low Emission Zones) but also knowledge policies (*e.g.* Energy consumption and CO_2 emissions label for new passenger vehicles).

To evaluate the efficiency of *market pull* measures, an in-depth analysis of the demand-side of the car system is needed. This is the purpose of the following Chapter.

2.2. What relevance for incentive-based mechanisms impacting on car purchase and use decisions in light of the rebound effect?

The second Chapter of this Thesis deals with the demand-side of the automobile system.

In this respect, miles driven and vehicle's energy efficiency are the two factors that impact on the total CO_2 emissions resulting from car use. And, given that these are two distinct levers to reduce CO_2 emissions, public decision-makers would be wrong not to target simultaneously both car purchase and use decisions. All the more so because both decisions are linked: the more efficient a vehicle is, the more it is used as cost per kilometre is reduced. This increase in the consumption of kilometres refers to the well-known phenomenon of "*rebound effect*", that is to say "increases in demand induced by efficiency gains". It seems instructive to note that this phenomenon clearly reflects the fact the car choice and the consumption of motorized kilometres are interdependent.

The specific aspect of this Chapter arises from a focus on the situations in which efficiency gains are observed at the fleet level while the vehicles' energy performances are not changed on the supply-side. We indeed investigate the effects of a differentiated purchase tax that encourages a new vehicle fleet profile in favour of low fuel-consuming vehicles, and thus participates in the efforts to improve the fleet's average fuel efficiency.

Our results are based on static comparative analyses of a basic model of consumer's behaviour. More specifically, for each car, the motorist chooses the distance to cover by car while maximising its direct utility. Then, given the different levels of direct utility, the vehicle that provides the highest indirect utility is chosen; the latter is found to be augmented by a random term reflecting the preferences for vehicles' characteristics (other than the energy efficiency) that differ among consumers.

We essentially find that a rebound effect does not necessarily accompany the reduction in the average fuel consumption per kilometre resulting from the implementation of a differentiated car purchase tax such as a Malus scheme. This is because improved fuel-efficiency is observed at the aggregate scale and not at the individual level. Thus, it is that a rebound effect is only found under certain conditions pertaining to the characteristics of the vehicles that make up the fleet (for instance when the gap in vehicles' unit consumptions is relatively high compared to the gap in vehicles' market prices). We also show that, from the moment that a rebound effect occurs, the higher the amount of the Malus, the higher the rebound effect. Said another way, the loss of efficiency of the differentiated tax, due to the rebound effect, increases with the pricing scheme's level. Going further, we investigate what effects the implementation of another pricing scheme, namely a fuel tax, has on the variation of CO_2 emissions caused by the Malus scheme. By using the numerical version of the model, we show that implementing an additional fuel tax is able to significantly contribute to limiting the *rebound effect* resulting from the first policy intervention, and thus generate a reduction in CO_2 emissions. Additionally, we argue that a fuel tax is rather efficient in that this particular pricing tool is able to achieve by itself CO_2 reduction levels equal to the combined car usage tax and Malus scheme

In any case, the reduction in CO_2 emissions should not be the single criterion used by public decision-makers when they have to decide between several policy tools. This is particularly true in the transport sector, and this is precisely addressed in the last Chapter of this Thesis.

2.3. Which CO_2 regulation is best suited to achieve the wider policy-makers' objectives of enhancing well-being and economic growth?

The last Chapter embraces the policy-maker's vision, while putting together elements from both the demand and supply sides.

Specifically, the first Part of this final Chapter gives the opportunity to discuss further the distinctive features of the transport sector that explain why policy-makers can, on the one hand, serve several objectives with a single instrument, whilst, on the other hand, a combination of two or more policy instruments could be useful in the pursuit of a given goal. Among the different objectives that can be pursued through a transport policy are theoretically a decrease in one of the transportation externalities such as local pollution, accidents, congestion, but also an augmentation of the well-being and of the economic growth. It follows that what drives the public authorities' choice in terms of a policy instrument aimed at reducing CO_2 emissions from passenger vehicles is not simply the ratio of "CO_2 emissions reduction to cost" of the alternative tools. Besides, the existence of four levers for cutting transportation GHG emissions – with reference to the aforementioned ASIF scheme – is one of the reasons supporting policy packages. However, to ensure that the effects are not just the same, public decision-makers have to examine whether the presence of a given tool accentuates or degrades the efficiency of another.

Hence, in the second Part of this Chapter, we recall our model (developed in the previous two Chapters) to examine the effects of three different policy tools on CO_2 emissions, on household's utility, and on the automotive sector's profit. To assess whether the global efficiency of policy action is enhanced or reduced overall, the first two variables help appraise the population's well-being, while the last one gives information on the economic growth. Said another way, this questions the relevance of the pursuit of cleaner car mobility for households and for the automobile sector. The three policy instruments at stake are a Bonus scheme[11], a fuel tax, and a tax on the purchase of low energy-efficient technologies. These policy tools are chosen for their distinct targets, namely the car purchase decision with the Bonus scheme, and the car usage decision for the fuel tax on the demand-side, and the supply of energy-efficient vehicles with a tax on low energy-efficient technologies. We start with a positive approach, and we find that, as already pointed above, a fuel tax makes motorist decrease the distances they travel by car, by simply increasing the cost per kilometre. If it helps mitigate CO_2 emissions due to car use, implementing a fuel tax also leads to a loss of utility for households from the moment that the consumption of kilometres provides them utility, such as argued in Chapter 2. In view of this trend, and favouring a normative approach with considerations for the whole car-purchasing population, introducing a Bonus on the purchase of low fuel-consuming vehicles seems to be an interesting additional incentive-based mechanism insofar as it provides an increase in the average households' utility. Furthermore, setting up such a differentiated car purchase subsidy also allows for increased profits in the automotive sector. By contrast, the value of targeting the supply-side with a tax on the purchase of low energy-efficient technologies remains unconvincing. On its own, such a tool provides an increased utility for households, but also leads to a decline in the producers' profits, and more importantly with regard to our prime objective, to a slight rise in CO_2 emissions. By demonstrating that the effects on emissions of the two incentive-based mechanisms impacting on the demand-side are synergetic, we come to the conclusion that the simultaneous use of a fuel tax and a Bonus scheme should be adopted. This kind of recommendation may lead to a subsidised economy; this is one of the shortcomings of partial equilibrium models.

[11] In Chapter 2, we consider a differentiated purchase tax, or in other words a Malus scheme, and we focus on its effects on the average fuel efficiency of the fleet and on the resulting rebound effect. In this final Chapter, we prefer to study a differentiated purchase subsidy, or in other words a Bonus scheme, because we look for pricing schemes capable of balancing the effects of the car use charge, notably the decrease in households' utility.

Chapter 1. To what extent is cooperation among producers of the automotive sector a substitute for a policy intervention to ensure the production of the least possible fuel-consuming vehicles?

Highlights

Enhancing passenger vehicles energy performance is considered as a key lever to respond to the issue of climate change caused by CO_2 emissions. As it is the automotive industry's job to make the improvement of vehicles' energy performances, this first Chapter deals with the supply-side of the automobile system.

The first Part deals with improvements of energy efficiency of vehicles. We first review the technical ways of improving the vehicle's energy efficiency, and then we discuss the role played by the different members of the industry, and more particularly that of car manufacturers and First Tier Suppliers (FTSs). We argue that using game theory helps determine which energy efficiency level will really characterise new vehicles, since the choice of energy performances of each producer is a strategic decision.

The second Part is dedicated to the policy tools that stimulate low-carbon innovations in the automobile sector. They typically take the shape of either innovation policies or environmental policies. Both are actually justified because of the so-called *double externality* – *i.e.* the coexistence of the environmental and knowledge externalities. Among policy tools that are put in place in France to reduce the CO_2 emissions due to car use, we also differentiate the *technology push* measures from the *market pull* measures.

The real contribution of this work consists of the two-fold approach developed in the third Part. On the one hand, we model the behaviours of car makers and First Tier Suppliers in a way in which the choice of the energy performances of the technology or the vehicle is a key element. On the second hand, we study the producer's decision to cooperate with the other manufacturers; the cooperation dealing actually with the vehicle's design. The research question resides in determining whether cooperation among the different members of the automotive sector results in the production of cleaner vehicles than without cooperation. To a certain extent, the analysis of this Chapter also helps decide whether such cooperation is a credible substitute for a policy intervention to ensure that the cleanest vehicle, given the available technologies, is produced.

1. Introduction

With increasing vehicle miles of travel, and tendency to purchase larger and more powerful vehicles (Gallachóir and al., 2009), – two trends of the demand-side – improving the vehicle's energy efficiency on the supply-side is particularly challenging in mitigating CO_2 emissions (Kobayashi and al., 2009). This is indeed one of the four levers identified within the ASIF scheme that help cut CO_2 emissions of the transport sector (in fact "I" in ASIF); in addition to the reduction of the transport activity ("A" in ASIF), the shifts towards less CO_2-emitting transport modes ("S" in ASIF), and the decrease of the CO_2 content of fuel ("F" in ASIF) (Schipper and al., 2000).

The automotive industry is however facing numerous structural challenges in which reducing CO_2 emissions from new cars is part of a wider strategy (ERIEP, 2013). Indeed, in the light of the economic downturn of 2008, the French car industry is struggling with overcapacity because of a saturated European market and an increasing competition with firms in India or China, where the markets are not yet saturated and are growing rapidly. In this context, the emerging questions surrounding "green cars" embody an additional challenge for the industry, but also a way-out from the other stakes by creating new strategic opportunities for innovation and growth.

Dealing with the issue of cutting CO_2 emissions, we generally differentiate two technological paths: the continuous improvement of conventional engine technologies on the one hand, and the development of alternative engine technologies on the other hand (Oltra and Saint Jean, 2009). In this work, we focus on conventional vehicles, while it is true that the French public authorities express a desire to promote electric vehicles (EV), and more generally 'electric transports'; the latter being perceived as a driver of growth (MINEFI, 2011). The reason of this choice is threefold. First, gains in terms of CO_2 emissions that can be attained in the short run with the vehicle electrification seem to be marginal, even when taking the most optimistic forecasts in terms of production and sales of EVs into account (MINEFI, 2011), while the potential reduction of consumption – and thus of CO_2 emissions – with combustion engines is still significant (from 20% to 40% compared to the 2009-situation, CAS, 2009). As regards the second reason, it deals more with modelling constraints. Indeed, excluding the hybrid and electric technologies enables us to leave aside from our analysis the issue of 'new players' (*e.g.* electricity producers, charging infrastructures providers, and so on). Third, factors impacting on the fuel consumption are numerous, and thus warrant an analysis as such. Thereby, the first Part of this Chapter is dedicated to a brief description of the supply-side strategies to reduce the conventional vehicle's fuel consumption per kilometre (cf. 2.1.). It seems instructive to clarify now that we do not put 'green' and 'grey' vehicles facing each other (it would have required to define what is a 'green vehicle'); we simply look for more energy-efficient vehicles.

More importantly, one can observe a new way of conceiving the car supply chain in recent years. In this regard and in the context of the issue of cutting CO_2 emissions, an interesting trend is the higher concerns – notably from the automakers (Frigant and Talbot, 2004) – for the end of the life cycle of the vehicle. Concurrently, the automotive sector has undergone profound changes in the way it coordinates the competencies and knowledge in design, manufacturing and assembly between the carmakers and their suppliers. This said, within the first Part, we also tackle the issue of identifying the type of actors that are capable of offering gains in energy efficiency. We discuss about car makers and First Tier Suppliers (FTSs) in particular (cf. 2.2.).

Besides, the co-existence of the knowledge and environmental externalities explains why automakers underinvest in energy-efficient technologies. This statement is enough of a signal for public authorities to set up public policy tools aiming at making the industrial actors take the plunge and produce more energy-efficient technologies and vehicles. All the more so because the impact of CO_2 emissions has become so much clearer that national authorities set objectives beyond the European standards. For illustrative purposes, we can note the objective set in the Grenelle I Act (JORF, 2009) to bring down CO_2 emissions from the *entire (existing plus new)* car fleet to 120gCO_2/km by 2020 (averaging 176gCO_2/km in 2011, MEDDTL, 2011), whilst the European standards require to achieve the level of 95gCO/km by 2020 for *new* vehicles only (the average was 127gCO_2/km in 2011; ADEME, 2014). Throughout the second Part of this Chapter (cf. 3.), we stress the need for both innovation and environmental policies, using the concept of *double externality*. We also describe and criticise the existing *technology push* and *market pull* measures that help stimulate low-carbon innovations in the automobile sector.

Finally, in the third Part of this Chapter (cf. 4), we propose to model the behaviours of car manufacturers and First Tier Suppliers in a way which focuses on the choice of the energy performances of the technology or vehicle. Furthermore, we investigate the producers' decision to cooperate on the vehicle design. This way, our producers do not only face optimisation problems (operational research), but are also involved in conflicts of interest because a cooperative behaviour generates a gain that has to be shared among players. Therefore, we also use game theory, or more exactly the theory of coalitions. This way, we propose a two-fold approach that helps conclude on whether cooperation among members of the automotive sector leads or not to the production of less fuel-consuming vehicles than without cooperation. To some extent, the research question lies also in determining whether this cooperation is a credible substitute for a policy intervention to ensure the production of the cleanest vehicle. To reply to these questions, a numerical illustration of our model, based on French data, is also provided.

2. The improvement of energy efficiency of new passenger vehicles

From the supply-side perspective, "*the final decision of the vehicle design is the car manufacturer's job, but achieving significant advances in performances (in terms of both function and costs) depends on the way the First Tier Suppliers propose, and are capable of addressing this opportunity*" (Fourcade and Midler, 2005). The "*way*" implicitly embraces two issues. The first one purely refers to technological options (see 2.1. The technological issue). The second one deals with the suppliers' room for manoeuvre (see 2.2. The organisational issue).

2.1.The technological issue

Technological solutions are an important lever to reduce the environmental impacts of passenger vehicles. But, designing new low-carbon vehicles is a long process. Very interestingly, the economic intuition suggests the introduction of new technologies accelerates the development of established technologies, both by introducing a spirit of technological competition and by offering new combinative possibilities (Bergrren and Magnusson, 2012). This is particularly important since different equipment play on the vehicle's fuel consumption. Before reviewing the different ways to reduce the vehicle's fuel consumption per kilometre and discussing their costs (2.1.2.), we start by decomposing the vehicle's fuel consumption per kilometre (2.1.1.).

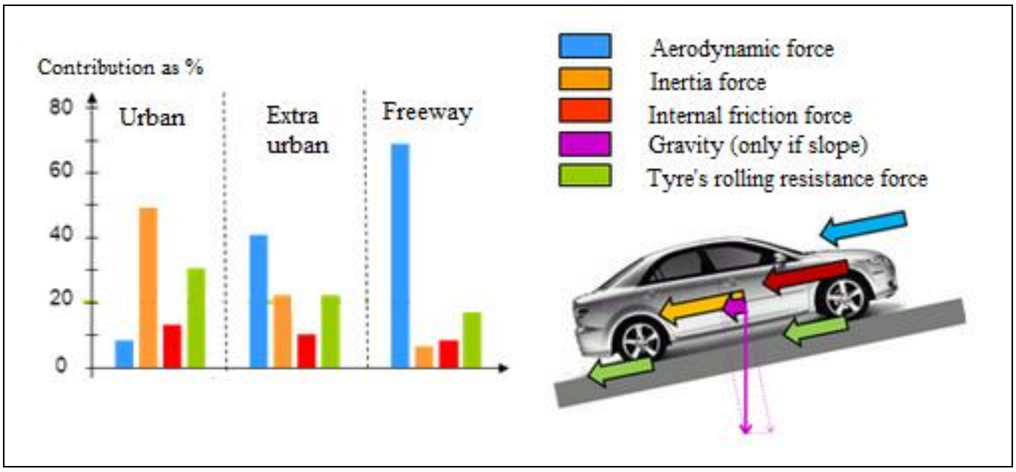
2.1.1. The decomposition of the vehicle's fuel consumption

The fuel consumption per kilometre can be broken into two independent components that are:

- the amount of fuel consumed to overcome the engine frictions, and
- the amount of fuel consumed to overcome the restraining forces acting on a vehicle, namely the rolling resistance, the aerodynamic drag and the inertial forces (*i.e.* internal friction force and mass).

A restraining force is likely to spread over more than one equipment. The most intuitive example is mass. Conversely, characteristics of a given equipment (*e.g.* tyres) may impact several restraining forces (in this case, rolling resistance force and weight in particular). That being so, the contribution to the vehicle's fuel consumption per kilometre of a given equipment is somewhat difficult to derive. By contrast, the contribution of the different restraining forces acting on a vehicle has been widely investigated in engineering studies. One of the lessons derived from those studies is that the relative contribution of each restraining force varies with the kind of journey (*i.e.* urban, extra-urban, and freeway, see Figure 1). By way of illustration, the weight of the aerodynamic force is slightly less than 10% for urban trips, whereas it is about 70% when driving on freeway. On the contrary, the inertia force (or 'mass') contributes to the fuel consumption more for urban trips (about 50%) than for trips on freeway (less than 10%). The weight of the tyre's rolling resistance force is between 20 and 30%.

Figure 1: Distribution of forces slowing a vehicle



Source: translated by the author, from Michelin

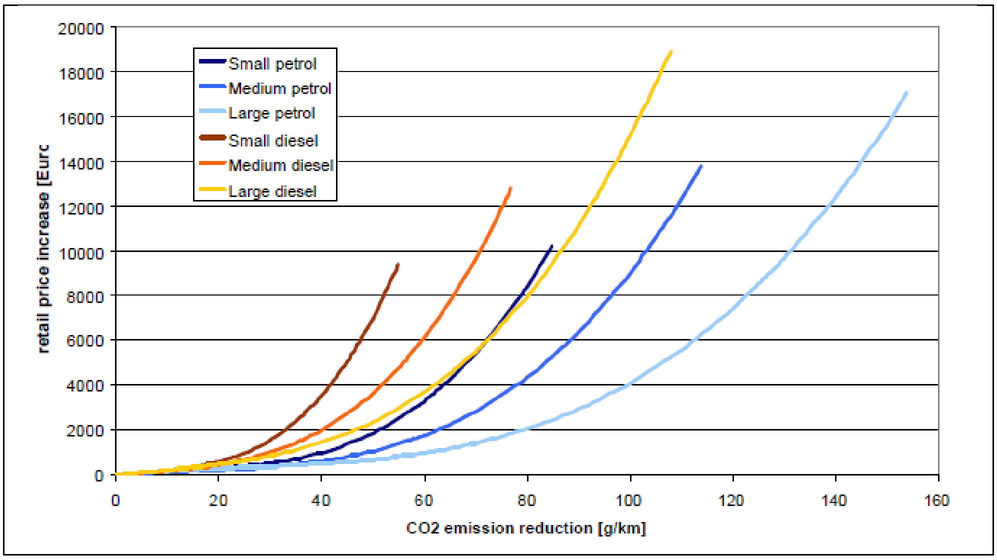
2.1.2. How to reduce the vehicle's fuel consumption per kilometre, and at which cost?

Establishing a Marginal Abatement Cost Curve (MACC) consists in estimating the cost of mitigation per ton CO_2 equivalent unit associated to a set of options available to an economy. It is a proper instrument to examine the economic impacts of the national objectives in terms of reduction in CO_2 emissions. One can either use a top-down approach based in most cases on computable general equilibrium models[12] (see for instance Tippichai and al. (2009) for the

[12] With a top-down approach, *"the marginal abatement cost is defined as the shadow cost that is produced by a constraint on carbon emissions for a given region and a given time, and is equal to the tax that would have to be*

transport sector), or a bottom-up approach based on engineering models. The latter models examine the different technical potentials to reduce CO_2 emissions. When it comes to analysing emissions from road transportation, options include either technologies that reduce the energy consumption per kilometre (*i.e.* 'I' in ASIF) or methods that reduce the CO_2 content of fuel (*i.e.* 'F' in ASIF). In any event, the MACC is first computed at the vehicle level, rather than at the fleet level, when using a bottom-up approach. This is highly relevant since the cost to reduce CO_2 emissions from passenger vehicles varies with the vehicle's size and motorisation in particular. This is, in a way, illustrated in Figure 2 below that plots the relation between the rise in retail price and the gain in CO_2 emissions for vehicles that differ in terms of size and motorisation.

Figure 2: Retail price increase according to the CO_2 emission reduction



Source: TNO (2009)

In order to be able to address in the present work the role played by automotive suppliers – except that of the fuel producer – in the improvements of the vehicle's energy efficiency, what we need to know is however the relation between a gain in fuel consumption per kilometre[13] and the cost at the *equipment* level, and not at the *vehicle* level (as it is with MACC). Since, as already said above, the contribution per equipment is somewhat difficult to derive, we consider, hereinafter, an intermediary level, namely the *restraining force* level. In this respect, the literature is divided into two types of studies: on the one hand some reports examine the links

levied on the emission to achieve the targeted level or the price of an emission permit in the case of emission trading" (in Tippichai and al., 2009, p79).

[13] Since we do not address the behaviour of the fuel producers, the CO_2 content of fuel is assumed to be constant so that we focus on reductions in fuel consumption per kilometer, rather than on reduction in CO_2 emissions per kilometer.

between a predefined variation of a restraining force and the resulting variation of the vehicle's fuel consumption per kilometre (see 1-a in Table 1); and on the other hand, some studies estimate the cost of a predefined reduction in vehicle's fuel consumption per kilometre achievable when playing on a given restraining force (but without specifying the order of magnitude of the variation of that force) (see 1-b in Table 1 above). Within Table 1, we prefer to keep a single (recent) reference for each kind of information (*i.e*. reduction in fuel use or cost), because comparing all the figures given in the literature would have been too costly because of the different units of measure (reduction in fuel use *versus* reduction in CO_2 emissions, cost expressed in euros or in dollars, and so on) and the different scopes (petrol cars *versus* diesel cars, different years of observation, etc.). More importantly, we would not have been able to conclude on the existence of a consensus because the sources are not explicitly given in most cases.

Table 1: Potential gains in fuel consumption – and their costs – when impacting on restraining forces acting on a vehicle

1-a: Variation in fuel use due to a variation of a given restraining force		
Variation of the restraining force	**Variation of the fuel use per kilometre**	
Frontal area (*i.e.* aerodynamic drag): -10%	-2.2%	
Mass (*i.e.* inertial forces) : -10%	-8.3%	
Mechanical loss: -10%	-15%	
Rolling resistance : -10%	-2%	
1-b: Cost of reducing the vehicle's fuel use by having an impact on a restraining force		
Involved restraining force	**Variation in fuel use**	**Cost (per vehicle)**
Aerodynamics improvement	-2%	€50
Lightweight components other than BIW*	-2%	€50 if petrol; €100 if diesel
Low friction design and materials	-2%	€35
Low rolling resistant tyres	-3%	€35

*Body In White (BIW) refers to the stage in automotive design in which a car body's sheet metal components have been welded together — but before moving parts.

Source: Author from Holmberg and al. (2012) and IEA (2012).

From Table 1, one can notice that reducing the tyre's rolling resistance is the cheapest way to reduce the vehicle's fuel consumption, but the potential in fuel savings is somewhat limited (only 2% for a 10%-reduction of the rolling resistance force). The potential fuel savings are for instance higher when impacting on the vehicle's mass (see the 8.3%-reduction), but the cost is more difficult to estimate (see the restriction 'other than BIW' in Table 1-b). In any event, it can be emphasised from Table 1 that this is technologically feasible to reduce the conventional vehicles' fuel consumption per kilometre, even at a reasonable cost. In the next subsection, we address the organisational issue, wondering what kind of actors is the most capable of improving the vehicle's energy efficiency.

2.2.The organisational issue

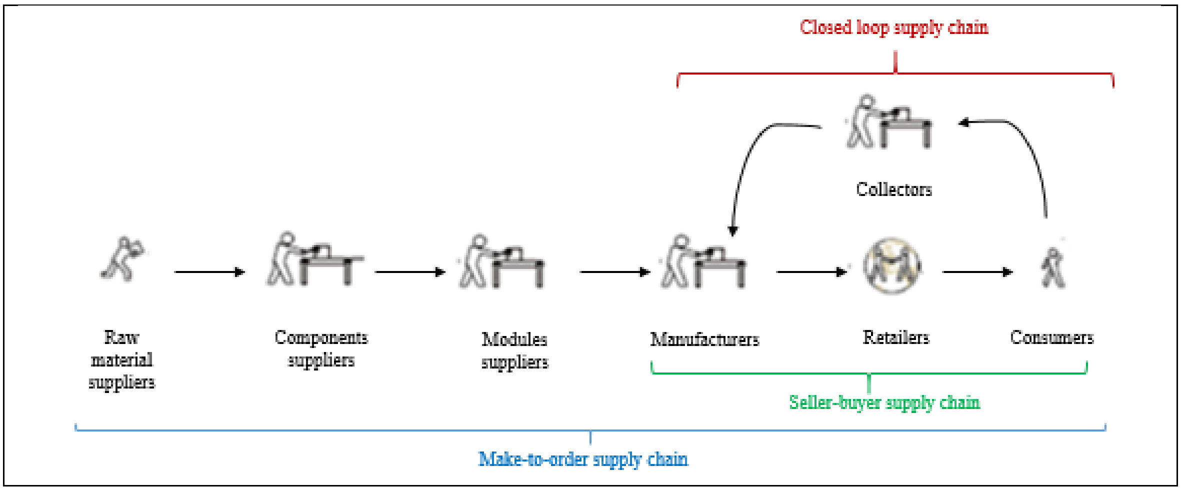
In all evidence, a multitude of actors are involved in the car production, since a vehicle results of the assembly of multiple equipment that themselves gather 15,000-20,000 components (Frigant and Talbot, 2004). The automotive production is actually based on a 'supply-chain' (see 2.2.1). As we adopt a purely manufacturing-oriented approach in this work, we nonetheless focus on tangible production; meaning that the service dimension of the automobile system is not taken into account (although it has become more and more important in recent years because of on the one hand the financial system's influence on the automotive industry, and on the other hand the growing concern for automobile usage systems; Lung, 2003). More specifically, we put emphasis, in this work, on car manufacturers and on First Tier Suppliers (FTSs). Their activities are discussed in the second subsection (2.2.2.). Concluding that both kinds of producers are likely to influence the vehicle's energy performances, we advocate, in the third subsection (2.2.3.), for using the game theory so as to better understand who is responsible for the improvement of the vehicles' energy efficiency, or on the contrary who gets in the way of improvements.

2.2.1. The concept of supply chain

A 'supply chain' is defined as "*a series of units that transforms raw materials into finished products and delivers the products to customers*" (Mabert and Venkataramanan, 1998). Likewise, Huang and al. (2011) says that "*a supply chain involves a variety of multiple products that are related to each other through common features*". Sedrasan (2013) adds the notion of "*complex network of business entities"* (*e.g.* suppliers, factories, warehouses, distribution centres and retailers).

The related literature discusses about different supply chain structures. To being with, a 'seller-buyer supply chain' represents "*a manufacturer who wholesales a product to a retailer, who, in turn, retails it to a consumer"* (Esmaeili and al., 2009). Clearly, the product is the same throughout that type of supply chain. In contrast, this is not the case along a 'make-to-order supply chain'. In fact, at the first stage of such a supply chain, the product consists of raw materials; at the second stage this is components; and the final product appears either at the third or fourth stages depending on the product architecture, namely respectively an integral or a modular one. When the retailing stage is included at the end of the 'make-to-order supply chain' (as in Li and al., 2010), the two structures of supply chain fit into each other, as illustrated in Figure 3 below. What is more, the two aforementioned supply chain structures may be considered as 'forward supply chains' in opposition to what is called in the literature 'closed loop supply chain' (CLSC). Precisely, "*collecting the products from downstream members and reusing them to create additional values*" are the activities investigated throughout the analysis of a CLSC (Huang and al., 2013[14]). Not surprisingly, the last years have seen an increase in research on CLSC (see a recent overview in Jena and Sarmah, 2014) because of pressure of regulations on environmental sustainability on the one hand, and take-back laws on the other (Choi and al., 2013).

Figure 3: Structures of supply chains



Source: Author from Li and al., 2010

In sum, there is no doubt that 'supply chain' is an important topic. Thereby, it has been explored from different perspectives, including: dominant player's strategies (the dominant player asks his suppliers (dominated players) to decrease their selling prices, in Li and al., 2010), bullwhip effects (this effect originally results from the variability of customer demands and information distortion in a supply chain; in Chan and Lee, 2012); local or global optimum (Lin and Lin, 2007), vertical and horizontal competitions (Wu and al., 2012), multi-generation durable goods (Jia and Zhang, 2013), and so on.

Focusing on car makers and First Tier Suppliers in the present research work, we are clearly interested in a 'make-to-order supply' chain. The automotive production has however been studied within a specific literature focussed on the modularisation (see Box 1 below), and issues

[14] in Choi and al.(2013)

are thus slightly different from the ones listed in the preceding paragraph. To briefly illustrate this point, we further discuss about car makers and FTSs in the next subsection.

Box 1: The move towards modularisation in the automotive sector

The ‘Smart’ car collaboration between Mercedes-Benz and the watchmaker Swatch clearly illustrates the trend towards modularisation in the car industry. According to Doran and al. (2007), “*the move toward modules*[15] *within the automotive sector has been influenced by declining profit per vehicle, shorter product life cycles and the increasingly sophisticated demands of consumers in global markets*”. Notwithstanding, according to Cabigiosu and al. (2013), “*the inherent complexity of automobiles reduces the chances of modularity to be effective”.*

Generally speaking, there are three arenas of modularity, namely design[16], production[17] and use[18]. On this topic, and within the automotive sector, it is worth mentioning that:

*Modularity-in-use is not a priority for car makers insofar as “*compatibility is currently not an important customer requirement [in the auto industry] and customers are content to buy a “total car” with a distinctive look and feel”* (Sako and Murray, 2001). Car purchasers are actually more interested in options (*e.g.* sun roof, wheel trims and so on), referring to the “*increasingly sophisticated demands of consumers”* mentioned above.

*In contrast, modularity-in-production is a priority for car manufacturers, at least for western automakers in that they are interested in outsourcing (Pandremenos and al., 2009). More importantly, according to Sako and Murray (2001), the adoption of modularity within the car sector was justified by the need of modularity-in-production in that it enables to “*assembly complex and ergonomically difficult tasks*”. Nonetheless, in the early 2000’s, there was not yet agreed mode of breaking up a car into modules (Sako and Murray, 2001). Indeed:

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[15] A *module* is defined as “*an unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units*” (Baldwin and Clark (2000), in Fourcade and Midler, 2004, p242).

[16] “*An architecture is considered modular if there is a one-to-one relationship between the function and the module and if the interfaces are sufficiently distinct that any modification of the module does not entail a redesign of the interface. With integral architectures, by contrast, there is no such one-to-one mapping, and functions are shared among several components*” according to Ulrich (1995) in Fourcade and Midler (2004) (p242).

[17] Modularity in production consists in pre-combining components in modules, and then assembling modules off-line. These modules are then brought onto the main assembly line that is shortened and whose task are made easier (Sako and Murray, 2001).

[18] The concept of modularity-in-use is easier to grasp when addressing the consumers’ requirement in terms of compatibility. The most appropriate example lies in the consumer’ demand of compatibility within a family of computers and across different generations of computers that arises because users want to read with a new computer files written with an old one on the one hand, and because workers exchange documents written with different computers on the other hand (see Sako and Murray, 2001).

*Modularity-in-design is difficult because of an extremely severe trade-off between modularity and global performance (see for instance the issue of decoupling the brake system from the shape of the wheel cover). It follows that most of products embody a hybrid or a modular-integral architecture (Sako and Murray, 2001). At that stage, making a distinction between 'modules' and 'systems' is particularly appropriate. Systems have single function (Fourcade and Midler, 2004). In many cases related to vehicles, "*a module satisfies more than one function (e.g. a door provides side impact protection as well as a rack for window regulators), and a system (e.g. climate control) is likely to spread over more than one module*" (Sako and Murray, 2001). Exceptions are the seats, the engine and to a certain extent the exhaust pipe (Frigant, 2013). This separation – that breaks the mapping one-to-one principle[19] (Frigant, 2013) – is one of the impediment to the move towards a 'traditional' modularisation within the automotive sector (Frigant and Talbot, 2004).
This said, it seems that the modular approach in the automotive sector is more likely to end up with "*a production of self-contained functional modules with standardised interfaces that can be fitted across vehicle brands and across geographic locations*" (this is the idea underlying the shared platforms among different car producers, Lung, 2003) rather than with "*a plug and play approach with modules that are completely interchangeable as in the computed sector*" (Doran and al., 2007). In other words, the automotive industry has developed its own definition of 'modularity' in terms of product (as an illustration, the tyre manufacturer Michelin has produced a motorised wheel comprising the electric motor, the gearing and the braking system), but also in terms of the organisational structure (Volpato, 2004).

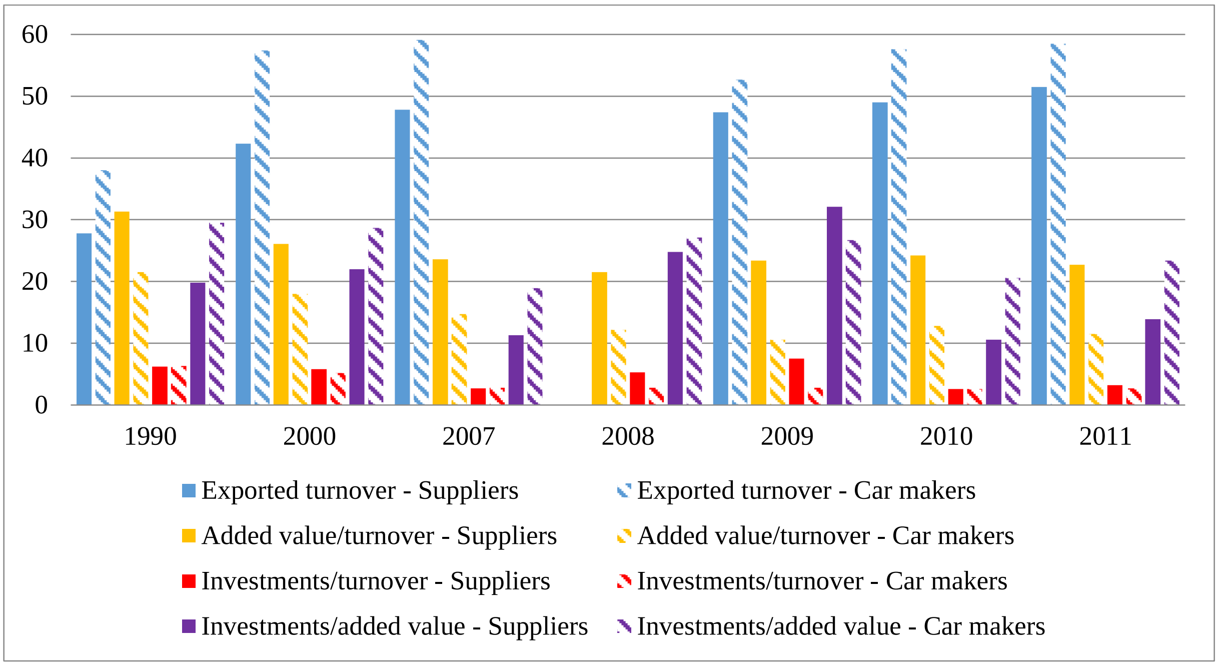
2.2.2. Car makers and First Tier Suppliers: who does what?

To begin, Figure 4 below illustrates some physical and financial data in France, both for car makers and automotive suppliers. Among other things, it teaches us that suppliers are less export-oriented[20] than car makers (in blue). It also shows that the production of equipment creates more added value relatively to the turnover than the production of cars (in yellow). As a matter of fact, outsourcing is widely practiced, and it is common that purchases account for from 75 to 80% of the car cost price (Frigant, 2007). The latter trend has to be distinguished

[19] The mapping one-to-one principle means "*to a function is devoted a subset*" (Frigant, 2013).
[20] Note that Frigant (2007) gives an overview of the percentages of exported turnover for twenty worldwide automotive suppliers, but the data are quite old (1990, 2002 and 2006).

from the modularisation that consists in moving towards a modular architecture. In contrast, outsourcing involves the contracting out of a business process to another party. If, in practice, the modularisation is in most cases based on outsourcing, the inverse is not true. Moreover, there exist different paths to outsource modules (see Sako and Murray, 2001).

Figure 4: Physical and financial data of car makers and automotive suppliers in France



Source: Author from CCFA (2012, 2014)

The significant use of outsourcing by car makers makes them be relegated to a position of secondary importance; that of '*technologies purchasers'*. In such a context, enhancing energy performances is the suppliers' job, even if there is clear evidence that the effects of the development of energy-efficient technologies are genuinely felt only if car manufacturers equip their cars with those technologies. In this regard, the *'innovation/customer orientation dilemma'* whereby the difficulty lies in determining whether the supplier should first innovate (innovation orientation) or identify the needs of the car maker and develop its technologies accordingly (customer orientation) takes on its full meaning. And because of the modularisation, this dilemma is more pronounced since a dynamic inefficiency exists due to the architectural lock-in (Fourcade and Midler, 2004). Indeed, the design falls into a so-called 'path-dependency' through "*the creation and embedding of certain manufacturing and design routines*" according to Sako and Murray (2001). Interestingly, Fourcade and Midler (2005) distinguishes in this regard '*key partners'* on the one hand, and '*loyal partners'* on the other. The former agents "*seek to influence the technology decisions of the client by occupying a key position"* (this is the innovation orientation) whilst the latter agents "*accept the dominance of the client, and* *develops flexibility in the face of the diversified demands of the automobile manufacturers*" (this is the customer orientation) (Fourcade and Midler, 2005; p10).

Among automotive suppliers, First Tier Suppliers (FTSs) are manufacturers who provide part and materials directly to the car maker. They play a greater role in designing and manufacturing motor vehicle subsystems with "*the transition towards a permanent innovation regime"* (Lung, 2003). Not without implications, the number of FTSs per car maker has fallen with the automotive modularisation (Lung, 2003; Frigant, 2013). This trend should indeed not be neglected since the selection of FTS is, as a consequence, more severe (see the for instance the Supplier Quality Insurance; in Gorgeu and Mathieu, 1995); and the compensation of that higher level of requirement is a delegation of more responsibilities to the few selected FTSs (Lung, 2003).

In the end, it is actually not a question of deciding whether FTSs are *key* or *loyal* partners. The reason is two-fold. Firstly, it seems that "*a pure loyal partner strategy is non-viable on the long term and a pure and stand-alone key partner strategy is non realist, and that a hybridation of strategies appears as a necessity*" (Fourcade and Midler, 2005). Secondly, we focus on only one characteristic of the product in the present work. We simply expect that alongside a particular dimension – *i.e.* the energy performance – FTSs benefit from a root of manoeuvre. In fact, from the moment that we do not degrade the function and we do not change the standard interfaces (that appear with the modularisation), there seems to be no reason to consider that the product's features are "constrained", leaving aside the obligation to respect security norms or other regulations. Quite the contrary, the environmental regulations, such as the European CO_2 emissions standards for passenger vehicles (see 3.2.1.) do encourage FTSs to offer energy efficiency improvements, by giving them a value insofar as penalties for missing the target are defined.

In a nutshell, the energy efficiency improvements are offered by different car maker's suppliers. That being so, we expect that the strategy that is definitely chosen by a given FTS depends on the other FTSs' strategies, and that the choice of the car maker varies with the decisions made by the FTSs. In view of those considerations, we advocate for using game theory (cf. 2.2.3.).

2.2.3. Using game theory to better understand who is responsible for improvements of vehicle's energy efficiency

Somewhat surprisingly, and to the best of the author's knowledge, game theory has not yet been called up in the literature addressing the strategies of the car industry to reduce CO_2 emissions[21]. Below, we broach matters pertaining to the players, the strategies and the payoffs of what could be the game enabling to tackle the aforementioned issue.

Focusing in this Chapter on the supply-side of the automotive sector, players are intuitively limited to manufacturers. Additionally, we are not interested in all evidence in the competition that takes place on a given market among its producers, but rather in the interactions among manufacturers who do produce different goods. That said, we will consider one car maker and a single First Tier Supplier per equipment (*e.g.* engine, tyre, and so on).

Going further, we also consider the possibility of forming coalitions, that is to say groups of players who enforce cooperative behaviour. By doing so, we should rather speak about "theory of coalitions" instead of "game theory". Nevertheless, since we limit ourselves to the economic dimension of the theory of coalitions – players make up a coalition just for obtaining a gain that they could not achieve otherwise – "game theory" and "theory of coalitions" will be used interchangeably in the remainder of this Chapter. Theoretically, the existence condition of a coalition is given by:

$$\sum_i \pi_s^i \geq \sum_i \pi_{ns}^i \qquad (1)$$

with π_s^i being the producer i's profit when he is part of the coalition (subscript 's' standing for 'signatory'), and π_{ns}^i being the producer i's profit when he does not cooperate (subscript 'ns' standing for 'non-signatory'). This refers to the *superadditivity* propriety: the value of two singletons (*i.e.* coalitions formed by a single player) will be no less than the sum of their individual values.

When three distinct producers are considered, the different possible coalitions or 'types of cooperation' are the following:

[21] The existing literature deals more with the strategic decisions of public authorities of different countries with the objective, in that case, to determine which CO_2 regulation is the most effective in a non-cooperative world (see a literature review in De Borger and Proost, 2012).

Table 2: The different possible coalitions involving two FTSs and a car maker

		Tyre manufacturer			
		Cooperates		Does not cooperate	
		Engine manufacturer		**Engine manufacturer**	
		Cooperates	Does not cooperate	Cooperates	Does not cooperate
Car maker	Cooperates	*Full cooperation*	*Cooperation vehicle-tyre*	*Cooperation vehicle-engine*	*No cooperation*
	Does not cooperate	*Cooperation engine-tyre*	*No cooperation*	*No cooperation*	*No cooperation*

Let us note that, albeit considering a unique producer for each type of good, we do not study monopolists. Quite the contrary, each producer is not large enough to influence the market prices on its market. Therefore, the strategies considered here are not prices. Nor are they quantities as such (the total quantity is fixed exogenously in our theoretical model, see 4.). In fact, to address the specific issue of improving environmental performances of vehicles, we choose the following strategies: the choice of energy performances of equipment as regards the FTS's strategy, and the choice of a given technology – more or less energy-efficient – for each equipment to assemble in vehicles as regards the car maker's strategy. That being so, the cooperation clearly concerns the design of the vehicle. It is worth highlighting that the above assumptions are consistent with the current situation of automotive suppliers who seem to be capable of benefiting from higher prices only by improving the performances of their product.

Moreover, in accord with the economic theory whereby the producer's behaviour is profit-maximising, profits constitute the payoffs of our game.

Finally, one should note that the tendency to cooperate depends on whether decisions are strategic complements or substitutes (in Potters and Suetens, 2009). We speak about "*strategic substitutes*" when "*B's optimal response to more aggressive play by A is to be less aggressive*" and about "*strategic complements*" when "*B responds to more aggressive play with more aggressive play*" (in Bulow and al. (1985), p494). Dealing with the focus of this work, one can imagine that the efforts to reduce the fuel consumption made by two FTSs producing different equipment are strategic substitutes when they play on the same restraining force acting on the vehicle, but rather strategic complements when they have an impact on a different force. In that context, that a FTS may be able to benefit from an innovation made by another FTS has to be taken into consideration. In this light, a representative of the International Transport Forum enjoyed reminding that *"there exist externalities related to technologies and innovations, since knowledge is a public good which development takes place in a context characterised by market* *failures"* (CEC and Michelin, 2013). The legitimacy of a public intervention is thus justified. This makes the transition to the next Part of this Chapter.

3. The policy instruments to put in place to stimulate low-carbon innovations

This Part puts emphasis on the policy instruments at the disposal of public authorities that help stimulate low-carbon innovations in the automobile sector. They typically consist of innovation policies and environmental ones. We start by setting out the rationale behind both types of policies (3.1.). Then, we propose to get some insight into (3.2.) as well as a brief discussion of (3.3.) the policy instruments that are put in place to promote and accelerate the introduction of clean technologies/vehicles onto the market.

3.1.The rationale of innovation and environmental policies

From a literature overview, Shi and Lai (2013) concludes that *"green and low-carbon technology innovation cannot be isolated from the policy or regulation regime"* (p839). Given the knowledge and environmental externalities, policies can be pro-innovation and environmental. The coexistence of both types of externalities constitutes the so-called '*double externality'*.

Regarding the knowledge externality, this is a question of public good's characteristics, namely *non-rivalry* (reproducing a unit of knowledge does not entail an additional cost, excluding transmission costs), and *non-excludability* (preventing someone from consuming knowledge would be too costly). These characteristics explain the "*knowledge dilemma*":

> *"Since agents expect to benefit from the knowledge accumulated by other agents through knowledge externalities, they do not engage themselves in the creation of new knowledge. Simultaneously, the almost zero cost of knowledge reproduction involves that the optimal price for knowledge is also zero […].The paradox is that profit-making companies, when engaging research activities for commercial purposes, must expect a positive price (at least) for investing in research and development (R&D)"* (in Bonnet and Renner, forthcoming, p5).

Said another way, the knowledge externality makes the social rate of return (*i.e.* the impact on the social welfare) of the innovation be higher than its private rate of return (*i.e.* the one that guides the inventor's fund allocation). This difference induces an incentive to invest in knowledge creation that is lower than the optimal level. In other words, that knowledge is a public good is precisely at the root of underinvestment (Arrow, 1962).

Being also a public good, environment suffers from negative externalities too. The social cost induced by the production of a polluting good – but also by the consumption of a polluting good, for instance car use – is actually higher than the private cost. It means that those who benefit from the production or consumption do not pay the whole (current and future) cost imposed by the related emissions. This is because pollution is mispriced. Interestingly, we should note that, compared to the problem with the knowledge externality, the one with the environmental externality is reversed. In the former case, a firm who invests in a new product creates benefit for others while bearing all the costs, whilst in the latter case the polluter enjoys all the benefits while imposing costs on others (Jaffe and al., 2005).

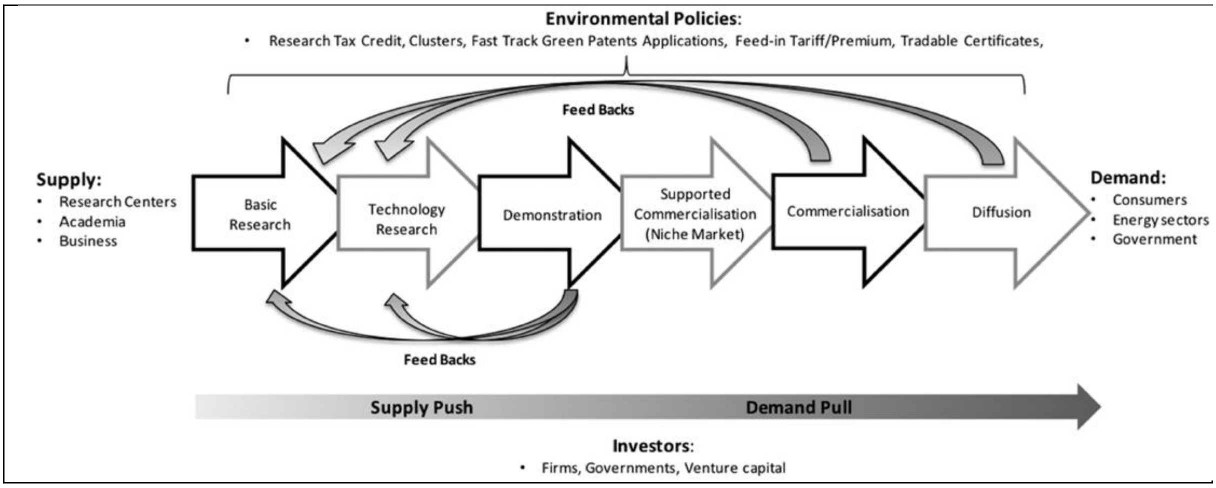
In a nutshell, Nordhaus (2011) summarises the *double externality* saying:

> *"The double externality in technologies to address global warming is that the social returns to innovation are well above the private returns, and the private returns are depressed because the market price of carbon is well below its true social cost"* (p 667).

3.2. Overview of *technology push* and *market pull* measures in the automotive sector

Innovation is a multifaceted phenomenon; and public authorities can *a priori* intervene at the different stages of the innovation process (Bonnet and Renner, 2013). In this light, we generally differentiate *technology push* (or *supply push*) and *market pull* (or *demand pull*) measures, as illustrated in Figure 5 below.

Figure 5: The innovation chain



Source: Bonnet and Renner (2013)

It seems that in practice *"the support to green innovation mostly relies on dedicated market pull policies and generic technology push policies"* (Bonnet and Renner, forthcoming, p26). We describe in the next two subsections some of *technology push* (3.2.1.) and *market pull* (3.2.2.) measures that are in effect in the European Union with the objective to reduce CO_2 emissions from passenger vehicles.

3.2.1. The *technology push* policies

Technology push policies are upstream measures. They are involved in the initial stages of the process without concerns about the consumers' needs.

The creation of a **competitiveness cluster**, that is to say the geographic concentration of related companies, research organisms, organisations and institutions, is a prime example of *technology push* measures. In all evidence, it is a policy instrument from the moment that it is launched by the governments, and does not merely result from a private initiative. In France, there exists a competitiveness cluster dedicated to vehicles, called "*Pôle Véhicule du Futur"* (competitivite.gouv.fr).

Technology push measures can also take the shape of **R&D aids** that help increase the project's private rate of return. In practice, "*support to R&D is generally applied in a generic way without distinguishing between clean or dirty technologies*" (Bonnet and Renner, forthcoming, p19). As regards the transport sector in France, R&D aids come from the PREDIT (€300M over the period 2002-2006), and from the European framework programme for R&D (about €120M over the same period; CAS, 2008). Beyond the R&D, other initial stages are likely to call upon public funding, or at least upon a public intervention. In this regard, the French Ministry of Industry underlines the European support to experimentations from 2007 (*i.e. Field Operational Test)*; the latter experimentations being more numerous in a context characterised by a major tendency to derive innovations from usages (MINEFI, 2011). In this regard, crowd funding is becoming a solution for funding mobility (not for infrastructures projects since the investment is very high). There exist only few examples (some of them are illustrated in Michelin, 2014), mainly because crowd funding is still poorly regulated. This is where a public intervention could help. All the more so because, according to Beard and al. (2009), the '*Valley of Death'*[22] occurs *"in the presence of 'non-economic' investments (such as government expenditures on basic*

[22] The '*Valley of Death'* is a widespread phenomenon in which *"a technology fails to reach the market because of an inability to advance from the technology's demonstration phase through the commercialisation phase"* (Frank and al. (1996), cited in Beard and al. 2009, p343).

research) that are made in very early stages research without sufficient attention to the likely investment decisions at later stages of the innovation process" (p343).

Lastly, one can also note the opportunity to protect the investment in innovation offered by **patents**. In this respect, according to the French Institute for Intellectual Property, 40% of the automotive patents were linked to environmental objectives in 2006 (INPI, 2006).

3.2.2. The *market pull* policies

Market pull policies are downstream measures. They play on the demand, and are precisely motivated by the need to enlarge the market's size (or to ensure the market's stability) so as to make the production cost fall (through economies of scale), and the technology become competitive.

Quite surprisingly, Command And Control (CAC) levers are part of the *market pull* policies. A CAC policy is essentially a restriction over characteristics of products (in Santos and al., 2010a). In this sense, implementing a CAC policy is tantamount to creating an artificial market in which consumers demand goods which characteristics correspond in average to the standards. For illustrative purposes, the European Union established in 2009 the **EU Tyre standard**, including standards for rolling resistance and wet grip for new tyres (European Commission, 2009a)[23]. The same year, the European Parliament (see the Regulation EC n°443/2009, European Commission, 2009b) approved the legally binding target of 130gCO_2/km to meet on average for the new fleet of passenger cars in Europe by 2015 (representing[24] fuel consumption of approximately 5.54L/100km for petrol cars and of 4.84L/100km for diesel cars) and the more stringent target of 95gCO_2/km to be achieved by 2020 (*i.e.* 4.05L/100km for petrol cars and 3.53L/100km for diesel cars). This refers to the well-known **CO_2 emissions standards for new passenger cars**. Dealing with implementation aspects, let us clarify that individual manufacturers' targets are differentiated on the basis of the average weight of the cars produced during the year under consideration[25]. Explicitly, regulation on CO_2 emissions takes to some extent the form of an average target for all cars sold,

[23] Among all the tyre characteristics (*e.g.* mass, wear, noise, ride, tread depth, dry grip, wet grip, handling, rolling resistance; TNO, IEEP and LAT, 2006), grip is the most important one for safety considerations, when rolling resistance is the most important one in terms of CO_2 emissions.

[24] using the CO_2 content of petrol of 2.346kgCO_2/L and that of diesel of 2.688kgCO_2/L (in EPA (2011) and using 1gallon=3.7878L)

[25] For example, if the car manufacturer's vehicles are 100kg heavier than the industry average by 2015, it will be granted an additional 4.57CO_2g/km as its target (Transport & Environment, 2012).

and does not consist of a fixed upper limit that may not to be breached by any car. At last, this regulation has been enforced gradually and through a system of fines[26].

Besides, **public procurement** is a more intuitive example of *market pull* policies. It aims at creating a 'club effect' for a given technology in order to generate economies of scale. In France, the most famous example is the convention signed in 2011 by 20 bodies for the public procurement of electric vehicles. This collective initiative was steered by the para-governmental enterprise La Poste (the French postal service), and coordinated and promoted by UGAP (the French public buying department). More generally, if different countries already have public procurement policies based on environmental or technological criteria, the latter criteria do not yet include the level of CO_2 emissions (TNO, IEEP, and LAT, 2006).

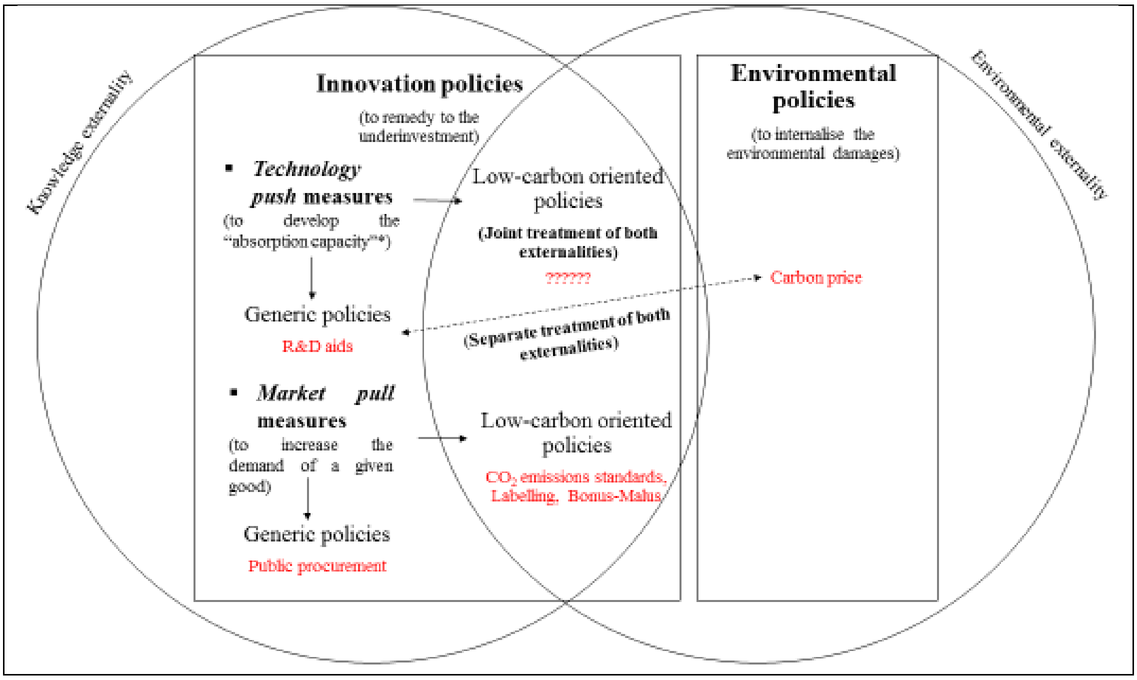
Lastly, *market pull* policies also include other CAC policies such as **Low Emission Zones**, 'communication and diffusion levers' such as the '**Energy consumption and CO_2 emissions**' label in France, and incentive-based mechanisms such as the **Bonus/Malus scheme**[27].

To conclude, and for clarity of exposition, Figure 6 below attempts to summarise these first two subparts (3.1. and 3.2.); by gathering the two different analysis grids, namely innovation policies *versus* environmental policies on the one hand, and *technology push* measures *versus* *market pull* measures on the other. It is worth noting that a carbon price (reported in Figure 6) is a typical example of policy that tackles the environmental issue without tackling the knowledge externality.

[26] The legally binding target of 130gCO_2/km to be reached by 2015 includes actually four different periods: a first one in which 65% of the compliance has to be done by 2012, a second in which 75% of the target has to be fulfilled by 2013, a third one in which 80% has to be completed by 2014 in order to be on track for 2015 (the fourth and last period). Between 2015 and 2018, penalties for missing the target are equal to 5€ for the first gCO_2/km in excess of 130gCO_2/km, to 15€ for the 2nd, to 25€ for the 3rd and to 95€ for the rest. From 2018, for each vehicle sold with CO_2 emissions in excess of its target, the manufacturer will have to pay a fine of 95€ per exceeding gCO_2/km (in Papaix and Meurisse, 2013 (p8), from Transport & Environment, 2012).

[27] Because of threshold effects, a Bonus/malus scheme typically impacts the producers' strategies. In this regard, Sallee and Slemrod (2012) argues that the policy notches (a Bonus/Malus is typically designed with notches) have real consequences: "*for many vehicles there is no incentive to incrementally improve fuel economy, but for others there are large and varying incentives for improvement*" to the point that "*there are significantly more vehicles produced (and purchased) just on the policy-beneficial side of the notches than otherwise would be expected"* (p998).

Figure 6: Insight on policy instruments when combining analysis grids



*absorption capacity: propensity of an industry to integrate and put into practice the new opportunities provided by the innovation (in Bonnet and Renner, forthcoming)

Source: Author

Figure 6 highlights the absence of *technology push* measures that are low-carbon oriented in the transport sector. This is to some extent in accord with the desire of the sector that claims *"it is the existence of a framework for other solutions than low-carbon technologies (for instance to meet security requirements) that would limit the interest of policy tools that precisely target low-carbon innovation"* (excerpt from a representative of Michelin during the CEC's annual conference in 2014; see CEC, 2014). In fact, emission regulations are only one piece of a larger regulatory framework – including legislations about end-of-life vehicles, noise, safety, and so on – that automotive manufacturers have to deal with in the design of new vehicles (Oltra and Saint Jean, 2009). The potential conflicts among the different vehicle's attributes on which the car maker has to play to comply with the different environmental objectives raise the necessity for the automaker to make some trade-offs.

We further discuss these measures in the next subsection.

3.3.Pros and cons of *technology push* and *market pull* measures

After having briefly reminded the general pros and cons of *technology push* and *market pull* measures (3.3.1.), we discuss somewhat longer the main strengths and shortcomings of the few policy instruments we have introduced above (3.3.2.).

3.3.1. General strengths and shortcomings of *technology push* and *market pull* measures

On top of the strengths of *technology push* measures, there is the increase in the likelihood that a firm puts into practice the opportunities offered by innovation. Conversely, that *technology push* measures are disconnected from consumers' needs is the main argument against this kind of innovation policies, insofar as the market's size impacts the profit that could be obtained with a new product. This precisely makes the strength of *market pull* measures. In this regard, Jaffe and al. (2005) underlines that "*so-called demand pull increases the return to developing such technologies. The spill over problem implies that firms can expect to capture only a portion of that return, but a portion of a large return is still more of an incentive than a portion of a small return*" (p170). This also explains why a consensus as to complementary of these two kinds of policy has emerged (Bonnet and Renner, 2013). It seems however worthwhile to highlight that the market measures are based on existing consumers, and the risk is to misevaluate the demand to the extent that once the support mechanism comes to an end, there is no market for the good at stake. Alternatively, there could exist a costly deadweight effect: all consumers collect the subsidy even those who would have purchased the good even in the absence of the incentive-based mechanism (Jaffe and al., 2005).

3.3.2. Strengths and shortcomings of the policy tools described in the previous subsection

First, the effects of standards and that of R&D aids or competitiveness clusters are likely to be felt later than those of *market pull* measures that target the would-be purchasers of innovations (*i.e.* Bonus/Malus scheme, labelling). The main reason deals with the implementation scheduling of a standard. In the example of the EU Tyre standard, that banning sales of tyres that do not meet the standards is undertaken only in second instance[28] creates certain inertia. In the same vein, the inertia that characterises the car production process explains why the targets defined in the CO_2 emissions standards are distant; in addition to be postponed in some cases as the result of lobbying engaged by industrial actors. This could also be a question of time frame of research; leaving aside the fact that the outcome of R&D programmes are also highly uncertain (Baudry, 2013). Notably, the development time for a car is counted in years, and once it is designed, the car remains in production several years. What is more, "*even*

[28] The restrictions over the tyres' characteristics are first applied on new models of tyres and on tyres fitted in new models of cars.

if it is technically possible to modify horsepower for instance quickly, the vehicle with its new characteristics must be certified before being distributed" (d'Haultfoeuille and al., 2014). In that context, setting a *"regulatory framework that is simple, stable, and predictable"* is minimally needed from the industrial perspective (in CEC, 2014). And, that public decision-makers can revise their instruments when they make mistakes in evaluating the impacts of the tools (sometimes several times, such as for the Bonus/Malus scheme) makes it very difficult for private players to anticipate, and consists in a real brake on their capacity and inclination to invest. In passing, the latter framework has also to be internationally re-known, from the moment that the industrial actors are evolving in an international market. This calls into question the need for standardising, among other tools, the CO_2 standards beyond the European borders[29]. Another good example [to illustrate the need for an international harmonisation of regulation] is that of Low Emission Zones (LEZs) insofar as the European cities are free to define their solutions (geographical scope, for example) and their LEZ criteria (vehicles concerned, EURO norms, etc.). Lastly, regarding the competitiveness cluster, it is true that there exists a risk of path dependency (the first decision will determine the technological path that the cluster will follow; Bonnet and Renner, forthcoming).

Still debating on the delay before effects are felt, it is also true that the inertia that characterises the vehicle fleet renewal rate, especially in Europe, may also make the public authorities revise downwards the interest of the aforementioned *market pull* measures which target the would-be buyers; all the more so when the purchase pricing schemes delay the car replacement (*e.g.* a Malus delays the car replacement of large cars in d'Haultfoeuille and al. (2014)). In that context, public procurement may be particularly useful.

Beyond the renewal rate, the willingness to pay for a low-carbon technology is also a decisive factor for its massive introduction onto the market. Labelling precisely aims at increasing the willingness to pay. More generally, labels are useful under asymmetric information, and all the more so for 'experience goods'[30] and 'search goods'[31] as suggested by Ismagilova and al. (2014). It also seems instructive to mention that a high quality product will generate repeat purchases to the point that the initial sale is more valuable to the producers according to Nelson (1970) (in Ismagilova and al. 2014). This is a reason why firms are ready to spend money in

[29] Fuel economy standards do also exist in other countries (see An and Sauer (2004) for a comparison of passenger vehicle fuel economy and GHG emission standards around the world).

[30] *Experience goods* are also called *durable goods*. They have a long service life. Yet, the longer the period of use, the lower consumers are able to know what utility they are going to obtain when purchasing the good at focus.

[31] *Search goods* are goods for which characteristics such as quality are rarely tested, even in the process of consumption (*e.g.* the amount of vitamin C in products).

advertising. Labelling is nonetheless somewhat different from advertising; all the more so when labelling is compulsory.

In any event, labelling alone is not sufficient, but there are interesting potential synergies when the label is part of a package of measures, including for instance a differentiated purchase tax (TNO, IEEP, and LAT, 2006). Incidentally, that effects of the French Bonus/Malus scheme have largely overcome the initial economic forecasts could be explained, as suggested in de Haan and al. (2009), not merely by the normative component (that is to say the psychological connotation of punishments and incentives, with the particular higher sensitiveness to losses when facing losses and gains of the same magnitude) which is often neglected, but also by the role of the “information part” of such a feebate scheme, namely the energy-label. In that sense, d’Haultfoeuille and al. (2013) has above all documented this impact of information for the French car market finding that “*the shift in preferences [for environmentally-friendly cars] explains 20% of the decrease [in CO_2 emissions of new vehicles] observed between 2003 and 2008. 75% of this shift are due to the energy label policy*” (p25).

Besides, as regard the impact on public finance, it is true that the French Bonus/Malus scheme led to a financial loss[32] (of about €525M in 2009 and €490M in 2010, MEDDTL, 2011) despite regulatory amendments had been made annually in order to reflect the Government’s financial equilibrium. The cost of R&D aids is also significant (see the figures given in 3.2.1.). That being so, it is true that labels and standards perform better with regard to the funding criteria.

Notwithstanding, labels and standards suffer from ‘cheating practices’ of car makers. As a matter of fact, car makers are ‘optimising’ the way they put cars through official tests to the point that test results do not reflect real-life driving conditions; meaning that some emissions reductions (30% according to Ricardo, AEA & TNO, 2012) are due to such test manipulation rather than to real improvements. Furthermore, CO_2 emissions standards may also be criticized insofar as, in spite of the existence of the fines scheme, CO_2 emissions would exceed the standards due to several loopholes[33] (Transport & Environment, 2012).

[32] In 2014, the French Bonus/Malus scheme generated for the first time a surplus (of more than 100 million of euros) (CCFA).

[33] Loopholes at focus include : 1/ ‘Eco-innovations’ are being rewarded with credits (up to 7 CO_2g/km); 2/ Manufacturers who produce low-emitting vehicles (LEVs) are being rewarded with ‘supercredits’, which allow them to count each LEV as more than one car (1.3 more exactly); 3/ Niche manufacturers (*i.e.* car makers with between 10,000 and 300,000 sales in the EU) should be allowed to benefit from an alternative target which is 25 % lower than their average specific emissions of CO_2 in 2007; and 4/ Carmakers with less than 10,000 sales in the EU can negotiate their own target with the Commission (in Papaix and Meurisse (2013), from Transport & Environment (2012)).

Some authors have already studied firm responses to environmental regulation. By way of example, Greene and Hopson (2002), Michalek and al. (2004) and Shiau and al. (2009) have examined firm responses to CAFE standards (*i.e.* the fuel efficiency standards in effect in the USA), while viewing the vehicle as a differentiated product from the car producer' and consumer's points of view. The next Part of the present work differs from this literature in that we do not examine the demand and supply-sides at a time. What is more, we look at the problem from a different perspective. Indeed, instead of examining effects of policy tools, we wonder if a policy intervention is really necessary when looking for the least fuel-consuming vehicles for sale. Precisely, we propose to build a model standing at the crossroads of operational research and the theory of coalition that could be called up for investigating whether cooperation among members of the automobile sector is a credible substitute for a policy intervention to ensure the production of the cleanest vehicles (given the available technologies).

4. A theoretical model to determine whether cooperation among producers of the automotive sector is a substitute for a policy intervention

A theoretical model aiming at better understanding the role played by car makers and First Tier Supplier(s) (FTSs) in improvements of vehicles' energy efficiency is developed in the first subpart (4.1.). Then, a numerical version of the model is proposed (4.2.).

4.1.The theoretical model

Herein, we introduce the main restrictions that define our theoretical framework on the one hand (4.1.1.) and the model formulations and notations on the other (4.1.2.). In the end, we address the market equilibrium (4.1.3.).

4.1.1. Theoretical framework

Our main restrictions are related to the vehicle's fuel intensity on the one hand, and to the car manufacturer' and FTS' behaviours on the other hand.

- **The vehicle's fuel intensity**

In this model, we select two different equipment for which the contributions to the vehicle's fuel consumption are rather well documented in the literature, namely engine and tyres, in order to be able to address the role played by FTSs in the improvements of vehicle's energy efficiency. In concrete terms, we assume that the vehicle's fuel consumption per kilometre diminishes solely with improvements of the energy performances either of engine or of tyres. Hence, our first restriction is the following:

R1. The energy performances of two equipment determine the vehicle's fuel efficiency: that of engine and that of tyres.

- **The car manufacturer' and FTSs' behaviours**

In accord with **R1**., we consider two different FTSs: an engine producer[34] and a tyre manufacturer, in addition to the car maker. Let us recall that in each market – *i.e.* tyre, engine and car markets – we consider a producer who operates in a competitive environment, implying that he is not large enough to influence the market prices on its market, as already said in 2.2.3.

Each manufacturer is supposed to produce two[35] different goods characterised by their energy performances; the other products' characteristics being assumed to be similar. Given that, and with a slight abuse of language, we will speak about a 'pollutant' or 'dirty' technology/vehicle and a 'clean' technology/vehicle. What is more, solely the performance of the clean technology/vehicle is a producer's decision variable; that of the dirty technology/vehicle is supposed to be fixed.

A further simplifying assumption is that the total supply per producer is fixed exogenously. It is tantamount to considering a car manufacturer who meets the total demand of vehicles which is fixed in a framework addressing the vehicle purchase decision (*i.e.* which car to purchase?) instead of the vehicle ownership decision (*i.e.* whether to own or not a vehicle?)[36]. In addition, considering that each FTS meets the car maker's demand of equipment, and that the equipment demand comes solely from the automaker (meaning that there is no replacement market) implies that the production of each equipment is also fixed. In such a context, the production distribution between the two goods is the second decision variable of each producer.

[34] We are well aware that most of the car makers design and produce themselves their engines, but our choice is justified by the need to consider more than one FTS while having available information in terms of potential gains in CO_2 emissions offered by a given technology as well as the associated production costs.

[35] The choice of two goods enables us to address the issue of the optimal distribution of production among goods of a different quality while keeping at the same time a simple model. But, albeit considering two different products that are more or less "clean", we draw the reader's attention to the fact that we completely differ from the growing literature dealing with the joint production of good and bad outputs that should be considered as conceptual foundations of ecological economics according to Baumgärtner and al. (2001). In fact, we do not have the following property: "*bad outputs are essentially by-products of production of good outputs*".

[36] We precisely address the question "which car to purchase?" in the following Chapter of this Thesis dealing with the demand-side.

In short, regarding the producers' behaviour, our theoretical framework is defined by the following restriction:

R2. Each producer maximises his profit while producing a fixed total quantity divided into two different goods. The producer's decision variables are the energy performance of the cleanest good on the one hand, and the production distribution between the two goods on the other hand.

4.1.2. Notations and problems formulation

Under **R2.**, there are clearly two steps for determining the optimal producer's behaviour, and we use backward induction to find it. The first step consists in determining the optimal production distribution between the two goods for each possible pair of products, and the second step is the choice of the products. Before addressing these two steps, we make clear that the total of production is the same for the three manufacturers[37]. We note it $\overline{S}$.

- **The FTSs' model formulation**

In what follows, we index the equipment by i in order to investigate at the same time the symmetric behaviours of the engine and tyre manufacturers. Later, we will replace i by e if we speak about engines or by ty if we speak about tyres.

The dirty technology is termed i_0, and the clean one is termed i_1. Besides, α^{i} is the share of the clean technology in the total production.

The FTS's profit (π^{i}) is given by:

$$\pi^{\mathrm{i}} = P^{\mathrm{i}_0}(1-\alpha^{\mathrm{i}})\overline{S} + P^{i_1}\alpha^{\mathrm{i}}\overline{S} - CT^{\mathrm{i}} \qquad (2)$$

where:

- P^{i_0} and P^{i_1} stand for the market prices of respectively the dirty technology i_0 and the more energy-efficient one i_1;
- CT^{i} is the total production cost. We assume the following simple quadratic function:

$$CT^{\mathrm{i}} = \sigma^{i_0}\left((1-\alpha^{\mathrm{i}})\overline{S}\right)^2 + \sigma^{\mathrm{i}_1}(\alpha^{\mathrm{i}}\overline{S})^2$$

  where σ^{i_0} and σ^{i_1} are the production costs of respectively the pollutant technology and the more efficient one. We will note $\sigma^{\mathrm{i}_1} = \sigma^{i_0} + \omega^{\mathrm{i}_1}$ with ω^{i_1} the extra production cost

[37] Needless to say that we assume that the unit of measurement of tyres, both for production and sales, is a pack of four tyres, in order to lighten up equations.

associated to the efficient technology i_1. And to lighten up expressions, subscripts 0 and 1 are removed from respectively σ^{i_0} and ω^{i_1} in the remainder of this work. We thus have σ^{i} (the cost of the dirty technology) and ω^{i} (the extra production cost for the more efficient technology). Eventually, the production cost can be written in the following manner:

$$CT^{i} = \sigma^{i}\overline{S}^{2}\left(1 + 2{\alpha^{i}}^{2} - 2\alpha^{i}\right) + \omega^{i}{\alpha^{i}}^{2}\overline{S}^{2} \tag{3}$$

Below are addressed one after the other the two steps of the FTS's profit-maximising programme. In fact, dealing with the mathematical resolution, this is because both α^{i} and ω^{i} have to be positive that we cannot tackle the two decision variables at the same time.

- First step

The optimisation programme corresponding to the first step – *i.e.* the choice of the production distribution between the two technologies – is the following:

$$\max_{\alpha^{i}} \pi^{i} = P^{i_0}(1-\alpha^{i})\overline{S} + P^{i_1}\alpha^{i}\overline{S} - \sigma^{i}\overline{S}^{2}\left(1 + 2{\alpha^{i}}^{2} - 2\alpha^{i}\right) - \omega^{i}{\alpha^{i}}^{2}\overline{S}^{2} \tag{P1}$$

Equalling to zero the derivative of π^{i} with respect to α^{i} gives the optimal share of efficient technology (${\alpha^{i}}^{*}$) in the total production. We obtain:

$${\alpha^{i}}^{*} = \frac{1}{2} * \frac{P^{i_1} - P^{i_0} + 2\sigma^{i}\overline{S}}{\overline{S}(\omega^{i} + 2\sigma^{i})} \tag{4}$$

The conditions such that $0 < {\alpha^{i}}^{*} < 1$ are:

- (> 0) $P^{i_1} - P^{i_0} > -2\sigma^{i}\overline{S}$;
- (< 1) $P^{i_1} - P^{i_0} < 2\overline{S}(\omega^{i} + \sigma^{i})$.

One should also note that we have ${\alpha^{i}}^{*} > 1/2$ as soon as $P^{i_1} - P^{i_0} > \overline{S}\omega^{i}$. It means that the order of magnitude of the extra cost associated to the most efficient technology compared to the order of magnitude of the gap in technologies' market prices explains the direction in which the supply of the most energy-efficient technology diverges from the half of the total supply. Said another way, and considering $\overline{S} = 1$, from the moment that the FTS earns more profit per unit with the efficient technology (*i.e.* $P^{i_1} - (\sigma^{i} + \omega^{i}) > P^{i_0} - \sigma^{i}$), the latter technology represents the major part (*i.e.* more than a half) of his production. To a certain extent, this result gives credit to our simplification of the cost function.

- Second step

The second step of the FTS's optimisation programme consists in determining which energy-efficient technology i_1 enables to maximise the profit. In all evidence, determining the extra cost ω^{i} associated to the energy-efficient technology is tantamount to choosing the type of the technology since ω^{i} is the single variable related to this technology in the FTS's profit (in addition to its market price, but the FTS is price taker). For ease of exposition of games (in which the cost of the clean technology constitutes the suppliers' strategy), ω^{i} is considered to take discrete values. That being so, the value of ω^{i} that maximises the profit results from the following optimisation programme:

$$\underset{\omega^{\mathrm{i}}}{argmax}\, \pi^{\mathrm{i}}\left(\omega^{\mathrm{i}} \middle| \alpha^{i^*}\right) \tag{P2}$$

In sum, the optimal FTS's strategy is characterised by the couple $\left(\omega^{i^*}, \alpha^{i^*}\right)$.

- **The car manufacturer's model formulation**

The car maker produces two types of vehicle. The most fuel-consuming vehicle is termed "vehicle d" ("d" stands for *dirty*). It is assumed to be equipped with the two pollutant technologies e_0 and ty_0. The least fuel-consuming vehicle is termed "vehicle c" ("c" stands for *clean*). The package of technologies fitted in that vehicle is a car maker's decision variable, noted q in what follows. α^v is the other decision variable of the car maker and refers to the share of clean vehicles in the total production.

The car maker's profit (π^v) is the following:

$$\pi^v = P^d(1-\alpha^v)\overline{S} + P^c\alpha^v\overline{S} - CT^v \tag{5}$$

with:

- P^d and P^c being the vehicles' market prices,
- CT^v being the total production cost. Once again, we assume a simple quadratic form:

$$CT^v = (\vartheta + P^{e_0} + P^{ty_0})\left((1-\alpha^v)\overline{S}\right)^2 + (\vartheta + P^{e_0} + P^{ty_0} + Z)\left(\alpha^v\overline{S}\right)^2$$

Or after rewriting:

$$CT^v = (\vartheta + P^{e_0} + P^{ty_0})\overline{S}^2\left(1 + 2\alpha^{v2} - 2\alpha^v\right) + Z\alpha^{v2}\overline{S}^2 \tag{6}$$

where $(\vartheta + P^{e_0} + P^{ty_0})$ stands for the production cost of the dirty vehicle (with P^{e_0} and P^{ty_0} the purchase costs of the two pollutant technologies e_0 and ty_0, and ϑ the other variable costs), and Z is the cost borne by the car maker when he produces a clean vehicle instead of a dirty one. In that light, Table 3 precisely gives the extra cost attributable to a clean vehicle according to its package of technologies (q):

Table 3: Extra production cost associated to a clean vehicle

Strategy of the car maker	$q = 1$	$q = 2$	$q = 3$
Package of technologies fitted in vehicle *c*	(e_0, ty_1)	(e_1, ty_0)	(e_1, ty_1)
Extra cost (Z_q)	$P^{ty_1} - P^{ty_0}$	$P^{e_1} - P^{e_0}$	$P^{e_1} - P^{e_0} + P^{ty_1} - P^{ty_0}$

- First step

The optimisation programme corresponding to the first step – *i.e.* the choice of the production distribution between the two vehicles – is the following:

$$\max_{\alpha^v} \pi^v = P^d(1-\alpha^v)\overline{S} + P^c\alpha^v\overline{S} - (\vartheta + P^{e_0} + P^{ty_0})\overline{S}^2\left(1 + 2\alpha^{v2} - 2\alpha^v\right) - Z_q\alpha^{v2}\overline{S}^2 \qquad \text{(P3)}$$

Equalling to zero the derivative of π^v with respect to α^v gives the optimal share of clean vehicles (α_q^{v*}) in the total production. We obtain:

$$\alpha_q^{v*} = \frac{1}{2} * \frac{P^c - P^d + 2\overline{S}(\vartheta + P^{e_0} + P^{ty_0})}{\overline{S}Z_q + 2\overline{S}(\vartheta + P^{e_0} + P^{ty_0})} \qquad (7)$$

The conditions such that $0 < \alpha_q^{v*} < 1$ are:

- (> 0) $P^c - P^d > -2\overline{S}(\vartheta + P^{e_0} + P^{ty_0})$;
- (< 1) $P^c - P^d < 2\overline{S}\left(Z_q + \vartheta + P^{e_0} + P^{ty_0}\right)$.

Here again, we have $\alpha_q^{v*} > 1/2$ if $P^c - P^d > \overline{S}Z_q$. Hence, the order of magnitude of the extra cost associated to the clean vehicle compared to the order of magnitude of the gap in vehicles' market prices explains the direction in which the supply of clean vehicles diverges from the half of the total supply.

- Second step

Determining the package of technologies to fit in the clean vehicle (q) constitutes the second step. The corresponding programme is written as follows:

$$\underset{q\in\{1,2,3\}}{argmax}\, \pi^v\left(q \middle| \alpha_q^{v*}\right) \qquad \text{(P4)}$$

In sum, the optimal car maker's strategy is given by the couple $\left(q^*, \alpha_q^{v*}\right)$.

4.1.3. The equilibrium

Our partial equilibrium is given by the balance between demand and supply for engines, tyres and vehicles. This means six markets as we consider two (more or less energy-efficient) products for each good. Our set of equations is however limited to three equations since we are reasoning in terms of distribution both for the production and the demand. It follows that with the equilibriums in the clean technologies and vehicle markets, we will find the relation between the market prices of the two technologies or the two vehicles – in other words the price differential –, not the two equilibrium market prices as such. In any case, to compute the equilibriums, we have to tackle the demands in addition to the supplies already addressed in the two previous subsections.

Focusing on the equipment markets, the demand of a given clean equipment is equal to the supply of vehicles that are equipped with that clean technology. Precisely, the demands for clean equipment are:

$$D^{e_1} = \begin{cases} 0 & \text{if } q = 1 \\ \alpha_2^v \overline{S} & \text{if } q = 2 \\ \alpha_3^v \overline{S} & \text{if } q = 3 \end{cases} \tag{8}$$

$$D^{ty_1} = \begin{cases} \alpha_1^v \overline{S} & \text{if } q = 1 \\ 0 & \text{if } q = 2 \\ \alpha_3^v \overline{S} & \text{if } q = 3 \end{cases} \tag{9}$$

where α_1^v, α_2^v and α_3^v are the shares of clean vehicles depending on the car maker's strategy (q).

As regards the car market, the demand of vehicles is not investigated here insofar as we focus on the supply-side in this Chapter. We will therefore consider exogenous levels of demand for clean vehicles (termed φ^c) in what follows. Let us note that this restriction will be relaxed in Chapter 3 in which we will be able to address simultaneously the demand- and supply-sides of the car market.

Lastly, it is worth noting that the system of equations characterising the three market equilibriums varies with the car maker's strategy (q) since the supply of clean vehicles (α_q^v) differs from a strategy to another, as pointed out above. Precisely:

* If $q = 1$, the market equilibriums are given with the following system of equations:

$$\begin{cases} 0 = \alpha^e(P^{e_1}) \\ \alpha_1^v\left(P^c,\ P^{ty_1}\right) = \alpha^{ty}(P^{ty_1}) \\ \varphi^c = \alpha_1^v\left(P^c,\ P^{ty_1}\right) \end{cases} \tag{S1.1}$$

*If $q = 2$, the market equilibriums are given with the following system of equations:

$$\begin{cases} \alpha_2^v\left(P^c,\ P^{e_1}\right) = \alpha^e(P^{e_1}) \\ 0 = \alpha^{ty}(P^{ty_1}) \\ \varphi^c = \alpha_2^v\left(P^c,\ P^{e_1}\right) \end{cases} \tag{S1.2}$$

*If $q = 3$, the market equilibriums are given with the following system of equations

$$\begin{cases} \alpha_3^v\left(P^c, P^{e_1},\ P^{ty_1}\right) = \alpha^e(P^{e_1}) \\ \alpha_3^v\left(P^c, P^{e_1},\ P^{ty_1}\right) = \alpha^{ty}(P^{ty_1}) \\ \varphi^c = \alpha_3^v\left(P^c, P^{e_1},\ P^{ty_1}\right) \end{cases} \tag{S1.3}$$

Expressions of market clearing prices and those of profits at the market equilibriums are given in Appendix A. From these expressions, we derive a proposition dealing with profits of the three producers (see Proposition 1). Note that the market prices share the same properties.

Proposition 1.

a) *The profit of a FTS is higher when there is a demand for the clean technology he produces. In such a case, the profit of the FTS increases with the demand for clean vehicles (this is also the demand for clean equipment).*
b) *From the moment that there is a demand for the clean technology, the profit of a FTS increases with the energy performance of the clean technology at focus, but does not vary with the type of equipment produced by the other FTS.*
c) *For a given car maker's strategy (*), the car maker's profit increases with the vehicle's energy efficiency (i.e. decreases with its fuel consumption per kilometre).*
d) *The profit of the car maker increases with the demand for clean vehicles.*

(*)We cannot, at this stage, argue that the car maker's profit increases with the vehicle's energy efficiency regardless of the car maker's strategy, since we have not already clarified what are neither the orders of magnitude of the gains in fuel consumption obtained with a new engine and a new tyre, nor those of the related costs.

Proof. See Appendix A.

Without specifying the orders of magnitude of the gains in fuel consumption obtained with a new engine and a new tyre, and the associated costs, we are not able to compare the profits of the three producers. Likewise, we cannot formulate proposition dealing with the total profit of all three manufacturers. Consequently, discussing the issues of the games depending on the size of the cooperation is not possible at this stage. We thus turn our attention to a numerical version of the model.

4.2.A numerical illustration of the model

4.2.1. Calibration of the model

Table 4 below precisely lists the variables (and their values) that are necessary to fix in order to compute the equilibrium market prices and the profits. Let us note that we consider petrol vehicles because of their higher level of CO_2 emissions per kilometre.

Table 4: Exogenous variables for our numerical illustration

Exogenous variables	**Value**	**Source / explanation**
Pollutant engine's market price (P^{e_0}) (€)	1,900	Value given in internet websites
Pollutant engine's production cost (σ^e) (€)	1,188	Computed with a coefficient for translation from cost to price of 1.6 (IEEP, 2005)[38]
Pollutant tyre's market price* (P^{ty_0}) (€) (* for a pack of four tyres)	250	Value given in internet websites
Pollutant tyre's production cost* (σ^{ty}) (€) (* for a pack of four tyres)	156	Computed with a coefficient for translation from cost to price of 1.6 (IEEP, 2005)
Dirty vehicle's fuel consumption (f^d) (L/km)	0.0524	Approximatively[39] the average fuel consumption of new petrol vehicles in 2013 (ADEME, 2014)
Dirty vehicle's purchase price (P^d) (€)	18,918	Approximatively[40] the average price of petrol vehicles in 2013 (L'Argus)
Dirty vehicle's production cost (except the purchase cost of engine and tyres) (ϑ) (€)	10,480	Computed with a coefficient for translation from cost to price of 1.6 (IEEP, 2005)

Besides, we have already attracted the reader's attention to the fact that the cost of energy-efficient technologies takes discrete values in the present work. Precisely, for ease of exposition, we consider three different energy-efficient technologies per equipment. These three technologies are termed e_a, e_b and e_c for engines, and ty_a, ty_b and ty_c for tyres. For both equipment, the technology indexed by a is the least energy-efficient one whilst the technology indexed with c is the most efficient one. More exactly, each engine technology is characterised by a decrease of the fuel consumed per litre of engine displacement and for 1,000 revolutions per minute (termed cff), and each tyre technology is characterised by a decrease of the rolling resistance force (termed Frr)[41]. Our assumptions regarding these technological variables, and the associated additional production costs are summarised in Tables 5 and 6 below. Note that the figures related to the characteristics of the dirty vehicle are given in Appendix B. These figures are useful in particular to compute the gain in fuel consumption obtained thanks to a given technology (second and third column in Tables 5 and 6).

[38] The share of the cost and margin of the dealer on the one hand and the margin of the manufacturer on the other hand in the price (excluding taxes) amounts to 38% on average (IEEP, 2005).
[39] The average fuel consumption per kilometre of petrol cars in France in 2013 was 5.2L/km. Here, we use 5.24L/100km, because it results from the assumptions we made on the different characteristics of the dirty vehicle (in particular the characteristics of its engine, see Appendix B).
[40] Precisely, in 2013, the average vehicle market price amounted to €23,407 in France (L'Argus). We assume that diesel vehicle are 5% more expensive than petrol vehicles and we take into account the distribution of registrations between diesel (about 69%) and petrol vehicles (about 31%) in 2013 to estimate the average market price of petrol vehicles in 2013. We obtain €22,626. This means €18,918 when taxes are excluded.
[41] A lower rolling resistance does not mean that the tyres are less robust; it rather means that the tyres make the car consume less fuel.

Table 5: Hypotheses related to the engine technologies' energy performances and costs[42]

Type of engine techno (e_1)	**Variation of "engine efficiency"**		**Variation of fuel consumption**		**Engine manuf.'s extra cost (ω^{e_1})**
	In absolute terms (Δcff)	In relative terms	In absolute terms*	In relative terms	
e_a	-0.03	-10%	-0.23L/100km	-4.33%	€54
e_b	-0.06	-20%	-0.45L/100km	-8.66%	€108
e_c	-0.09	-30%	-0.68L/100km	-12.98%	€162

*Using equation B.2 in Appendix B.

Table 6: Hypotheses related to the tyre technologies' energy performances and costs[43]

Type of tyre techno (ty_1)	**Variation of rolling resistance**		**Variation of fuel consumption**		**Tyre manuf.'s extra cost (ω^{ty_1})**
	In absolute terms (ΔFrr)	In relative terms	In absolute terms*	In relative terms	
ty_a	-10N	-8.93%	-0.07L/100km	-1.42%	€17
ty_b	-20N	-17.86%	-0.15L/100km	-2.83%	€33
ty_c	-30N	-26.79%	-0.22L/100km	-4.25%	€50

*Using equation B.3 in Appendix B.

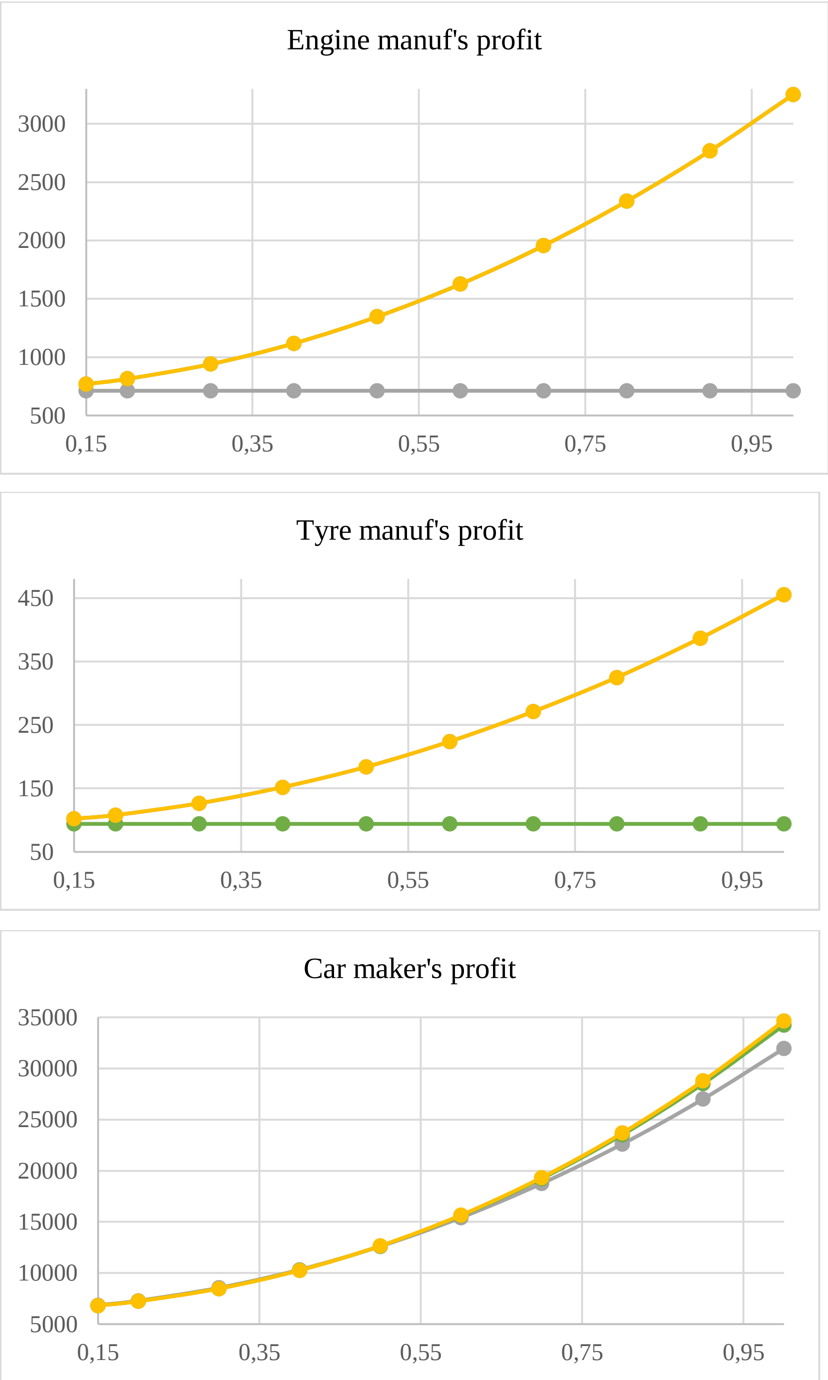
4.2.2. Description of market equilibriums

This Part is dedicated to a description of the market equilibriums. Recall that we reason with exogenous levels of demand for clean vehicles (φ^c). More exactly, we consider φ^c is between 15% and 100%. This is because below a certain level of demand for clean vehicles, the market price of the clean vehicle is negative (in fact $P^c > 0$ as soon as $\varphi^c > 0.127$ if $q = 1$, $\varphi^c > 0.135$ if $q = 2$, and $\varphi^c > 0.136$ if $q = 3$). Furthermore, as producing the most energy-efficient technology (*i.e.* e_c or ty_c) is a dominant strategy for each FTS (cf. Proposition 1 above) – or said another way since the least efficient technologies (indexed by a or b) are never produced – we plot in Figure 7 below the individuals profits and the sum of the three profits for only three different combinations of technologies, namely (e_0, ty_c), (e_c, ty_0) and (e_c, ty_c).

[42] The energy performances improvements are realistic orders of magnitude (in fact chosen after discussions with representatives of the automotive sector), and the associated costs are approximated from the value reported in TNO, IEEP and LAT (2006) namely a cost of €50 for a 4%-reduction of fuel consumption achievable with lower engine friction losses.

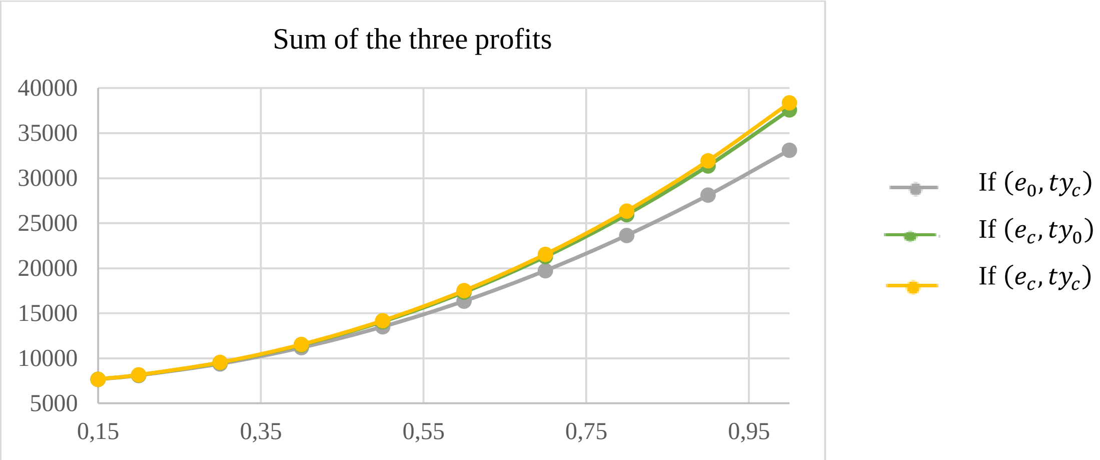
[43] The energy performances improvements are realistic orders of magnitude (in fact chosen after discussions with representatives of the automotive sector), and the associated costs are approximated from the value reported in IEA (2012), namely a cost of €35 for a 3%-reduction in fuel consumption obtained with low rolling resistant tyres.

Figure 7: Producers' profits (Y-axis, in €) as a function of the demand for clean vehicles (X-axis)



Note: the yellow and green curves are superimposed on each other (cf. e_c for both).

Note: the yellow and grey curves are superimposed on each other (cf. ty_c for both).



We do not comment the first three charts as such since they precisely illustrate our Proposition formulated in 4.1.3. By contrast, the last chart provides additional information. Indeed, it gives a clue on what is likely to constitute the issue of the game in which the three producers cooperate: it shows that maximising the profit of the whole car industry comes hand in hand with looking for the least fuel-consuming new vehicle (cf. the profit with the package of clean technologies (e_c, ty_c) in yellow). This result comes from the fact that, in the present numerical exercise:

* for low levels of demand for clean vehicles, the increase of profits of the FTSs obtained thanks to the production of a cleanest vehicle (cf. the gap between the yellow and grey curves on the first chart for the tyre producer, and the gap between the yellow and green curves in the second chart for the engine producer) more than compensates the small reduction in profit of the car maker (corresponding to the gap between the grey or the green curve and the yellow one, but non visible in the third chart above).

* for high levels of demand for clean vehicles, every producer is better off with the production of the cleanest vehicle (cf. the yellow curves in the first three charts).

We discuss longer about the strategies of the producers in the next part.

4.2.3. Games

Thanks to the numerical version of the model, and to a scrutiny of the five types of cooperation on the vehicle design (see Appendix C), we obtain the following chief result:

When the demand for clean vehicles is above 47% (included), the size of the cooperation does not affect the issue of the game, and this is the cleanest vehicle that is produced in any case.

Below that level of demand, a full cooperation among the manufacturers leads to the production of the cleanest vehicle, but this is not always the case with the other types of cooperation.

The above findings beg the question of whether the full cooperation is stable or not. We address this issue in Appendix C for the scenarios in which the nature of cooperation modifies the outcomes of the games. Our main finding is the following:
Below a certain level of demand,

- *that the car maker obtains his minimum of profit when all producers cooperate implies that the full cooperation is not stable;*
- *the gain obtained thanks to the cooperative behaviour is not high enough to allow transfers of profits among manufacturers that could make them be better off in the large cooperation than in all the other types of cooperation.*

Regarding the situations with transfers, there exists in fact a player (the tyre manufacture as it happens here) who has to *perceive* money – or at least to not give money – to be better off with a full cooperation than within the scenario where none of the producers cooperate, but has to *give* money in order to prevent the other two producers (the engine manufacturer and the car maker) from forming a sub-coalition together. These two conditions are obviously mutually exclusive.

With the analysis carried out in this subsection, it appears that the free functioning of the market does not always lead to the production of the least fuel-consuming vehicle. A public intervention seems thus to be relevant, provided that policy stakeholders are assumed to pursue the definite objective of achieving the highest energy performances for new vehicles. This objective seems to be relevant in the context of the issue of fighting against climate change. Said another way, cooperation among members of the automotive sector is a not a substitute for a policy intervention to ensure the production of the cleanest vehicles. We can already emphasise that in Chapter 3 of this Thesis – that is to say once the demand and supply-sides have been put together – we will go beyond this simple objective; and will consider the case wherein the public authorities look for the lowest total of CO_2 emissions that result from car use. We draw some first conclusions in terms of policy implications in the last subpart.

4.2.4. Lessons in terms of policy intervention

Our illustration teaches us that two actions are conceivable to ensure that the automotive industry produces the least fuel-consuming vehicle. The first action consists in making the producers' incentive to all cooperate together be greater than that to be divided into sub-coalitions when the demand for clean vehicles is low. The second action consists in making more households purchase a clean vehicle; this would promote a scenario in which the cleanest vehicle is produced regardless of the players' collaboration strategies

With the objective to make the full cooperation be stable, one can imagine a regulatory constraint that makes the cooperative behaviour compulsory for all producers. We do not know such policy instruments; but, without going as far as constraining producers, public decisions-makers do encourage cooperative behaviours by creating competitiveness clusters (introduced in 3.2.1.). Yet, as production costs of members of a competitiveness cluster are theoretically reduced (through the sharing of infrastructures costs, and the reduction of transportation costs for example), the outcome of a game is likely to vary in the presence of the competitiveness cluster. In the present work, we cannot examine the effects of such an intervention because of evident reasons related to the simple form of our costs functions that does not enable us to take the cost sharing among members of the cluster into account.

Regarding the policy tools capable of increasing the demand for low fuel-consuming vehicles, they typically take the shape of *market pull* measures such as a Bonus/Malus scheme, a label on energy consumption or CO_2 emissions, or a Low Emission Zone. Notwithstanding, there is nothing more that can be said about those particular tools in the present Chapter that focuses on the supply-side.

5. Conclusion

In this Chapter, we stand at the crossroads of operational research – with agents facing an optimisation problem – and theory of coalitions – with a gain obtained thanks to a cooperative behaviour that has to be shared among players. More specifically, this Chapter offers a framework of particular relevance to investigate the strategies of car makers and automotive suppliers, and more precisely to discuss their efforts to improve the energy efficiency of conventional passenger vehicles. What is more, this work distinguishes itself by investigating an environmental externality in a framework limited to the supply-side of an industry, but not with a purely engineering approach. As a matter of fact, there exist different levers to reduce the vehicle's fuel consumption per kilometre (because of the multiple restraining forces acting on a vehicle), and engineering studies show that fuel consumption gains can be achieved at a reasonable cost. But, beyond the technological issue, the root of manoeuvre of each industrial actor is also a key element in the move towards less fuel-consuming passenger cars. We focus on this Chapter on the role played by the car makers and the First Tier Suppliers (FTSs), and call upon game theory to better understand who does what. More specifically, we investigate the producer's decision to cooperate on the vehicle design with the other manufacturers, beside the producers' decision in terms of energy performance of the products.

We illustrate our model while unveiling the role of the level of demand for clean vehicles in the industrial actors' strategies. We essentially find that when the demand for clean vehicles is more than 47%, this is of the interest for all the producers (*i.e*. the car maker and the FTSs) to produce the least fuel-consuming vehicle, and that regardless of the nature of cooperation that could appear among producers. By contrast, when less than 47% of households purchase clean vehicles, the type of cooperation among producers distorts the outcome of the games. Very interestingly, when the three producers take into consideration the objective function of all of them – with a full cooperation – the goods that are definitely produced are not only able to make the whole industry earn more profit than when one producer is left aside from the decision-making process, but are also the most energy-efficient ones. Going further, considerations in terms of stability of a full cooperation are also provided for this second scenario. When transfers are allowed in every type of coalition, it seems that, below a certain level of demand for clean vehicles, our three producers are not able to make the incentive to cooperate all together higher than that to be divided into sub-coalitions. It is thus worth noting at this stage that the cooperation among the members of the automotive sector does not constitute a credible substitute for a policy intervention.

Indeed, in a context where the impact of CO_2 emissions from car use is so clear, that the free functioning of the market does not always lead to the production of the least emitting vehicles makes a public intervention legitimate. Among all the policy tools aiming at supporting low-carbon innovations that are at the disposal of public decisions-makers, one can distinguish innovation policies and environmental policies because of the so-called *double externality*. We can also differentiate *technology push* policies (chiefly competitiveness cluster, R&D aids, patents) from *market pull* measures (*e.g.* command and control policies such as the CO_2 emissions standards or a Low Emission Zone; incentive-based mechanisms such as a Bonus/Malus scheme, or communication levers such as a label).

Our illustration and the results thereof lead us to recommend two types of public intervention. More exactly, we identify two policy objectives. On the one hand, when the demand for clean vehicles is low, public decision-makers should make the manufacturers' incentive to all cooperate together be greater than that to be divided into sub-coalitions (with competitiveness clusters for instance). Policy instruments capable of addressing this issue could be the *technology push* measures. On the other hand, public authorities should encourage more people to purchase a clean vehicle; so as to be in a scenario characterised by a sufficiently high demand for clean vehicles, and in which the cleanest vehicle is produced regardless of the cooperation strategies of the producers. This time, the policy instruments best suited are the *market pull* measures. Nothing can be said however in this Chapter about the latter tools since we focus on the supply-side of the car market. We thus refer the reader to the two next Chapters in which the demand-side is further examined first as such (Chapter 2), and then simultaneously with the supply-side (Chapter 3).

Appendices

A – Proofs of Proposition 1

Expressions of the market prices are:

*If $q = 1$:

$$\begin{cases} P^{e_1} = P^{e_0} - 2\overline{S}\sigma^e & \text{(A1.1)} \\ P^{ty_1} = P^{ty_0} + 2\overline{S}[\varphi^c(\omega^{ty} + 2\sigma^{ty}) - \sigma^{ty}] & \text{(A2.1)} \\ P^c = P^d + 2\overline{S}\{(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^c - 1) \\ \qquad + 2\overline{S}\varphi^c[\sigma^{ty}(2\varphi^c - 1) + \varphi^c\omega^{ty}]\} & \text{(A3.1)} \end{cases}$$

*If $q = 2$:

$$\begin{cases} P^{e_1} = P^{e_0} + 2\overline{S}[\varphi^c(\omega^e + 2\sigma^e) - \sigma^e] & \text{(A1.2)} \\ P^{ty_1} = P^{ty_0} - 2\overline{S}\sigma^{ty} & \text{(A2.2)} \\ P^c = P^d + 2\overline{S}\{(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^c - 1) \\ \qquad + 2\overline{S}\varphi^c[\sigma^e(2\varphi^c - 1) + \varphi^c\omega^e]\} & \text{(A3.2)} \end{cases}$$

*If $q = 3$:

$$\begin{cases} P^{e_1} = P^{e_0} + 2\overline{S}[\varphi^c(\omega^e + 2\sigma^e) - \sigma^e] & \text{(A1.3)} \\ P^{ty_1} = P^{ty_0} + 2\overline{S}[\varphi^c(\omega^{ty} + 2\sigma^{ty}) - \sigma^{ty}] & \text{(A2.3)} \\ P^c = P^d + 2\overline{S}\{(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^c - 1) \\ \qquad + 2\overline{S}\varphi^c[(2\varphi^c - 1)(\sigma^e + \sigma^{ty}) + \varphi^c(\omega^e + \omega^{ty})]\} & \text{(A3.3)} \end{cases}$$

At the market equilibriums, the profits are given by the following expressions:

*If $q = 1$:

$$\begin{cases} \pi^e = P^{e_0}\overline{S} - \sigma^e\overline{S}^2 & \text{(A4.1)} \\ \pi^{ty} = P^{ty_0}\overline{S} - \sigma^{ty}\overline{S}^2 + \varphi^{c2}\overline{S}^2(\omega^{ty} + 2\sigma^{ty}) & \text{(A5.1)} \\ \pi^v = \overline{S}\left\{P^d + \overline{S}(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^{c2} - 1)\right. \\ \qquad \left. + 2\overline{S}^2\varphi^{c2}[\varphi^c(\omega^{ty} + 2\sigma^{ty}) - \sigma^{ty}]\right\} & \text{(A6.1)} \end{cases}$$

*If $q = 2$:

$$\begin{cases} \pi^e = P^{e_0}\overline{S} - \sigma^e\overline{S}^2 + \varphi^{c2}\overline{S}^2(\omega^e + 2\sigma^e) & \text{(A4.2)} \\ \pi^{ty} = P^{ty_0}\overline{S} - \sigma^{ty}\overline{S}^2 & \text{(A5.2)} \\ \pi^v = \overline{S}\Big\{P^d + \overline{S}(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^{c2} - 1) \\ \qquad + 2\overline{S}^2\varphi^{c2}[\varphi^c(\omega^e + 2\sigma^e) - \sigma^e]\Big\} & \text{(A6.2)} \end{cases}$$

*If $q = 3$:

$$\begin{cases} \pi^e = P^{e_0}\overline{S} - \sigma^e\overline{S}^2 + \varphi^{c2}\overline{S}^2(\omega^e + 2\sigma^e) & \text{(A4.3)} \\ \pi^{ty} = P^{ty_0}\overline{S} - \sigma^{ty}\overline{S}^2 + \varphi^{c2}\overline{S}^2(\omega^{ty} + 2\sigma^{ty}) & \text{(A5.3)} \\ \pi^v = \overline{S}\Big\{P^d + \overline{S}(\vartheta + P^{e_0} + P^{ty_0})(2\varphi^{c2} - 1) \\ \qquad + 2\overline{S}^2\varphi^{c2}[\varphi^c(\omega^e + 2\sigma^e + \omega^{ty} + 2\sigma^{ty}) - \sigma^e - \sigma^{ty}]\Big\} & \text{(A6.3)} \end{cases}$$

Proposition 1.

a) *The profit of a FTS is higher when there is a demand for the clean technology he produces. In such a case, the profit of the FTS increases with the demand for clean vehicles (this is also the demand for clean equipment).*
b) *From the moment that there is a demand for the clean technology, the profit of a FTS increases with the energy performance of the clean technology at focus, but does not vary with the type of equipment produced by the other FTS.*
c) *For a given car maker's strategy (*), the car maker's profit increases with the vehicle's energy efficiency (i.e. decreases with its fuel consumption per kilometre).*
d) *The profit of the car maker increases with the demand for clean vehicles.*

Proof.

a) When $q = 1{,}3$, π^{ty} is higher than when $q = 2$. In the same way, when $q = 2{,}3$, π^e is higher than when $q = 1$. Besides, π^e (when $q = 2{,}3$) and π^{ty} (when $q = 1{,}3$) increase with φ^c.
b) When $q = 2{,}3$, π^e is the same and increases with ω^e. Similarly, when $q = 1{,}3$, π^{ty} is the same, and increases with ω^{ty}.
c) π^v is an increasing function of ω^e and/or ω^{ty}, depending on the value of q.
d) π^v increases with φ^c (for $q = 1{,}2{,}3$).

B – Hypotheses made in the numerical version

Expressed mathematically, the fuel consumption per kilometre (explaining the factors 100 at the denominators) is given by:

$$f = \frac{cff * \frac{e_{size}}{1000} * \frac{e_{speed}}{1000} * 3}{100} + \frac{EN(Frr)}{0.41 * 0.755 * 43.5 * 100} \quad \text{(B.1)}$$

where:

- cff is the fuel consumption per litre of engine displacement and for 1,000 revolutions per minute (expressed in L/h);
- e_{size} is the engine size (expressed in cm^3);
- e_{speed} is the engine speed (expressed in revolutions per minute, or rpm);
- 3 is the number of hours to run 100km that corresponds to the average speed over a NEDC-cycle of 33.58km/h;
- EN is the energy needed (expressed in MJ) to overcome the restraining forces, including the rolling resistance force (termed Frr and expressed in newton);
- 0.41 is the thermodynamic efficiency;
- 0.755 is the petrol's density (expressed in g/cm^3), and
- 43.5 is the petrol's lower heating value by mass (expressed in MJ/L).

Clearly, the first term of equation B.1 refers to the fuel consumed to overcome the engine frictions, and the second one to the fuel consumed to overcome the restraining forces.

In our numerical exercise,

- the pollutant engine e_0 is characterised by a) an amount of fuel consumed per litre of engine displacement and for 1,000 revolutions per minute of 0.3L/h (we have $cff = 0.3L/h$); b) an engine size of $1{,}200cm^3$ ($e_{size} = 1200cm^3$), and c) an engine speed of 2,100 revolutions per minute ($e_{speed} = 2100rpm$).

- the pollutant tyres ty_0 are characterised by a rolling resistance coefficient of 10kg/t. It corresponds to a rolling resistance force of 112 Newton for a vehicle weighting[44] 1.14tonne (we note $Frr^{baseline} = 112N$). We draw the reader's attention to the fact that we make the

[44] This weight corresponds to the average tare weight of gasoline vehicles in France in 2013 (1.04t, ADEME, 2014) plus 100kg to take into account the weight of the driver plus that of ½-passenger, as is commonly assumed.

simplifying assumption whereby the vehicle's weight does not vary when the engine or the tyre changes.

Recall that the dirty vehicle is equipped with the two pollutant technologies e_0 and ty_0. It implies – among other things – that the first term of equation B.1 above is equal, for the dirty vehicle, to 2.27L/100km. Beside, we assume that the restraining forces (including the rolling resistance force characterising the pollutant tyres) are such that $EN^{dirty} = 40MJ$. It means that the second term of equation B.1 amounts to 2.97L/100km. Eventually, the dirty vehicle's fuel consumption is 5.24L/100km (*i.e.* $f^{baseline} = 0.0524L/km$). It is close to the average fuel consumption of gasoline vehicles (over an NEDC-type cycle) in France in 2013 that is 5.2L/100km (ADEME, 2014).

Variations in fuel consumptions (expressed in litre per kilometre) associated to a given new technology are obtained using the following equations:

- For a new engine technology (characterised by Δcff):

$$(\Delta f)^{e} = \frac{\Delta cff * \frac{e_{size}}{1000} * \frac{e_{speed}}{1000} * 3}{100} \quad \text{(B.2)}$$

- For a new tyre technology (characterised by ΔFrr):

$$(\Delta f)^{ty} = \frac{\Delta Frr}{1000 * 0.41 * 0.755 * 43.5} \quad \text{(B.3)}$$

The clean vehicle's fuel consumption f_q^c is thus given by:

- If it is equipped with e_0 and ty_1: $f_1^c = f^d - (\Delta f)^{ty_1}$
- If it is equipped with e_1 and ty_0: $f_2^c = f^d - (\Delta f)^{e_1}$
- If is equipped with e_1 and ty_1: $f_3^c = f^d - (\Delta f)^{e_1} - (\Delta f)^{ty_1}$

Hence, for information, using hypotheses related to the new technologies given in Tables 5 and 6, the fuel consumption per kilometre of the clean vehicle takes the following value according to its package of technologies:

Table B.1: Clean vehicle's fuel consumption depending on the package of technologies fitted in the vehicle

Car manuf.'s strategy	FTS's strategy	Clean vehicle's fuel consumption
$q = 1$ (e_0, ty_1)	(e_0, ty_a)	5,17 L/100km
	(e_0, ty_b)	5,09 L/100km
	(e_0, ty_c)	5,02 L/100km
$q = 2$ (e_1, ty_0)	(e_a, ty_0)	5,01 L/100km
	(e_b, ty_0)	4,79 L/100km
	(e_c, ty_0)	4,56 L/100km
$q = 3$ (e_1, ty_1)	(e_a, ty_a)	4,94 L/100km
	(e_a, ty_b)	4,86 L/100km
	(e_a, ty_c)	4,79 L/100km
	(e_b, ty_a)	4,71 L/100km
	(e_b, ty_b)	4,64 L/100km
	(e_b, ty_c)	4,56 L/100km
	(e_c, ty_a)	4,49 L/100km
	(e_c, ty_b)	4,41 L/100km
	(e_c, ty_c)	4,34 L/100km

C – Discussion of the results

This Appendix is dedicated to the explanation of the two results obtained within the numerical version of our model (and presented in 4.2.3.).

- **The first result was:**

When the demand for clean vehicles is above 47% (included), the size of the cooperation does not affect the issue of the game, and this is the cleanest vehicles that is produced in any case. Below that level of demand, a full cooperation among the manufacturers leads to the production of the cleanest vehicle, but this is not always the case for the other types of cooperation.

To be concise, we consider in what follows the cases in which the demand for clean vehicles amounts to 46% and 47%, and we only inform the reader that for levels of demand below 46%, the type of cooperation does affect the outcome of the game (the way it does may however vary with the level of demand) and for levels above 47%, the type of cooperation does not impact the outcomes (such as with 47%). Before that, let us underline that the FTSs are supposed to play (in terms of clean technology to produce, not in terms of production distribution) before the car maker. This is consistent with the fact that, in practice, the car maker observes the existing clean technologies before arbitrating between a clean and a dirty technologies for each equipment.

- **Scenario in which the demand for clean vehicles is 46%:**

Table C.1: Individual and total profits (in euros) when the demand for clean vehicles amounts to 46%

Car manuf.'s strategy (q)	FTS's strategy (e_1 and ty_1)	Profit of the engine manuf. π^e	Profit of the tyre manuf π^{ty}	Profit of the car maker π^v	Total profit $\prod$
$q = 1$ (e_0, ty_1)	(e_0, ty_a)	712	164	11,631	12,506
	(e_0, ty_b)	712	167	11,634	12,513
	(e_0, ty_c)	712	**171**	**11,637**	12,520
$q = 2$ (e_1, ty_0)	(e_a, ty_0)	1,226	94	11,603	12,924
	(e_b, ty_0)	1,238	94	11,614	12,946
	(e_c, ty_0)	**1,249**	94	11,624	12,967
$q = 3$ (e_1, ty_1)	(e_a, ty_a)	1,226	164	11,601	12,991
	(e_a, ty_b)	1,226	167	11,604	12,998
	(e_a, ty_c)	1,226	**171**	11,608	13,004
	(e_b, ty_a)	1,238	164	11,612	13,013
	(e_b, ty_b)	1,238	167	11,615	13,020
	(e_b, ty_c)	1,238	**171**	11,618	13,026
	(e_c, ty_a)	**1,249**	164	11,622	13,035
	(e_c, ty_b)	**1,249**	167	11,626	13,042
	(e_c, ty_c)	**1,249**	**171**	11,629	13,048

From the last column in Table C.1 above, it is clear that the outcome of the game in which the three producers cooperate is (e_c, ty_c) (in green). Alternatively, when none of producers cooperate, the outcome is (e_0, ty_c) (in bold in Table C.1 above, and reminding that a given technology is fitted in the vehicle only if the car maker decides to do so).

The outcome of the games in which two producers only cooperate are found with the normal forms of the games:

Table C.2: The normal form of the game with a 'cooperation engine-tyre'

Tyre manuf. + Engine manuf. (e_1, ty_1)	Car maker. (q)		
	$q=1$ (e_0, ty_1)	$q=2$ (e_1, ty_0)	$q=3$ (e_1, ty_1)
(e_a, ty_a)	876 ; 11,631	1,320 ; 11,603	1,390 ; 11,601
(e_a, ty_b)	879 ; 11,634	1,320 ; 11,603	1,393 ; 11,604
(e_a, ty_c)	883 ; 11,637	1,320 ; 11,603	1,397 ; 11,608
(e_b, ty_a)	876 ; 11,631	1,332 ; 11,614	1,401 ; 11,612
(e_b, ty_b)	879 ; 11,634	1,332 ; 11,614	1,405 ; 11,615
(e_b, ty_c)	883 ; 11,637	1,332 ; 11,614	1,408 ; 11,618
(e_c, ty_a)	876 ; 11,631	1,343 ; 11,624	1,413 ; 11,622
(e_c, ty_b)	879 ; 11,634	1,343 ; 11,624	1,416 ; 11,626
(e_c, ty_c)	883 ; 11,637	1,343 ; 11,624	1,420 ; 11,629

Reading note: the first term is the profit in € of the coalition formed by the tyre and engine manufacturers, and the second term is the profit in € of the car maker.

Table C.2 above constitutes the normal form of the game wherein the two FTSs cooperate. The outcome of that game is clearly (e_0, ty_c).

Table C.3: The normal form of the game with a 'cooperation vehicle-tyre'

Tyre manuf. + car maker (ty_1, q)	Engine manuf. (e_1)		
	e_a	e_b	e_c
$(ty_a, q=1)$ =>(e_0, ty_a)	11,794 ; 712	11,794 ; 712	11,794 ; 712
$(ty_a, q=2)$ =>(e_1, ty_0)	11,697 ; 1,226	11,708 ; 1,238	11,718 ; 1,249
$(ty_a, q=3)$ =>(e_1, ty_a)	11,765 ; 1,226	11,775 ; 1,238	11,786 ; 1,249
$(ty_b, q=1)$ =>(e_0, ty_b)	11,801 ; 712	11,801 ; 712	11,801 ; 712
$(ty_b, q=2)$ =>(e_1, ty_0)	11,697 ; 1,226	11,708 ; 1,238	11,718 ; 1,249
$(ty_b, q=3)$ =>(e_1, ty_b)	11,772 ; 1,226	11,782 ; 1,238	11,793 ; 1,249
$(ty_c, q=1)$ =>(e_0, ty_c)	11,808 ; 712	11,808 ; 712	11,808 ; 712
$(ty_c, q=2)$ =>(e_1, ty_0)	11,697 ; 1,226	11,708 ; 1,238	11,718 ; 1,249
$(ty_c, q=3)$ =>(e_1, ty_c)	11,778 ; 1,226	11,789 ; 1,238	11,799 ; 1,249

Reading note: the first term is the profit in € of the coalition formed by the tyre manufacturer and the car maker, and the second term is the profit in € of the engine producer.

In all evidence from Table C.3, the outcome of the game with a cooperation between the car maker and the tyre producer is also (e_0, ty_c).

Table C.4: The normal form of the game with a 'cooperation vehicle-engine'

Engine manuf. + car maker (e_1, q)	Tyre manuf. (ty_1)		
	ty_a	ty_b	ty_c
$(e_a, q = 1)$ =>(e_0, ty_1)	12,343 ; 164	12,346 ; 167	12,349 ; 171
$(e_a, q = 2)$ =>(e_a, ty_0)	12,830 ; 94	12,830 ; 94	12,830 ; 94
$(e_a, q = 3)$ =>(e_a, ty_1)	12,827 ; 164	12,831 ; 167	12,834 ; 171
$(e_b, q = 1)$ =>(e_0, ty_1)	12,343 ; 164	12,346 ;167	12,349 ; 171
$(e_b, q = 2)$ =>(e_b, ty_0)	12,852 ; 94	12,852 ; 94	12,852 ; 94
$(e_b, q = 3)$ =>(e_b, ty_1)	12,849 ; 164	12,853 ; 167	12,856 ; 171
$(e_c, q = 1)$ =>(e_0, ty_1)	12,343 ; 164	12,346 ;167	12,349 ; 171
$(e_c, q = 2)$ =>(e_c, ty_0)	12,873 ; 94	12,873 ; 94	12,873 ; 94
$(e_c, q = 3)$ =>(e_c, ty_1)	12,871 ; 164	12,875 ; 167	12,878 ; 171

Reading note: the first term is the profit in € of the coalition formed by the engine maker and the car maker, and the second term is the profit in € of the tyre manufacturer.

Lastly, when the car maker cooperates with the engine maker, the outcome is (e_c, ty_c) (since we said that the car maker is supposed to observe the existing technologies before playing, and recognising that producing ty_c is a dominant strategy of the tyre producer; in red in Table C.4 above).

- **Scenario in which the demand for clean vehicles is 47%:**

Table C.5: Individual and total profits (in euros) when the demand for clean vehicles amounts to 47%

Car manuf.'s strategy (q)	FTS's strategy $(e_1$ and $ty_1)$	Profit of the engine manuf. π^e	Profit of the tyre manuf π^{ty}	Profit of the car maker π^v	Total profit $\prod$
$q = 1$ (e_0, ty_1)	(e_0, ty_a)	712	167	11,867	12,746
	(e_0, ty_b)	712	170	11,871	12,753
	(e_0, ty_c)	712	**174**	11,874	12,760
$q = 2$ (e_1, ty_0)	(e_a, ty_0)	1,249	94	11,848	13,190
	(e_b, ty_0)	1,261	94	11,859	13,214
	(e_c, ty_0)	**1,273**	94	11,870	13,237
$q = 3$ (e_1, ty_1)	(e_a, ty_a)	1,249	167	11,847	13,262
	(e_a, ty_b)	1,249	170	11,850	13,269
	(e_a, ty_c)	1,249	**174**	11,854	13,277
	(e_b, ty_a)	1,261	167	11,858	13,286
	(e_b, ty_b)	1,261	170	11,862	13,293
	(e_b, ty_c)	1,261	**174**	11,865	13,300
	(e_c, ty_a)	**1,273**	167	11,869	13,309
	(e_c, ty_b)	**1,273**	170	11,873	13,316
	(e_c, ty_c)	**1,273**	**174**	**11,876**	13,323

When the three producers cooperate, the outcome is (e_c, ty_c) (in green in Table C.5). At the other extreme, when none of producers cooperate, the outcome is also (e_c, ty_c) (in bold in Table C.5).

Likewise, we use the normal forms of the games to find the outcomes for the other types of cooperation:

Table C.6: The normal form of the game with a 'cooperation engine-tyre'

Tyre manuf. + Engine manuf. (e_1, ty_1)	Car maker. (q)		
	$q = 1$ (e_0, ty_1)	$q = 2$ (e_1, ty_0)	$q = 3$ (e_1, ty_1)
(e_a, ty_a)	879 ; 11,867	1,343 ; 11,848	1,415 ; 11,847
(e_a, ty_b)	882 ; 11,871	1,343 ; 11,848	1,419 ; 11,850
(e_a, ty_c)	886 ; 11,874	1,343 ; 11,848	1,423 ; 11,854
(e_b, ty_a)	879 ; 11,867	1,355 ; 11,859	1,427 ; 11,858
(e_b, ty_b)	882 ; 11,871	1,355 ; 11,859	1,431 ; 11,862
(e_b, ty_c)	886 ; 11,874	1,355 ; 11,859	1,435 ; 11,865
(e_c, ty_a)	879 ; 11,867	1,367 ; 11,870	1,439 ; 11,869
(e_c, ty_b)	882 ; 11,871	1,367 ; 11,870	1,443 ; 11,873
(e_c, ty_c)	886 ; 11,874	1,367 ; 11,870	1,447 ; 11,876

Reading note: the first term is the profit in € of the coalition formed by the tyre and engine manufacturers, and the second term is the profit in € of the car maker.

The outcome of the game characterised by a cooperation between the two FTSs is (e_c, ty_c) (since we said that the car maker is supposed to observe the existing technologies before playing, and recognising that producing e_c and ty_c are the dominant strategies of the two FTS; not really visible in Table C.6 above, but rather derived from Table C.5).

Table C.7: The normal form of the game with a 'cooperation vehicle-tyre'

Tyre manuf. + car maker (ty_1, q)	Engine manuf. (e_1)		
	e_a	e_b	e_c
$(ty_a, q = 1) \Rightarrow (e_0, ty_a)$	12,034 ; 712	12,034 ; 712	12,034 ; 712
$(ty_a, q = 2) \Rightarrow (e_1, ty_0)$	11,942 ; 1,249	11,953 ; 1,261	11,964 ; 1,273
$(ty_a, q = 3) \Rightarrow (e_1, ty_a)$	12,014 ; 1,249	12,025 ; 1,261	12,036 ; 1,273
$(ty_b, q = 1) \Rightarrow (e_0, ty_b)$	12,041 ; 712	12,041 ; 712	12,041 ; 712
$(ty_b, q = 2) \Rightarrow (e_1, ty_0)$	11,942 ; 1,249	11,953 ; 1,261	11,964 ; 1,273
$(ty_b, q = 3) \Rightarrow (e_1, ty_b)$	12,021 ; 1,249	12,032 ; 1,261	12,043 ; 1,273
$(ty_c, q = 1) \Rightarrow (e_0, ty_c)$	12,048 ; 712	12,048 ; 712	12,048 ; 712
$(ty_c, q = 2) \Rightarrow (e_1, ty_0)$	11,942 ; 1,249	11,953 ; 1,261	11,964 ; 1,273
$(ty_c, q = 3) \Rightarrow (e_1, ty_c)$	12,028 ; 1,249	12,039 ; 1,261	12,050 ; 1,273

Reading note: the first term is the profit in € of the coalition formed by the tyre producer and the car maker, and the second term is the profit in € of the engine manufacturer.

In the case of a cooperation between the tyre producer and the car maker, the outcome of the game is (e_c, ty_c) (since we said that the car maker is supposed to observe the existing technologies before playing, and recognising that producing e_c is a dominant strategy of the engine producer; in red in Table C.7 above).

Table C.8: The normal form of the game with a 'cooperation vehicle-engine'

Engine manuf. + car maker (e_1, q)	Tyre manuf. (ty_1)		
	ty_a	ty_b	ty_c
$(e_a, q = 1)$ =>(e_0, ty_1)	12,579 ; 167	12,583 ; 170	12,586 ; 174
$(e_a, q = 2)$ =>(e_a, ty_0)	13,096 ; 94	13,096 ; 94	13,096 ; 94
$(e_a, q = 3)$ =>(e_a, ty_1)	13,096 ; 167	13,099 ; 170	13,103 ; 174
$(e_b, q = 1)$ =>(e_0, ty_1)	12,579 ; 167	12,583 ; 170	12,586 ; 174
$(e_b, q = 2)$ =>(e_b, ty_0)	13,120 ; 94	13,120 ; 94	13,120 ; 94
$(e_b, q = 3)$ =>(e_b, ty_1)	13,119 ; 167	13,122 ; 170	13,126 ; 174
$(e_c, q = 1)$ =>(e_0, ty_1)	12,579 ; 167	12,583 ; 170	12,586 ; 174
$(e_c, q = 2)$ =>(e_c, ty_0)	13,143 ; 94	13,143 ; 94	13,143 ; 94
$(e_c, q = 3)$ =>(e_c, ty_1)	13,142 ; 167	13,146 ; 170	13,149 ; 174

Reading note: the first term is the profit in € of the coalition formed by the engine manufacturer and the car maker, and the second term is the profit in € of the tyre maker.

As regards the situation in which the car maker cooperates with the engine producer, the outcome is (e_c, ty_c) (since we said that the car maker is supposed to observe the existing technologies before playing, and recognising that producing ty_c is a dominant strategy of the tyre producer; in red in Table C.8 above).

- **The second result was:**

Below a certain level of demand,

- *that the car maker obtains his minimum of profit when the cooperation is total implies that the full cooperation is not stable;*
- *the gain obtained thanks to the cooperative behaviour is not high enough to allow transfers of profits among manufacturers that could make them be better off in the large cooperation than in all the other types of cooperation.*

We consider below the scenario in which the demand for clean vehicles amounts to 46% (*i.e.* the maximum level of demand for which the type of cooperation modifies the outcomes of the games among industrial actors), as well as – for illustrative purposes, the case wherein the latter demand is 40%. In the first case, the full cooperation is stable with transfers (see the first bullet point below), whereas it is not neither in the second scenario (see the second bullet point below), nor when the demand for clean vehicles is even lower (but for the sake of concision, we do not report the analysis of such situations in this Appendix). It teaches us that there exists a level of demand below which the full cooperation is not stable (even when transfers of profits are allowed among producers).

- **Scenario in which the demand for clean vehicles amounts to 46%:**

Table C.9: Outcomes and profits when the demand for clean vehicles is 46%

	Outcome of the game	Profit of the engine manuf. π^e	Profit of the tyre manuf π^{ty}	Profit of the car maker π^v	Total profit Π
Full cooperation	(e_c, ty_c)	€1,249	€171	€11,629	€13,048
Cooperation engine-tyre	(e_0, ty_c)	€712	€171	€11,637	€12,520
Cooperation vehicle-tyre	(e_0, ty_c)	€712	€171	€11,637	€12,520
Cooperation vehicle-engine	(e_c, ty_c)	€1,249	€171	€11,629	€13,048
No cooperation	(e_0, ty_c)	€712	€171	€11,637	€12,520

The full cooperation is not stable at first sight, since the car maker earns more profit outside the coalition formed by the two FTSs than in the full cooperation (meaning that the car maker has no interest to join the coalition). We thus examine below the conditions pertaining to the amounts of transfers under which the three producers obtain a higher profit (or at least the same profit) with a full cooperation than in all the other types of cooperation:

*The conditions pertaining to the transfers under which the full cooperation is more desirable than the option 'no cooperation' are the following:

$$\begin{cases} 11\,629 + T^v \geq 11\,637 & \text{(the car maker prefers the full cooperation than no cooperation)} \\ 1\,249 + T^e \geq 712 & \text{(the engine manufacturer prefers the full cooperation than no cooperation)} \\ 171 + T^{ty} \geq 171 & \text{(the tyre maker prefers the full cooperation than no cooperation)} \end{cases}$$

where T^v, T^e and T^{ty} are the transfers earned (if positive) or given (if negative) by respectively the car maker, the engine manufacturer and the tyre maker when they all cooperate. Let us note additionally that we need at least one strict inequality (*i.e.* $>$) among the three inequalities above. Indeed, the full cooperation performs better than the 'no cooperation' situation as soon as one of the three producers earns more profit.

*The full cooperation performs better than the cooperation between the two FTSs if:

$$1\,249 + T^e + 171 + T^{ty} \geq 712 + 171$$

i.e. the sum of the profits of the two FTSs after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

*The full cooperation performs better than the cooperation between the car maker and the tyre manufacturer if:

$$11\,629 + T^v + 171 + T^{ty} \geq 11\,637 + 171$$

i.e. the sum of the profits of the car maker and the tyre manufacturer after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

*The full cooperation performs better than the cooperation between the car maker and the engine producer if:

$$11\,629 + T^v + 1\,249 + T^e \geq 11\,629 + 1\,249$$

i.e. the sum of the profits of the car maker and the engine producer after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

Finally, and using $T^v = -(T^e + T^{ty})$, the set of equations is the following:

$$\begin{cases} -537 \leq T^e \leq -8 \\ 8 \leq T^v \leq 537 \\ T^{ty} = 0 \end{cases}$$

- $-537 \leq T^e \leq -8$: so as to perform better than the 'no cooperation' situation (≥ -537) and the cooperation vehicle-tyre (≤ -8);
- $8 \leq T^v \leq 537$: so as to perform better than the 'no cooperation' option (≥ 8) and the cooperation engine-tyre (≤ 537);
- $T^{ty} = 0$: so as to perform better than the 'no cooperation' situation (≥ 0) and the cooperation vehicle-engine (≤ 0).

The three inequalities are not mutually exclusive. We thus conclude that the full cooperation is able to perform better than all other situations when transfers are allowed among producers.

- **Scenario in which the demand for clean vehicles amounts to 40%:**

We content ourselves with reporting the issues of the different games and the associated profits for this new scenario, since the way we find the different outcome is similar to the one described above, and it would have brought things any further to display once again the normal forms of the different games here.

Table C.10: Outcomes and profits when the demand for clean vehicles is 40%

	Outcome of the game	Profit of the engine manuf. π^e	Profit of the tyre manuf π^{ty}	Profit of the car maker π^v	Total profit $\prod$
Full cooperation	(e_c, ty_c)	€1,118	€152	€10,271	€11,541
Cooperation engine-tyre	(e_0, ty_c)	€712	€152	€10,326	€11,190
Cooperation vehicle-tyre	(e_0, ty_c)	€712	€153	€10,326	€11,190
Cooperation vehicle-engine	(e_c, ty_0)	€1,118	€94	€10,274	€11,486
No cooperation	(e_0, ty_c)	€712	€152	€10,326	€11,190

- From Table C.10, it is obvious that the full cooperation is not *stable* since the car maker obtains his minimum of profit in this game configuration (see €10,271 in Table C.10).

- We examine the conditions pertaining to the amounts of transfers under which the three producers obtain a higher profit (or at least the same profit) with a full cooperation than in all the other types of cooperation:

*The conditions pertaining to the transfers under which the full cooperation is more desirable than the option 'no cooperation' are the following:

$$10\,271 + T^v \geq 10\,326$$ (the car maker prefers the full cooperation than no cooperation)

$$1\,118 + T^e \geq 712$$ (the engine manufacturer prefers the full cooperation than no cooperation)

$$152 + T^{ty} \geq 152$$ (the tyre maker prefers the full cooperation than no cooperation)

where T^v, T^e and T^{ty} are the transfers earned (if positive) or given (if negative) by respectively the car maker, the engine manufacturer and the tyre maker when they all cooperate. Let us note additionally that we need at least one strict inequality (*i.e.* $>$) among the three inequalities above. Indeed, the full cooperation performs better than the 'no cooperation' situation as soon as one of the three producers earns more profit.

*The full cooperation performs better than the cooperation between the two FTSs if:

$$1\,118 + T^{e} + 152 + T^{ty} \geq 712 + 152$$

i.e. the sum of the profits of the two FTSs after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

*The full cooperation performs better than the cooperation between the car maker and the tyre manufacturer if:

$$10\,271 + T^{v} + 152 + T^{ty} \geq 10\,326 + 152$$

i.e. the sum of the profits of the car maker and the tyre manufacturer after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

*The full cooperation performs better than the cooperation between the car maker and the engine producer if:

$$10\,271 + T^{v} + 1\,118 + T^{e} \geq 10\,274 + 1\,118$$

i.e. the sum of the profits of the car maker and the engine producer after transfers with a full cooperation (left-hand of the inequality) is higher than the sum of their profits when they cooperate together (right-hand).

Finally, and using $T^{v} = -(T^{e} + T^{ty})$, the set of equations is the following:

$-406 \leq T^{e} \leq -55$	so as to perform better than the 'no cooperation' situation (≥ -406) and the cooperation vehicle-tyre (≤ -55);
$55 \leq T^{v} \leq 406$	so as to perform better than the 'no cooperation' option (≥ 55) and the cooperation engine-tyre (≤ 406);
$T^{v} + T^{ty} \geq 38$	so as to perform better than the cooperation vehicle-tyre and the 'no cooperation' situation;
$T^{ty} \geq 0$	so as to perform better than the 'no cooperation' situation;
$T^{ty} \leq -3$	so as to perform better than the cooperation vehicle-engine.

Obviously, the last two conditions are mutually exclusive. We thus conclude that the full cooperation is not able to perform better than all other situations.

Chapter 2. What relevance for incentive-based mechanisms impacting on car purchase and use decisions in light of the rebound effect?

Highlights

This Chapter focuses on the demand-side of the automobile system. We typically address the issue dealing with miles driven and household's choice of vehicle's energy efficiency. These are two factors that impact the total CO_2 emissions resulting from car use.

In the first Part of this Chapter, the link between the car purchase and use decisions (referring to the two aforementioned factors) is presented. We argue that both decisions are interrelated, and have to be jointly modelled; and we describe the methods to do so, namely the indirect utility approach.

Besides, from the moment that there are two distinct decisions that affect CO_2 emissions due to passenger vehicles, public decision-makers would be wrong not to target both decisions at the time when fighting against climate change. The second Part gives an overview, and a discussion, of the pricing instruments targeting either the purchase or the use of vehicles.

Finally, in the last Part of this Chapter, emphasis is placed on the effects of the interdependency between car choice and car use on the efficiency of car purchase and use taxes. Precisely, we examine the effects of a differentiated purchase tax that encourages new vehicle distribution in favour of low fuel-consuming vehicles. As it participates in the efforts to improve the fleet's average fuel efficiency, implementing such tax can be accompanied by a rebound effect. We thus investigate, in a second step, the capacity of a fuel tax to limit this rebound effect. In this Part, the policy tool's effects are investigated within the framework of static comparative analyses of a basic model of consumer's behaviour. The analytical model is followed by a numerical application based on French data in 2013.

1. Introduction

"The automobile system affords the user the benefits of club, fleet and network effects"[45] (Dupuy, 1999, p10). If the combination of all three effects creates a '*magic circle*'[46], it also makes difficult to do without a car. This 'car dependence' has to be considered as a negative externality, especially because of a lack of alternatives transport modes, borne by those who cannot enter the automobile system or those who have to leave it (*e.g.* elderly, adolescents, inhabitants of rural areas, ethnic minorities and disadvantaged social classes; Dupuy, 1999). Likewise, Webber said in 1992 "*those who lack discretionary use of cars are deprived to some degree, and they are deprived because the auto has been so successful*" (Webber, 1992, p281). Not surprising is thus the upward trend over the last two decades everywhere in the European Union – and in all developed countries – in the automobile equipment (PIPAME, 2010). In fact, the higher disposable incomes, the growing mobility needs induced by new lifestyles, as well as a more pronounced culture of self-reliance and an optimisation of the transport time on the demand-side, and a lack of public transports combined with an efficient road network on the supply-side have favoured the automobile equipment, according to the French interministerial unit monitoring and anticipating economic change (PIPAME, 2010). According to Webber (1992), this is the car system's "*capacity to offer no-wait, no-transfer, door-to-door service*" that makes its superiority emerge. Not forgetting the steadily improvements of performance, comfort, style and safety of vehicles (King Review, 2007).

Particularly with the objective to explain the growing rate of car ownership in developing countries wherein the access to the automobile is not (yet) the rule[47], the determinants of car ownership are well studied within the literature. Indeed, it is widely agreed for instance that the degree of urbanisation is an important determinant of car ownership. The degree of urbanisation actually embraces different determinants, including the density of population and that of public

[45] One of the benefits of having a driving licence is the right to drive a car according to the highway code and to drive fast (unlicensed vehicles are not allowed to drive as fast as licensed vehicles). The access to after-sales services, maintenance and emergency repairs are benefits of a car owner. And, the improvement of the network benefits to the users of the road network. The club, fleet and network effects can exactly be measured through the three examples listed at the beginning of this footnote. For further details, we refer the reader to Dupuy (1999).

[46] The magic circle refers to the following trends: "*the increase in automobile traffic led to the expansion of the road network, thus encouraging car owners to drive more, more people to buy cars; an increase in traffic was once again followed by the growth of the network, and so on and on*" (Dupuy, 1999, p1).

[47] The growing automobile equipment is well illustrated with the rise in vehicle density figures. The vehicle density refers to the number of cars per 1,000 inhabitants. This rise is observed all around the world, albeit it is significantly lower in developed countries (*e.g.* +15.8% in France, +14.2% in Japan, or +2.2% in the United States between 1995 and 2013) than in developing countries (*e.g.* +316% in India or + 912% in China over the same period; CCFA, 2014). Very interestingly, it has been claimed that even 'one car per adult' – after having thinking about 'one car per worker' and 'one car per household' – does not constitute an upper-limit for this indicator (in Dupuy, 1995).

transport modes. Clearly, the car ownership is negatively correlated with both the first variable (in Button and al. (1993) for low income countries, but also illustrated in France – for developed countries – in CGDD (2010)), and the second one (also illustrated in CGDD (2010) for France). Besides, regarding the households' characteristics, the probability to be motorized increases with age and income of the person of reference within the household, with the household's size, and when the person of reference is a man (in Prieto, 2007 or CGDD (2010); both in France). Likewise, the higher the household's size, and/or income, and/or the higher the urban sprawl, the higher the probability to be multi-motorized (CGDD, 2011).

However, from an environmental perspective, that is to say with a major concern for the pollutions due to car use, nothing can be concluded based on car ownership. Needless to say that information on car use and distance travelled is required to draw conclusions. We thus have to consider another decision related to the vehicle: the continuous decision in terms of consumption of kilometres. In this respect, it is noteworthy that in France, the private car represents the major travel mode: 65% of trips and 83% of total distances are made by car (CGDD, 2010).

Going further would involve taking also the car's energy efficiency into account. This is where investigating the car purchase decision (*i.e.* which car to purchase?) becomes worthwhile for the analysis. Indeed, the number of vehicles and the extent to which they are used are not enough to compute the total of CO_2 emissions due to passenger vehicles insofar as vehicles greatly differ in terms of CO_2 emissions per kilometre. Without delving into accurate figures, the case of electric vehicles, emitting no CO_2 while consuming energy, is enough to understand the latter assertion.

Furthermore, in a context characterised by steady improvements of vehicles' energy performances, investigating the determinants of the car replacement decision is also of interest, as it enables to better estimate the fleet renewal rate. Indeed, the effects of new technologies will be felt only if vehicles that are equipped with these new technologies are sold. Factors that may make an agent renew its car consist of owner-related variables (*e.g.* birth of a child or any changes in the household structure), market-related variables (*e.g.* emergence of a new technology since the product performance is actually a key motivator for replacement buying for any durable good; Liberali and al., 2011), context-related variables (*e.g.* interest rate), but also public policy tools (*e.g.* scrapping premium[48], feebate scheme[49], fuel tax[50]).

In a nutshell, there are four different decisions on the demand-side of the automobile system, namely the car ownership, purchase, use and replacement decisions. In this Chapter, we focus on the car purchase and use decisions; and this is the reason why they are less discussed than the other two decisions in the previous paragraphs. It means that an important point to keep in mind is our focus on a fixed car-purchasing population. In any event, from the economist's point of view, investigating the car purchase and use decisions is of particular interest. On the one hand, the first decision intervenes in a discrete framework (in which the alternatives are predefined, namely a set of different vehicles) whereas the second one intervenes in a continuous one (in which the distance travelled can take any numerical value). This means that methods to address these two decisions are theoretically different. On the other hand, both decisions are interrelated and have thus to be jointly modelled, as will be thoroughly explained in the first Part of this Chapter (cf. 2.).

Besides, from the moment that there are two distinct decisions, public decision-makers would be wrong not to target both decisions at the time, when tackling CO_2 emissions due to passenger vehicles. Indeed, car purchase and use are both decisive factors in reducing CO_2 emissions as suggested within the Schipper's ASIF scheme that decomposes GHG emissions of transport into four factors: transport Activity, modal Share, energy Intensity and carbon intensity of Fuel (Schipper and al., 2000), as already said. In that context, public decision-makers have implemented policy tools targeting the car purchase (*e.g.* purchase tax, feebate scheme and so on), and others targeting the car use (*e.g.* emissions tax, fuel tax, toll, parking pricing and so on). Both of these two categories of policy tools are investigated in the second Part of this Chapter (cf. 3.).

We examine, in the last Part of this Chapter (cf. 4.), the effects in terms of CO_2 emissions of setting a penalty on the purchase of high emitting cars, and those of a fuel tax, while taking the links between car purchase choice and car use into account. More specifically, we propose

[48] The effect of a scrapping premium on the replacement decision is discussed in the literature, but without leading to a consensus. By way of illustration, De Palma and Kilani (2008) argues that implementing a scrapping premium tends to delay replacement time of old cars, because the subsidy increases their value. In contrast, Yamamoto and al. (2004) finds (with data of French households' vehicle ownership from 1984 to 1998) that the average duration of keeping a vehicle is 3.3 years shorter when the scrappage premium applies.

[49] To be precise, the Malus postpones the replacement of large cars, while the Bonus reduces the optimal lifetime of small cars (d'Haultfoeuille and al., 2014).

[50] A fuel tax delays the car replacement according to De Palma and Kilani (2008), whereas it *"speeds the scrappage of older, less fuel efficient used vehicles"* in Li and al. (2008).

to investigate the capacity of a fuel tax to limit the rebound effect (*i.e.* increase in demand induced by efficiency gains) that could occur when a penalty is charged on the purchase of high emitting vehicles. The latter instrument actually encourages new vehicle distribution in favour of low fuel-consuming vehicles, and thus translates into higher energy efficiency over the whole car fleet. The policy tool's effects are investigated within the framework of static comparative analyses of a basic model of consumer's behaviour. The theoretical model is followed by a numerical application reflecting the French situation.

2. The car purchase and use decisions

The co-existence of a discrete decision with respect to the car purchase and a continuous decision in terms of kilometres travelled is particularly important since the two decisions are interrelated (cf. 2.1.). That being so, these two decisions have to be modelled within an integrated model (cf. 2.2.).

2.1. The interdependency of the car purchase and car use decisions

This subpart summarises reasons why the decision of purchasing a vehicle and that of using a vehicle are closely linked. First, the car choice determines to some extent the car use, and the inverse is also true (see 2.1.1.). Second, characteristics that make an agent use more or less intensively his vehicle may also affect the agent's car purchase decision (see 2.1.2.).

2.1.1. The two-way causal linkages between car purchase and car use

"Household choices of vehicle and utilization of the vehicle are closely linked: vehicle choice is affected by how much consumers anticipate using it, and the characteristics of the good such as fuel efficiency in turn influences subsequent usage".

(De Borger and al., 2013, p3)

First, the car choice determines the car usage cost, or at least the energy cost per kilometre through the vehicle's energy performance. This way, the car choice plays indirectly on the car use provided that the car mobility is a normal good in that its consumption decreases with its price (Collet, 2007; Collet and al., 2010)[51]. Indeed, it is true that this causal linkage does really make sense only if we consider *non-constrained* car mobility. The latter kind of mobility accounts for about three quarters of journey purposes and for about 60% of the distances in

[51] in Hivert and Wingert (2010).

France, when considering that the *constrained* mobility includes journeys to work, study locations, or child-care centres (*i.e*. trips you have to make at least once a week; CGDD, 2010). In this regard, it seems instructive to mention that the price elasticity of mileage demand is about -0.23 in the short term and -0.37 in the long term in France (Collet, 2007; Collet and al., 2010)[52].

In addition, the car purchase cost has an impact on the car use. Theoretically, the higher the car purchase cost, the lower the disposable income to travel, explaining why we could expect a negative relation between the car purchase cost and the number of kilometres travelled. However, in practice, high car ownership cost (including the car purchase cost) seems to "*distort car usage by encouraging car owners to drive frequently, since the car has already been paid for"* (in Muthukrishnan, 2010, p403), explaining why the relation could rather be positive, at least at high car purchase costs. In this light, it is true that the automobile is designed for a privative use while being ostentatious (reported in Prieto, 2007).

When the household's car mobility is constrained, for commuting to work for example if there are no alternative transport modes, the other way causal linkage makes sense – *i.e.* the car use determines the car purchase decision. Specifically, this is more a question of *expected* car use. The latter use determines the time spent in the vehicle, and thus plays on the value attached to some car characteristics within the car purchase decision, such as the degree of comfort. Indeed, it appears for instance that those who live far from work are likely to prefer a large and comfortable vehicle (Lave and Train, 1979). In the same vein, Choo and Mokhtarian (2004) found more recently that "*people who think they engage in a great deal of long-distance travel are less likely to drive compact cars*" (in Baltas and Saridakis, 2013). Such result could be considered counterintuitive, when considering that more equipment of comfort may make the vehicle consume more fuel (because of a heavier vehicle) while an intensive car use is expected to make a rational agent purchase a low fuel-consuming vehicle.

2.1.2. The common explanatory variables for car purchase and use

"The choices of vehicle and VMT [vehicle-miles-travelled] are related because characteristics that influence a household to purchase a certain vehicle may also influence that household's choice of miles".

(West, 2004, p737)

[52] in Hivert and Wingert (2010).

Explanatory variables of car purchase and use decisions are related to the car purchaser or user, to the vehicle or to the context.

For example, regarding the car purchaser/user's characteristics:

- The place of residence affects the choice of motorization (see CGDD (2010) for 'diesel *versus* petrol'[53], and, in all evidence, for reasons related to the access to a garage – possibly equipped with a charging plug – for electric vehicles). It also clearly determines the car use (particularly through commuting trips).
- The phase of life cycle in which the car driver is – and thus the age – has an impact on the number of kilometres travelled on a daily basis (CGDD, 2010). In addition, the age also explains the car purchase choice: among other things, it plays on the vehicle's size (Lave and Train, 1979)[54], on the 'age of vehicle' (*i.e.* new *versus* used vehicle, in Prieto (2007)[55]), and on the motorisation (in Ziegler, 2012[56]).
- The household's size plays on the car choice (in particular on the vehicle's size; CGDD 2011), and on the distances covered with the car (notably because of the accompanying purpose).
- The income intervenes through the choice of the vehicle's size (Lave and Train, 1979), or car segment (Prieto, 2007). And, from the moment that motorized kilometer is a normal good, its consumption is positively correlated with income (verified in France, since the number of daily trips by car varies by a factor of 1 to 2.4 between the lowest and the highest income groups; CGDD, 2010).

As concern the characteristics peculiar to the vehicle, one should note that:

- The type of vehicle currently owned should have an impact on car purchase and use decisions. The reason is two-fold. First, motorists tend to compare – when purchasing a new car – new vehicles to their current vehicle [rather than comparing the new vehicles available to each other] (Turrentine and Kurani, 2007). Second, the current vehicle's characteristics affect the current car use, what constitutes in most cases the new car's expected use.
- The fuel consumption per kilometre plays on the car use, but also on the car purchase decision (see for instance Li and al., 2008).

[53] Diesel vehicles are over-represented in rural areas (CGDD, 2010).
[54] Older people tend to choose larger cars (Lave and Train, 1979).
[55] Purchases of new vehicles are positively correlated with the age of the person of reference (Prieto, 2007).
[56] Younger potential car buyers have a higher stated preference for hydrogen and electric vehicles (Ziegler, 2012).

Among the variables related to the global context, the fuel price is the principal factor that play on both decisions (Moghadam, 2011) (in the same way as the vehicle's fuel consumption per kilometre, since the fuel consumption per kilometre and fuel price are two independent parameters, though their variations modify the price per kilometre travelled by car).

Finally, dealing with the variables related to the local context, we can emphasize that:

- The density determines the car use (in VTPI, 2013; McIntosh and al., 2014), and plays on the car segment choice in some areas (*e.g.* small vehicles are more likely to be purchased by consumers who live in city centres, when Sport Utility Vehicles (SUV) are more likely to be purchased by consumers who live in rural areas).
- That car rental services are expanding quickly may affect the car purchase decision and the private car use. On the former point, this is true that individuals used to make their car purchase decision based on their extraordinary trips (*e.g*. holidays). Being now given the opportunity to rent a car for the latter trips, individuals are likely to readjust their car purchase decision towards smaller vehicles when the car is intensively used for short and commuting trips.
- The quality of the public transport network[57] determines the car use (McIntosh and al., 2014), but it seems that it *does not* affect the car purchase decision.

2.2. How to jointly model the car purchase and use decisions?

Modelling the decision of purchasing a vehicle and that of using a vehicle requires a unified model since the two decisions are interrelated, as stated above. Otherwise, there exist endogeneity problems within discrete choice models from the moment that the car use (for example in Lave and Train, 1979) or the "*past utilization of vehicle*" (in Mannering and Winston, 1985) is introduced in the explanatory variables of the car choice. We first make some preliminary remarks on the method (2.2.1.), before further describing the two stages of the approach (2.2.2. and 2.2.3.).

2.2.1. A method based on the maximisation of the indirect utility

The households' car purchase and use decisions are traditionally addressed within a utility-maximising programme. In such a specific framework – *i.e*. the demand for a durable good –

[57] The direction in which car use varies following an improvement of the (financial and spatial) accessibility of public transports (PT) actually depends on whether car use is complementary to PT (in case of multimodality in particular) or substitute to PT. What is more, the density and the quality of public transport are positively correlated (because offering a public transport network is too costly below a given level of density).

the choice of the utility function's attributes is particularly worthwhile. In that light, the economic theory suggests "*the demand for consumer durables arises from the flow of services provided by durables ownership. The utility associated with a consumer durable is then best characterised as indirect*" (in Dubin and McFadden (1984), p346). Similarly, Erzurumlu (2013) claims *"in order for a consumer to continue to derive value from the durable, she must continue to buy the contingent"* (p574). It follows that the consumption of the 'contingent' or 'the flow of services provided by the durable' performs well as an attribute within the utility function, [while the utility derived from the durable good ownership may be introduced in the indirect utility function (see 2.2.3.)]. That the durable good's purchase price and usage cost enter the budget constraint explains why the optimum level of consumption of the contingent is conditional of the durable good type.

Generally, two methods are called up for jointly modelling a discrete and a continuous choices. They distinguish themselves by the order in which the indirect utility function on the one hand and the consumption levels on the other hand are addressed. Exactly, the two methods can be summarised as follows:

- Method a. 1. Indirect utility function → 2. Conditional consumption levels → 3. Discrete choice probabilities.
- Method b. 1. Conditional consumption levels → 2. Indirect utility function → 3. Discrete choice probabilities.

Explicitly, it is as the consumers use backward induction in order to find their optimal behaviour dealing with durable good purchase and use:

- first, for each kind of durable good, the consumer chooses the level of contingent that maximises his utility (see 2. or 1. in methods a. and b.);
- then, the consumer chooses the type of durable good that provides the maximum of utility. Within the random utility theory, discrete choice models are used to determine such a choice (see 3. in methods a. and b.).

These two steps are detailed below.

2.2.2. The first step: which optimal conditional continuous decision?

The first step deals with the continuous decision, *i.e.* the consumption level of the contingent. The case wherein the conditional consumptions level are derived from the indirect utility function (see method a. above) is further explained below; first within the Dubin and Mc Fadden (1984)'s framework of residential electric appliance holdings and consumption, and then in the context of car purchase and use. When the optimal consumption levels pre-exist the indirect utility function (see method b. above), either they are obtained with a parametric specification (see for instance the parametric specification of the unit electricity consumption function in Dubin and McFadden, 1984), or they result from a direct utility-maximising programme. This is the case in our theoretical model presented in the last Part of this Chapter, and this is why we do not discuss longer the method b. hereinafter.

- **The electricity consumption: conditional on the residential electric appliance type**

The consumers' responses to changes in the electricity price differ greatly as households adjust their appliance portfolios, as claimed in Dubin and McFadden (1984). Therefore, the discrete portfolio choice and the continuous choice in terms of energy consumption have to be modelled under an integrated framework. In what follows, we focus on the continuous choice (*i.e.* the level of electricity consumption), and we describe how the latter is derived from an indirect utility function (cf. method a. above). This is the 'indirect utility approach' initiated by Dubin and McFadden (1984).

Firstly, the indirect utility function needs to be specified. Note that the subscript i and the exponent j are used for respectively indexing the different consumers and appliances portfolios. First and foremost, consumers are supposed to derive utility from the consumption of energy – *i.e.* electricity (x_1) or alternative energy (x_2) – and from the consumption of non-energy commodities (x_3) treated as numeraire good. Consequently, next to the annual consumer i's income (termed y_i), the budget constraint takes also the price of electricity (p_1) and that of alternative energy (p_2) as well as the annual portfolio cost (*i.e.* the annual owning cost, termed r^j) into account. What is more, vectors of unobserved characteristics related to the consumer and to the appliances portfolio are added into the indirect utility function in addition to the vectors of observed characteristics of consumer and portfolio. All of these variables enter a general vector termed ε_i^j. Let us note that some of these variables can be introduced directly into the indirect utility function – rather than in the utility function – from the moment that they play on the durable good choice, but not on the consumption level of the contingent (typically, the colour of the durable good). In this respect, Jia and Zhang (2013) points out that, because of shortened product life cycles and the quick product innovations, "*new features emerge and* *become important factors in consumers' decision"* while durables goods used to be purchased for their useful physical functions. In sum, the consumer i's indirect utility is conditional on the portfolio j, as shown with the following expression:

$$V_i^j = V\left(y_i - r^j, p_1, p_2, \varepsilon_i^j\right) \tag{10}$$

Secondly, when $V(y, p_x)$ is the indirect utility function with p_x the price of good x and y the income, then the Roy's identity computes the Marshallian demand for good x in the following manner:

$$x = \frac{-\partial V(y, p_x)/\partial p_x}{\partial V(y, p_x)/\partial y} \tag{11}$$

Hence, given portfolio j, the consumer i's consumption levels of electricity ($x1_i^j$), of alternative energy ($x2_i^j$), and of non-energy commodities (${x_3}_i^j$) – *i.e.* the continuous choices at focus in this subpart – are computed as follows:

$${x_1}_i^j = \frac{-\partial V\left(y_i - r^j, p_1, p_2, \varepsilon_i^j\right)/\partial p_1}{\partial V\left(y_i - r^j, p_1, p_2, \varepsilon_i^j\right)/\partial (y_i - r^j)}$$

$${x_2}_i^j = \frac{-\partial V\left(y_i - r^j, p_1, p_2, \varepsilon_i^j\right)/\partial p_2}{\partial V\left(y_i - r^j\ p_1, p_2, \varepsilon_i^j\right)/\partial (y_i - r^j)}$$

$${x_3}_i^j = y - r^j - p_1 {x_1}_i^j - p_2 {x_2}_i^j$$

- **The car use: conditional on the vehicle type**

In the present case, car is the durable good, and the distance covered by car is the service provided by the vehicle through fuel consumption (that is to say the 'contingent'). To derive the optimal level of distance from the indirect utility function, we will use the Dubin and McFadden's framework described above. Nonetheless, two preliminary remarks are useful.

First, that the vehicle ownership does not appear in the direct utility function contrasts, at first glance, with the idea whereby households derive utility from owning a vehicle whatever the car use thanks to values of freedom or success attached to car ownership (argued in Dubois and

Moche, 2006; and taken into account in Gavazza and al., 2014[58]). However, on the one hand, it seems that the 'sociological effect' of owning a car is no longer as strong as it used to be (explaining the growing interest for rental vehicles). On the other hand, the ostentatious character of the automobile may explain this sociological effect. It follows that the utility derived from owning a vehicle is likely to be function of the vehicle's characteristics (according to the Lancaster's theory; Lancaster, 1966) to the point that it appears within the indirect utility – the one the consumer maximises when choosing his vehicle (see 2.2.3. below) – instead of within the direct utility – the one he maximises when determining the optimal consumption of kilometres.

Second, introducing the consumption of kilometres into the direct utility function clearly means that we assume that the higher the car use, the higher the utility (implicitly needed for using the Roy's identity). In fact, that kilometres enter the utility function is behind the phenomenon of "rebound effect" (increases in distances covered) that results from the improvement of the vehicle's energy efficiency enabling a lower cost per kilometre. Indeed, if the consumption of kilometres did not provide utility, there would be no reason for a rise in kilometres following a decrease in price. Introducing the consumption of kilometres within the utility function is thus a common practice in the literature (*e.g.* Muthukrishnan, 2010; Wei, 2013; De Borger and Rouwendal, 2014).

We now turn to the description of the indirect utility function.

Each consumer derives utility from the consumption of vehicle-kilometres-travelled (k), and from the consumption of a composite good (C) treated as a numeraire. By doing so, the most restrictive assumption lies in the fact that consumers are supposed not to be able to consume kilometres with public transports. If this assumption was quite realistic some years ago (people used to take their car whenever possible from the moment that it has already been paid for), we are well aware that this is less and less the case nowadays (explaining why this is a *restrictive* assumption). It may be a question of externalities related to car use, such as congestion, that people are less and less inclined to bear. Interestingly, the automobile sector has fully understood this behavioural change, and has been offering more and more multimodal solutions (see for example the new services offered by the web portal Citroën Multicity in

[58] In a quantitative analysis of the used-car market, Gavazza and al. (2014) capture the lower valuation of the second car for a bi-motorised household.

France or by the smartphone app Moovel of Daimler in Germany). In any event, this assumption is driven by the desire to simplify the formalisation.

The cost per kilometre (*i.e.* the price of k) is noted σ^j, and varies with the vehicle type. Some authors, including Mandell (2009), argue that – when investigating the car choice decision – σ^j may be limited to the fuel cost per kilometre since other costs associated with driving a car (*e.g.* parking fees, road tolls, and so on) do not affect the choice of vehicle. One could nonetheless nuance the latter assertion by saying either that the maintenance cost varies with the vehicle type (at least with the motorization), or that the depreciation cost depends on the vehicle type (at least on the brand image (in Spitzley and al., 2005), and on the motorisation (in Gilmore and Lave, 2013[59])). Besides, the annual cost of owning vehicle j is $y_i - \frac{P^j}{T}$ where y_i is the consumer i's income, P^j is the vehicle j's market price, and T is the car of length ownership (see Box 2 below). Finally, here again, we note ε_i^j the vector of observed and unobserved characteristics of consumer i and vehicle j. We thus have:

$$V_i^j = V\left(y_i - \frac{P^j}{T}, \sigma^j, \varepsilon_i^j\right) \tag{12}$$

For comparison purposes with the so-called mode choice models of the transport economics, let us note that adding vehicle's characteristics into the indirect utility function is tantamount to introducing an 'alternative-specific constant' – which value differs from a transport mode to another – within the consumer i's indirect utility when estimating the consumer i's mode choice. It echoes this way the fact that the utility results not merely from the origin-to-destination trip, but also from several services, such as the possibility to drive people, to carry heavy loads, and so on. All transport modes do actually not offer the same levels of services (Drut, 2014).

Using the above Roy's identity (see equation (11) above), we are able to address the continuous choice of kilometres (k). We have:

$$k_i^j = \frac{-\partial V\left(y_i - \frac{P^j}{T}, \sigma^j, \varepsilon_i^j\right) / \partial\, \sigma^j}{\partial V\left(y_i - \frac{P^j}{T}, \sigma^j, \varepsilon_i^j\right) \Big/ \partial\left(y_i - \frac{P^j}{T}\right)} \tag{13}$$

[59] "*At five years, higher fuel economy vehicles retain a higher proportion of their initial price than conventional options*" (Gilmore and Lave, 2013, p200).

Box 2: Taking into account the durable character of the good within the budget constraint

Introducing the length of car ownership into the annual budget constraint enables us to reflect the tendency to keep one's car for several years.

Within a static framework, the simplest method consists in dividing the vehicle's market price by the length of car ownership as proposed above (see equation (12)). Such reasoning is tantamount to considering first equally weighted years, and second identical years over the total length of car ownership. It is worth noting that the 'identical years' assumption holds only with myopic (or risk-neutral) consumers who do not anticipate fuel price or income changes over the length of car ownership. Regarding the 'equally weighted years' assumption, we may consider that cars are financed by credit with a zero interest rate, albeit it is not enough to justify that we do not consider the consumer's preference for the present.

To tackle the consumers' preference for the present, the introduction of a discount rate is widely practiced in the literature dealing with durable goods. It enables to avoid the two underlying assumptions aforementioned, and thus clearly means that we evolve in a dynamic framework. In that context, the budget constraint (taken into account when purchasing a vehicle at date t) is distinctly more complex:

$$\sum_{t=0}^{T} \frac{y_{i,t}}{(1+\rho)^t} - P^j = \sum_{t=0}^{T} \frac{\sigma_t^j k_{i,t}^j}{(1+\rho)^t} + \sum_{t=0}^{T} \frac{C_{i,t}^j}{(1+\rho)^t}$$

where ρ is the pure present preference rate. Naturally, the value of this discount rate is important. In this regard, Greene (2010) offers an overview of reasons why consumers tend to discount too heavily the potential fuel savings, or in other words, why their discount rate is too high. The main reasons deal either with the information (information asymmetry[60] and imperfect information[61]), or with the consumer's behaviour (bounded rationality[62], lack of skill to perform necessary calculations, and consumer's myopia[63]).

[60] Information asymmetry: car manufacturers know more about the vehicle's energy performances and cost than consumers.

[61] Imperfect information: there exist differences between the 'official' vehicle's fuel intensity and the amount of fuel that is really consumed per kilometre because of external factors such as driving style, traffic environment and so on.

[62] Bounded rationality: consumers seem to optimize only three or four attributes, among all the attributes that characterise a vehicle (*e.g.* price, size, styling, fuel economy, comfort, safety, reliability, and so on).

[63] Consumer's myopia: consumers seem to estimate fuel savings only for the period over they plan to own the vehicle. Consumer myopia also reflects risk aversion.

2.2.3. The second step: which optimal discrete decision?

The second step deals with the discrete decision, *i.e.* the choice of the durable good type.

From the moment that the indirect utility function contains non-observed variables, it is not possible to predict exactly the consumer i's durable good choice but only the probability of this choice. This latter is calculated as the probability that a given durable good has a higher utility value than all others, since the behaviour of a consumer is utility-maximising. The probability that the consumer i chooses the durable good l is actually given by:

$$Pr_i(l) = Pr\left(V_i^l > V_i^j; \forall j \neq l\right) \tag{14}$$

Depending on the assumptions made in terms of the distribution of the unobserved variables, discrete choice decisions can be modelled using either a logit model or a probit model. Specifically, a logit model – that allows a simpler model formulation – is used when the unobserved component of the utility function is independently identically distributed (iid) for each alternative, and follows the extreme value (double exponential) distribution. Under these assumptions, the probability that a consumer i chooses portfolio l from set J can be derived as:

$$Pr_i(l/J) = \frac{e^{\mu V_i^l}}{\sum_{l \in J} e^{\mu V_i^l}} \tag{15}$$

with μ the scale parameter of the distribution.

Probit models are based on the Normal distribution. They are capable of capturing all correlations among alternatives but their formulation is more complex (Ben Akiva and Bierlaire, 1999) to the point that writing it here would not have brought things any further.

Eventually, the model choice is the analyst's one, and depends above all on the type of the random variables included in the utility function.

We now turn our attention to the policy tools that play on the two decisions we are interested in since the beginning of this Chapter: the vehicle choice and the car use.

3. The policy tools impacting on the demand-side

The policy tools impacting on the demand-side of the automobile system consist of Incentive Based (IB) mechanisms, Command And Control (CAC) levers, as well as complementary measures, mainly including communication and diffusion levers. Hereinafter, only IB mechanisms are addressed. Reasons of this choice are exposed in the first subpart below (3.1). Afterwards, we detail the different pricing schemes related to vehicle purchase and use (3.2), and we highlight some of their strengths and shortcomings (3.3.).

3.1. The rationale for focusing on pricing schemes

First, dealing with policy tools except IB mechanisms, one should note that:

- The CAC levers playing on the demand-side often only target the car use (*e.g.* speed limit, Low Emission Zones, High Occupancy Vehicle lanes). We are well aware that implementing a Low Emission Zone for example is likely to have an impact on the purchase decision (it may amend upward the weight accorded to the level of vehicle's CO_2 emissions into the indirect utility function), but this impact will be observed locally (within the concerned area).
- Estimating the impact of a communication and diffusion lever is a difficult task, all the more so because it is often combined with another policy tool (*e.g.* the 'Energy-CO_2 label' for new passenger cars[64] is combined with the Bonus/Malus scheme).

Then, as regards the IB mechanisms as such, one has to admit that:

- Pricing schemes are effective to reduce negative externalities (see Box 3 below).
- The IB mechanisms are numerous (cf. 3.2.), and their strengths and shortcomings differ from a mechanism to another (cf. 3.3.) to the point that they warrant a discussion as such.

[64] Tackling the issue of increasing the awareness about the passenger vehicles' impact on climate change, French car manufacturers have been obliged, from the 10th May 2006 (order of the 10th November 2005, JORF, 2005), to inform customers on the fuel consumption and CO_2 emissions of new passenger cars, through an "**Energy – CO_2" label**. This informational tool aims at dissuading consumers from buying high polluting vehicles. Such passenger cars labelling scheme has also been put in place in other countries (see for instance Atabani and al., 2011 that describes the labelling practices in United States, Canada, United Kingdom, Sweden, Switzerland, China, Brazil, Australia, Korea and New Zealand).

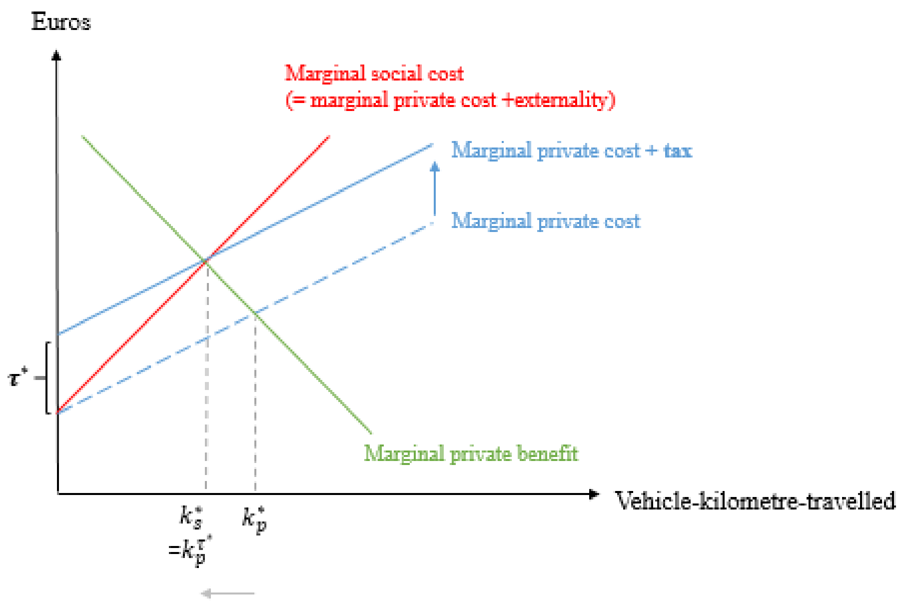
Box 3: Relevance of pricing schemes to fight against negative externalities

In economic theory, pricing policy tools (such as taxes) are claimed to be capable of correcting a market failure. Negative externalities – defined as the costs that affect a party who did not choose to incur those costs – are market failures. The negative externality at focus in this work is precisely CO_2 emissions due to car use.

Figure 8 below illustrates why the difference in private and social marginal costs resulting from the negative externality leads to – without a policy tool to internalise the externality – an over-consumption of kilometres. Indeed, when no pricing scheme is implemented, the consumption of kilometres is k_p^*. It results from the intersection of the lines for "private marginal benefit" and "private marginal cost". This is above the social optimal quantity k_s^* that results from the intersection of the lines for "private marginal benefit" and "social marginal cost".

If a pricing scheme is introduced, the total private marginal cost increases (cf. the upward shift of the line "private marginal cost") so that the optimal distance is reduced and achieves k_p^{*t} provided that the pricing scheme is set equal to the initial gap between the two marginal costs (see t^* in Figure 8. This is the well-known Pigovian tax (Pigou, 1932)).

Figure 8: A car usage tax to avoid the over-consumption of kilometres



Source: Author

3.2. Overview of the pricing schemes related to vehicle purchase and use

In this subpart, we highlight the variety of price-incentive mechanisms related to vehicle purchase and use. It is worth mentioning that pricing schemes targeting the car ownership do also exist (*e.g.* the French authorities abolished the tax disk (called '*vignette*') in 2001 (it is still in effect in some European countries such as Germany (*Kraftfahrzeugsteuer*), Ireland (*Motor tax*), Spain (*Impuesto sobre Vehículos de Tracción Mecánica*), and so on), but it still exist in France the annual tax for company vehicles and the annual tax or 'annual Malus scheme'[65] for polluting vehicles which tariffs are CO_2 dependent; see Papaix and Meurisse, 2013). However, they do not enter the scope of our analysis.

Pricing schemes related to vehicle purchase consist of purchase/registration taxes as well as fiscal incentives to renew its car (*e.g.* **scrapping premium,** in effect in numerous European countries, see Papaix and Meurisse, 2013) or to purchase a less CO_2-emiting vehicle (*e.g.* **Bonus/Malus scheme**[66]**,** in force in numerous European countries, see Papaix and Meurisse, 2013). Regarding the **registration taxes**, tax levels and criteria for calculating the tax rate vary greatly among countries (CO_2 emissions, EURO class, value of the vehicle, engine power, etc.). For example, CO_2 emissions are largely included in the registration taxes calculation in nine countries (Austria, France, Latvia, Malta, the Netherlands, Portugal, Romania, Slovenia and Spain) and in the Flemish region of Belgium and constitute a minor parameter in four other countries (Cyprus, Denmark, Finland and Ireland) and in the Walloon region in Belgium (European Commission, 2012). **VAT (value added tax) exemptions** do also exist, in particular for electric vehicles (*e.g.* Norway).

Pricing schemes related to vehicle use are also varied. The two most intuitive usage charges are the **vehicle-kilometre-travelled (VKT) tax** and the **fuel tax**. The former tax is far less widespread (actually non-existent in the EU, since the one discussed in Belgium did not proceed beyond the experimentation stage. The closest example is the Heavy Vehicle Fee in Switzerland, but as its name implies, it targets heavy-duty vehicles, not passenger vehicles; see Santos and al., 2010a) than the latter one (*i.e.* everywhere in the EU). Besides, **carbon tax** also enters the category of usage taxes, more exactly that of fuel taxes. It is in effect in France since

[65] According to the French Strategic Analysis Council (CAS, 2008), a generalized annual Malus would enable to heighten the Malus effect on the vehicle fleet development; its effect is actually considered too short in its current design since the Malus accounts for a too small part of the vehicle's purchase price.

[66] A Bonus/Malus scheme consists of a "*combination of a vehicle purchase tax/fee and a rebate/subsidy used to reward buyers that are more fuel efficient than the average vehicle in that class and penalise buyers of less efficient vehicles*" (Brand and al., 2013, p135).

2014, and for longer in a small number of European countries (*i.e.* Finland, Norway, Sweden, Denmark and Ireland, see El Beze and de Perthuis, 2011). Conversely, the incorporation of biofuels in petrol or diesel oil benefits from tax reductions (under the Directive 2003/96/EC on energy products and electricity taxation; see European Commission, 2003). In addition, regarding the **congestion charges**, they consist in most cases of urban tolls**.** The latter tolls may vary upon (Papaix and Meurisse, 2013) a) the spatial configuration: cordon charging (*e.g.* Stockholm) or charging area (*e.g.* London); b) the tariff which may depend upon the hour, the day, the duration, the mileage, the emissions class, or may include a rate base; c) the objective: reducing congestion (*e.g.* London), fighting against pollution (*e.g.* Milan), financing infrastructures (*e.g.* Oslo), or a mix of these objectives (*e.g.* Stockholm); and d) the revenue allocation[67]: road infrastructures (*e.g.* Stockholm), or sustainable mobility development (*e.g.* Milan). Finally, **parking pricing** management generally deals with an increase in parking tariffs and/or an extension of the priced area (either geographically or in terms of duration). Parking may also be free for electric vehicles (such as in France, Norway, United Kingdom, Denmark, Sweden; Papaix and Meurisse, 2013).

3.3. Towards evaluating the policy tools

In practice, multiple objectives can be pursued at the same time by a single instrument on the one hand, and several instruments can serve the same objective on the other. Hence, evaluating policy tools is not a straightforward exercise.

3.3.1. Which evaluation criteria?

In evaluating any public policy, it is broadly admitted that performance with respect to effectiveness and equity has to be addressed (Nordhaus and Danish, 2003). With regard to the aim of mitigating climate change, the effectiveness criterion is concerned with the best relationship between resources employed and CO_2 emissions reductions achieved. Equity is concerned with efforts made by each person or group, initially targeted or not by the policy tool. With a wider scope, the aforementioned IB mechanisms can be judged on the basis of the following factors: a) CO_2 emissions variation, b) impact on public finances, c) time horizon, d) practicality / flexibility / consistence with law, e) equity, and f) acceptability. To go further, in

[67] Another redistribution of revenue is towards public transports. In this regard, Mirabel and Reymond (2011) shows that this kind of revenue redistribution "*leads to an increase in city public transport usage, and to an increase in social cost*" (cf. Proposition 1, p21). The authors also remind that "*in economic literature, Goodwin (1989) proposes that a third of the toll revenue be used to improve the effectiveness of public transport, that a third be used for new road infrastructure and maintenance, and that a third be used for general city funds*" (p18).

a context where decoupling mobility and CO_2 emissions is technological feasible, adding the criteria ‘mobility by passenger car variation’ and ‘new technologies promotion’ is highly appropriate for the analysis. Finally, equally interesting is to report the interactions among the negative externalities of urban mobility. With this aim in view, criteria in terms of other externalities variation such as ‘air pollution variation’, ‘congestion variation’ could also be added.

3.3.2. Some key lessons

Based on a literature review, Table 7 below offers a non-exhaustive list of strengths and shortcomings for IB mechanisms targeting either the car purchase (column 2) or the car use (column 3)[68]. For a simple comparison with command and control levers impacting on the supply-side, the first column deals with CO_2 emissions standards.

Table 7: Advantages and disadvantages of some policy tools

	Command and Control	**IB mechanisms dealing with car purchase:**	**IB mechanisms dealing with car use:**
	CO_2 emissions standard	Registration tax (1) / Bonus-malus (2) / Scrapping premium (3)	Fuel tax (1) / Kilometres travelled tax (2) / Emission tax (3)
Advantages	-Higher acceptability -Quicker responses than taxes	-Easy implementation (1) (2) (3) -Higher acceptability than usage taxes (1) (2) (3) -Incentive to purchase cleaner vehicles (2) -Increased public revenues (1)	-Reduced car use (reduction of the rebound effect and of car use externalities) (1 except if EV) (2) (3 except if EV) -Large scope (whole fleet in circulation (1 except if EV) (2) (3 except if EV) - Incentive to purchase cleaner vehicles (1) (3) -Increased public revenues (1) (2) (3)

[68] Note that ownership taxes allow adjustment on the basis of time-variant characteristics that are linked to pollution, and can foster maintenance activities that reduce emissions. Another strength of that kind of tax comes from the trend of consumers to be more sensitive to taxes they will pay every year (Santos and al., 2010a).

	Command and Control	IB mechanisms dealing with car purchase:	IB mechanisms dealing with car use:
	CO_2 emissions standard	Registration tax (1) / Bonus-malus (2) / Scrapping premium (3)	Fuel tax (1) / Kilometres travelled tax (2) / Emission tax (3)
Disadvantages	-No incentive to reduce car use (no reduction in congestion, accidents, etc.)	-Restricted scope (new vehicles) (1) (2) (3) -No incentive to reduce car use (*) (no reduction in congestion, accidents, etc.) (1) (2) (3) -Delayed car renewal (3) -Problem of equity: higher market prices of used vehicles in the second-hand market (3) -Uncertainty about the impact on the public budget (2) -Increased public expenditures (3)	-Low acceptability (1) (2) (3) -Low short-run impacts (because of a low price elasticity of the fuel demand) (1) (3) -No incentive to purchase cleaner vehicles (2) -Difficulties of measuring kilometres/emissions (2) (3), and problem of confidentiality (2) (3) -Equity problem: hits harder those with low incomes who own high fuel-consuming or high emitting vehicles (1) (3), and those who are car dependent (1 except if EV) (2) (3 except if EV)

EV: electric vehicle

Source: Author from Clerides and Zachariadis (2008), d'Haultfoeuille and al. (2014), de Palma and Kilani (2008), Moghadam (2011), Santos and al. (2010a), TIS (2002).

Key lessons are the following. Regarding the acceptability, there is a common understanding that IB mechanisms (columns 2 and 3) lag behind CO_2 emissions standards (column 1). Among IB mechanisms, vehicle purchase pricing schemes (column 2) – that are easy to implement and less rejected – have a real impact on the car choice, and effectively lead to a decrease of CO_2 emissions of new vehicles[69], but they are claimed not to convey the correct incentive for mileage choice to car drivers. In contrast, vehicle usage charges (column 3) do have an immediate and downward impact on the car use decision, and can even limit the rebound effect arising following the setting up of CO_2 emissions standards (see 3.1.3. below). In the same vein, car usage charges limit investments in road capacity while at the same time reducing traffic flow. This way, we avoid the Downs Thomson paradox whereby creating road infrastructures attracts yet more traffic and all the associated externalities. As a matter of fact, because of this paradox,

[69]Quite recently, a report of Transport & Environment concludes purchase taxes that are steeply differentiated by CO_2 boosted the purchase of lower-emissions cars in the Netherland, Denmark and France. In contrast Germany, Poland, Czech Republic, Sweden, Finland and Austria were among the countries with the highest CO_2 emissions from new cars and weakest national tax policies (Transport & Environment, 2014).

the National Transport Infrastructure Plan (SNIT) emphasises that "*State policy must give priority to making optimum use of existing networks before envisaging their extension*". Besides, another interest of usages taxes (column 3) is their wider scope; incidentally to the point that they (especially fuel taxes) are an important source of annual revenue for public budget. Actually, purchase pricing schemes (column 2) target only the new vehicles fleet, and the inertia phenomenon – due to the low renewal rate – is not merely real but may be greater with especially a scrapping premium scheme because some individuals may be encouraged to keep their vehicle longer[70] insofar as the subsidy enhances the value of old cars. This could be in fact a negative effect of a scrapping premium that is implemented first for supporting the car industry. Incidentally, this rise in market price of used vehicles may create regressive distributional effects insofar as lower income groups are over-represented in the second-hand market. Regarding now the different forms of car usages taxes (column 3) – which are based on the "polluter pays" principle – one can argue that the massive deployment of information and communication technologies (ICT) reduces the (initially high) administrative cost of monitoring kilometres; one of the main drawbacks of VKT taxation compared to the usage taxes based on the energy consumption. Furthermore, VKT taxation seems to be less inequitable insofar as it does not hit harder those who own a high-fuel consuming vehicle, among which low income people are numerous because they own old vehicles. This argument is however not valid from the moment that the VKT tax varies with the vehicle's energy performances, what is technological feasible thanks to the ICT. The latter technologies actually enable us to make intelligent and discriminating use of the appropriate economic tools (*e.g*. the sophisticated pricing scheme Lkw-Maut for heavy duty vehicles in Germany, described in CEC and Michelin, 2013). That VKT taxation enables to charge car use based on the full cost, that is to say taking all road transport's externalities (*e.g.* noise, lack of safety, pollution, and congestion)[71] into account could actually justify a move towards VKT taxation in place of fuel taxation. But, from the moment that it does not cover the whole network, this tax is also synonymous with room of

[70] Lengthening the lifespan does not necessarily help reduce energy consumption and emissions. In fact, it does for products that do not consume energy in their use phase or for products with energy involved in their use phase only if the new product involves the same energy content in the use phase. For the other kinds of products, it could be better to replace the product by a more efficient one. It actually depends on the energy intensity involved in both manufacturing and use phases (see the analysis of Nansai and al., 2007 that covers different sectors but also several environmental variables (energy, CO_2, NOx, waste)).

[71] The prime objective of a Pay-as-you-drive (PAYD) insurance is also to reduce mileage, especially that of high-risk drivers. This way, it also contributes to the fight against all the road transportation's externalities. For instance, Parry (2005) discusses the PAYD insurance, while comparing it with fuel taxes. The author highlights the fact that driving costs of the average motorist does not increase with a PAYD insurance, whereas it does with a fuel tax; explaining this way the lower political opposition for the former policy tool.

manoeuvre for motorists, and traffic diverts onto roads not subject to taxes[72]. This is a harmful phenomenon since CO_2 emissions are likely to grow because of the bypass effect. Lastly, what is also noticeable to note is that a VKT tax is likely to trigger shift in vehicle demand towards less consuming vehicles only if it is defined on the basis of the vehicle's energy performances, such as fuel or emissions taxes.

In the next subpart, we put emphasis on a well-known phenomenon – *i.e.* the rebound effect – which has to be taken into account when examining the effects of policy instruments.

3.3.3. Policy tools and the phenomenon of rebound effect

It is widely acknowledged that improving the vehicle's fuel efficiency through the adoption of new technologies cannot be expected to result in proportional cuts in CO_2 emissions, since efficiency improvements are highly correlated with mileage and thus with total fuel consumption. This phenomenon is referred to in the literature as the "*rebound effect*", that is to say an increase in demand induced by efficiency gains. More precisely, an initial reduction in consumption per kilometre resulting from an improvement in energy efficiency will also lead to an effective decrease in the price of transportation per kilometre. As a result, car use may increase, partially offsetting the impact of the efficiency gain in fuel use. This response to the improvement of the energy efficiency actually corresponds to the *direct* rebound effect that is generally estimated using elasticity methods[73]. The *indirect* effect results from the fact that the real income rises in response to decreasing energy costs; and consequently, the demand for other goods, including fuel consumption, increases.

Public authorities have a part to play in tackling the so-called rebound effect; all the more so when energy efficiency gains result from the implementation of a policy tool – and not only from private initiatives. CAFE regulation (*i.e.* the fuel economy standards that exist in the United States) is for example qualified in Small and Van Dender (2007) as something "*exerting a force on every state toward greater fuel efficiency of its fleet, regardless of the desired fuel efficiency in that particular state*" (p13). We can note that these authors estimated the rebound effect for motor vehicles in the USA over the period 1966-2001, while allowing the rebound

[72] Interestingly, congestion pricing (*e.g.* urban toll) also plays on the "departure time" in addition to having an impact – like the VKT taxation – on the following sequences of travel demand formation process: route change, mode shift, destination change and trip generation (in VTPI, 2013).

[73] In France, for diesel cars, the price elasticity of mileage demand is -0.13 in the short term and -0.21 in the long term. For petrol cars, the price elasticity is 2.5 times higher: -0.32 in the short term, and -0.52 in the long term (Collet, 2007; Collet and al., 2010; in Hivert and Wingert, 2010).

effect to vary with income, urbanization and fuel cost of driving; and they found that on average the short- and long-run rebound effects are 4.5% and 22.2%.

Leaving aside now the improvements in energy performances, and considering exclusively the fact that low fuel-consuming vehicles are likely to be more intensively used than high fuel-consuming vehicles leads us to envision that implementing a differentiated purchase tax could also result in a rebound effect. In that scenario, the higher energy efficiency over the whole car fleet is actually not due to technological improvements (*i.e.* vehicles are not more energy-efficient), but results from a new distribution of households among different kinds of vehicles – more or less fuel consuming – so that the average fuel consumption is reduced.

That the cost per kilometre varies on the one hand with the fuel consumption per kilometre, and on the other with the fuel price implies that increasing the fuel price – with a fuel tax for instance – enables to compensate for rebound effects (Ajanovic and Haas, 2012; Clerides and Zachariadis, 2008). The other way round, when a fuel tax already exists, tightening the CO_2 emissions standards is claimed to partially offset the capacity of the fuel tax to reduce fuel consumption, because consumers' response to fuel price variation strongly depends on the vehicle's fuel intensity, so that the effects of both policies are complementary[74] but less than additive[75] (see Liu, 2015).

In the last Part of this Chapter, we will put emphasis on this rebound effect when addressing the effects of two different policy instruments: a differentiated car purchase tax and a fuel tax.

4. The relevance of a differentiated car purchase tax and of a fuel tax in light of the rebound effect

In this final Part, we call into question the relevance of a differentiated car purchase tax and that of a fuel tax in light of the rebound effect. To some extent, the question addressed in this Part is which CO_2 regulation[76] – involving a differentiated car purchase tax and/or a usage tax – is the most efficient one when taking account of the phenomenon of rebound effect. The

[74] Effects are complementary when the use of two instruments has greater impacts than the use of either alone (in May and al., 2006).
[75] Effects are additive when the benefit from the use of two instruments is equal to the sum of the benefits of using each in isolation (in May and al., 2006).
[76] Above all, note that we will not take into account the normative component of a tax, that is to say the physiological connotation of punishments (that could have explain a different response to the implementation of a tax than to an increase in the car market price or in the fuel price due to market conditions).

theoretical model is first described (4.1.), and a numerical study is then carried out to illustrate the model (4.2.).

4.1.The theoretical model

4.1.1. The consumer's behaviour

Herein, the car purchase decision (*i.e.* which vehicle to purchase?) – and not the car ownership decision (*i.e.* to purchase or not a car?) – is investigated, implying that we consider a fixed vehicle-purchasing population.

Specifically, we consider a continuum of consumers who have two options: purchasing a low emitting vehicle termed "vehicle c" ("c" standing for "clean") or purchasing a high emitting vehicle termed "vehicle d" ("d" standing for "dirty"). At that stage, we draw the reader's attention to the fact that we do not put 'green' and 'grey' vehicles facing each other in that we do not define what is a 'green vehicle'. We content ourselves with comparing two vehicles with the same motorisation (and thus the same CO_2 emissions factor) which consume a different amount of fuel per kilometre. And this is for ease of exposition that, with a slight abuse of language, we speak about a "clean" and a "dirty" vehicles. More specifically, the fuel consumption figures are such that $f^c < f^d$ with f^j being the vehicle j's fuel consumption per kilometre.

All consumers derive utility from the consumption of vehicle-kilometres-travelled (termed k), and from the consumption of a composite good (termed C). Recall that the most restrictive assumption stemming from this choice of attributes of the utility function lies in the fact that consumers are supposed not to be able to consume kilometres with public transports. What is more, all consumers are supposed to have the same preferences in terms of kilometres (see θ that does not depend on consumer i in equation (16) below). Specifically, we have the following utility function:

$$U(k, C) = C^{1-\theta} k^{\theta} \tag{16}$$

We further assume that consumers earn annually the same income to the point that the income allocation between the two utility function's attributes is the same for all consumers (y and θ are the same for all consumers). However, consumers distinguish themselves by their taste for vehicle j. Let η_i^j denote this additional utility; it varies both with the vehicle type (j) and among consumers (i).

In accord with the economic theory whereby the consumer's behaviour is utility-maximising, the decision rule of consumer i underlying the car choice is written as follows:

If $V_i^c > V_i^d$ he/she chooses to purchase vehicle c
If $V_i^c < V_i^d$ he/she chooses to purchase vehicle d (DR1)

with:

$$V_i^j = U^j + \eta_i^j \quad (17)$$

where V_i^j is the indirect utility, and U^j is the direct utility.

In all evidence, we can also write the decision rule in the following manner:

If $U^c - U^d > \eta_i^d - \eta_i^c$ he/she chooses to purchase vehicle c
If $U^c - U^d < \eta_i^d - \eta_i^c$ he/she chooses to purchase vehicle d (DR1bis)

Interestingly, the left-hand term of the inequality in DR1bis is the same for all households, and varies solely with the vehicles' market price and fuel consumption per kilometre. The value of this gap in utility is typically behind the distribution of households between the two vehicles. We note $U^* = U^c - U^d$. Indeed, whether $\eta_i^d - \eta_i^c$ is below or above U^* makes household i purchases respectively vehicle c or vehicle d.

4.1.2. Towards computing the total of CO_2 emissions

Intuitively, public authorities implement policy tools provided that they really help reduce CO_2 emissions. The annual total of CO_2 emissions due to the use of both vehicles is given by:

$$E = Ne(\varphi^c k^c f^c + \varphi^d k^d f^d) \quad (18)$$

where N is the size of the vehicle-purchasing population, e is the CO_2 content of fuel (expressed in kilograms of CO_2 per litre of fuel), and φ_c and φ_d are the shares of vehicles c and d at the aggregate level. These latter shares are obtained by summing the choice of individuals constituting the whole vehicle-purchasing population. Considering a given distribution of households for the different values of $\eta_i^d - \eta_i^c$, we have:

$$\varphi^c = P\left(\eta_i^d - \eta_i^c < U^*\right), \text{ and } \varphi^d = 1 - \varphi^c \quad (19)$$

4.1.3. Effects of a Malus scheme

In this Part, we investigate the effects of a Malus scheme. To this end, we differentiate two public policy regimes:

- a "no-policy regime" (all variables referring to this regime are termed with a tilde symbol in the remainder of the part);
- a "penalty regime" (the variables are termed with an over bar).

Table 8: Analytical expressions of our model

	"No-policy regime" (for both vehicles, indexed by *j*)		**"Penalty regime" (for vehicle *c* or vehicle *d*)**
Budget constraint	$y-\frac{P^j}{T}=\widetilde{C^j}+pf^j\widetilde{k^j}$	Or	$y-\frac{P^c}{T}=\overline{C^c}+pf^c\overline{k^c}$ $y-\frac{P^d+M}{T}=\overline{C^d}+pf^d\overline{k^d}$
Distance travelled	$\widetilde{k^j}=\frac{\left(y-\frac{P^j}{T}\right)\theta}{pf^j}$	Or	$\overline{k^c}=\frac{\left(y-\frac{P^c}{T}\right)\theta}{pf^c}$ $\overline{k^d}=\frac{\left(y-\frac{P^d+M}{T}\right)\theta}{pf^d}$
Consumption of composite good	$\widetilde{C^j}=(1-\theta)\left(y-\frac{P^j}{T}\right)$	Or	$\overline{C^c}=(1-\theta)\left(y-\frac{P^c}{T}\right)$ $\overline{C^d}=(1-\theta)\left(y-\frac{P^d+M}{T}\right)$
Indirect utility	$\widetilde{V_i^j}=\left(y-\frac{P^j}{T}\right)(1-\theta)^{1-\theta}\left(\frac{\theta}{pf^j}\right)^{\theta}+\eta_i^j$	Or	$\overline{V_i^c}=\left(y-\frac{P^c}{T}\right)(1-\theta)^{1-\theta}\left(\frac{\theta}{pf^c}\right)^{\theta}+\eta_i^c$ $\overline{V_i^d}=\left(y-\frac{P^d+M}{T}\right)(1-\theta)^{1-\theta}\left(\frac{\theta}{pf^d}\right)^{\theta}+\eta_i^d$
Shares of clean and dirty vehicles	$\widetilde{\varphi^c}=P\left(x<\widetilde{U^*}\right)$, and $\widetilde{\varphi^d}=1-\widetilde{\varphi^c}$		$\overline{\varphi^c}=P\left(x<\overline{U^*}\right)$, and $\overline{\varphi^d}=1-\overline{\varphi^c}$
Total of CO_2 emissions	$\tilde{E}=Ne\left(\widetilde{\varphi^c}\widetilde{k^c}f^c+\widetilde{\varphi^d}\widetilde{k^d}f^d\right)$		$\overline{E}=Ne\left(\overline{\varphi^c k^c}f^c+\overline{\varphi^d k^d}f^d\right)$

Table 8 above summarises the analytical expressions of: the distance covered with each vehicle, the consumption of composite good, the indirect utility, the shares of clean and dirty vehicles, and the total of CO_2 emissions in the "no-policy regime" (first column) and in the "penalty regime" (second column). The first two listed variables are simply obtained by maximising the utility (equation (16)) under a budget constraint (supposed to be saturated) which expression is given in the first row in Table 8. Clearly, the differences between both regimes result from the penalty that is introduced in the budget constraint in the second regime (see M for 'Malus' in the budget constraint in the second regime). Notations are detailed below.

The budget constraint is function of the following variables:

- y is the annual income, P^j is the vehicle j's market price, and T is the length of car ownership;
- M is the amount of penalty[77] charged on the purchase of a dirty vehicle;
- C^j is the expenditure on composite good (the price of the composite good is normalized to one);
- pf^jk^j is the expenditure on fuel, with p being the fuel price (expressed in euros per litre), and f^j the vehicle j's fuel consumption (expressed in litre per kilometre).

The effects of the Malus scheme can be easily deduced from Table 8. They are:

- a reduction in the distance covered with a dirty vehicle ($\overline{k^d} < \widetilde{k^d}$) because of a lower disposable income after the car purchase, on the one hand; and
- a decrease of the share of dirty vehicles ($\overline{\varphi^d} < \widetilde{\varphi^d}$) on the other hand. This reduction in the share of dirty vehicles due to the Malus scheme translates into a higher average energy efficiency of vehicles over the whole fleet.

Given the higher energy efficiency of the fleet in the Malus scheme regime, tackling the issue of the rebound effect takes on its full meaning. To some extent, the rebound effect measures the decision-maker's error of assessment of the efficiency of the Malus scheme, due to the fact they do not anticipate the response of motorists in terms of car use. This is also a loss of efficiency of the policy instrument. In concrete terms, the rebound effect corresponds to the CO_2 emitted because the distance covered with the clean vehicle in the "penalty regime" by the motorists who would have purchased a dirty vehicle in the absence of the penalty does not equal (more precisely, it exceeds) the distance they would have covered with the dirty vehicle in the

[77] Actually, we have $M(f^d)$. Since f^d is not a decision variable, the penalty is here simply termed M.

"no-policy regime". Expressed in absolute terms, that is to say in kilograms of CO_2 per household and per year, the rebound effect (RE) amounts to[78]:

$$RE = Ne\left(\overline{\varphi^c} - \widetilde{\varphi^c}\right)\left(k^c - \widetilde{k^d}\right)f^c \qquad (20)$$

where $\left(\overline{\varphi^c} - \widetilde{\varphi^c}\right)$ is the share of motorists who change their car purchase decision because of the Malus scheme, and $\widetilde{k^d}$ is the distance the public decision-makers think it will be travelled by the latter motorists, while they cover k^c kilometres in reality (with a vehicle consuming f^c litres of fuel per kilometre). It is noteworthy that this specific way of computing the rebound effect is tantamount to considering that the policy stakeholders do not anticipate the effect of the Malus amount on the distance travelled with the dirty vehicle. Indeed, we use $\widetilde{k^d}$ instead of $\overline{k^d}$. We draw the reader's attention to the fact that this reasoning explains why we can observe some situations in which the rebound effect is higher than 100% while the CO_2 emissions in the "penalty regime" are still lower than the emissions in the "no-policy regime". In fact, conventionally, when the rebound effect is higher than 100%, the CO_2 emissions are higher after the improvement of the energy efficiency. This particular situation is referred to in the literature as the *"Jevons Paradox"*. In the present analysis, we slightly differ from this traditional result because the improvement of the energy efficiency is due to the implementation of a Malus scheme – and not because of technological progress – which effect is not limited to the improvement of the energy efficiency; this public intervention also leads to a reduction in the distance covered with the dirty vehicle. This is the reason why there is no interest in computing the rebound effect in relative terms in the remainder of this Part.

That said, and from equations (20), we derive the following Proposition:

Proposition 2.

a) There is a rebound effect provided that $\frac{yT-P^c}{f^c} > \frac{yT-P^d}{f^d}$;

b) The rebound effect (in absolute terms) increases with the Malus amount.

[78] It results from the following difference between the two decreases in CO_2 emissions caused by the Malus scheme (when taking into account or not the change in the motorists' car use): $Ne\left(\overline{\varphi^c} - \widetilde{\varphi^c}\right)\widetilde{k^d}\left(f^d - f^c\right) - Ne\left(\overline{\varphi^c} - \widetilde{\varphi^c}\right)\left(\widetilde{k^d}f^d - k^c f^c\right)$.

Proof.

a) Using equation (20), the rebound effect is positive from the moment that $k^c > \widetilde{k^d}$. We obtain the condition under which this is verified by using the expressions of the distances covered k^c and $\widetilde{k^d}$ given in Table 8 above.

b) We have $\frac{\partial RE}{\partial M} = Ne\left(k^c - \widetilde{k^d}\right)f^c \frac{\partial \overline{\varphi^c}}{\partial M}$. The latter derivative is positive since $\frac{\partial \overline{\varphi^c}}{\partial M} > 0$ (see $\overline{\varphi^c}$ in Table 8) and $k^c - \widetilde{k^d} > 0$ (condition under which a rebound effect does exist).

First of all, since the improvement of the fuel-efficiency is observed at the aggregate scale and not at the individual level, it happens that we observe a rebound effect only under certain conditions pertaining to the characteristics of the vehicles that make up the fleet. Indeed, the order of magnitude of the gap in market prices of the dirty and clean vehicles compared to that of the gap in fuel consumptions of both vehicles determines whether a less fuel-consuming vehicle is effectively more used than a more fuel-consuming vehicle. Besides, when a rebound effect occurs, its amount in absolute terms increases with the level of Malus. This is because the higher the penalty, the higher the number of consumers who purchase a clean vehicle in the Malus scheme regime while they would have purchased a dirty vehicle in the "no-penalty" regime.

We now turn our attention to the effects of a fuel tax.

4.1.4. Effects of a fuel tax

In this subpart, we discuss the capacity of a fuel tax to limit the rebound effect caused by the implementation of the Malus scheme.

We start by shedding light on the direct effects of the fuel tax. First and foremost, the implementation of a fuel tax simply affects the consumers' budget constraint. Specifically, the cost per kilometre is now equal to $p(1+\tau)f^j$ where τ corresponds exactly to the amount of the fuel tax. In all evidence, the distance travelled with the vehicle decreases with the tax ($k_\tau^c < k^c$, and $\overline{k_\tau^d} < \overline{k^d}$), insofar as it translates into a higher cost per kilometre. In the same time, the consumption of the composite good does not change since it is not function of the cost per kilometre. Interestingly, it implicitly means that the allocation of the income between the two utility function's attributes does not vary with the tax; and that the consumption of kilometres has to be re-adjusted so that the expenditure on fuels remains unchanged in spite of the usage tax.

Moreover, the distribution of households between the two vehicles is also likely to be influenced by the fuel tax (see for instance Busse and al., 2013). Precisely, two cases have to be considered depending on whether the fuel tax is implemented after (first scenario) or before (second scenario) the consumers' car purchase. In the first case, public authorities do not anticipate the rebound effect resulting from charging the penalty, and thus implement the fuel tax while consumers have already purchased their vehicle. It implicitly means that the distribution of households between the two types of vehicle does not take the fuel tax into account. In the second one, the policy-makers foresee the rebound effect and thus simultaneously implement the fuel tax and the penalty. In that case, the distribution of households among vehicles is function of the fuel tax. Precisely, the share of clean vehicles is magnified when fuel is taxed ($\overline{\varphi_\tau^c} > \overline{\varphi^c}$).

As regards the rebound effect caused by the Malus scheme when fuel is taxed in the "penalty regime" (but not taxed in the "no-policy" regime), it is given by:

- when the fuel tax is implemented after the car purchase:

$$RE\left(k_\tau^c, \widetilde{\varphi^c}\right) = Ne\left(\overline{\varphi^c} - \widetilde{\varphi^c}\right)\left(k_\tau^c - \widetilde{k^d}\right)f^c \qquad (21)$$

- when the fuel tax is implemented before the car purchase:

$$RE\left(k_\tau^c, \overline{\varphi_\tau^c}\right) = Ne\left(\overline{\varphi_\tau^c} - \widetilde{\varphi^c}\right)\left(k_\tau^c - \widetilde{k^d}\right)f^c \qquad (22)$$

Given that, when it comes to analysing the effect of the fuel tax on the rebound effect, we have the following Proposition:

Proposition 3. *The rebound effect accompanying the implementation of a Malus scheme is:*

a) reduced when the fuel tax is set up after the car purchase;
b) more or less large compared to the rebound effect in the absence of the fuel tax, when the fuel tax is set up before the car purchase.

Proof.

a) Compare equations (20) and (21) and note that $k_\tau^c < k^c$.

b) Compare equations (20) and (22) and note that $k_{\tau}^{c} < k^{c}$ on the one hand, and that $\overline{\varphi_{\tau}^{c}} > \overline{\varphi^{c}}$ on the other hand.

As argued above, that a rebound effect occurs with the penalty charged on the purchase of dirty vehicles is explained by the shifting from dirty vehicles to clean vehicles while the consumption of kilometers with a clean vehicle outdistances the consumption of kilometers with a dirty vehicle. In that context, diminishing the distance covered with a clean vehicle in the “penalty regime” – by implementing a fuel tax – helps reduce the rebound effect. The latter reasoning is quite intuitive from the moment that the fuel tax only affects the distance travelled, and does not impact the distribution of vehicles (see a)). But, that the distance travelled with both vehicles are lower, thanks to the fuel tax, in the “penalty regime” may be not enough to compensate the enlargement of the share of clean vehicles (that are more intensively used) that results from the introduction of the fuel tax provided that the latter tool is implemented before the car purchase (see b)). Whether one or the other of these two opposite trends prevails depends on the share of dirty vehicles in the “penalty regime” before the implementation of the fuel tax on the one hand, and on the extent to which the distribution of households between the two types of vehicles varies with the fuel tax on the other hand. To some extent, it depends on the assumption we make regarding the distribution of households along the different values of preferences for the dirty vehicle’s characteristics.

In the next section, we use our theoretical model to investigate numerically the impact of the current French Malus scheme, as well as the capacity of the French carbon tax introduced in 2014 to limit the rebound effect.

4.2. A numerical illustration in France

4.2.1. Calibration of the model

This numerical illustration is carried out with data from 2013. For ease of explanation, the size of the vehicle-purchasing population is normalized to one (*i.e.* $N = 1$). This way, the total of emissions is exactly the amount of kilograms of CO_2 emissions that results on average from the distances travelled by private car over one year per household. Let us note that this figure (slightly less than one tonne of CO_2 per year and per household in this illustration) differs from the one given by the French General Commission on Sustainable Development (*i.e.* on average, a French person emits two tonnes of CO_2 emissions per year because of its trips, CGDD, 2010) as we consider only the private car and not the other modes of transport.

As already said in the preceding Chapter, we consider solely petrol vehicles because of their higher level of CO_2 emissions per kilometre. What is more, penalties largely target petrol vehicles. Besides, an important point to mention is that – contrarily to what we assume in the first Chapter of this Thesis – the characteristics of the average petrol car in France in 2013 (*i.e.* a fuel consumption of 5.2L/100km and a market price of €18,918) define the *clean* vehicle in this second Chapter, and not the *dirty* vehicle. This choice is justified by the purpose of the model introduced in the previous Part that is to study the effects of a Malus scheme that target dirty vehicles. Indeed, the characteristics of dirty vehicles can vary this way. More specifically, based on the minimum amount of fuel above which a Malus is charged in France in 2013 (*i.e.* 5.8L/100km), and on the amount of fuel above which the amount of Malus does not change (8.6L/100km) (see Appendix D for a description of the French Malus scheme), we will consider two gaps in the fuel consumptions of our two types of vehicles, namely +0.6L/100km (*i.e.* the dirty vehicle consumes 5.8L/100km) and +3.4L/100km (*i.e.* the dirty vehicle consumes 8.6L/100km). And for reasons of clarity of charts, we will consider only three gaps in market prices of both vehicles, namely -3,000€ (*i.e.* the dirty vehicle is €3,000 less expensive than the clean one); +0€ (*i.e.* both vehicles have the same market price), and +3,000€ (*i.e.* the dirty vehicle is €3,000 more expensive).

In terms of consumers' behaviour, we first assume that each consumer makes his car purchase decision based on the total revenue of the household rather than on his own income on the one hand, and that the car purchase decision is based on the average income earned the year before the time of observation because of the uncertainty on the level of income during the current year on the other hand. In 2012, the French average annual income per household amounted to €36,190 (INSEE). Similarly, because of the uncertainty about the fuel price level, consumers are supposed to consider the fuel price the year before the car purchase decision, namely €1.5753[79] per litre of petrol in 2012 (DGEC). A further consideration in terms of consumers' behaviour is that households keep on average their vehicle for 5.3 years (CCFA, 2014). Finally, the preference parameter value θ is chosen such that the model roughly reflects realistic orders of magnitude in terms of annual distance covered with a petrol car (*i.e.* 7,751km in 2013; CCFA,

[79] Weighted (according to the national annual total consumption, see DGEC) average of annual prices of Super SP95 (€1.5367) and Super SP98 (€1.5943).

2014). More precisely, the value $\theta = 0.02$ is used as the benchmark, and a sensitivity analysis conducted with a higher value is given in Appendix E.

Regarding the policy tools, we will adopt, in the first instance, a positive approach; this means that we examine the effects of predefined incentive-based mechanisms. More exactly, we will consider the following range for the amount of Malus: $M \in$ [€0, €6,000] with €6,000 being the maximum amount of Malus charged in France in 2013 (see Appendix D). Besides, in this application, the fuel tax is a carbon tax. On top of the reasons of this choice, there is the availability of realistic orders of magnitude for an additional fuel tax thanks to the French carbon tax project. In accordance with the 2014 Finance Law, we consider a carbon tax of 1.72c€ per litre of petrol, what actually is levied in 2015[80] (El Beze, 2014).

We summarise all these values in Table 9 below.

Table 9: Variables used to illustrate the model

Exogenous variables	**Value in 2013**
Household's average income ($\boldsymbol{y}$) (€)	36,190
Length of car ownership ($\boldsymbol{T}$) (years)	5.3
Preference parameter ($\boldsymbol{\theta}$)	0.02
Clean vehicle's fuel consumption ($\boldsymbol{f^c}$) (L/km)	0.052
Clean vehicle's purchase price ($\boldsymbol{P^c}$) (€)	18,918
Fuel price ($\boldsymbol{p}$) (€/L)	1.5753
CO_2 content of fuel ($\boldsymbol{e}$) ($kgCO_2/L$)	2.346
Malus amount ($\boldsymbol{M}$) (€)	From 0 to 6,000
Carbon tax ($\boldsymbol{\tau}$) (c€/L)	1.72

4.2.2. Results

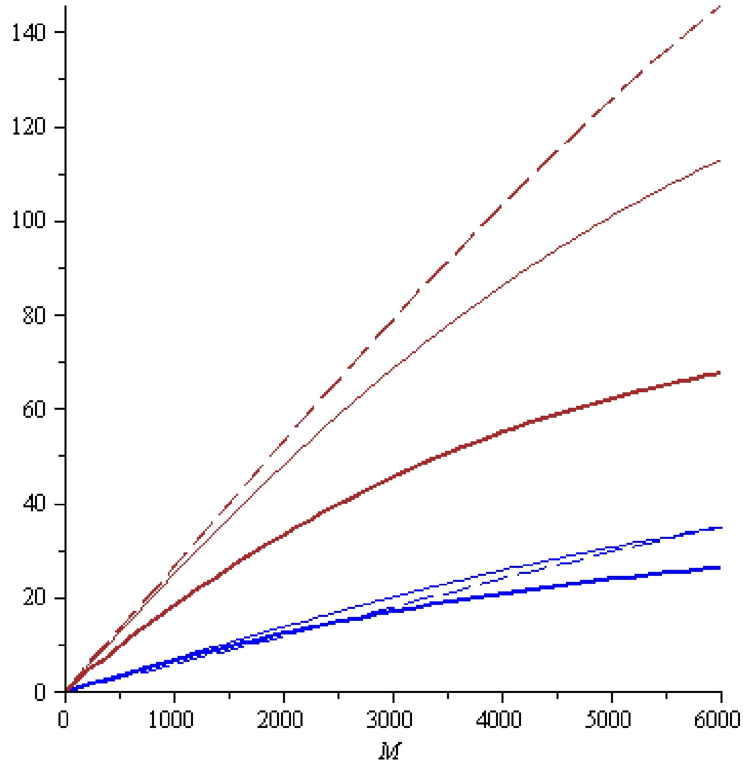
This Part aims at illustrating our two Propositions. More precisely, we examine deeper the effects of a Malus scheme, and those of a carbon tax. Note that we consider a standard normal distribution of households for the different values of the relative preferences for dirty vehicle's characteristics. A sensitivity analysis regarding the distribution law is offered in Appendix F.

[80] Article 32 of the 2014 Finance Law added a carbon component to the base of the Domestic Consumption Tax (DCT). In 2014, the rate of carbon taxation amounted to €7 per ton of CO_2. However, during 2014 (the year of transition), the introduction of the carbon component did not have any impact, since it was totally compensated by a symmetrical reduction of the classical component of the DCT. In 2015, an increase of €7.5 makes the rate reach 14.5€/tCO_2. The annual increase of the DCT in 2015 is thus c€1.72.

- **Effect of the Malus scheme**

We start by plotting the rebound effect (in absolute terms) that accompanies the implementation of the Malus scheme in Figure 9 below, while considering the two gaps in fuel consumptions of our dirty and clean vehicles $f^d - f^c$: +0.6L/100km (in blue) and +3.4L/100km (in brown), and for the three different gaps in market prices of both vehicles $P^d - P^c$: -3,000€ (dashed curves), +0€ (thine curves), and +3,000€ (bold curves).

Figure 9: Rebound effect (in Y-axis, in $kgCO_2$/household/year) as a function of the Malus amount (X-axis, in €)



Legend:

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$

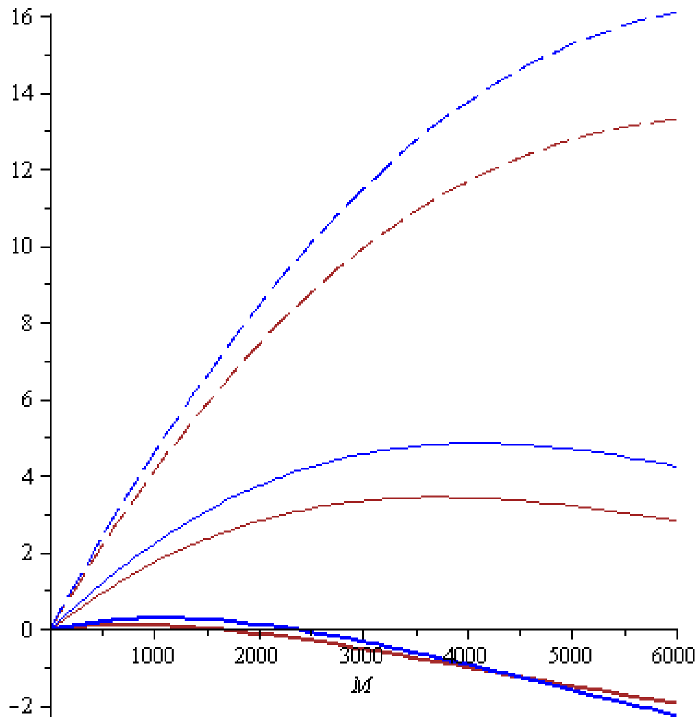
$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$

First of all, for the latter characteristics of both vehicles, we always observe a rebound effect with the implementation of the Malus scheme, as shown in Figure 9. Furthermore, Figure 9 highlights that the higher the amount of Malus, the higher the rebound effect. In addition, as expected, the higher the gap in the fuel consumption of both vehicles, the higher the rebound effect (compare the brown curves with the blue ones in Figure 9 above). In contrast, the role played by the gap in market prices of vehicles on the order of magnitude of the rebound effect is more ambiguous: for a large gap in fuel consumptions (+3.4L/100km, in brown), the higher the gap in market prices, the higher the rebound effect, whereas when the gap in fuel consumptions is low (+0.6L/100km, in blue), whether the rebound effect is higher with a larger gap in market prices depends on the amount of the Malus.

Despite the rebound effect, the Malus scheme is able to reduce the CO_2 emissions from car use, as illustrated in Figure 10 below. This Figure plots the gap in CO_2 emissions between the two policy regimes we consider – *i.e.* CO_2 emissions without policy tools minus CO_2 emissions with a Malus scheme – while keeping considering two gaps in fuel consumptions (+0.6L/100km (in blue) and +3.4L/100km (in brown)), and for three gaps in market prices (-3,000€ (dashed curves), +0€ (thine curves), and +3,000€ (bold curves)). Clearly, the Malus scheme helps mitigate emissions provided that the gap we chose to plot is positive.

Figure 10: Emissions without policy tools minus Emissions with a Malus scheme (Y-axis, in $kgCO_2$/household/year) as a function of the amount of Malus (X-axis, in €)



Legend:

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$ — $f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$ — $f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$ — $f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$

Figure 10 shows that increasing the amount of Malus reinforces the effects of the Malus scheme in the first instance, but there exists an amount of Malus above which the reduction in CO_2 emissions attained with the Malus scheme decreases with the Malus amount. More specifically, the lower the gap in the vehicle market prices (in dashed lines compared to the thine lines), the higher the effects of the Malus scheme on the one hand, and the higher the malus threshold above which the efficiency of the Malus deteriorates with the Malus amount on the other hand. More astonishing is the effect of the Malus scheme when the dirty vehicle costs more to purchase than the clean vehicle (cf. the curves in bold that correspond to a gap in market prices of +3,000€). Indeed, in that case, it happens that the effects of the Malus scheme are counterintuitive above a certain level of Malus: the CO_2 emissions are higher in the Malus scheme regime (cf. points below the X-axis in Figure 10 above). This particular situation is referred to as the *Jevons Paradox*.

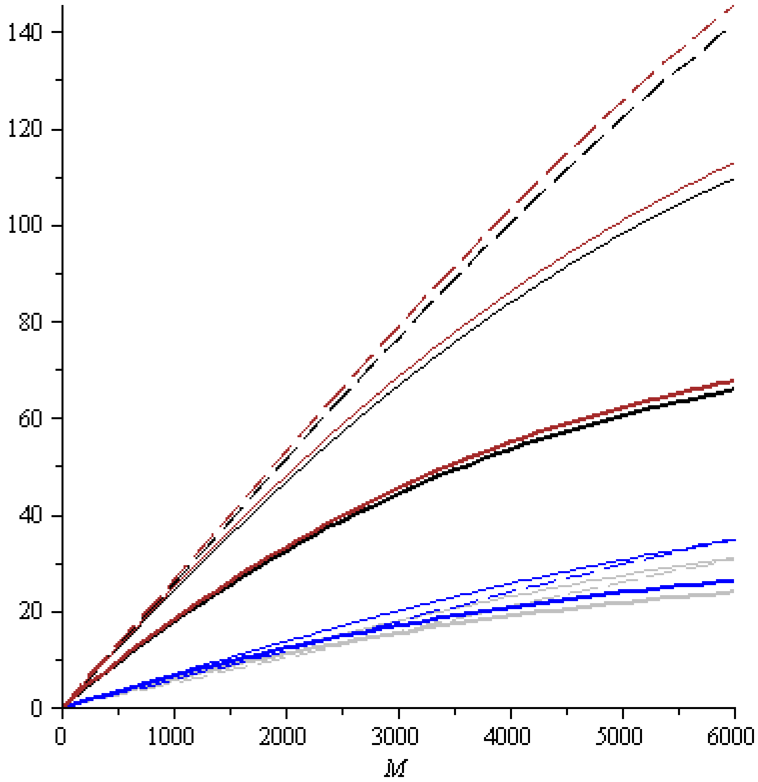
The latter results highlights the importance of designing the Malus scheme appropriately. In the same vein, and as a remark, d'Haultfoeuille and al. (2014) also argues "*while feebates may be efficient tools for reducing CO_2 emissions, they should thus be designed carefully to achieve their primary goal*" (F444). In their analysis, the potential increase in CO_2 emissions coming with the French feebate results from two effects: the rebound effect and a large scale effect (*i.e.* a rise of total sales of new cars).

- **Effects of a carbon tax**

Herein, we only represent the situation wherein the carbon tax is implemented after the car purchase insofar as results do not vary significantly with the time of implementation of the tax in the present illustration.

We start by putting emphasis on the capacity of the carbon tax of reducing the rebound effect. To do so, we plot in Figure 11 below the rebound effect caused by the Malus scheme in the presence of the carbon tax (grey or black in colour respectively for a gap in fuel consumptions of +0.6L/100km and +3.4L/100km) and in the absence of the carbon tax (respectively blue or brown in colour as in Figure 9). Clearly, whatever the gap in the market prices of the dirty and clean vehicles, and that in their fuel consumptions per kilometre, the carbon tax is able to slightly reduce the rebound effect.

Figure 11: Effect of the fuel tax on the rebound effect caused by the Malus scheme (Y-axis, in $kgCO_2$/household/year) as a function of the amount of Malus (X-axis, in €)



Legend:

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$

Same as above, plus $\tau = 1.72c€$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$

Same as above, plus $\tau = 1.72c€$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$

Same as above, plus $\tau = 1.72c€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$

Same as above, plus $\tau = 1.72c€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$

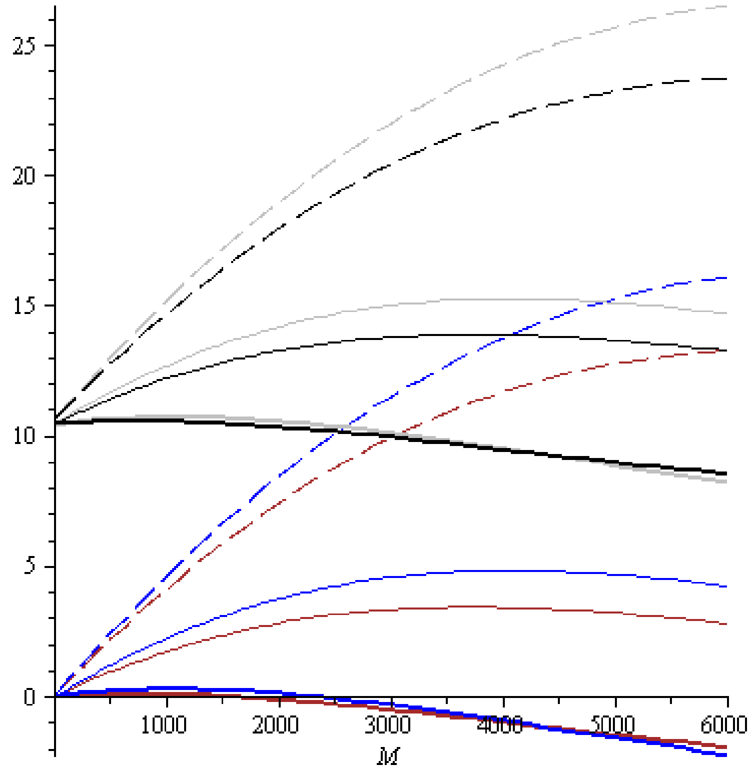
Same as above, plus $\tau = 1.72c€$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$

Same as above, plus $\tau = 1.72c€$

In view of this result, we compare the reduction in CO_2 emissions obtained with a Malus scheme on the one hand, and with a Malus scheme coupled with the carbon tax on the other hand in the following Figure.

Figure 12: Effect of the fuel tax (implemented in the Malus scheme regime) on the gap between emissions without policy tools and emissions with a Malus scheme (Y-axis, in $kgCO_2$/household/year) as a function of the amount of Malus (X-axis, in €)



Legend:

- $f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$
- Same as above, plus $\tau = 1.72c€$
- $f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$
- Same as above, plus $\tau = 1.72c€$
- $f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$
- Same as above, plus $\tau = 1.72c€$
- $f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$
- Same as above, plus $\tau = 1.72c€$
- $f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$
- Same as above, plus $\tau = 1.72c€$
- $f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$
- Same as above, plus $\tau = 1.72c€$

Lessons driven from Figure 12 are three-fold. Firstly, implementing a carbon tax in addition to the Malus scheme helps further reduce the CO_2 emissions (the grey or dark curves are always higher than the blue or brown ones), and this way, it enables to avoid the *Jevons Paradox*.

Secondly, the effects of the carbon tax, when taken in isolation, do not greatly vary neither with the gap in market prices nor with the gap in fuel consumptions (approximately -10.5kgCO_2/household/year, see the intercept of the grey and black curves). Thirdly, adding a Malus scheme to a carbon tax may potentially lead to a higher reduction in CO_2 emissions than the one obtained with solely the tax (cf. the points of the grey and black curves that are higher than 10.5kgCO_2). Caution is however needed to derive such a result since it requires to consider that both tools are taken into account in the car purchase decision (remind that in this numerical version, the impacts of the carbon tax do not vary significantly with its time of implementation).

- **Capacity of a carbon tax to achieve CO_2 reduction levels equal to the combined carbon tax and Malus scheme**

Last but not least, we address the capacity of a carbon tax to achieve the same reduction in CO_2 emissions than the one achieved when the tax is coupled with a Malus scheme. We choose to consider solely the impacts of a carbon tax of 1.72c€ coupled with a Malus of 100€ for the situation in which the gap in fuel consumptions is +0.6L/100km on the one hand, and those of a carbon tax of 1.72c€ coupled with a Malus of €6,000 for the situation in which the gap in fuel consumptions is +3.4L/100km. This choice is based on the current amounts of Malus that are charged on the purchase of vehicles that consume respectively 5.8L/100km and 8.6L/100km (the French Malus scheme is described in Appendix D). The impacts of the latter policy mixes are displayed in Table 10 below for the three different gaps in the market prices of the clean and dirty vehicles (in column).

Table 10: Effects on CO_2 emissions (per household and per year) of a combination of a carbon tax of 1.72c€ and a Malus of either €100 or €6,000

	$P^d - P^c = -3,000€$	$P^d - P^c = 0€$	$P^d - P^c = 3,000€$
$f^d - f^c = 0.6L/100km$ $M = 100€$, and $\tau = 1.72c€$	-11.10kgCO_2	-10.75kgCO_2	-10.49kgCO_2
$f^d - f^c = 3.4L/100km$ $M = 6,000€$, and $\tau = 1.72c€$	-23.73kgCO_2	-13.29kgCO_2	-8.53kgCO_2

For each configuration characterized by a gap in market prices and a gap in fuel consumptions of our two types of vehicles, we compute the carbon tax which provides the same reduction that the policy mixes defined above. We report them in Table 11 below. If one of the carbon tax levels is below the one we consider until now (c€1.40<c€1.72), this is because in that situation,

the Malus scheme leads to an increase of the CO_2 emissions (cf. the brown curve in bold in Figure 12 above, and for an amount of Malus of €6,000).

Table 11: Carbon taxes required to achieve the same reduction in CO_2 emissions than a combination of a carbon tax of 1.72c€ and a malus amount of either €100 or €6,000

	$\boldsymbol{P^d - P^c = -3,000€}$	$\boldsymbol{P^d - P^c = 0€}$	$\boldsymbol{P^d - P^c = 3,000€}$
$\boldsymbol{f^d - f^c = 0.6L/100km}$	$\tau^* = 1.80c€$	$\tau^* = 1.76c€$	$\tau^* = 1.73c€$
$\boldsymbol{f^d - f^c = 3.4L/100km}$	$\tau^* = 3.90c€$	$\tau^* = 2.18c€$	$\tau^* = 1.40c€$

All in all, the orders of magnitude of the carbon taxes reported in Table 11 are quite realistic. It means that a carbon tax is rather efficient. This result is particularly interesting when taking account of the fact that the carbon tax has a wider scope than the one we examine here. Indeed, the usage tax applies to the whole fleet in circulation, not only to the new car-purchasing population.

5. Conclusion

Economic theory offers an integrated framework (composed of two steps) for jointly modelling the decision of purchasing a vehicle and that of using it. Such a model is justified by the interdependency between the two decisions. Indeed, the car choice determines, at least partially, the car use, and the inverse is also true; and characteristics that make an agent use more or less intensively his vehicle may also affect the agent's car purchase decision. Thereby, the first step consists in determining the optimal consumption of kilometres, conditional on the vehicle type; and the choice of the vehicle that gives the highest utility corresponds to the second step.

We use this methodological framework to investigate the impacts of policy tools supporting low-carbon road mobility. In this Chapter, we leave aside from the analysis the command and control levers and the complementary policies such as labels that play on the demand-side, and we focus on the pricing schemes related to vehicle purchase (registration taxes, Bonus/Malus) and those related to car use (fuel taxes, or VKT taxation). These two categories of policy instruments do not play on the same lever to reduce CO_2 emissions. Public decision makers should therefore encourage ***both*** individual vehicle-use reduction (with the instauration of usage charges) and average fleet energy efficiency increase (through the implementation of a differentiated purchase tax for example). All the more so as kilometres driven and vehicle fuel efficiency are linked: the more efficient a vehicle is, the more it is used as cost per kilometre is reduced. This increase in kilometre consumption is known as *rebound effect.*

Generally speaking, the rebound effect is defined as increases in demand induced by efficiency gains. In this Chapter, we consider more deeply the scenario where the efficiency gains are observed at the aggregate level, that is to say, when the vehicles' energy performances are not changed on the supply-side, but the share of low fuel-consuming vehicles is higher so that the average fuel consumption per kilometre over the whole fleet is reduced. Interesting and not trivial is that a rebound effect does not necessarily accompany the reduction in the average fuel consumption per kilometre resulting from the implementation of a differentiated car purchase tax such as a Malus scheme. In fact, since the improvement of the fuel-efficiency is observed at the aggregate scale and not at the individual level, whether a *rebound effect* actually occurs when such a purchase tax is implemented depends on the characteristics of the vehicles that make up the fleet. Additionally, from the moment that a rebound effect occurs, we show that the higher the amount of Malus, the higher the rebound effect. It implies that because of the *rebound effect*, the higher the pricing scheme, the less efficient the purchase tax. Thereby, the Malus scheme should be designed carefully to achieve its primary goal. This is moreover without taking account two other feedback effects of a differentiated purchase tax, or more precisely of the increase in the share of energy-efficient vehicles: the reduction in fuel price – that accentuates the rebound effect – caused by the lower fuel demand on the one hand; and the reduction of the car lifespan due to a more intensive use on the other hand (Stepp and al., 2009).

Going further, we investigate what effects the implementation of a fuel tax has on the variation of CO_2 emissions caused by the Malus scheme. We differentiate two cases. In the first one, the fuel tax is implemented while consumers have already purchased their car (*i.e.* consumers do not take the tax into account in their car purchase decision). In the second case, the fuel tax is implemented before the car purchase and the consumers take it into account when they purchase their vehicle. Distinguishing these two cases helps highlight that the effects of the tax are not theoretically as predictable as it first appears. Indeed, at the individual level, the tax helps reduce the upward variation in the distance travelled with a less fuel-consuming vehicle (in both cases). But, at the aggregate scale, the rebound effect can also be magnified because of a higher gain in fuel efficiency over the whole fleet provided that motorists have taken the tax into account in their car purchase decision and thus purchase a cleaner car than the one they would have purchased in the absence of the tax (only in the second scenario). As it deals with the numerical version of the model carried out in this Chapter, the effects of a carbon tax do not however really vary with its time of implementation: the tax really helps cut the rebound effect. Another interesting result of the numerical illustration is that a carbon tax is rather efficient in that this pricing scheme is able to achieve by itself CO_2 reduction levels equal to the combined car usage tax and Malus scheme. This result is interesting when taking account of the fact that the carbon tax has a wider scope than the one examined in this work, insofar as it applies to the whole fleet in circulation, and not only to the car-purchasing population.

To some extent, the latter finding supports the implementation of a single carbon tax and calls into question the need for combining policy tools. In fact, albeit combining policy instruments runs counter to the economic theory whereby policy-makers should prefer one specific measure to achieve one particular goal (Tinbergen, 1952), there exist different reasons that justify policy mixes. They are – in addition to the existence of the rebound effect – the growing concern for equity and acceptability purposes (see Papaix, 2015) and the financing requirement of pricing schemes (subventions, as it happens). In this Chapter, we focus on the rebound effect, but it is worth recognising that the reasons to implement a package of policies are not mutually exclusive, and that solving a given problem does not necessarily mean than the others are solved at the same time. More importantly, addressing a given issue is sometimes shown to translate into the exacerbation of another. For example, implementing a Bonus simultaneously with the Malus enables to improve the acceptability but increases at the same time the rebound effect by accentuating the encouragement to purchase a less fuel-consuming vehicle, what typically increases the improvement of the average energy efficiency.

To conclude, it is worth recognising that we concentrate in this Chapter on consumers' behaviours, and thus on policy measures that lead people to purchase less consuming vehicles, or to travel less. These policies can be perceived as 'soft measures', while those playing directly on vehicles' energy performances improvements on the supply-side may be considered as 'hard interventions'. More generally, addressing the policy tools in a global model that covers both the demand- and supply-sides of the automotive system is particularly relevant. We thus now turn our attention to the equilibrium that is examined in the third and final Chapter of this Thesis.

Appendices

D – The design of the French Bonus/Malus scheme

Table D.1: Bonus amounts in 2013 in France

CO_2 Emissions (g/km)	Fuel consumption (L/100km)	Bonus amount in 2013 (€)
x < 20	x < 0.9	7,000
20 < x < 50	0.9 ≤ x < 2.1	5,000
50 < x < 60	2.1 ≤ x < 2.6	4,500
60 < x < 90	2.6 ≤ x < 3.8	550
90 < x <105	3.8 ≤ x < 4.5	200

Table D.2: Malus amounts in 2013 in France

CO_2 Emissions (g/km)	Fuel consumption (L/100km)	Malus amount in 2013 (€)
135 < x < 140	5.8 ≤ x < 6.0	100
140 < x < 145	6.0 ≤ x < 6.2	300
145 < x < 150	6.2 ≤ x < 6.4	400
150 < x < 155	6.4 ≤ x < 6.6	1,000
155 < x < 175	6.6 ≤ x < 7.5	1,500
175 < x < 180	7.5 ≤ x < 7.7	2,000
180 < x < 185	7.7 ≤ x < 7.9	2,600
185 < x < 190	7.9 ≤ x < 8.1	3,000
190 < x < 200	8.1 ≤ x < 8.5	5,000
> 200	≥ 8.5	6,000

Source: Author from the French General Tax Code

and using the CO_2 content of petrol (*i.e.* 2.346kgCO_2/L; EPA, 2011 and using 1 gallon=3.7878L)

E – Sensitivity analysis on the preference parameter

This Appendix aims at highlighting the extent to which the preference parameter plays on our results. With this aim in view, we plot in Figure E.1 the rebound effect (cf. left-hand chart) and the gap in CO_2 emissions between a regime without policy tools and a regime with a Malus Scheme (cf. right-hand chart) for two different values of the parameter: $\theta = 0.02$ and $\theta = 0.033$. These values are chosen because they give a distance covered with respectively the clean vehicle and with the dirty vehicle (when the latter car costs €21,918 and consumes 8.6L/100km) relatively close to the average distance covered with a petrol car in France in 2013, namely 7,751km (CCFA, 2014) (see Table E.1 below).

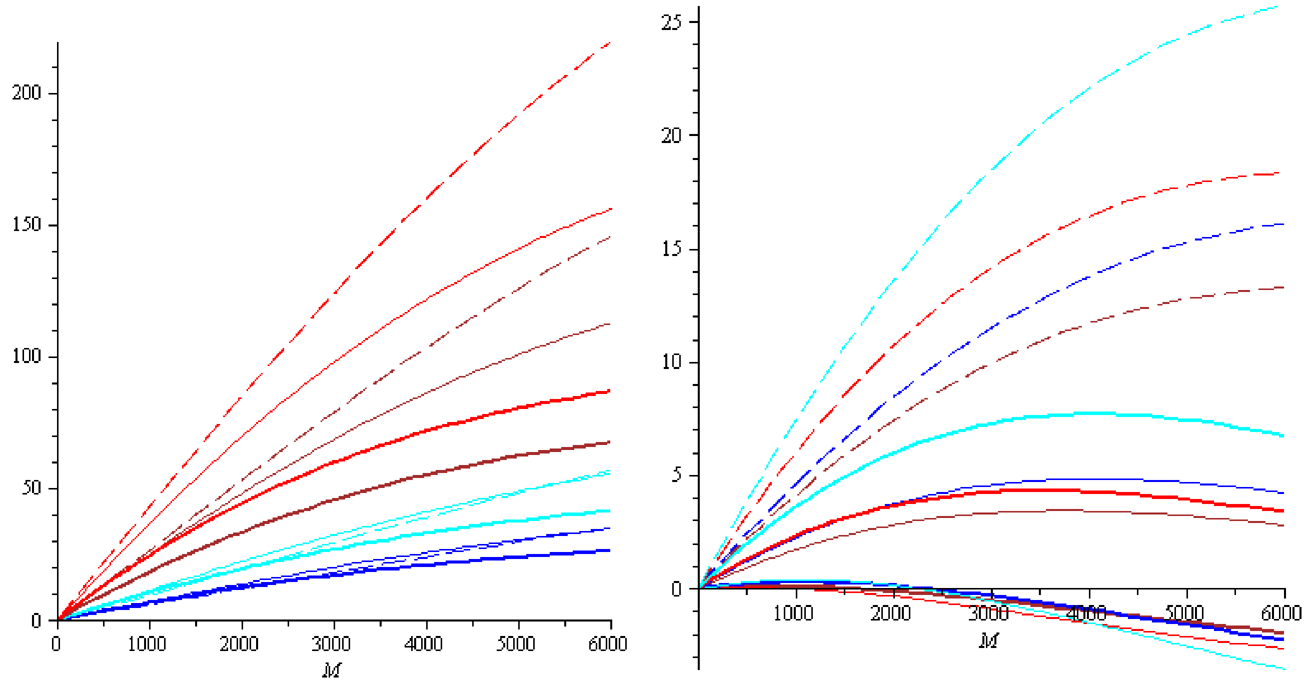
Table E.1: Distances covered by car depending on the preference parameter

	k^c	k^d
$\theta = 0.02$	7,964km	4,732km
$\theta = 0.033$	13,141km	7,808km

Figure E.1: Impact of the preference parameter

Rebound effect (in kgCO_2/household/year)

Emissions without policy tools minus Emissions with a Malus scheme (in kgCO_2/household/year)



Legend:

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$

Same as above, but $\theta = 0.033$ instead of $\theta = 0.02$

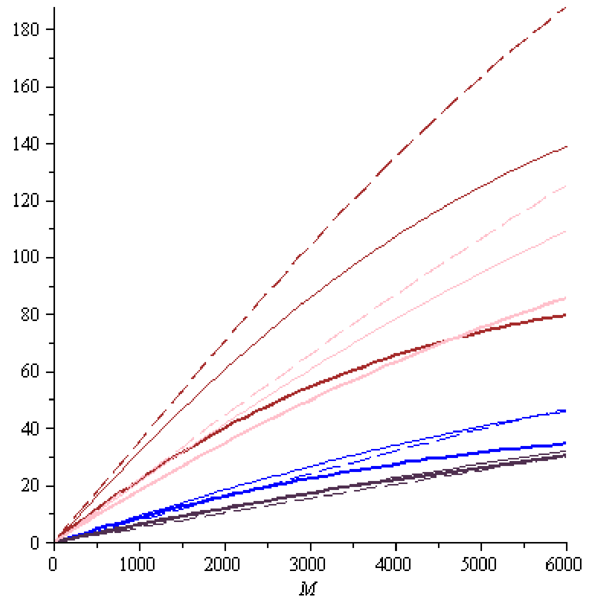
When it comes to analysing the effects of the carbon tax, remind that the latter tax leads to a slight reduction of the rebound effect whatever the amount of Malus. Graphically, all the curves moves downwards (cf. Figure 11). When the preference parameter is higher ($\theta = 0.033$), we observe the same shifting of the curves. Hence, we do not plot the effects of the tax on the rebound effect when the preference parameter is higher.

In the same vein, the impact of the tax on the gap in CO_2 emissions between the two regimes characterized or not by the presence of a Malus scheme is the same regardless the amount of Malus. Graphically, the intercept moves from zero to around 10.5kgCO_2 when the preference parameter amounts to 0.02 (see Figure 12). With a higher value ($\theta = 0.033$), the intercept becomes approximately 17.2kgCO_2.

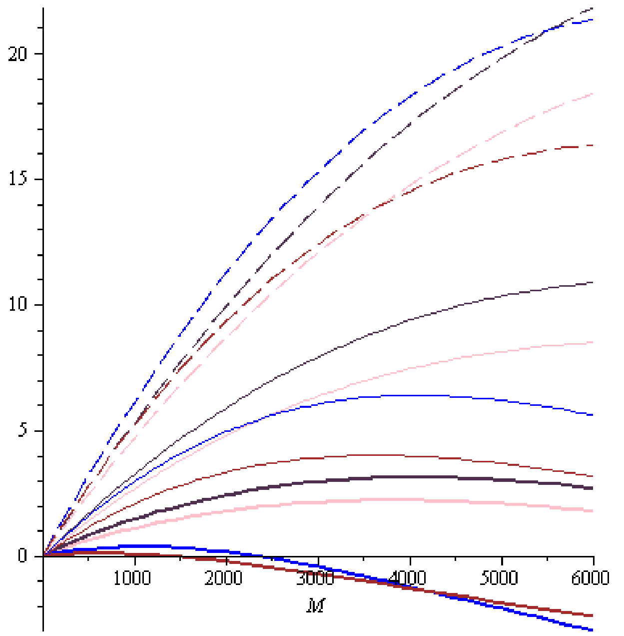
F – Sensitivity analysis on the distribution law

Figure F.1: Impact of the distribution law

Rebound effect (in kgCO_2/household/year)



Emissions without policy tools minus Emissions with a Malus scheme (in kgCO_2/household/year)



Legend:

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = -3000€$

Same as above, but with L(1) instead of N(0,1)

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 0€$

Same as above, but with L(1) instead of N(0,1)

$f^d - f^c = 0.6L/100km$, and $P^d - P^c = 3000€$

Same as above, but with L(1) instead of N(0,1)

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = -3000€$

Same as above, but with L(1) instead of N(0,1)

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 0€$

Same as above, but with L(1) instead of N(0,1)

$f^d - f^c = 3.4L/100km$, and $P^d - P^c = 3000€$

Same as above, but with L(1) instead of N(0,1)

In our simulation carried out in 4.2., we use a standard normal distribution. To highlight the sensitivity of our results to the distribution law, Figure F.1 above plots the rebound effect (cf. the left-hand chart) and the gap in CO_2 emissions due to the Malus scheme (cf. the right-hand chart) assuming either a standard normal distribution (*i.e.* N(0,1), in brown and blue) or a logit distribution with a scale parameter equal to 1 (*i.e.* L(1) in pink and violet).

The left-hand chart of Figure F.1 clearly shows that we overestimate the rebound effect when we consider a standard normal distribution. In a coherent manner, we underestimate the effect of the Malus scheme in terms of CO_2 emissions reduction, as shown in the right-hand chart in Figure F.1 above.

Dealing with the effects of the carbon tax on the rebound effect, we observe a slight move downwards of the curves – meaning that the rebound effect is reduced – with the logit distribution such as with the normal distribution (in Figure 11). This is why the graphical representation is omitted in this Appendix. For the same reason, we do not plot the gap in CO_2 emissions when fuel is taxed when considering a logit distribution since the effect of the tax is of the same magnitude regardless the distribution law.

Chapter 3. Which CO_2 regulation is best suited to achieve the wider policy-makers' objectives of enhancing well-being and economic growth?

Highlights

The interest of this third and last Chapter is two-fold. On the one hand, we simultaneously consider the supply- and demand-sides of the automotive sector. On the second hand, this Chapter embraces more deeply the public authorities' vision.

The first Part offers a general discussion of policy objectives. Specifically, we start by putting emphasis on the specificities of transportation activities that explain why public authorities can pursue several objectives at a time with a single policy or instrument in that sector on the one hand, and why they can combine several policy tools to serve a single objective on the other hand. Afterwards, with the intention of using our model to derive policy recommendations, we broach the subject of the public authorities' objectives in our definite framework.

In the second Part, we take the plunge and recur to our model in order to determine which policy instrument(s) enable(s) to maximise a global surplus in which the total of CO_2 emissions from car use is only a component among others, in accordance with the messages formulated in the preceding Part. In fact, we attach now importance to the total CO_2 emissions, to the households' utility and to the automotive sector's profit. Furthermore, the second Part combines two complementary approaches. The positive one simply consists in examining the effects of policy tools which designs are predefined. The normative approach gives recommendations on the CO_2 regulation that should be implemented.

1. Introduction

The automotive sector, in which we are particularly interested in this Thesis, is only a part of the transport sector. This sector gathers indeed all the activities directly participating to displacements and also other ancillary activities of transport such as storage, infrastructures management, logistics, and so on (CGDD, 2015). For information, since 2009, the production in volume of transportation activities progresses more quickly (+1.7%) than the whole economy (+1.3%) in France. "Transport" is however not only a business sector. Above all else, "transport" refers to the activity consisting in moving a physical good or a person from one point to another, with an objective that differs from a mere displacement (CGDD, 2015). The peculiarity of transport stemming from this definition is that transport underlies all activities. In a way, it is also perceived as a human right accordingly.

As transport brings into play economic but also social considerations, in addition to the environmental ones that are increasingly added to the landscape, it is the stage of public projects facing difficulties in their implementation (*e.g.* the Seine-North-Europe canal project as regards freight transport, or the Greater Paris project as concerns the passenger transport). We propose in this Chapter to consider more deeply the policy-maker's vision, keeping the transport sector as its playing field. In fact, it goes without saying that we implicitly assumed, in the first two Chapters, that the public authorities have a purely environmental objective. Indeed, to begin with, we assumed that the policy-makers' objective was to make the automobile sector produce the least possible fuel-consuming vehicles (Chapter 1). Afterwards, we went a step further, and we assumed that public decision-makers looked for the lowest total CO_2 emissions resulting from car use (Chapter 2). In the first Part of this last Chapter (cf. 2.), we will shed light on the distinctive features of transportation activities that explain why public authorities can pursue several objectives at a time with a single policy or instrument on the one hand, and why they can combine several policy tools to achieve a given goal on the other hand.

In the second Part (cf. 3.), we will take the plunge and recur to our model in order to determine which policy instrument(s) enable to maximise a global surplus, in which the total of CO_2 emissions from car use is a component among others. In theory, *a priori* public economic calculation should indeed take variations in producer and consumer surplus into account. Precisely, we will consider the households' welfare (labelled *utility*) and that of the automotive sector (labelled *profit*), in addition to the variation of CO_2 emissions, resulting from the implementation of different policy tools. Specifically, we will propose two complementary approaches. The positive one consists in examining the effects of three different policy tools.

The levels of the policy tools are considered exogenous in this first approach. Conversely, the normative approach gives recommendations on the CO_2 regulation that should be implemented; and the policy tools' levels are endogenously defined. It is pointless to say that these exercises differ from the one carried out in the second Chapter dealing exclusively with the effects of policy tools on the demand-side. In all evidence, here, we study wider impacts than the ones examined in the previous Chapter; but this is not the sole contribution. Indeed, by gathering frameworks doing with the supply- and demand-sides of the car sector, we propose to go beyond the partition between on the one hand the analysis of improvements of technologies (supply-side), and on the other hand that of motorists' behaviours (demand-side). Furthermore, considering simultaneously the supply- and demand-sides is a necessary condition to discuss about the tax incidence[81], that is to say the distribution of the burden of a tax.

2. The public authorities' vision

The present Part embraces the public decision-maker's point of view. More exactly, emphasis is placed on the distinctive features of transportation activities that play on what could be the objectives of the public authorities, and on the policy instruments at their disposal to achieve the objectives at stake (2.1.). Afterwards, anticipating that we will recur in the second Part to our model to examine the effects of policy instruments, we call into question the public authorities' objectives with regard to the restrictions and hypotheses made in our particular framework (2.2.).

2.1. The public authorities' objectives and instruments: the repercussion of the distinctive features of transportation activities

This subpart focuses on three characteristics of transportation activities that have to be taken into consideration by public authorities when they define their objectives, and the instruments to put in place to achieve these objectives. Firstly, transport is a derived demand and generates positive externalities so that it provides wider cross-benefits across other sectors (2.1.1.) Secondly, transport brings into play several negative and highly interrelated externalities so that tackling a single externality is not possible (2.1.2). Thirdly, and with a focus on the objective

[81] The idea behind the tax incidence is that the tax burden does not depend, as might be thought, on where the revenue is collected, but rather on the demand and supply price elasticities.

of fighting against climate change, different levers can be activated to cut transport GHG emissions (2.1.3.).

2.1.1. Transportation provides wider cross-benefits across other sectors

Transport is often a '*derived demand'* (Crozet and Lopez-Ruiz, 2013); this means that it is generally not requested for its own sake but is largely associated with the consumption of other goods. At first blush, this definition makes transport be relegated to a position of secondary importance. But, "*it would be more accurate to say that the trip is subsidiary in the sense that it provides something in addition to the activity, simply by making it possible"* as argued by Crozet and Lopez-Ruiz (2013) (p299). Activities at destination include working, studying, shopping, seeking medical advice, and many other social activities. Thereby, it is readily acknowledged that transport is a positive component of economic growth, and that "*the human and economic development of a world whose population is rapidly rising cannot take place without increasing the mobility of people and goods"* (in Meurisse and Papaix, 2013). More specifically, the contribution of transport to the economic growth is traditionally measured in terms of 'time savings'. Those gains actively contribute to the market expansion, to the growing trade, to the increasing labour productivity and so on. Overall, the links between transport infrastructures and economic growth have already long ago been underlined; *i.e.* since the theories of Adam Smith[82] (CGSP, 2013).

As a matter of fact, road transport also generates positive externalities. The most often cited are the redesignation of buildings, the Mohring effect[83], and the economies of agglomeration[84]. Additionally, investing in public transport provides specific assets for endogenous growth, which are especially useful in a situation of heightened territorial rivalry. At the local level, transport policies are indeed not alone in looking for these external benefits: housing, shops, offices, universities, etc.; all want to cohabit in city centres.

In a different vein, transport is also a key element for addressing other challenges including the access to education, to employment and to social activities. From this angle, access to transport is perceived as a mean to avoid social exclusion. More generally, according to the European

[82] Smith, A. (1776), The Wealth of Nations.
[83] Mohring (1972) showed that there exist economies of scale in the production of transit services. In fact, a rise in demand for urban public transport enables to increase frequencies and thus to reduce waiting times.
[84] Economies of agglomeration consist of gains in competitiveness and effects on innovation and employment derived from the spatial concentration of economic activities which come from the development of transport networks enabling businesses to be located near to each other. Venables (2007) argues "*The same forces that cause cities to exist – agglomeration benefits – provide additional effects that should be included in urban transport appraisal*" (p16).

Commission "*urban transport systems should seek to meet the requirements of sustainability, balancing the need for economic viability, social equity, health and environmental quality*" (European Commission, 2013b).

From the above reviews, there is no doubt that a transport policy has wider positive effects on other sectors; meaning that it can serve several objectives at a time. More importantly, the interdependence of public transport policies and those in other sectors creates a major challenge for public policy-makers. The latter have indeed to coordinate their transport policies with urban development policies, housing policies and economic development policies, insofar as they constitute government decisions that can affect transport supply and demand. This is distinctly put forward in Garcia-Sierra and Van den Bergh (2014) in that the authors insist on the different factors underlying commuting patterns, including built environment (*e.g.* urban density), transportation factors (*e.g.* parking opportunities), market factors (*e.g.* labour and housing markets), socioeconomic factors, and behavioural factors. In sum, a reduction in CO_2 emissions from transportation activities can be obtained with a package of policies covering different sectors. Said in a little more daring manner, "*a drastic reduction in CO_2 emissions is achievable only if the production system, the distribution system and the mode of inhabiting the territory are changing in a coordinated manner"* (excerpt from the address by a member of the Transport Economics Laboratory, during the CEC's conference in Paris on the 6th of December 2012, in CEC and Michelin, 2013). Similarly, the report "*Better Growth, Better Climate*" coordinated by Nicholas Stern, positions the choices of urbanisation at the first place among the actionable levers towards a low-carbon economy over the next fifteen years (in de Perthuis and Trotignon, 2015). This is line with the need – emphasized in the literature (*e.g.* Bertolini and al., 2005) – for jointly defining environmental policies, transportation policies and urban planning measures.

Next to the external benefits of transportation activities are also the negative externalities of transport. They are more often cited than the positive ones, and it seems easier to appraise them, albeit being interrelated. In the next subpart, emphasis is placed on the interactions among those negative externalities.

2.1.2. Road transport generates multiple negative externalities

As pointed out repeatedly, road transport brings into play a series of negative externalities, as global pollution (CO_2 emissions), local air pollution (chiefly particles), congestion[85], problems of road safety[86], noise, and so on.

Since all the externalities are interrelated (*i.e*. self-augmenting or self-reducing effects), it seems impossible to only target one of them. This statement runs counter to the standard economic theory – known as the "Rule of Tinbergen" (Tinbergen, 1952) – whereby for each imperfection of the market, there should be a single regulatory instrument. More exactly, it provides a good illustration of the first case – among two – wherein the rule is compromised; that is to say the situation in which one instrument can serve several objectives of public policies. This is the example of a carbon tax that aims at fighting against climate change. The reduction of the total fuel consumption (and thus of CO_2 emissions) goes through a reduction in miles driven caused by the increase of the cost per kilometre. Yet, decreasing the kilometres covered by car also reduces all the other attendant externalities, and thus the congestion, the risk of accidents, and so on. In sum, taking into account the system of interactions among the negative externalities generated by road transport is essential, since it reinforces the social benefits of actions which prime objective consists in cutting CO_2 emissions. This is of a particular interest, especially in the case of an underestimated 'climate friendly' transport project, insofar as considering these actions in isolation may not be of interest to the policy-maker. Indeed, CO_2 emissions often seem to be the least concern of the policy-makers when estimating the costs and benefits of an urban transport project. By way of illustration, climate gains are evaluated at over 30 times less than congestion improvements following a decrease in passenger-km on the road (in 2011, they represented, for example, at 0.54 euro cents per passenger-km reduced in high density areas, while the corresponding congestion value was 16.6 euro cents per passenger-km reduced; CGDD, 2013a, p19).

In the second situation where the Rule of Tinbergen is compromised, several instruments can serve the same objective. This is illustrated in the next paragraph.

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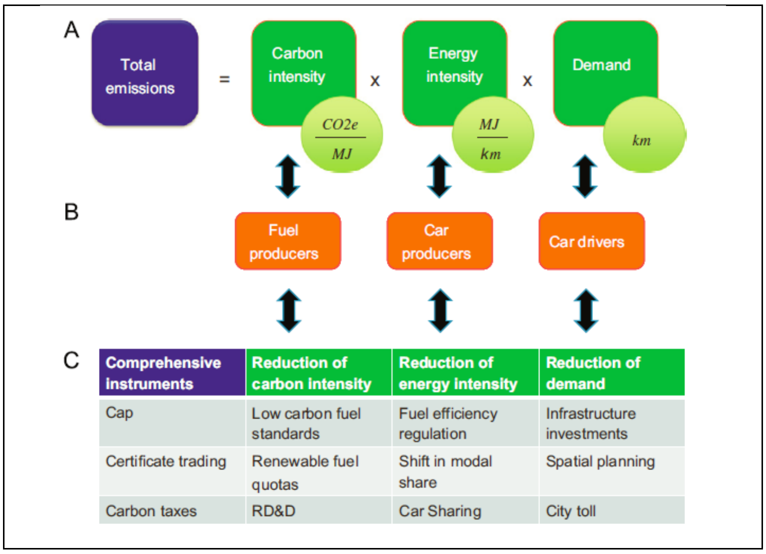
[85] Congestion is defined as "*the difference between the average network travel rate and the uncongested (free-flow) network travel rate in minutes per vehicle-kilometre*" (TfL, 2003, p46).

[86] Accident externalities arise "*whenever extra vehicles on the road increase the probability that other road-users will be involved in an accident*" (Newbery, 1990, p24).

2.1.3. Transport GHG emissions can be tackled through several levers

With reference to Schipper's ASIF scheme, GHG emissions of transport can be tackled through the four following levers: the transport **A**ctivity, the modal **S**hare, the energy **I**ntensity, and the carbon intensity of **F**uel (Schipper and al., 2000). Policy instruments having an impact on these levers are different, as illustrated by Creutzig and al. (2011) with the following Figure:

Figure 13: Decomposition of GHG emission in transportation (A), relevant actors (B), and corresponding policy instruments (C)



Source: Creutzig and al., 2011

In the same vein, strategies to reduce CO_2 emissions from transport can also be addressed through the "Avoid, Shift, Improve" (ASI) approach (GIZ, 2007) that distinguishes policies that encourage people and firms to **A**void or reduce the need to travel, **S**hift to more carbon-efficient transport modes, and **I**mprove vehicle and fuel technologies. For example, this typology is used by Michelin (see the third column in Figure 14 below), who – as an industrial actor – supports an approach first based on the technology type that has to be promoted (see the first column).

Figure 14: Decisional chart combining best choices and strategies technologies => public policies => strategies => economic instruments

Technologies	Policy objectives	Strategies	Instruments and other supporting funding solutions
Thermal vehicles	• Cleaner • Less congestion	Rationalize	• Taxes on usage of a vehicle: fuel taxes, congestion pricing, parking pricing
Electric vehicles: (in particular: Ultralight Urban Vehicles and Individual Public Transportation)	• Cleaner • Less noise	Improve	• Charging infrastructures subsidies • Binding targets related to EV charge plug (on-street / in buildings) • Regulatory measures to standardize EV charge plugs • Bonus for purchasing an EV/ VAT reductions • Urban toll (preferential tariff) • Free parking • Access allowed to High Occupancy Vehicles (HOV) lanes • Low Emission Zones (LEZ)/Zero Emission Zones (ZEZ) • Reserved parking places
Hybrid vehicles	• Cleaner	Improve	• Bonus for purchasing a hybrid vehicle • Urban toll (preferen-tial tariff) • Access allowed to HOV lanes • LEZ/NEZ
Shared mobility: car sharing, bike sharing	• Cleaner • Travel optimization / Less congestion	Improve	• Public-Private Partnership (PPP)
Public Transport Systems (BRT and metro…)	• Cleaner • Travel optimization / Less congestion • Intermodality	Shift	• Finance infrastructures: land value capture • Promote public transport use: public transport fare setting
Autonomous vehicle	• Travel optimization / Less congestion • Travel time saving	Improve	• Restriction on vehicle circulation: Reserved lanes • Legal framework (liability in case of accidents) • Purchase subsidies

Note: "Rationalize" is used in place of "Avoid" here.

Source: Michelin (2014)

At present, the need for action to cut CO_2 emissions is become so much clear that one is tempted to combine policy tools so that no potential reductions in CO_2 emissions is neglected. Playing on each lever of the ASI(F) approach appears thus as a solution. More generally speaking, this is true that *sufficiency* and *efficiency* measures can act as complements to help achieve a sustainable economy (Cooper, 2005)[87].

Furthermore, it is also possible to combine different policy tools that play on a single lever. This is argued for the "energy intensity" lever in Mandell (2009). Precisely, the author proposes an analytical model providing a structured overview wherein "*future car fleet efficiency depends on several steps that are linked to each other in a distinct order*": the dependent variable of one step is also the independent variable of the next step (see Figure 15 below). The steps at stake consist of:

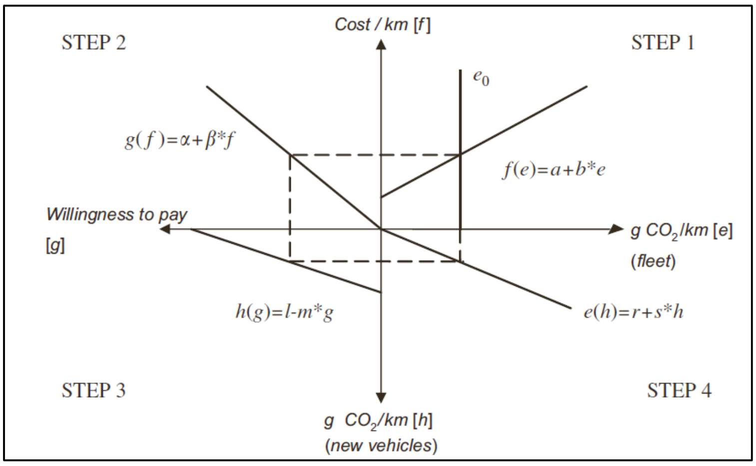
- Step 1: the transportation cost per kilometre is an increasing function of the level of CO_2 emissions per kilometre (through the fuel consumption per kilometre);

- Step 2: the Willingness To Pay (WTP) for a less fuel-consuming car is a positive function of the cost per kilometre;

[87] In a broad sense, *efficiency* measures consist in increasing the output produced from a given amount of inputs or in diminishing the amount of inputs required to obtain a predefined level of output. This way, they help reduce the energy consumption and emissions in relative terms. In contrast, *sufficiency* measures lead to a decrease of energy use and emission in absolute terms by reducing the throughput of goods or services.

- Step 3: the level of CO_2 emissions of new cars (that measures the car makers' response) decreases with the WTP for a cleaner car;
- Step 4: the average level of CO_2 emissions over the whole fleet (*i.e.* existing plus new vehicles) is a positive function of new cars' CO_2 emissions.

Figure 15: The four steps of Mandell (2009) towards a less consuming fleet



Mandell (2009)

According to Mandell (2009), examples of instruments impacting on these four steps are: a fuel tax (step 1), a differentiated annual circulation tax (step 2), a Bonus/Malus scheme (step 3), and a scrapping premium (step 4). More importantly, the author concludes that "*the impacts of policy instruments targeting early steps are influenced by latter steps but not the other way around*" (p5191). More generally, impacts of the various instruments cannot be separated. In other words, the effects of different policy measures are not cumulative and all these policies thus have to be addressed simultaneously because the more or less direct effects of one policy can cancel out those of another but one policy can also amplify the effectiveness of another. This assertion is clearly at the core of the substantial literature on the complementarity of policy tools (see for instance Van der Vooren and Brouillat, 2015).

For synthesis, we have elaborated since the beginning of this Chapter on the following points – that are characteristic of the transport sector – (from the most to the least accurate):

- Public decision-makers have at their disposal several policy tools to reduce CO_2 emissions from transport, because different factors influence those emissions.

Combining policy instruments is therefore possible, but examining the additivity of the effects of the different policy tools is all the same needed.

- A reduction of CO_2 emissions may come hand in hand with a decrease of the other attendant externalities of road transport, especially when the reduction of CO_2 emissions goes through a decrease of the distances covered by car.
- A transport policy has effects on other sectors, in that trips have this in particular to make activities possible. It implies that there also exist more global objectives to be pursued such as enhancing growth or improving welfare.

The choice of one or several policy instruments to implement has thus to be based on a comparison of a set of impacts, and not merely of the effects in terms of CO_2 emissions.

Since we focus on CO_2 emissions, and as the links between CO_2 and the other negative externalities of road transport are not considered in the present research work, we cannot examine the effects of a policy tool on the other externalities. As it concerns the effects in terms of growth and well-being that can be addressed in our model, they are called into question in the next subpart.

2.2. The public authorities' objectives when taking the specific features of our framework into account

Most often in general equilibrium models, whether a public intervention enhances – or not – the economic growth is determined by the variation of the global consumption attributed to the intervention at focus. In parallel, when it comes to analysing the well-being, it is generally approached with a damage function. We explain hereinafter why, in this particular framework, we do not deviate from the aggregated profit of the automotive sector for judging the economic growth (2.2.1.), and from the average households' utility on the one hand and the total of CO_2 emissions per household on the other hand for appraising the well-being (2.2.2.).

2.2.1. The aggregated profit of the automotive sector to approximate the economic growth in the present work

In this part, efforts are made to explain our focus on the aggregated profit of the automotive sector to judge the economic growth. To begin with, and as already said just above, the standard approach used in general equilibrium models consists in considering that the variation of the households' consumption is a good measure of the economic growth of a country. This is because firms are supposed to be owned by households so that the production and the consumption are blended. In our analytical model, it does not seem relevant to admit this simplifying assumption insofar as we focus on a single industrial sector. In a more explicit manner, the household's income is not closely linked to the profit of the automobile sector; and this is why we prefer to keep the profit, rather than the consumption, as an indicator of economic growth. The implicit assumption is that profit is reinvested.

More exactly, we prefer to simply use the sum of individual profits without discriminating among manufacturers. This sum (we will also speak about "aggregated profit") is termed Π, and is given by:

$$\Pi = \pi^v + \pi^e + \pi^{ty} \tag{23}$$

with π^v the profit of the car maker, π^e that of the engine manufacturer, and π^{ty} that of the tyre producer.

Regarding the objective function of the public decision-makers, this is true that it may differ from the aggregated profit given above from the moment that the public authorities are influenced by lobbying engaged by different producers. As lobbying is the act of attempting to influence to its advantage decisions made by public decision-makers, the latter actors may indeed assign different weights to the profits of the different producers in their decision-making process. Interestingly, two trends dealing with lobbying practices are widely acknowledged. First, "*the smaller the group, the better it will further its common interests*" (Olson, 1971). Second, interest groups engage in more actions – and are more successful – when they seek to avoid loses than when they seek to obtain benefits (Baldwin, 1993). In our particular context, determining what kind of actors is likely to lose more profit because of a given policy instrument is not as easy as it first appears. One of the complexities arises from the scale of implementation of policy tools. The case of the European CO_2 emissions standards – described in Box 4 below – is a good illustration.

Box 4: The role of lobbying in the CO_2 emissions standards

The members of the car industry organise themselves in a more or less centralised way to lobby, and influence regulatory decisions concerning the environment. For illustrative purposes, it should be noted that the European CO_2 emission standards for passenger vehicles were more ambitious (from 1994, the intention was to get down to 120gCO_2/km by 2005) than those which were finally voted and which are in effect today (130gCO_2/km by 2015 and 95gCO_2/km by 2020, Transport & Environment, 2012). As an explication, Greenpeace denounced in a report published in 2008 *"frantic lobbying led by the European motor industry*" (Greenpeace, 2008). However, one should recognise that it is difficult to talk of a European motor industry insofar as the national industries are so different in terms of the environmental performance of their cars: "*French cars pollute considerably less than their German counterparts. Thus, for example, the models launched onto the market by Peugeot in 2006 gave off on average 142gCO_2/km against 166gCO_2/km for Volkswagen and 184gCO_2/km for BMW. This is also true of the way the industry players organise themselves to weigh on the negotiations. German industry seems better able to defend its interests than French industry. Lobbying in Europe is in fact led by German manufacturers who have been manipulating the European Union for years*" (Greenpeace. 2008).

Source: Meurisse and Papaix (2013)

As a matter of fact, depending on the policy instrument at stake – and inherently depending on the scale of implementation of the tool and thus the number of targeted actors – a group of producers or another one may engage in lobbying; it means that the weights attached to the different producers in the public authorities' objective function may vary with the policy tool. Hence, we prefer to leave the lobbying practices aside from the present analysis; all the more so because taking it into account would have required to introduce the cost of the lobbying practices in the producers' objective function.

In any event, one has to bear in mind that the chief implicit consequence of using the automotive sector's profit to gauge the economic growth is that our evaluation of a policy tool will be limited to its impacts on the targeted sector without taking into account its potential wider effects on other sectors (brought out in the first subpart). This is primarily the partial nature of our equilibrium model that prevents us from taking account of those indirect effects. In other words, it must be noted that we will content ourselves, in the second Part, with calling into question the relevance of the pursuit of a cleaner car mobility from the auto sector's perspective, without considering the other sectors.

2.2.2. The average households' utility and the average total of CO_2 emissions to approximate the well-being in the present work

First and foremost, recall that on the demand-side of our model, households are supposed to directly derive utility from kilometres travelled by car on the one hand, and from the consumption of a composite good on the other hand. This way, it goes without saying that households do not take into account into their utility function the negative externalities generated by the kilometres they travel by car. This assumption is relevant from the moment that the only externality we are interested in is the CO_2 emissions, that is to say a global pollution. Indeed, the fight against climate change is a public good, as already said, which characteristics (*i.e.* non-rivalry and non-excludability) spur everybody to behave as a free-rider. In extreme cases, it means that households do not pay attention to the CO_2 emissions their behaviour causes.

That households dot not take into account the CO_2 emissions caused by their use of vehicles does however not mean that policy stakeholders do not take them into consideration. Quite the reverse, the public authorities have to arbitrate between a loss of utility for households on the one hand, and a reduction of the damages caused by CO_2 emissions on the other hand when they implement policy tools that result in a reduction of the distance covered by car. In what follows, we clarify which utility should be considered by the public authorities, and we explain why we content ourselves with considering the CO_2 emissions as such rather than the damages caused by the emissions at focus.

- **Taking into account the weighted direct utility of car purchasers**

Since the households' behaviour is utility-maximising, the optimal situation from the households' point of view consists of the situation in which the utility is the highest. Here, the households' utility depends on the type of vehicle they own. As the utility differs among individuals, it is tempting to look for the highest weighted average utility (termed U); the weights being the shares of dirty $(1-\varphi^c)$ and clean vehicles (φ^c) in the whole fleet. We have:

$$U = (1-\varphi^c)U^d + \varphi^c U^c \tag{24}$$

with U^d and U^c the utilities of respectively a dirty vehicle's owner and a clean vehicle's owner.

What is more, from the moment that individuals do not initially enjoy the same utility, the objective of public decision-makers in terms of variation of utility, when they implement policy tools, may vary according to their *idea of justice.* We start by concisely summarising the different theories of justice (cf. i)) before reminding the key elements of our theoretical framework in terms of households' behaviour presented in Chapter 2 (cf. ii)). This enables us to explain why we prefer to assume in this particular framework that the public authorities look for the highest weighted average utility; the weights being simply the shares of clean and dirty vehicles in the whole fleet of new cars.

i) The different theories of justice

Different theories of justice have emerged since the 1950's and their own definitions are still somewhat confused in certain cases. In any case, we propose to expose in general the main theories of justice below, without insisting on the debates currently encountered in the literature since it would have not brought things any further, as outlined in the next paragraph (see ii)).

The *Prioritarianism approach*, developed by Parfit (1991), is satisfied with an improvement of the situation of the ones who are worse-off, regardless of whether the situation of the ones who are well-off is getting better or not. In all evidence, it differs from the older *Egalitarianism approach*, which finds its origin in the theory of social choice (Arrow, 1951), since the oldest approach claims differences in people's welfare should be annihilated. With this objective in mind, policy tools have to readjust the initial gaps in allocations among individuals; and any unequal treatment among individuals within a policy should be in favour of poor people. In this sense, unequal distribution takes the shape of 'positive discrimination'. Alternatively, the *Utilitarianism approach*, from the Marginalist school, gives the priority to another type of individuals, namely the ones who contribute the most to the welfare maximisation. Indeed, within this approach, the best policy is the one that provides the highest total welfare. Yet, following Bentham, and according to the aggregation theorem of Harsanyi (1982), the total welfare is given by the sum of individual utilities. As concerns the *Capability approach* developed by Sen (1979), it goes beyond the *Utilitarianism approach* by taking into account what individuals are able to do (or what they are *capable* of doing), meaning that it considers the process that lead to the situation that is at focus in the *Utilitarianism approach.* Lastly, the *Sufficientarianism approach* distinguishes itself from the previous approaches by assuming that there is a sufficient level (of the goods to redistribute) to be reached; the latter being defined geared to the needs of people. Sen is among its instigators with its concept of 'basic capability' (Sen, 1982).

In sum, whether the treatment of household heterogeneity is more or less fair depends to some extent on the type of heterogeneity. We recall the way households differ in our model in the next paragraph.

ii) Our assumptions dealing with households' behaviour (presented in Chapter 2) and implications

In the present work, households are assumed to earn the same income, and to have the same preferences for mobility by car. They distinguish themselves only by their taste for vehicle' characteristics. This variable enters the *indirect* utility; the one that is maximised by households when they make their car purchase decision. Even more important is that this variable is considered as a random term within the indirect utility (see $\eta_{i,d} - \eta_{i,c}$ in Chapter 2). It implicitly means that what makes consumers purchase a vehicle or the other, when they cost the same thing to purchase and to use, is not explained in our model. That being so, we are not able to determine whether purchasing a given vehicle is constrained or not. For instance, car purchasers could prefer to purchase a large vehicle because they have a large family (in that case, the car purchase decision is somewhat constrained), or simply because of the ostentatious character of a large vehicle (this time, the choice is not constrained). Consequently, we cannot assume that the policy-makers use the *Capability approach.*

More importantly, to deal with the other *ideas of justice*, one has to identify who are the worse-off and the well-off among the two groups of car purchasers. In this regard, one could consider that the dirty vehicle's owners are the worst-off insofar as they bear the highest cost per kilometre. Behind this statement is actually the idea whereby the ones who own a dirty vehicle are those who face the highest risk in terms of unexpected additional costs that could result from an increase either in distances travelled (if motorists are led to use their car more intensively than they previously thought) or in fuel price. Because of such a change, purchasing the dirty vehicle may simply not have been the optimal choice. But, without going so far, one can also argue that, since all households choose the vehicle type that maximises their (indirect) utility, no car purchaser is clearly better off than the others. This is why it seems not appropriate in this work[88] to assume that the public decision-makers perceive some individuals as worse-off. Sais another way, we prefer not to assume that public authorities attach to a given group of car purchasers a weight that differs from the share of those car purchasers in the whole vehicle-purchasing population. Note that we also suppose that policy-makers take all the car-purchasing population into account when they implement a policy tool that benefits to only a part of that population (such as a Bonus scheme).

[88] Identifying who are the well-off and the worse-off would have made sense if we had assumed for instance that what makes individuals purchase a vehicle or the other is the level of income.

- **Taking into account the CO_2 emissions as such rather than the damages of CO_2 emissions**

The damages of global pollution are clearly of a distinct nature of those of local pollution (primarily mortality and morbidity[89]), and include crop failures, water resources stress, flooding, biodiversity losses and so on. Since those physical impacts are not estimated using a unique unit of measurement, one is naturally tempted to attribute a monetary value to each impact, particularly with the objective to compare the reduction of the damages of CO_2 emissions enabled by different projects. This method is one among two that are usually used to estimate the cost of environmental damages. It is referred to in the literature as the *damage cost approach:* the physical impacts are first estimated, and then an economic evaluation of these impacts is carried out. The other method is the *avoidance cost approach*. It consists in determining the lowest cost option which enables to avoid a predefined environmental damage (Tscharaktshiew, 2014). Both methods are useful to make a cost/benefit analysis, which remains "*the best way of measuring the effectiveness of public policies by allowing the figures to be compared and an evaluation made of how a policy uses economic and environmental resources"* (in Bureau, 2003). In any event, both methods deserve a specific analysis that is not carried out here, since it would have taken us away from the object of this research work. That said, we assume that public authorities concentrate their efforts on minimising the total of CO_2 emissions from car use, and not the environmental damages. Recall that average CO_2 emissions are simply given by:

$$E = e[\varphi^c k^c f^c + (1 - \varphi^c) k^d f^d] \tag{25}$$

with e the CO_2 content of petrol (in $kgCO_2/L$), φ^c the share of clean vehicles, k^c and k^d the distances covered respectively with a clean vehicle and a dirty one, and f^c and f^d the unit fuel consumptions of respectively the clean car and the dirty one. This total of emissions is exactly the average amount of kilograms of CO_2 emissions due to car use per household and per year.

Now that the public objectives are defined, we turn our attention to the way different policy instruments can serve these objectives, while using our model.

[89] See for instance CGDD (2013b) for a discussion of the monetary valuation of morbidity and mortality due to local air pollution.

3. Policy implications when using our model

From the above part, there is clear evidence that the global surplus we can consider here is an increasing function of the aggregated profit of the automotive sector (Π), an increasing function of the average utility (U), and a decreasing function of the average total of CO_2 emissions (E). This Part studies different policy tools with respect to their impacts on these three global surplus' components. First, we describe the situation before any public intervention (3.1.). Then, we examine the effects of three different policy tools in a purely positive approach (3.2.). At last, we propose to adopt a normative approach. Notably, recommendations are provided about the policy package that should be implemented (3.3.).

Prior to these exercises, we want to make clear that our approach is based on a partial model: we focus indeed on the automobile sector, without taking the interactions with the rest of the economy into account. In addition, we focus on the car-purchasing population, and that specific population accounts for a small part of the total population[90]. This way, we typically differ from general equilibrium models, and we are thus not constrained to make the assumptions generally encountered in such models. For example, it is stated in general equilibrium models that a specific subsidy is funded by an increase of taxes on households. Among other implications, it means that granting a Bonus on the purchase of clean vehicles is supposed to result in higher taxes on households. In our framework, that the Bonus is granted on a small number of vehicles (less than the sample considered here), while the rise in taxes concerns the whole population, makes the increase of taxes per household be insignificant. We can thus make the assumption whereby implementing a Bonus does not entail additional taxes on households.

3.1.The free functioning of the market

In the two succeeding sections, we succinctly recall what constitutes the market equilibriums (3.1.1.), and we comment the numerical version of the model (3.1.2.).

3.1.1. Theoretical formulation

Our partial equilibrium is given by the balance between demand and supply for engines, tyres and vehicles. The supply of energy-efficient engines (e_1), tyres (ty_1) and vehicles (vehicles c), expressed in percentage of the total production, is respectively termed α^e, α^{ty} and

[90] As an order of magnitude, note that the number of gasoline vehicle registrations in France in 2013 was 532,109 (CCFA, 2013).

α^v. On the other side, the demand of clean equipment equal the number of vehicles equipped with the energy-efficient equipment at focus, namely 0, α^v or 1, depending on whether the car maker 1. puts only efficient tyres on his clean vehicles ($q = 1$), 2. puts only efficient engines ($q = 2$), or 3. assembles together efficient tyres and engines ($q = 3$). Finally, the demand for clean vehicles is termed φ^c. In this regard, it is worth mentioning that what makes the difference here with the way we computed the equilibrium market prices in Chapter 1 lies in the present consideration of the car demand function $\varphi^c(P^c)$ while we considered exogenous levels of demand for clean vehicles φ^c before. We recall below the systems of equations characterising the three market equilibriums:

* If $q = 1$, the market equilibriums are given with the following system of equations:

$$\begin{cases} 0 = \alpha^e(P^{e_1}) \\ \alpha_1^v(P^c, P^{ty_1}) = \alpha^{ty}(P^{ty_1}) \\ \varphi^c(P^c) = \alpha_1^v(P^c, P^{ty_1}) \end{cases} \tag{S2.1}$$

*If $q = 2$, the market equilibriums are given with the following system of equations:

$$\begin{cases} \alpha_2^v\left(P^c,\ P^{e_1}\right) = \alpha^e(P^{e_1}) \\ 0 = \alpha^{ty}(P^{ty_1}) \\ \varphi^c(P^c) = \alpha_2^v(P^c, P^{e_1}) \end{cases} \tag{S2.2}$$

*If $q = 3$, the market equilibriums are given with the following system of equations

$$\begin{cases} \alpha_3^v(P^c, P^{e_1}, P^{ty_1}) = \alpha^e(P^{e_1}) \\ \alpha_3^v(P^c, P^{e_1}, P^{ty_1}) = \alpha^{ty}(P^{ty_1}) \\ \varphi^c(P^c) = \alpha_3^v(P^c, P^{e_1}, P^{ty_1}) \end{cases} \tag{S2.3}$$

That the demand function $\varphi^c(P^c)$ is based on a distribution law (*i.e.* the distribution of households along the different values of preferences for the dirty vehicle's characteristics) explains why, without specifying that distribution law, we are not able to write the analytical expressions of the market prices here. We will compute them within the numerical illustration carried out hereinafter.

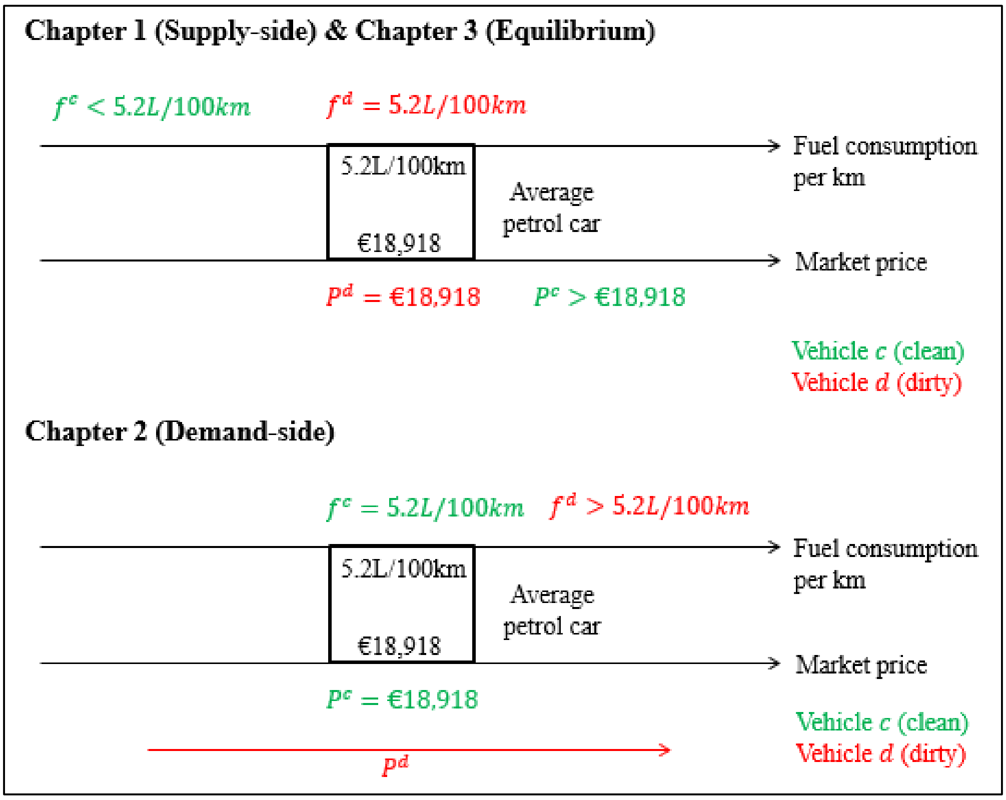
3.1.2. Numerical illustration

We start by briefly summarising the data used in the two previous numerical applications, before tackling the market equilibriums.

- **Reminder of the data used**

First and foremost, we have to insist on the fact that we have considered two different approaches in the first two Chapters in terms of vehicles' characteristics. This is illustrated in Figure 16 below. In this final Chapter, since we are interested in the move towards a cleaner road transport system, we prefer to continue with the first approach in which the characteristics of the dirty vehicle are fixed, and those of the clean vehicle vary.

Figure 16: Characteristics of the clean and dirty vehicles all along this Thesis



As a reminder, Table 12 below summarises the values used in the numerical versions of the models developed in Chapters 1 and 2. Recall that we consider three different energy-efficient technologies per equipment termed e_a, e_b and e_c as concern the engines, and ty_a, ty_b and ty_c as regard the tyres. Each time, the technology indexed by c is the most energy-efficient one, and the one indexed with a the least efficient one.

Table 12: Values used for exogenous variables

Exogenous variables	Value	Source / Explanation
Fuel price in 2013 ($\boldsymbol{p}$)	1.5753€/L	Average price of petrol in France in 2012 (DGEC)
Household's average income in 2013 ($\boldsymbol{y}$)	€36,190	Average household income in France in 2012 (INSEE)
Length of car ownership in 2013 ($\boldsymbol{T}$)	5.3 years	Average length of car ownership in France in 2013 (CCFA, 2014)
Preference parameter ($\boldsymbol{\theta}$)	0.02	Calibrated to as to roughly reflect realistic distances covered with a petrol car
Baseline engine's market price ($\boldsymbol{P^{e_0}}$)	€1,900	Value given in internet websites
Baseline engine's production cost ($\boldsymbol{\sigma^{e_0}}$)	€1,188	Assuming a coeff. for translation from cost to price of 1.6 (IEEP, 2005)[91]
Additional production cost for $\boldsymbol{e_a}$ ($\boldsymbol{\omega^{e_a}}$) (reduction in fuel consumption thanks to $\boldsymbol{e_a}$)	€54 (-0.23L/100km)	Using a cost of €50 for a 4%-reduction in fuel consumption with lower engine friction losses (TNO, IEEP and LAT, 2006) (realistic order of magnitude, chosen with representatives of the sector)
Additional production cost for $\boldsymbol{e_b}$ ($\boldsymbol{\omega^{e_b}}$) (reduction in fuel consumption thanks to $\boldsymbol{e_b}$)	€108 (-0.45L/100km)	Same as above
Additional production cost for $\boldsymbol{e_c}$ ($\boldsymbol{\omega^{e_c}}$) (reduction in fuel consumption thanks to $\boldsymbol{e_c}$)	€162 (-0.68L/100km)	Same as above
Baseline tyre's market price ($\boldsymbol{P^{ty_0}}$)	€250	Value given in internet websites
Baseline tyre's production cost ($\boldsymbol{\sigma^{ty_0}}$)	€156	Assuming a coeff. for translation from cost to price of 1.6 (IEEP, 2005)
Additional production cost for $\boldsymbol{ty_a}$ ($\boldsymbol{\omega^{ty_a}}$) (reduction in fuel consumption thanks to $\boldsymbol{ty_a}$)	€17 (-0.07L/100km)	Using a cost of €35 for a 3%-reduction in fuel consumption with low rolling resistant tyres (IEA, 2012) (realistic order of magnitude, chosen with representatives of the sector)
Additional production cost for $\boldsymbol{ty_b}$ ($\boldsymbol{\omega^{ty_b}}$) (reduction in fuel consumption thanks to $\boldsymbol{ty_b}$)	€33 (-0.15L/100km)	Same as above
Additional production cost for $\boldsymbol{ty_c}$ ($\boldsymbol{\omega^{ty_c}}$) (reduction in fuel consumption thanks to $\boldsymbol{ty_c}$)	€50 (-0.22L/100km)	Same as above

[91] The share of the cost and margin of the dealer on the one hand and the margin of the manufacturer on the other hand in the price (excluding taxes) amounts to 38% on average (IEEP, 2005).

Dirty vehicle's fuel consumption ($\boldsymbol{f^d}$)	0.0524L/km	Approximately[92] the average fuel consumption of petrol cars in France in 2013 (ADEME, 2014)
Dirty vehicle's purchase price ($\boldsymbol{P^d}$)	€18,918	Average market price of petrol cars in France in 2013 (from l'Argus)
Dirty vehicle's production cost (except the purchase cost of engine and tyres) ($\boldsymbol{\vartheta}$)	€10,480	With a coeff. for translation from cost to price of 1.6 (IEEP, 2005)

Note that figures related to the dirty vehicle's characteristics are given in Appendix B. They are needed in particular to compute the unit fuel consumption of the clean vehicle according to the package of technologies fitted in the vehicle.

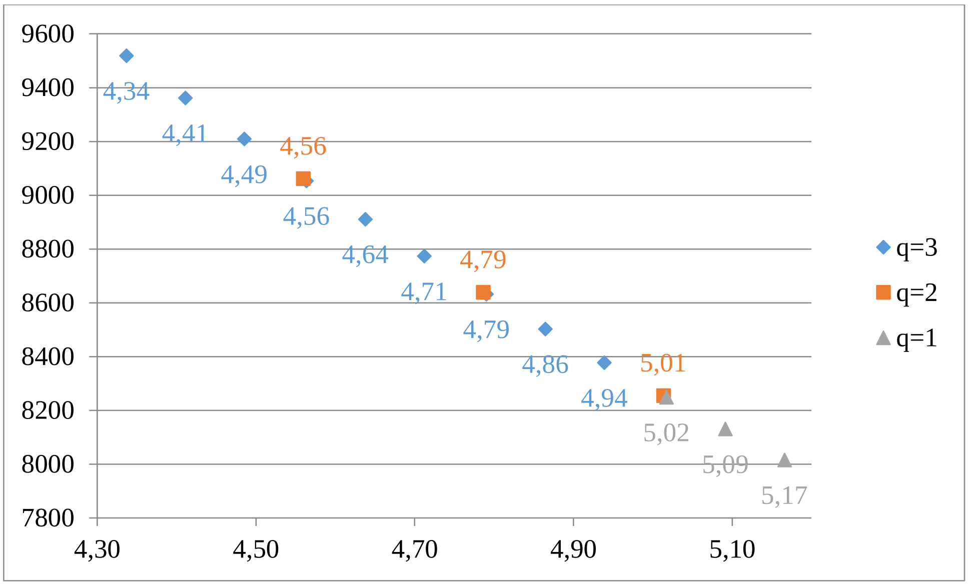
- **Equilibriums description**

To describe the equilibriums, we address separately the demand- and supply-sides.

On the demand-side, we comment the most important or surprising results based on graphical representations. Note that detailed figures are given in Appendix G.

From the first Figure below, there is clear evidence that the least fuel-consuming vehicle is also the most used.

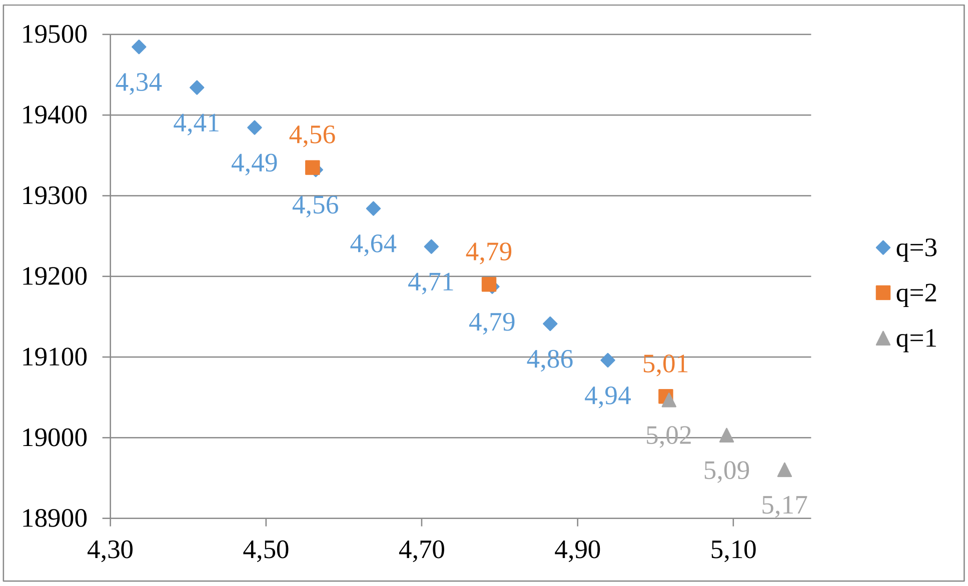
Figure 17: Distance covered with the clean vehicle (Y-axis, in km) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



[92] The average fuel consumption per kilometre of petrol cars in France in 2013 was 5.2L/km. Here, we use 5.24L/100km, because it results from the different assumptions we made on the characteristics of the dirty vehicle (including the characteristics of its engine, see Appendix B).

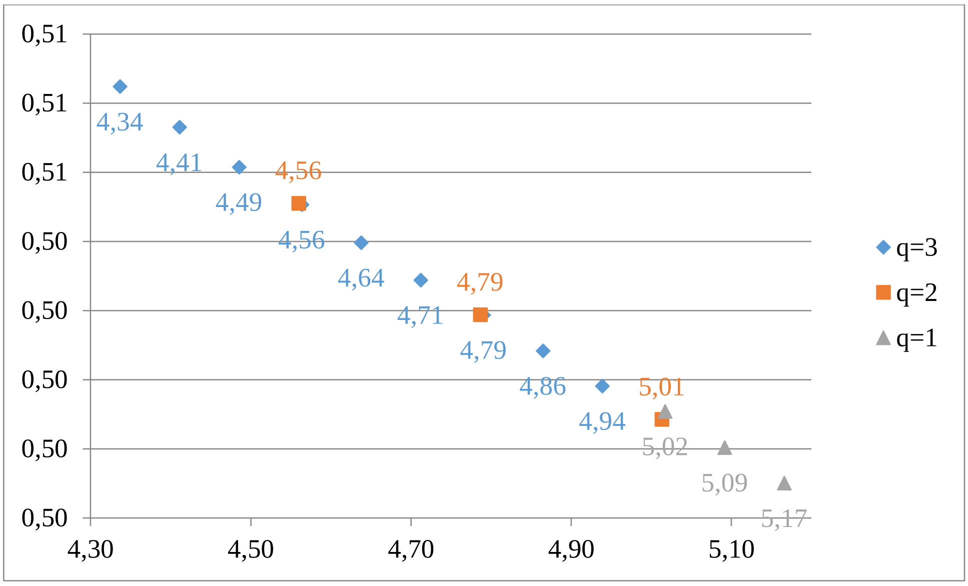
Nevertheless, Figure 17 above is misleading: the distance covered with the clean vehicle is not a linear function of the fuel consumption. Here, each point depicts a different clean vehicle characterized not merely by its fuel consumption per kilometre but also by its market price. Yet, the vehicle's market price decreases linearly with the vehicle's fuel consumption, as plotted in the following Figure:

Figure 18: Clean vehicle's market price (Y-axis, in €) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



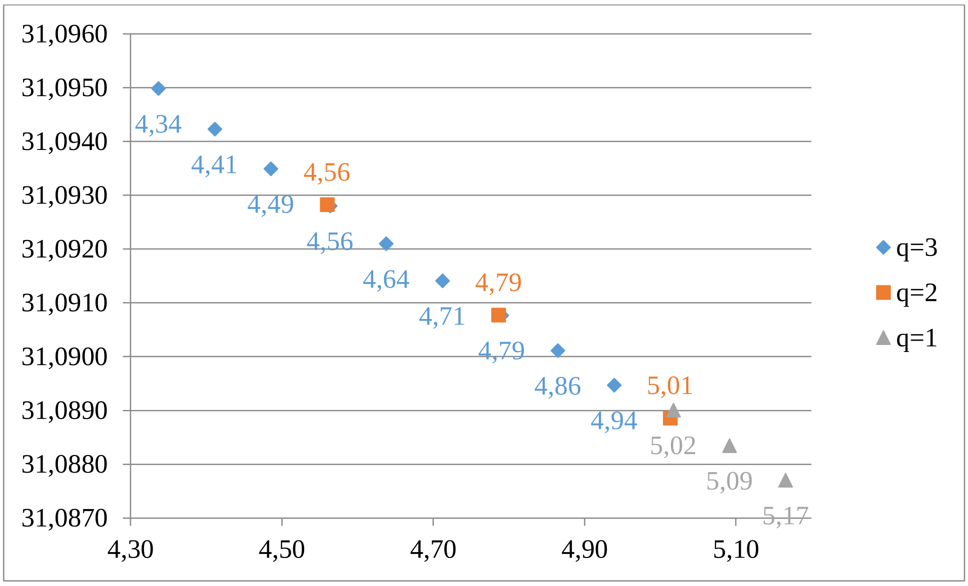
Likewise, Figure 19 below, that plots the share of clean vehicles as a function of the clean vehicle's fuel consumption, may be misinterpreted. That the relation is clearly linear in the following chart is also due to the relation between the vehicle's unit fuel consumption and the vehicle's market price.

Figure 19: Share of clean vehicles (Y-axis) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



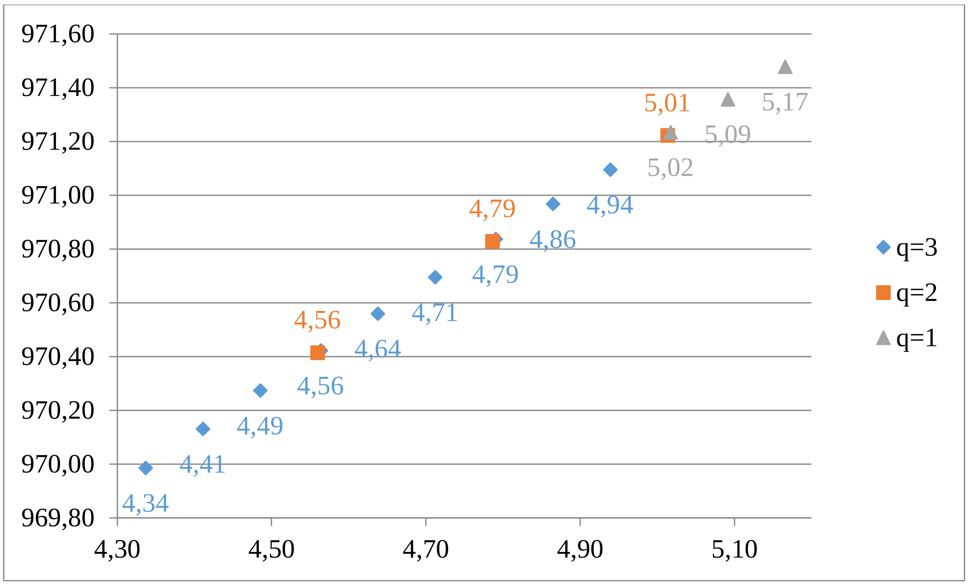
Moreover, since the clean vehicle owner's utility and the share of clean vehicles increase when the unit fuel consumption decreases on the one hand, and the (fixed) utility of a dirty vehicle's owner is always lower than that of a clean vehicle's owner, it is logical that the weighted average utility augments with the improvement of the clean vehicle's energy efficiency, such as illustrated in Figure 20.

Figure 20: Average utility (Y-axis) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



Finally, despite that the higher the energy efficiency of the clean vehicle, the longer the distance covered with that vehicle on the one hand (in Figure 17), and the larger the share of clean vehicles on the other hand (in Figure 19), the average total of CO_2 emissions per household decreases conspicuously with the vehicle's energy efficiency (see Figure 21). It implicitly means that looking for the most energy-efficient vehicle is consistent with looking for the lowest total of CO_2 emissions due to car use.

Figure 21: Average total of CO_2 emissions (Y-axis, in kg/household/year) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



On the supply-side, we give the detailed figures in terms of market prices, and profits in Appendix H; and we only comment some results below based on graphical representations.

We start with the profit of the two FTSs. Firstly, when a single energy-efficient equipment is fitted in the clean vehicle ($q = 1{,}2$), the profit of the supplier that produces that equipment increases with the energy performance of the technology. To observe this result on Figure 22 below, one has to remind that the vehicle's energy efficiency progresses solely with the improvements of tyre's energy performances when $q = 1$ (in grey), and with engine's energy performances when $q = 2$ (in orange). Secondly, when two energy-efficient technologies are put together in the clean vehicle ($q = 3$), the profit of a given FTS increases with the energy performance not merely of its product but also of the equipment produced by the other FTS. To see it, one has to observe simultaneously Table 13 below and Figure 22 (for the engine producer) or Figure 23 (for the tyre maker). This is also visible in Table G.2 in Appendix G. It is worth mentioning that this result also implies that the strategies of the two FTS are strategic complements. This is shown in Table G.3 in Appendix G by using the mathematical definition of strategic complements.

Table 13: Clean vehicle's fuel consumption depending on the package of technologies fitted in the vehicle

Car manuf.'s strategy	FTSs' strategies	Clean vehicle's fuel consumption
$q = 1$ (e_0, ty_1)	(e_0, ty_a)	5,17 L/100km
	(e_0, ty_b)	5,09 L/100km
	(e_0, ty_c)	5,02 L/100km
$q = 2$ (e_1, ty_0)	(e_a, ty_0)	5,01 L/100km
	(e_b, ty_0)	4,79 L/100km
	(e_c, ty_0)	4,56 L/100km
$q = 3$ (e_1, ty_1)	(e_a, ty_a)	4,94 L/100km
	(e_a, ty_b)	4,86 L/100km
	(e_a, ty_c)	4,79 L/100km
	(e_b, ty_a)	4,71 L/100km
	(e_b, ty_b)	4,64 L/100km
	(e_b, ty_c)	4,56 L/100km
	(e_c, ty_a)	4,49 L/100km
	(e_c, ty_b)	4,41 L/100km
	(e_c, ty_c)	4,34 L/100km

Figure 22: Engine manufacturer's profit (Y-axis, in €) as a function of the vehicle's fuel consumption (X-axis, in L/100km)

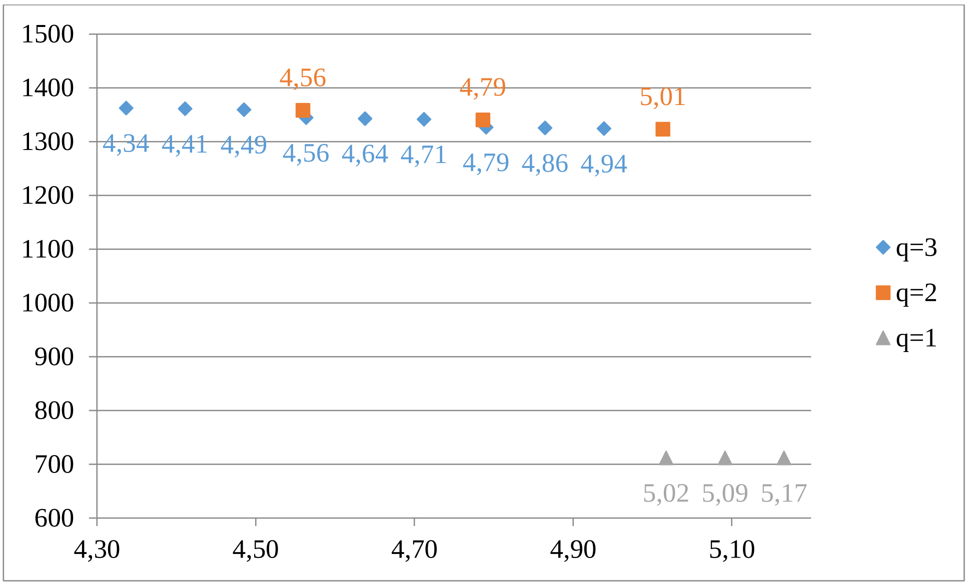
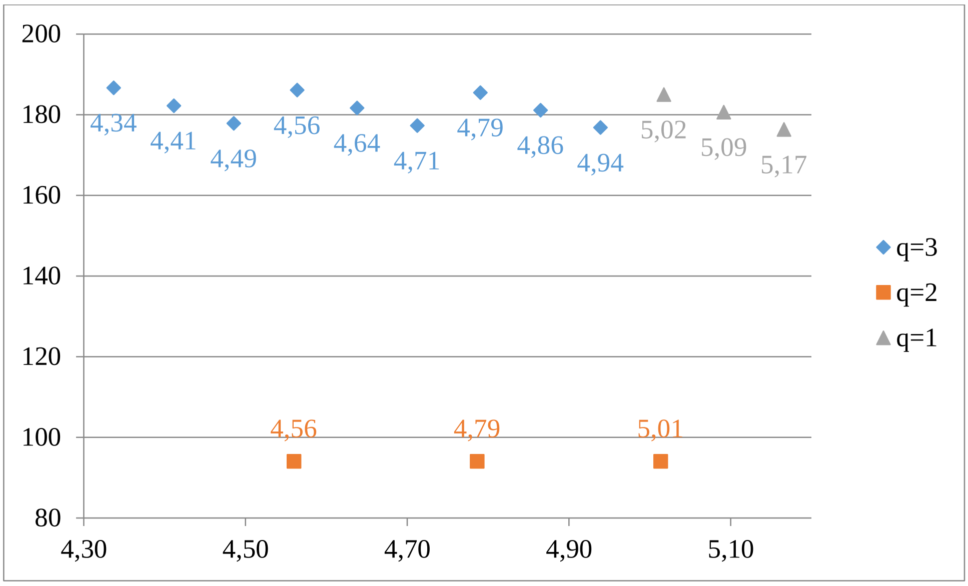
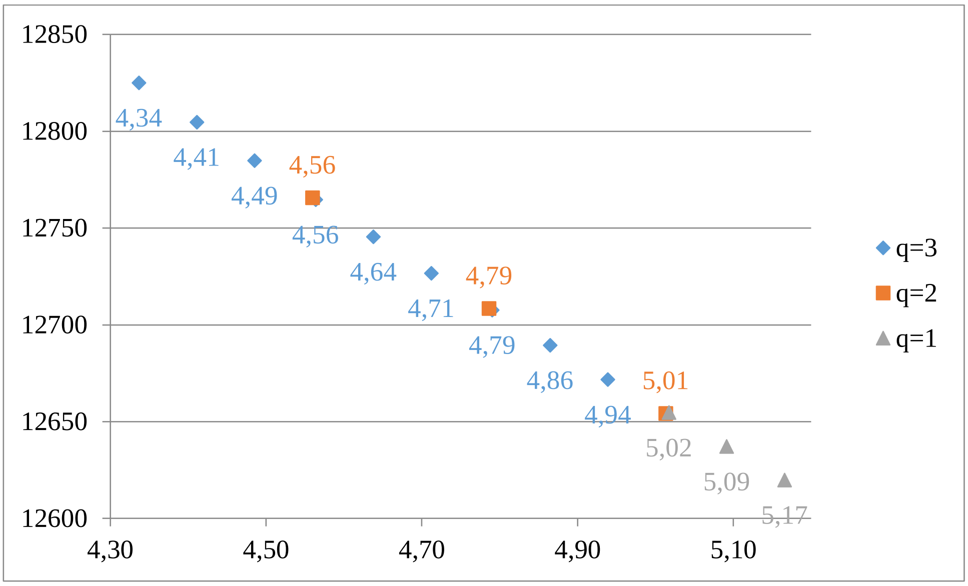


Figure 23: Tyre manufacturer's profit (Y-axis, in €) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



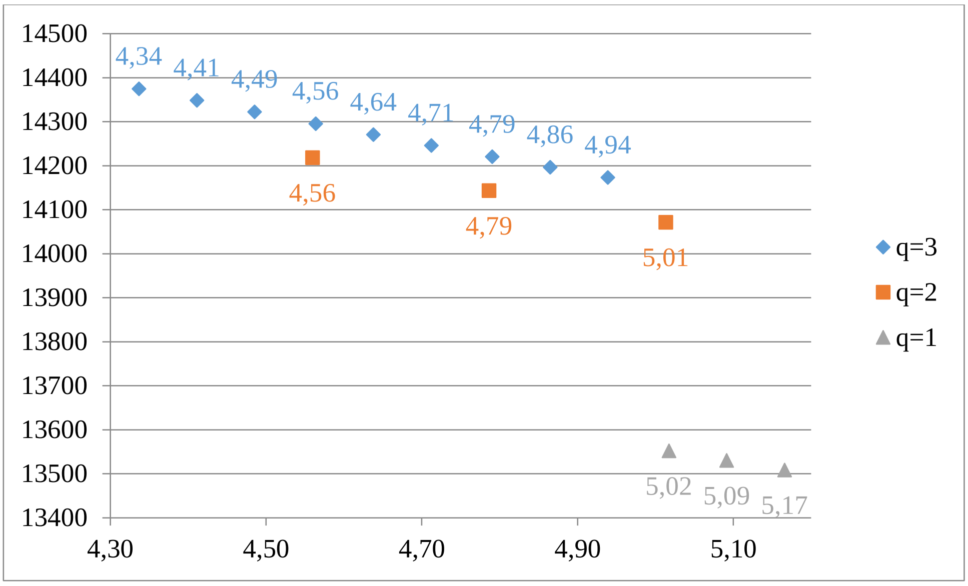
As concerns the profit of the car maker, it is clearly a decreasing function of the unit fuel consumption, or said another way an increasing function of the vehicle's fuel efficiency, as plotted in Figure 24.

Figure 24: Car maker's profit (Y-axis, in €) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



In the end, that the profit of all producers increases with the energy performance of the technology or vehicle they produce, and that the profit of a given FTS is positively correlated with the energy performance of the equipment produced by the other FTS explain why the sector earns more profit when it produces the cleanest vehicle, such as illustrated in the next chart[93].

Figure 25: Aggregated profit of the automotive sector (Y-axis, in €) as a function of the vehicle's fuel consumption (X-axis, in L/100km)



Said another way, Figure 25 teaches us that maximising the profit of the whole industry comes hand in hand with looking for the least fuel-consuming new vehicle. This finding also implicitly implies that the outcome that results from the free functioning of the market is the same regardless of the cooperation level among producers: this is the cleanest vehicle that is produced in every game configuration. This is why we omit, in this Chapter, the normal forms of those games. Indeed, the result is quite intuitive from the above charts, and the reasoning is the same than the one given in Appendix C for the scenarios characterised by a sufficiently high demand for clean vehicles.

For synthesis, both from an environmental perspective and from the household's point of view, it seems that one is wise to be offered the possibility to purchase a vehicle that consumes as little fuel as possible. In parallel, it appears that producing the vehicle that consumes the least amount of fuel makes the whole automotive sector earn the highest total profit. In view of these findings, one is tempted to conclude that a public intervention is not legitimate. This would be without taking into account that a policy intervention is able to change the level of emissions, utilities or profits associated to the production (for profit) and use (for utility and emissions) of

[93] We inform the reader that the significantly lower total profit with $q = 1$ (in grey) is due to the gap in the order of magnitude of the differences in profits that comes from the production – or not – of the clean equipment for the tyre producer on the one hand and for the engine maker on the other (compare the gap in profits between $q = 1$ and $q = 2$ for the engine and tyre producers in Figures 22 and 23).

the cleanest vehicle. Below, we thus examine what effects different policy tools have on these variables (cf. 3.2.).

3.2.The positive approach: which effects of policy instruments?

In this subpart, we successively discuss about the effects of a Bonus scheme (3.2.1.), those of a fuel tax (3.2.2.), and those of a tax on the purchase of low energy-efficient technologies (3.2.3.). These policy tools are chosen for their distinct targets, namely the car purchase decision for the Bonus scheme, and the car usage decision for the fuel tax on the demand-side, and the supply of energy-efficient vehicles as regards the tax on low energy-efficient technologies. Each time, we start by briefly laying out the theoretical framework in which the policy instrument is introduced, and then we turn to the effects of the tool using the numerical version of our model. More specifically, we attempt to express each impact of a policy intervention as a function of the level of the policy tool at focus over a predefined interval chosen so as to reflect the French current policy design. By doing so, the sign of the coefficient of the policy instrument indicates the direction in which the latter instrument plays on a given variable; and the order of magnitude of the coefficient explains the extent to which a given incentive-based mechanism is able to significantly impact the different variables. We can already emphasize that the R^2 associated to our regressions are roughly equal to one. We thus omit them in what follows.

Before that, let us note that we focus on the policy tools' effects when the least fuel-consuming vehicle is produced, that is to say the one equipped with e_c and ty_c. This choice is driven by the desire to simplify the exposition of the results, but is also consistent with the fact that regardless of the producers' strategies to cooperate on the vehicle design, this is the cleanest vehicle that is always produced, as already said above. We inform the reader that this result remains true in the presence of one or the other of the three policy tools considered in this work. We however omit the normal games that help demonstrate the latter affirmation.

3.2.1. Effects of a Bonus scheme

- **Introduction of a Bonus scheme into the theoretical framework**

A Bonus is a differentiated subsidy that is granted on the purchase of the least fuel-consuming vehicles. We suppose that solely what we call the 'clean vehicle' is eligible to the

Bonus in this application. Specifically, when a Bonus is granted on the purchase of the clean vehicle, the budget constraint of the household is given by:

$$y - \frac{P^c - B}{T} = C^c + pf^c k^c \tag{26}$$

where:

- y is the annual income, P^c is the vehicle c's market price, and T is the length of car ownership;
- B is the amount of Bonus granted on the purchase of the clean vehicle;
- C^c is the consumption of the composite good (the price of the composite good is normalized to one);
- $pf^c k^c$ is the expenditure on fuel, with p being the fuel price (expressed in euros per litre), f^c the vehicle c's fuel consumption (expressed in litre per kilometre), and k^c the distance covered with the clean vehicle.

Maximising the utility $U(k, C) = C^{1-\theta} k^{\theta}$ under this new budget constraint gives the following optimal levels of consumption for the clean vehicle's owner. Note that for notational simplicity, we use the subscript "B" in the following notations to mention that the levels of consumption are function of the Bonus amount.

$$(k^c)_B = \frac{\left(y - \frac{P^c - B}{T}\right)\theta}{pf^c} \tag{27}$$

$$(C^c)_B = (1-\theta)\left(y - \frac{P^c - B}{T}\right) \tag{28}$$

The indirect utility of the clean vehicle's owner becomes:

$$(V_i^c)_B = \left[(1-\theta)\left(y - \frac{P^c - B}{T}\right)\right]^{1-\theta} \left[\frac{\left(y - \frac{P^c - B}{T}\right)\theta}{pf^c}\right]^{\theta} + \eta_i^c \tag{29}$$

The remainder of our theoretical formulation remains unchanged. In particular, the consumer's decision rule is still the following:

$$\begin{array}{ll} \text{If } (V_i^c)_B > V_i^d & \text{he/she chooses to purchase vehicle } c \\ \text{If } (V_i^c)_B < V_i^d & \text{he/she chooses to purchase vehicle } d \end{array} \tag{DR2}$$

- **Simulation**

Under the French General Tax Code in 2013, vehicles that consume less than 4.5L/100km are eligible to a Bonus of €200 (the French Bonus scheme is described in Appendix D). In this application, the clean vehicle equipped with e_c and ty_c consumes 4.34L/100km, and is thus eligible to a Bonus of €200. We express in Tables 14 and 15 the effects of the Bonus scheme as a function of the amount of the Bonus for values from 0€ to 400€.

Table 14: Impacts of the Bonus amount on the demand-side variables

Demand-side variables	Impacts of the Bonus amount
Clean vehicle's market price (in €)	$\Delta P^c(B) = 0.8043B$
Distance covered with the clean vehicle (in km)	$\Delta k^c(B) = 0.0113B$
Direct utility of the clean vehicle's owner	$\Delta U^c(B) = 3 * 10^{-5}B$
Ratio "clean vehicles / whole fleet"[94]	$\Delta \varphi^c(B) = 1 * 10^{-5}B$
Average direct utility	$\Delta U(B) = 2 * 10^{-5}B$
Average total of emissions (in $kgCO_2$/household/year)	$\Delta E(B) = 0.0005B$

First of all, on the demand-side, there is clear evidence that the distance covered with the *dirty* vehicle as well as the utility of a dirty car's owner are not impacted by the Bonus scheme. Regarding the distance travelled with a *clean* vehicle, Table 14 reveals that implementing a Bonus scheme has little impact on this variable; in fact +100€ of Bonus leads to an increase of the annual distance of slightly more than one kilometre (1.13km). In addition, albeit being ridiculous, it should nonetheless be emphasised that the impact of the Bonus on total CO_2 emissions is contrary to what we might have expected (+0.05kg CO_2 each time the Bonus increases of €100, in the last row of the above Table). This Paradox is due to the upward change of the share of clean vehicles (that are more used than the dirty vehicles; referring to the rebound effect) on the one hand (fourth row), and of the distance travelled with a clean vehicle on the other (already discussed). Interestingly, one can note that these variations would have been higher if the rise of the demand or clean vehicles caused by the Bonus scheme would have not led to an augmentation of the clean vehicle's market price (*i.e.* +€80 when the Bonus increases of €100, in the first row). As the latter increase in market price remains below the amount of Bonus (0.8043 < 1), both the distance covered with a clean vehicle and the share of clean vehicles are still higher in the situation with the Bonus scheme. This also explains why the utility of the clean vehicle's owner (third row), and thus the average utility (fifth row), are higher with the Bonus scheme.

[94]This figure is clearly the share of clean vehicles, but it is not expressed as a percentage. We have for instance 0.5062, rather than 50.62%. This explains the order of magnitude of the coefficient in the second column.

Moreover, it should be emphasised that, because of the car price adjustment, what is perceived at first sight as a subsidy – which cost is born by the public authorities – actually entails a cost for the car purchasers, the latter benefiting to the car makers. As a remark, a parallel that makes sense can be done with the upward trend in rents resulting from the granting of housing benefits[95]. As suggested by the economic theory, the above finding comes from a lower price elasticity of the demand compared to that of the supply. Therefore, we cannot generalise this result beyond the present numerical exercise from the moment that the car demand is approached with discrete choice models based on distribution laws – with a price elasticity of the demand that is thus not constant – as it is usually the case. All the more so because empirically it seems difficult to find evidence for the changes in vehicles' market prices following the implementation of a Bonus scheme, and more generally of a feebate scheme, because list prices are modified only once a year. Consequently, they do not reflect the real transaction prices, since it is true that most of the car dealers negotiate prices with consumers (d'Haultfoeuille and al., 2014).

Table 15: Impacts of the Bonus amount on the supply-side variables

Supply-side variables	**Impacts of the Bonus amount**
Clean engine's market price (in €)	$\Delta P^{e_1}(B) = 0.0717B$
Clean tyre's market price (in €)	$\Delta P^{ty_1}(B) = 0.0102B$
Clean vehicle's market price (in €)	$\Delta P^{c}(B) = 0.8043B$
Ratio "clean vehicles (or technologies) / whole fleet"	$\Delta \varphi^{c}(B) = 1 * 10^{-5}B$
Profit of the engine manuf. (in €)	$\Delta \pi^{e}(B) = 0.0365B$
Profit of the tyre manuf. (in €)	$\Delta \pi^{ty}(B) = 0.0052B$
Profit of the car maker (in €)	$\Delta \pi^{v}(B) = 0.388B$
Aggregated profit (in €)	$\Delta \Pi(B) = 0.4297B$

When it comes to analysing the way the Bonus scheme affects the supply-side, Table 15 above shows that the aggregated profit of the industry is increased when a Bonus is granted on the purchase of clean vehicles (+€43 for a Bonus of 100€, in the last row). This result comes to a large extent from the rise in the car maker's profit (+€39 for a Bonus of €100, thanks to the increase in the clean vehicle's market price; already underlined in the previous paragraph) but also from a slight rise of the profit of the two FTSs (+€3.7 and only +€0.5 respectively for respectively the engine producer and the tyre manufacturer). In fact, the market prices of the

[95] For instance, for the French housing market, Fack (2006) finds that "*one additional euro of housing benefit leads to an increase of 78 cents in the rent paid by new benefit claimants, leaving only 22 cents available to reduce their net rent and increase their consumption*" (p747).

energy-efficient technologies are also slightly higher with the Bonus scheme since the car maker's demand of clean technologies follows the increase in the demand of clean vehicles (see the first two rows in the above Table).

3.2.2. Effects of a fuel tax

- **Introduction of a fuel tax into the theoretical framework**

The fuel tax – termed τ – is expressed in euros per litre of fuel, and impacts the households' budget constraint in the following manner:

$$y - \frac{P^j}{T} = C^j + (p + \tau) f^j k^j \tag{30}$$

Maximising the utility $U(k, C) = C^{1-\theta} k^{\theta}$ under the above budget constraint gives the following optimal level of consumptions for the owner of a vehicle j. Here again, we simply use the subscript "τ" to indicate that the variables are function of the fuel tax.

$$\left(k^j\right)_\tau = \frac{\left(y - \frac{P^j}{T}\right)\theta}{(p + \tau) f^j} \tag{31}$$

$$C^j = (1 - \theta)\left(y - \frac{P^j}{T}\right) \tag{32}$$

Clearly, the expenditure on composite good C^j does not change with the implementation of the fuel tax, and the household adjusts their distance travelled by car so as to keep unchanged the expenditure on fuels, as already said in Chapter 2. Modifying the car use is indeed the first way to respond to the implementation of a fuel tax. A second way consists in changing the car purchase decision. Indeed, the fuel tax also appears within the indirect utility (see equation (33) below), the one that is maximised when choosing the car to purchase.

$$\left(V_i^j\right)_\tau = \left[(1 - \theta)\left(y - \frac{P^j}{T}\right)\right]^{1-\theta} \left[\frac{\left(y - \frac{P^j}{T}\right)\theta}{(p + \tau) f^j}\right]^{\theta} + \eta_i^j \tag{33}$$

This time, the decision rule underlying the vehicle choice is written in the following manner:

If $(V_i^c)_\tau > \left(V_i^d\right)_\tau$ he/she chooses to purchase vehicle c

If $(V_i^c)_\tau < \left(V_i^d\right)_\tau$ he/she chooses to purchase vehicle d (DR3)

- **Simulations**

Under the French carbon tax project, a level of c€1.72 is recommended for 2015 (El Beze, 2014). We express in Tables 16 and 17 the effects of the carbon tax as a function of the tax level for values from c€0 to c€3.4.

Additionally, in the second Chapter focussed on the demand-side, we have already alerted the reader to the distinction to be made when evaluating the effects of a fuel tax depending on whether the tax is implemented after or before the car purchase. Hereinafter, we consider a household who is going to purchase a new vehicle for whom the fuel tax is likely to impact both the car purchase and use decisions.

Table 16: Impacts of the fuel tax on the demand-side variables

Demand-side variables	Impacts of the fuel tax
Clean vehicle's market price (in €)	$\Delta P^c(\tau) = -0.0091\tau$
Distance covered with the clean vehicle (in km)	$\Delta k^c(\tau) = -59.189\tau$
Distance covered with the dirty vehicle (in km)	$\Delta k^d(\tau) = -49.148\tau$
Direct utility of the clean vehicle's owner	$\Delta U^c(\tau) = -0.0039\tau$
Direct utility of the dirty vehicle's owner	$\Delta U^d(\tau) = -0.0039\tau$
Ratio "clean vehicles / whole fleet"	$\Delta \varphi^c(\tau) = 1 * 10^{-7}\tau$
Average direct utility	$\Delta U(\tau) = -0.0039\tau$
Average total of emissions (in $kgCO_2$/household/year)	$\Delta E(\tau) = 0.0378\tau^2 - 6.1558\tau$

First and foremost, it is noteworthy that the fuel tax has a downward impact on the distance covered with both vehicles: each time the tax goes up by one cent, we observe a decrease of the distance of 59km with the clean vehicle and of 49km with the dirty vehicle (in rows 2 and 3). The fuel tax has also a negative impact on the utility of both kinds of car owners (rows 4 and 5), resulting in a diminution of the average direct utility (row 6). Furthermore, the last row of Table 16 shows that the fuel tax helps mitigate CO_2 emissions. The variation in CO_2 emissions is slightly more than -6$kgCO_2$ per household for a tax of 1c€, and is due to the decline of the distance covered with both vehicles. As a remark, that households tend to use less intensively their car when fuel is taxed is entirely explained by a higher cost per kilometre. Indeed, the disposable income after the car purchase remains unchanged, since the market price of the vehicle is practically not impacted by the fuel tax (see the first row). The reason is the following: households get used to the higher cost per kilometre by reducing the distance covered by car – it typically explains the high price elasticity of the demand for kilometre – and not by purchasing a cleaner vehicle[96]. Thereby, the demand of clean vehicles does not change with the

[96] This result is due to the fact that we do not consider a lower-limit of the distance covered by car.

tax; implying that the market price remains the same. It follows that the situation does not significantly change from the producers' perspective: market prices and profits are quite the same than before the implementation of the fuel tax, as shown in Table 17 below. Indeed, all the coefficients in Table 17 are very small. By contrast, and just as a remark since it is beyond the scope of our work, the profit of oil companies fails since the decrease of the distances covered by car is shown to translate into a reduction of the fuel demand. It has to be taken into account when discussing the tax incidence[97].

Table 17: Impacts of the fuel tax on the supply-side variables

Supply-side variables	Impacts of the fuel tax
Clean engine's market price (in €)	$\Delta P^{e_1}(\tau) = -0.0008\tau$
Clean tyre's market price (in €)	$\Delta P^{ty_1}(\tau) = -0.0001\tau$
Clean vehicle's market price (in €)	$\Delta P^{c}(\tau) = -0.0091\tau$
Ratio "clean vehicles (or technologies) / whole fleet"	$\Delta \varphi^{c}(\tau) = 1 * 10^{-7}\tau$
Profit of the engine manuf. (in €)	$\Delta \pi^{e}(\tau) = -0.0004\tau$
Profit of the tyre manuf. (in €)	$\Delta \pi^{ty}(\tau) = -6 * 10^{-5}$
Profit of the car maker (in €)	$\Delta \pi^{v}(\tau) = -0.0044\tau$
Aggregated profit (in €)	$\Delta \Pi(\tau) = -0.0048\tau$

3.2.3. Effects of a tax on low energy-efficient technologies

- **Introduction of a tax on low energy-efficient technologies into the theoretical framework**

Implementing a tax on the purchase of 'pollutant' technologies impacts the demand of equipment of the car maker by modifying the relative market prices of technologies. Precisely, the demand for clean technologies, that is equal to the supply of clean vehicles, is given by[98]:

$$\alpha_q^{v*}(\tau^e, \tau^{ty}) = \frac{1}{2} * \frac{P^c - P^d + 2\overline{S}[\vartheta + P^{e_0}(1+\tau^e) + P^{ty_0}(1+\tau^{ty})]}{\overline{S}(Z_q) + 2\overline{S}[\vartheta + P^{e_0}(1+\tau^e) + P^{ty_0}(1+\tau^{ty})]} \quad (34)$$

where τ^e and τ^{ty} are the taxes imposed on respectively the pollutant engine and the pollutant tyre, and Z_q is the cost born by the car maker when he produces a clean vehicle (with the package of technologies q) instead of a dirty one. The latter cost is given by:

[97] To do things right when discussing the tax incidence, we however need minimally to consider an endogenous fuel price, and to discuss about the degree of competition on the fuel market, since whether the consumers or the suppliers bear the tax burden depends not merely on the price elasticities but also on the degree of competition.
[98] This supply function results of the maximisation of the profit of the car maker (see the optimisation programme P3 in Chapter 1).

Table 18: Extra production cost associated to a clean vehicle when the baseline technologies are taxed

Package of technologies fitted in vehicle c	(e_0, ty_1) $q = 1$	(e_1, ty_0) $q = 2$	(e_1, ty_1) $q = 3$
Extra cost (Z_q)	$P^{ty_1} - P^{ty_0}(1 + \tau^{ty})$	$P^{e_1} - P^{e_0}(1 + \tau^{e})$	$P^{e_1} - P^{e_0}(1 + \tau^{e}) + P^{ty_1} - P^{ty_0}(1 + \tau^{ty})$

- **Simulation**

Herein, the tax that applies to the purchase of pollutant technologies is assumed to be the same for engine and tyre. We note it τ^i and we consider values from 0% to 20%. Note that, this time, we prefer to start with comments on the supply-side variables for reason related to the target of the tool we study here.

Table 19: Impacts of the tax on pollutant technologies on the supply-side variables

Supply-side variables	**Impacts of the tax on pollutant technologies**
Clean engine's market price (in €)	$\Delta P^{e_1}(\tau^i) = 1.4954\tau^i$
Clean tyre's market price (in €)	$\Delta P^{ty_1}(\tau^i) = 0.205\tau^i$
Clean vehicle's market price (in €)	$\Delta P^{c}(\tau^i) = -4.1056\tau^i$
Ratio "clean vehicles (or technologies) / whole fleet"	$\Delta \varphi^{c}(\tau^i) = 0.0003\tau^i$
Profit of the engine manuf. (in €)	$\Delta \pi^{e}(\tau^i) = 0.7655\tau^i$
Profit of the tyre manuf. (in €)	$\Delta \pi^{ty}(\tau^i) = 0.109\tau^i$
Profit of the car maker (in €)	$\Delta \pi^{v}(\tau^i) = -7.72\tau^i$
Aggregated profit (in €)	$\Delta \Pi(\tau^i) = -6.8456\tau^i$

As expected, the car maker's demand of high energy-efficient technologies increases with the tax on low energy-efficient technologies. It makes the price of energy-efficient technologies rise (+€7.5 and +€1 for a tax of 5% respectively for the efficient engine and the efficient tyre; see the first two rows). Accordingly, we observe a small increase of the profits of both FTSs (rows 5 and 6). By contrast, this translates into a fall of the car maker's profit (-€39 for a tax of 5%, in row 7) who has to bear a decrease of the gap between the production cost and the market price for both vehicles. Indeed, regarding the dirty vehicle, its market price remains unchanged (recall that it is fixed exogenously) while it becomes more expensive to produce because of the tax added up to the purchase prices of the dirty technologies that equip the dirty vehicle; and regarding the clean vehicle, its production cost increases as the market prices of the clean technologies rise, while its market price diminishes (-€21, in row 3) at the same time insofar as its supply grows. Eventually, the total profit of the automotive sector falls (-€34, in the last row) because the augmentation of FTSs' profits is not high enough to compensate the reduction of the car maker's one.

Table 20: Impacts of the tax on pollutant technologies on the demand-side variables

Demand-side variables	**Impacts of the tax on pollutant technologies**
Clean vehicle's market price (in €)	$\Delta P^c(\tau^i) = -4.1056\tau^i$
Distance covered with the clean vehicle (in km)	$\Delta k^c(\tau^i) = 0.2386\tau^i$
Direct utility of the clean vehicle's owner	$\Delta U^c(\tau^i) = 0.0007\tau^i$
Ratio "clean vehicles / whole fleet"	$\Delta \varphi^c(\tau^i) = 0.0003\tau^i$
Average direct utility	$\Delta U(\tau^i) = 0.0004\tau^i$
Average total of emissions (in $kgCO_2$/household/year)	$\Delta E(\tau^i) = 0.0108\tau^i$

On the demand-side, the downward impact of the tax on the clean vehicle's market price translates into a rise in the disposable income so that the distance covered with a clean vehicle slightly increases (+1.2km for a tax on the purchase of pollutant technologies of 5%). Combined with the small enlargement of the share of clean vehicles (row 4), the rise in the distance covered with the clean vehicle leads to a very modest augmentation in the average total of CO_2 emissions per household (+0.05$kgCO_2$, in the last row).

For synthesis, we propose in the next paragraph to compare the effects of the three policy tools.

3.2.4. Comparisons of the effects

In Table 21 below, we display the variations of the aggregated profit, of the average utility and of the average total of CO_2 emissions per household caused by the implementation of the three different policy instruments examined above.

Table 21: Variations in profit, utility and emissions caused by a Bonus, a fuel tax, and a tax on low energy-efficient technologies

		Δ Aggregated profit (€)	**Δ Average direct utility**	**Δ Average emissions ($kgCO_2$)**
(1)	Bonus (B in €)	$+0.4297B$	$+2 * 10^{-5}B$	$+0.0005B$
(2)	Fuel tax (τ in €)	-0.0048τ	-0.0039τ	$0.0378\tau^2 - 6.1558\tau$
(3)	Tax on low energy-efficient techno (τ^i in %)	$-6.8456\tau^i$	$+0.0004\tau^i$	$+0.0109\tau^i$

Two complementary approaches are possible to comment Table 21: either we focus on a given policy tool (in row) and we investigate its effects on the different variables of interest, or we focus on a given variable of interest (in column) and we determine which policy tool impacts that variable in the right direction. Both approaches are relevant, and refer actually to two different issues discussed in the first Part of this Chapter. They are thus successively adopted below.

On the one hand, by adopting the first approach, we investigate whether a policy instrument is able to serve several objectives at the same time. Lessons from Table 21 in this regard are the following. Solely the Bonus scheme seems to make public authorities able to achieve several objectives at the same time; here to raise the profit of the car industry, and to extent the average utility of households. The other two tools serve only one objective, that is to say the environmental objective as regards the fuel tax, and the increase in utility as concerns the tax on pollutant technologies.

On the second hand, we show that several policy instruments are able to play on the same variable of interest through the second approach. Table 21 highlights that, as might be expected, the average total of CO_2 emissions from car use per household and per year is the lowest when fuel is taxed. More surprising is that the other two IB mechanisms make the total of CO_2 emissions slightly increase. In view of these effects, it seems instructive to recall that a fuel tax is part of policy tools impacting on the car use, and thus directly on the CO_2 emissions resulting from car use, while the other two instruments are part of the policy tools playing on the composition of the fleet (by modifying either the car demand or the car supply). In contrast, setting up a fuel tax is the least desirable policy intervention from the households' point of view since the average direct utility deteriorates in that policy regime while it rises with the other two policy tools. Lastly, with regard to the automotive sector's profit, it falls with the instauration of a tax on pollutant technologies, and grows with the other two policy instruments.

The above findings do not however give a clue on whether implementing simultaneously several policy instruments is of interest with regard to a given objective or to the set of them. This is because we content ourselves in the previous paragraphs with elaborating on the effects of policy tools on their own. We now propose (in 3.3.) to address the interest of combining policy tools, while adopting a normative approach.

3.3.The normative approach: to combine – or not – policy tools?

First of all, when it comes to tackling the effects of a policy package, one should keep in mind that effects are (in May and al., 2006):

- *complementary* when the use of two instruments has greater impacts than the use of either alone;
- *additive* when the benefit from the use of two instruments is equal to the sum of the benefits of using each in isolation;
- *synergetic* when the simultaneous use of two instruments yields higher benefits than the sum of the benefits of using either one of them alone;
- *substitutable* when the use of one instrument completely eliminates any benefits from using another.

In what follows are successively examined the three following packages of policy tools: 1. "Bonus scheme + fuel tax" (cf. 3.3.1.), 2. "Bonus scheme + tax on low energy-efficient technologies" (cf. 3.3.2.), and 3. "Fuel tax + tax on low energy efficient technologies" (cf. 3.3.3.). We draw the reader‘s attention to the fact that the following findings are not generalisable, and are true given our starting point, that is to say the partial equilibrium described in 3.1.2.

3.3.1. To combine – or not – a Bonus scheme and a fuel tax?

This subpart is dedicated to an in-depth analysis of the effects of a Bonus scheme and a fuel tax when implemented together.

Dealing with the aggregated profit (first column), Table 22 below teaches us that from the moment that the amount of Bonus is more than 1.2 times higher[99] than the fuel tax (what is expected), effects are complementary but less than additive. Let us note that the dependence of the effects of the fuel tax on the amount of Bonus (see "$-(0.0005B + 0.0042)\tau$" in the last row) is due to the fact that the fuel tax targets a different fleet of vehicles when the amount of Bonus changes. Moreover, there is clear evidence from the second column of Table 22 that the effects of both tools are purely additive when focussing on the utility criterion (second column). Conversely, in terms of CO_2 emissions (in column 3), effects are synergetic. This is because the

[99] Effects are synergetic if: $-(0.0005B + 0.0042)\tau > -0.0048\tau$. It gives $B < 1.2\tau$. This is not true, meaning that effects are rather only complementary.

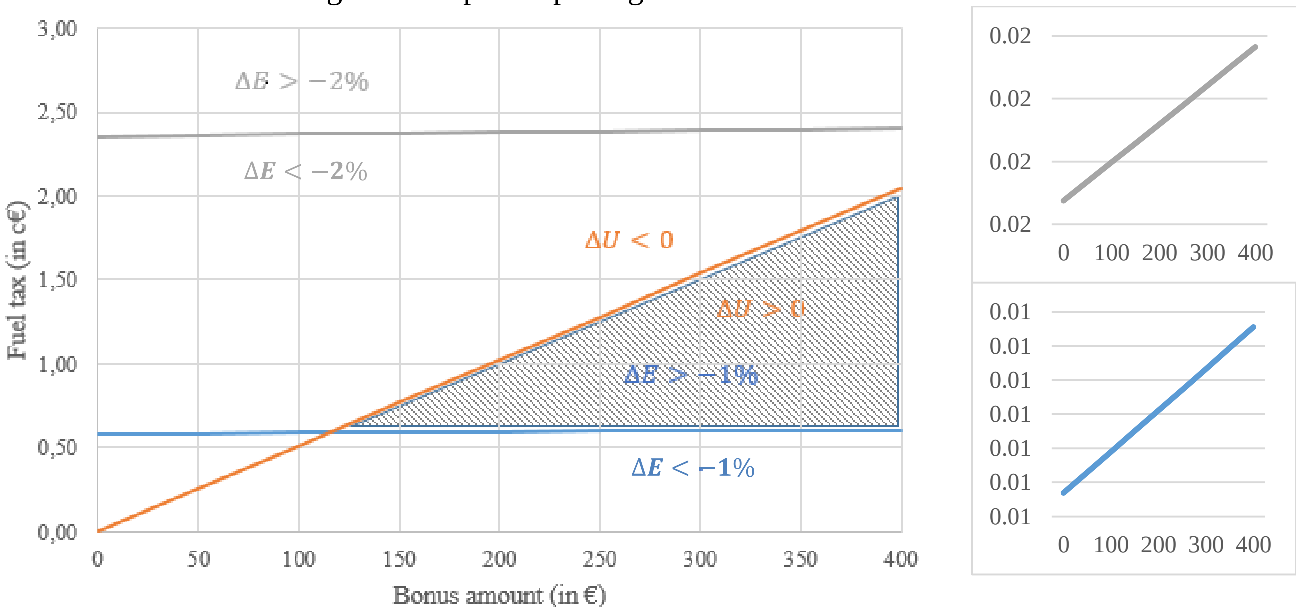
presence of the Bonus scheme reinforces the efficiency of the fuel tax (see the additional term "$-3 * 10^{-6}B$ ", in the last row); and this result comes from the fact that that the basis of the fuel tax is larger thanks to the Bonus scheme (because of the well-known rebound effect). The latter finding deserves to be emphasised given the intended target of policy-makers.

Table 22: Effects of the package "Bonus scheme + fuel tax"

	Δ Aggregated profit (€)	**Δ Average direct utility**	**Δ Average emissions (kgCO₂)**
(1) Bonus (B in €)	$+0.4297B$	$+2 * 10^{-5}B$	$+0.0005B$
(2) Fuel tax (τ in €)	-0.0048τ	-0.0039τ	$+0.0378\tau^2 - 6.1558\tau$
(1) + (2)	$+0.4297B - (0.0005B + 0.0042)\tau$	$+2 * 10^{-5}B - 0.0039\tau$	$+0.0005B + 0.0378\tau^2$ $-(3 * 10^{-6}B + 6.1558)\tau$

In view of these findings, another interesting exercise consists in determining the level of a given tool, as a function of the other, so that the variation in a given variable of interest (profit, utility or emissions) is equal to zero, since the two IB mechanisms play on opposite directions on the three variables. We choose to carry out this exercise solely for utility and emissions, since considering a revenue-neutral combination of policy tools is not relevant in this framework. Indeed, the fuel tax is also paid by the households who have purchased their car the years before and who do not enter the scope of the present work. Precisely, we plot, in Figure 26 below, the fuel tax as a function of the Bonus amount that leaves the utility unchanged (*i.e.* unchanged between a situation without policy tool, and a situation with the package "Bonus scheme + fuel tax") (see the orange line). And, rather than considering the fuel tax that leaves unchanged the average total of CO_2 emissions in the presence of a Bonus scheme, we choose to assume a reduction of 1% (in blue) or 2% (in grey) of emissions so as to obtain fuel taxes with similar orders of magnitude with the ones computed when dealing with the average utility. In fact, this is true that the amount of fuel tax that enables to keep unchanged the CO_2 emissions when a Bonus is granted on the purchase of the clean vehicles is insignificant (less than 0.0001c€ for a Bonus of €250 for instance). Note that the two charts on the left of Figure 26 better illustrate the increase of the optimal fuel tax with the amount of Bonus.

Figure 26: Optimal packages of Bonus scheme and fuel tax



By doing so, we are able to identify which combinations of Bonus scheme and fuel tax enable to reduce the CO_2 emissions by more than 1% without reducing the average utility (depicting by the hatched triangle in Figure 26 above). Let us note that one cannot conclude from Figure 26 that this is not possible to reduce the CO_2 emissions by more than 2% without degrading the utility. This is probably possible, but the amount of Bonus required is higher than €400, and our regressions are not estimated for such an amount.

3.3.2. To combine – or not – a Bonus scheme and a tax on a low energy-efficient technologies?

Herein, we address the interest of combining a tax on the purchase of low energy-efficient technologies with a Bonus scheme.

First and foremost, effects of a package made with a Bonus scheme and a tax on pollutant technologies on the aggregated profit seem to be synergetic: the increase of profit obtained with the Bonus is magnified with the tax (see "$+(0.000265\tau^i + 0.4297)B$"), and the decrease in profit resulting from the tax also goes up with the Bonus (see "$-(2 * 10^{-8}B^2 - 0.0003B + 6.8456)\tau^i$"). Under realistic assumptions[100], the first effect prevails over the second one, explaining why effects are synergetic. Besides, similarly with the effects of the package "Bonus scheme + fuel tax", the effects on the average utility of the package "Bonus scheme + tax on

[100] The first effect prevails over the second one when: $0.000265\tau^i B > (2 * 10^{-8}B^2 - 0.0003B)\tau^i$. It gives $B < 28250$. Recall that we consider an interval for the Bonus of $[€0, €400]$.

low energy-efficient technologies" are purely additive. Lastly, from an environmental perspective, one can note that the way the Bonus scheme impacts the level of CO_2 emissions is the same whatever the tax on pollutant technologies (see "$+0.0005B$" in the last row), whereas the impact of the tax changes with the amount of Bonus but the relation is non-linear and non-monotonic. In any event, both tools lead to a rise in CO_2 emissions explaining why public authorities whose chief objective consists of a reduction of the global pollution exclude straightaway this policy package.

Table 23: Effects of the package "Bonus scheme + tax on low energy-efficient technologies"

	Δ Aggregated profit (€)	**Δ Average direct utility**	**Δ Average emissions ($kgCO_2$)**
(1) Bonus (B in €)	$+0.4297B$	$+2 * 10^{-5}B$	$+0.0005B$
(3) Tax on low energy-efficient techno (τ^i in %)	$-6.8456\tau^i$	$+0.0004\tau^i$	$+0.0109\tau^i$
(1) + (3)	$+(0.000265\tau^i + 0.4297)B - (2 * 10^{-8}B^2 - 0.0003B + 6.8456)\tau^i$	$+2 * 10^{-5}B + 0.0004\tau^i$	$+0.0005B + f(\tau^i, B)$

3.3.3. To combine – or not – a fuel tax and a tax on low energy-efficient technologies?

Whether implementing simultaneously a fuel tax and a tax on the purchase of low energy-efficient technologies is interesting – or not – is discussed based on Table 24 below.

In terms of profit (first column), the way the fuel tax impacts the profit varies with the tax on pollutant technologies (see "$-\left(2 * 10^{-7}{\tau^i}^2 + 0.0002\tau^i + 0.0048\right)\tau$"). More exactly, the higher the tax on technologies, the larger the reduction in profit caused by the fuel tax. The link the other way round between both taxes is however more difficult to find, since the decline in profit caused by the tax on technologies varies with the fuel tax in a non-monotonic manner. We do not discuss longer those effects, insofar as both tools play on the same wrong direction on the profit. Besides, effects on the average utility are once again additive. Finally, with regard to CO_2 emissions, the effects of both taxes, when they are implemented together, are ambiguous. Indeed, when taken in isolation, the two taxes have opposite impacts on the average total of CO_2 emissions. What is more, when they are combined, the presence of one tax influences the effects of the other, but in a non-monotonic manner; and this is true for both ways of influences. Hence, we cannot conclude on the benefit of setting up a fuel tax and a tax on the purchase of pollutant technologies at the same time.

Table 24: Effects of the package "fuel tax + tax on low energy-efficient technologies"

	Δ Aggregated profit (€)	**Δ Average direct utility**	**Δ Average emissions (kgCO2)**
(2) Fuel tax (τ in €)	-0.0048τ	-0.0039τ	$0.0378\tau^2 - 6.1558\tau$
(3) Tax on low energy-efficient techno (τ^i in %)	$-6.8456\tau^i$	$+0.0004\tau^i$	$+0.0109\tau^i$
(2) + (3)	$-\left(2 * 10^{-7}{\tau^i}^2 + 0.0002\tau^i + 0.0048\right)\tau - g_1(\tau^i, \tau)$	$-0.0039\tau + 0.0004\tau^i$	$g_2(\tau^i, \tau) + g_3(\tau^i, \tau)$

4. Conclusion

Generally speaking, this is true that the reduction in CO_2 emissions should not be the single criterion used by the public decision-makers when they arbitrate among several policy tools. Hence, that reducing the CO_2 emissions from car use may also come hand in hand with other external benefits is of paramount importance. Some of these additional benefits are due to the fact that the road transport negative externalities are interrelated to the point that targeting only one of them is impossible. External benefits take in that case the shape of a decrease in local pollution, in congestion, in accidents, etc. The other extra positive effects come from another distinctive feature of transport; namely that it is a '*derived demand'*. It follows that transport underlies all activities. This way, a transport policy actively contributes to the economic growth and to the well-being, by directly modifying the producer and consumer surplus. Ultimately, the key would be to achieve good coordination among the multi-lateral effects of policies or tools, in order to ensure that the transport system moves in the desired direction.

Within our illustrative exercise, we propose to approximate the effects of policy instruments on economic growth and well-being respectively with the variation of profit, and with the average household's utility and the average total of CO_2 emissions. This way, we call into question the relevance of the pursuit of cleaner car mobility for the automobile sector and for households. We find that solely a fuel tax enables to reduce CO_2 emissions from car use, and that implementing either a Bonus scheme or a tax on the purchase of low energy-efficient technologies – with the objective to heighten either the demand or the supply of low fuel-consuming vehicles – results in the end in a slight augmentation of CO_2 emissions. Notwithstanding, granting a Bonus on the purchase of the 'cleanest' vehicles makes the households' utility raise while empowering at the same time the automotive sector to increase its profit. If setting up a tax on the purchase of low energy-efficient technologies also helps heighten the household's utility, it however leads to a decline of the sector's profit. In view of these first findings, a policy package made up with a Bonus system and a fuel tax appears at first sight as a good CO_2 regulation when taking into consideration the CO_2 emissions, the utility and the profit. To confirm the latter assertion, we examine the extent to which these two incentive-based mechanisms interact with each other. The most noticeable result given our focus is that effects on emissions are synergetic; *i.e.* the simultaneous implementation of the two tools yields higher benefits than the sum of the benefits of setting up either one of them alone. That the fuel tax is more efficient in the presence of a Bonus scheme thanks to a larger basis is indeed at the roof of this synergy effect. Thus, we could in the end advocate for the simultaneous use of a fuel tax and a Bonus scheme; although it may create a subsidised economy. This is indeed one of the shortcomings of partial equilibrium models.

Appendix

G – Market equilibriums description

In Tables G.1 and G.2 we display the variables related to the demand-side first and to the supply-side then, that characterise the market equilibrium.

Table G.1: Distances travelled, utilities and emissions at the market equilibriums

Package of techno fitted in the clean vehicle	Clean vehicle's fuel cons. (L/100km)	Distance covered with the clean vehicle (km)	Direct utility of the clean vehicle's owner	Share of clean vehicles	Average direct utility	Average total of emissions ($kgCO_2$)
(e_0, ty_a)	5.17	8,015	31,088	0,5005	31,088	971.48
(e_0, ty_b)	5.09	8,130	31,090	0,5010	31,088	971.36
(e_0, ty_c)	5.02	8,249	31,091	0,5015	31,089	971.23
(e_a, ty_0)	5.01	8,255	31,091	0,5014	31,089	971.22
(e_b, ty_0)	4.79	8,639	31,094	0,5029	31,091	970.83
(e_c, ty_0)	4.56	9,061	31,099	0,5046	31,093	970.41
(e_a, ty_a)	4.94	8,377	31,092	0,5019	31,090	971.10
(e_a, ty_b)	4.86	8,502	31,093	0,5024	31,090	970.97
(e_a, ty_c)	4.79	8,632	31,094	0,5029	31,091	970.84
(e_b, ty_a)	4.71	8,773	31,096	0,5034	31,091	970.69
(e_b, ty_b)	4.64	8,911	31,097	0,5040	31,092	970.56
(e_b, ty_c)	4.56	9,053	31,098	0,5045	31,093	970.42
(e_c, ty_a)	4.49	9,209	31,100	0,5051	31,094	970.27
(e_c, ty_b)	4.41	9,361	31,101	0,5056	31,094	970.13
(e_c, ty_c)	4.34	9,518	31,103	0,5062	31,095	969.99

We draw the reader's attention to the fact that each row in Table G.2 corresponds to a given vehicle. Accordingly, in no case, the pairs formed by the market price of the clean vehicle (P^c) and the share of the clean vehicles (α^v) can be compared in order to obtain a supply curve. Likewise, caution is needed to derive a supply curve for technologies since every row do not necessarily correspond to the same clean technology.

Table G.2: Market prices and profits at the market equilibriums

Package of techno fitted in the clean vehicle	**Clean vehicle's fuel cons. (L/100km)**	**Clean vehicle's price (€)**	**Clean tyre's price (€)**	**Clean engine's price (€)**	**Share of clean tyres**	**Share of clean engines**	**Share of clean vehicles**	**Profit of the tyre manuf. (€)**	**Profit of the engine manuf. (€)**	**Profit of the car maker (€)**	**Total profit (€)**
(e_0, ty_a)	5.17	18,960	267	<0	0,5005	0,0000	0,5005	176	712	12,620	13,508
(e_0, ty_b)	5.09	19,003	284	<0	0,5010	0,0000	0,5010	181	712	12,637	13,530
(e_0, ty_c)	5.02	19,047	301	<0	0,5015	0,0000	0,5015	185	712	12,655	13,552
(e_a, ty_0)	5.01	19,051	<0	1,961	0,0000	0,5014	0,5014	94	1,323	12,654	14,071
(e_b, ty_0)	4.79	19,190	<0	2,023	0,0000	0,5029	0,5029	94	1,340	12,708	14,143
(e_c, ty_0)	4.56	19,335	<0	2,085	0,0000	0,5046	0,5046	94	1,358	12,766	14,218
(e_a, ty_a)	4.94	19,096	268	1,963	0,5019	0,5019	0,5019	177	1,324	12,672	14,173
(e_a, ty_b)	4.86	19,141	285	1,966	0,5024	0,5024	0,5024	181	1,325	12,690	14,196
(e_a, ty_c)	4.79	19,187	302	1,968	0,5029	0,5029	0,5029	185	1,327	12,708	14,220
(e_b, ty_a)	4.71	19,237	269	2,025	0,5034	0,5034	0,5034	177	1,342	12,727	14,246
(e_b, ty_b)	4.64	19,284	286	2,028	0,5040	0,5040	0,5040	182	1,343	12,746	14,270
(e_b, ty_c)	4.56	19,332	303	2,031	0,5045	0,5045	0,5045	186	1,344	12,765	14,295
(e_c, ty_a)	4.49	19,384	270	2,088	0,5051	0,5051	0,5051	178	1,360	12,785	14,322
(e_c, ty_b)	4.41	19,434	287	2,091	0,5056	0,5056	0,5056	182	1,361	12,805	14,348
(e_c, ty_c)	4.34	19,484	304	2,094	0,5062	0,5062	0,5062	187	1,363	12,825	14,374

Additionally, from Table G.2, it can be derived that the suppliers' strategies are strategic complements. Mathematically, the actions of two producers i and j – termed a^i and a^j – are strategic complements when:

$$\left(\pi^i(a_2^i) - |a_1^j\right) - \left(\pi^i(a_1^i)|a_1^j\right) < \left(\pi^i(a_2^i)|a_2^j\right) - \left(\pi^i(a_1^i)|a_2^j\right) \quad \text{(H.1)}$$

where π^i is the producer i's profit; and a_2^i (respectively a_2^j) is a more 'aggressive' action than a_1^i (respectively a_1^j).

We use this definition in our case. In this regard, let us note that producing the cleanest technology (indexed by "c") is the most aggressive strategy.

Table G.3: The FTSs' strategies as strategic complements

Differences in tyre manuf.'s profit when:	e_a is produced	e_b is produced	e_c is produced
$\pi^{ty_c} - \pi^{ty_b}$	€4.36	€4.40	€4.44
$\pi^{ty_b} - \pi^{ty_a}$	€4.34	€4.38	€4.42
$\pi^{ty_c} - \pi^{ty_a}$	€8.70	€8.78	€8.86
Differences in engine manuf.'s profit when:	ty_a is produced	ty_b is produced	ty_c is produced
$\pi^{e_c} - \pi^{e_b}$	€17.89	€18.02	€18.15
$\pi^{e_b} - \pi^{e_a}$	€14.45	€15.57	€17.68
$\pi^{e_c} - \pi^{e_a}$	€35.35	€35.59	€35.83

General Conclusion

1. Synthesis of the Thesis

The main objective of this Thesis was to better understand the extent to which the distinctive features of the transport sector modify the relevance of policy tools aiming at cutting CO_2 emissions produced by car use. We proceed with a three-stage approach: successively examining the supply-side, the demand side, and the equilibrium in the car market. The key messages formulated in this Thesis are the following.

Full cooperation among members of the automotive sector is not a credible substitute for policy intervention to ensure the production of the most fuel-efficient vehicles

Focussing on the supply-side of the car market, our first finding was that car makers and automotive suppliers, in reacting to the imperatives of demand and supply, do not systematically equip new vehicles with high energy-efficient equipment to optimize fuel consumption. This is because the car maker's incentive to fit new vehicles with high energy-efficient equipment is a function of the demand for low fuel-consuming vehicles. When such demand is relatively low, a full cooperation on vehicle design between car makers and their suppliers is sufficient to make them produce the least-fuel consuming vehicle. However, there is no guarantee that manufacturers individually are interested in cooperating. In that respect, public authorities have to encourage manufacturers to do so. To this end, they can resort to *technology push* measures (*e.g*. competitiveness clusters, R&D aids, and so on). Interestingly, this result suggests that cooperation among producers is not a credible substitute for policy tools. By contrast, when the demand for 'clean' vehicles is relatively high, the "cleanest" vehicle is produced regardless of the nature of cooperation. Therefore, public authorities should encourage more people to purchase a 'clean' vehicle; this would indeed promote a scenario whereby the 'cleanest' vehicle is produced whatever the cooperation strategies of the producers. Policy instruments capable of addressing this issue are the *market pull* measures, including incentive-based mechanisms (*e.g*. Bonus-Malus), command and control levers (*e.g*. Low Emission Zones), and knowledge policies (*e.g.* labels).

To evaluate the efficiency of the latter *market pull* measures, an in-depth analysis of the demand-side of the car system is required. The second Chapter was dedicated to this particular analysis. This is particularly pertinent given that another relatively significant factor impacting on total of CO_2 emissions from road transportation is the distance travelled by car (*i.e.* "transportation Activity" in ASIF).

Car usage taxes are more efficient than differentiated purchase taxes in reducing passenger vehicles' CO_2 emissions because of the rebound effect

On the demand-side, people tend to use their cars more intensively when they are more fuel-efficient, since the cost per kilometre is reduced. This increased mileage refers to the well-known "*rebound effect*", that is to say an increase in demand induced by efficiency gains. A differentiated car purchase tax may create a rebound effect by improving the average fuel efficiency of the fleet. Whether the rebound effect happens or not actually depends on the gap in market prices and unit consumptions of the different vehicles for sale. Interestingly, we have shown that – where it exists – the rebound effect increases with the level of Malus. Said another way, efficiency of the tax decreases with the level of tax. We have also found that adding a fuel tax helps limit the rebound effect, and thus enhances the reductions in CO_2 emissions achieved via the purchase tax. This happens because the fuel tax reduces the overall car mileage. Finally, we argued that a fuel tax is relatively efficient because it is capable of providing by itself the same reduction than a policy mix made up with the fuel tax and the Malus scheme.

In any case, the reduction in CO_2 emissions is not the single objective of public authorities. We discussed in the last Chapter of this Thesis the capacity to simultaneously serve several objectives with one or several policy instruments.

Combining a fuel tax and a Bonus scheme enables policy-makers to reduce CO_2 emissions while improving the households' well-being and the automotive sector's profit

Implementing a fuel tax makes motorists revise downwards the distances they travel by car. If it helps cut CO_2 emissions due to car use, it also leads to a loss of utility for households from the moment that the consumption of miles driven is of value to them. In view of this trend, applying a Bonus on the purchase of low fuel-consuming vehicles seems to be an interesting additional incentive-based mechanism insofar as it improves the average households' utility (by decreasing the car purchase cost). What is more, setting up such a differentiated car purchase subsidy also leads to a growth of the automotive sector's profit (by increasing the market prices of 'clean' vehicles and technologies). We thus advocated in the end for the simultaneous implementation of a fuel tax and a Bonus scheme; notably by demonstrating that effects on CO_2 emissions of these two incentive-based mechanisms are synergetic.

2. Related issues and research opportunities

This Thesis allows policy-makers' objectives and instruments aimed at cutting CO_2 emissions from passenger vehicles to be put into context. Notably, the value of car usage charges, such as fuel taxes, has been demonstrated

Implementing car usage charges instead of car purchase taxes should be even more relevant in the next years if account is taken of the still marginal but growing trend away from personal possession of one's own vehicle. In fact, until recently, one could argue that the cultural preference for private property was part of the societal characteristics that helped stabilise the 'automobility regime' (Geels, 2012). To some extent, users were actually influenced by non-economic variables such as social norms, prestige or fashion. However, given that the 'sociological effect' of owning a car is no longer as strong as it used to be [except in countries where being motorized is not yet the rule] (Dupuy, 1999) provides an explanation for the emergence of new services such as car-pooling, car sharing and car renting. Simultaneously, individuals seem to be less and less inclined to bear the costs of driving a private car. Both monetary and non-monetary costs are indeed going up. Individuals tend to rent a vehicle when monetary costs increase; especially when the owning cost rises (*i.e.* purchase price and taxes, depreciation cost, insurance cost and so on). The owning cost is actually increasingly considered to be too high by consumers who now have the opportunity to bear only the usage cost (*i.e.* fuel cost, parking fees, etc.). This is particularly valid given the increasing availability of public transports, which is leading to multimodality that results in a lower car use. In fact, the logic behind this is that there is a diminishing interest in purchasing a durable good that is not used as much; insofar as it becomes increasingly difficult to make the initial investment profitable. We draw the reader's attention to the fact that this behavioural change has implications on the supply-side of the automotive system: from the moment that the car is used by more than just the members of a given household, new business models appear. On the one hand, cars are likely to be more intensively used, meaning that they need to be designed in a different manner. On the other hand, cars are now purchased by firms (*i.e. Business to Business*) which behave differently from households (*i.e. Business to Consumers*). Indeed, the car purchase decision of firms is based on the minimisation of the Total Cost of Ownership (further discussed in Meurisse, 2014) while that of households is based on the maximisation of utility. This distinction has to be considered by car manufacturers; all the more so because the share of newly registered vehicles being fleet vehicles (*i.e.* rental vehicles, distribution vehicles, and company cars) has risen steadily in France from about 25% in the early 1990's to reach 43% in

2012 (OVE, 2012). Interestingly, researchers have also to modify the way they model car choices. While considering vehicles as more or less risky assets, research works dealing with the portfolio theory could be useful (see for instance Ansaripoor and al., 2014).

In this regard, it is true that attention has initially been paid to technological innovations, but the idea that behavioural changes can help achieve low-carbon mobility has become more widespread. This is the example of the development of car sharing or carpooling practices. Another structural change is the reductions in travelling that is partly facilitated by the development of static activities (for example home working) including *'e-activities'* (*e.g.* e-shopping, e-working, etc.); the development of which is not to be ignored, because it certainly reduces the stress of travelling. However, a thorough analysis of the potential of e-mobility as a means of achieving aggregate European and national commitments to reductions in GHG is required. Indeed, were individuals to consume less fuel by avoiding certain journeys, they might potentially increase their Internet use, so that the total consumption of energy would not necessarily be reduced. To a certain extent, this is also a question of substitution effects; this time among different energy uses, instead of among different energy sources for a given use (*e.g.* diesel *versus* petrol for cars), as more generally studied in existing research works. That said, it would be highly relevant to think at a larger scale than the sole transport sector. Dealing with the public intervention, the main reason supporting a larger scope of analysis is that all sectors cannot be subsidised. Using a general equilibrium model would, in this regard, enable to highlight the trade-offs to be made between sectors.

Additionally, new services (car sharing but also e-shopping, etc.) clearly illustrate that, if public authorities have policy instruments at their disposal to reduce CO_2 emissions in the transport sector, it happens that in parallel private players of the transport sector but also of another sectors (energy, new technologies of information and communication, etc.) can also develop internal tools to make the transition to low-carbon mobility easier. Sometimes, however, the response of private actors requires the involvement of public authorities (cf. for example the need for a legal framework for car-sharing, or the different kinds of support for innovation). But, the opposite is also true; and public decision-makers increasingly call on the private sector for funding and expertise (*e.g.* Public-Private Partnership). Overall, public and private players are together mapping the transition towards low-carbon mobility. One of the major issues is to decide how the transition process can be accelerated. In fact, the division of responsibilities for transport explains why the public decision-making process is generally slow; in respect of environmental policies, the process is further delayed by the difficulty in obtaining the data necessary to carry out prior economic evaluations (quantifying CO_2 emissions for example). It is indeed true that, as well as the difficulty in reaching a political consensus between decision-makers, there is also the challenge of sharing information openly. Building the regulatory framework in cooperation with the different stakeholders of the system could thus turn out to be a real driving force in transforming the sector in the pursuit of sustainable mobility. As a matter of fact, a better cooperation among actors appears as the only way to create "win-win" development in the industry. The rationale is two-fold. Firstly, individuals involved in the decision-making process should be more sensitive to collective issues. Secondly, private players who have themselves adopted proactive strategies will no doubt be better placed to turn these public policies into real economic opportunities, rather than constraints. Finally, one of the future research directions is to investigate more deeply the decision-making process underlying the policy design, in order to identify success factors for policies which are peculiar to the designing process of the latter policies. This issue is sufficiently interesting and complex to warrant separate studies, definitively beyond the ambition of the present research.

Résumé substantiel de la Thèse

Cette Thèse s'intéresse aux politiques publiques permettant de réduire les émissions de CO_2 liées à l'usage des véhicules particuliers. Les éléments de contexte ayant guidé notre réflexion vers la question de recherche de ce travail sont exposés dans la section introductive ci-dessous. Dans cette première section, nous discutons également l'approche méthodologique retenue dans cette Thèse, à savoir une modélisation théorique en équilibre partiel et statique du marché automobile (cf. 1.). Puis, dans une seconde section, nous présentons la structure de la Thèse ainsi que les principaux messages de ses différents Chapitres (cf. 2.). Enfin, des problématiques proches, dont la prise en compte pourrait constituer l'objet d'extensions possibles à ce travail, sont abordées dans la dernière section (cf. 3.).

1. Eléments d'introduction

1.1. Contexte et motivations de la Thèse

La forte probabilité de l'origine anthropique du réchauffement climatique, via les émissions de gaz à effet de serre (GES), fut confirmée en 2013 par le Groupe d'Experts Intergouvernemental sur l'Evolution du Climat dans leur cinquième rapport. Le réchauffement climatique et ses impacts – tels qu'une montée du niveau des mers, des inondations, une perte de biodiversité, de mauvaises récoltes, etc. – constituent autant d'externalités que l'on peut qualifier de menaçantes pour nos sociétés. C'est pourquoi, au cours des deux dernières décennies, la nécessité d'infléchir les émissions de GES pour éviter les risques d'un réchauffement de la planète supérieur à 2°C est rappelée chaque année lors des Conférences des Parties de la Convention Cadre des Nations Unies sur les Changements Climatiques. Au-delà de cette hausse des températures, tout le monde s'accorde sur le fait que les impacts du réchauffement climatique menaceront le bien-être de nos sociétés. Aussi, l'objectif de maintenir le réchauffement mondial en deçà de 2°C a été approuvé par l'Accord de Copenhague en 2009 lors de la quinzième Conférence des Parties (COP 15). Depuis, l'IPPC a alerté la communauté internationale sur le fait, qu'en 2015, plus des deux tiers du « budget carbone » ont d'ores et déjà été consommés. Ce « budget carbone » correspond au cumul d'émissions de CO_2 d'origine anthropique depuis le début de la révolution industrielle (environ 3 000 milliards de tonnes) ne devant pas être dépassé de manière à limiter la hausse de la température à +2°C (dans de Perthuis et Trotignon, 2015).

La réduction d'émissions de GES requise pour satisfaire l'objectif des +2°C nécessite de nouveaux modes d'opération et de développement pour le secteur des transports. De tels changements entrent dans le champ des actions d'*atténuation* du changement climatique dans la mesure où ils portent sur les causes du réchauffement climatique, tandis que les actions d'*adaptation* portent sur les effets du réchauffement climatique sur nos sociétés. Dans cette Thèse, nous choisissons de nous intéresser aux actions d'*atténuation*. A ce sujet, il est à noter que la France a adopté, dans la Loi Grenelle I, l'objectif de réduire ses émissions de gaz à effet de serre de 23% par rapport aux niveaux de 1990 et notamment celles du secteur des transports de 20% d'ici 2020 (JORF, 2009). Ce dernier objectif revient à ramener les émissions du secteur des transports à leur niveau de 1990 d'ici 2020. A l'échelle européenne, le plan dit des « 3 fois 20 » d'ici 2020 (*i.e.* 20% de baisse des émissions, 20% d'énergies renouvelables et 20% d'économies d'énergie) adopté en 2009 fut actualisé en 2014 et affiche comme objectifs d'ici 2030 : 40% de réduction des émissions, 27% d'énergies renouvelables et 27% d'économies d'énergie.

Le secteur des transports mérite une attention particulière dans la mesure où les activités de transport contribuent à hauteur de 29% et 24% aux émissions de GES respectivement en France et en Union Européenne en 2010 (Commission Européenne, 2013a). Cela place le secteur des transports en tête des secteurs les plus émetteurs en France, et en deuxième position de ce même classement, derrière le secteur de l'énergie, à l'échelle européenne. En termes d'émissions de CO_2, la responsabilité du secteur des transports est davantage marquée qu'en termes de GES[101]. En France, les activités de transport représentent 38% des émissions de CO_2 tous secteurs confondus en 2010. C'est le premier secteur émetteur de CO_2, devant le secteur des bâtiments résidentiels et tertiaires (26%) et l'industrie manufacturière (25%)[102]. Au sein du secteur des transports, le mode routier domine largement en termes d'émissions de CO_2, puisqu'il représente à lui seul 80.2% en 2010 en France (Commission Européenne, 2013a). A un niveau plus fin d'analyse, on note que les véhicules particuliers pèsent pour 57.4% dans les émissions du transport routier ; le reste étant divisé entre les véhicules lourds (23.2%), les véhicules utilitaires (18.1%) et les deux roues (1.3%) (également en France en 2010 ; CGDD, 2012).

[101] Les principaux gaz à effet de serre sont la vapeur d'eau (H_2O), le dioxyde de carbone (CO_2), le méthane (CH_4), le protoxyde d'azote (N_2O), l'ozone (O_3) ou encore les hydrocarbures halogénés pour les gaz à effet de serre industriels.

[102] Les émissions de GES et de CO_2 par secteur, au format « Plan Climat » en France (périmètre Kyoto) sont disponibles à l'adresse suivante : http://www.developpement-durable.gouv.fr/Part-et-evolution-des-secteurs.html.

1.2.Problématique de la Thèse

Dans cette Thèse, nous nous n'intéressons aux émissions de CO_2 liées à l'usage des véhicules particuliers. Notre question de recherche est la suivante : Quels instruments de politique publique, ciblant les décisions de production, d'achat et d'usage des véhicules particuliers, sont les plus efficaces dans la lutte contre les émissions de CO_2 liées à l'usage des véhicules particuliers ?

Le réchauffement climatique est en effet l'un des enjeux les plus importants du 21ème siècle. C'est à ce titre qu'il justifie une intervention publique. De nombreux aspects du secteur automobile doivent néanmoins être pris en compte lorsqu'il s'agit d'instaurer des instruments de politique publique, à savoir :

- le nombre important d'acteurs de la filière automobile (*i.e.* constructeurs automobiles et divers équipementiers et fournisseurs), auxquels viennent s'ajouter de nouveaux acteurs de plus en plus diversifiés (notamment les acteurs du secteur des nouvelles technologies de l'information et de la communication, ou encore les énergéticiens) ;
- le lien entre décision d'achat et décision d'usage d'un véhicule particulier, à l'origine du phénomène d'effet rebond, comme nous l'expliquerons par la suite ;

et du point de vue des décideurs publics :

- le fait que le transport fasse l'objet d'une demande dérivée, en ce sens qu'il n'est généralement pas demandé pour lui-même, mais est très largement impliqué dans la consommation d'autres biens ; ce qui explique que le transport génère des externalités positives (notamment des économies d'agglomération), et par conséquent des bénéfices pour d'autres secteurs ;
- le fait que l'usage des véhicules particuliers génère un ensemble d'externalités négatives qui sont inter reliées (pollution locale, pollution globale, congestion, accidents, bruit, etc.), de sorte qu'il est impossible de ne cibler que l'une d'entre elles.

Pour tenir compte de ces caractéristiques du secteur du transport, les autorités publiques ont à leur disposition, pour lutter contre les émissions de CO_2 résultant de l'usage de véhicules privés, un large panel d'instruments de politique publique.

Premièrement, chaque instrument peut cibler soit la demande, soit l'offre du marché automobile ou plus largement du système de transport routier. Par exemple, certains instruments s'appliquent plus précisément :

- aux usagers de la route : limitation de vitesse, zone à faibles émissions, politique de stationnement, taxes portant sur l'achat, la possession ou l'usage d'un véhicule, etc.

- aux acteurs industriels : normes d'émissions de CO_2, contenu minimum de biocarburants, label sur les pneumatiques, etc.
- aux professionnels du secteur des transports : obligation d'information sur les émissions de CO_2 des services de transport, formation à l'éco-conduite, etc.
- aux autorités publiques elles-mêmes : normes sur les infrastructures publiques de recharge pour véhicules électriques, etc.

Deuxièmement, les outils de politique publique peuvent être soit réglementaires, c'est-à-dire contraignants (*e.g.* zone à faible émissions, restriction du stationnement, etc.), soit économiques, ou autrement dit « incitatifs » (*e.g.* taxes à l'achat du véhicule, taxes sur le carburant, péage urbain, tarification des transports en commun, etc.). Aussi, si les instruments de la première catégorie peuvent être assimilés au « bâton », ceux de la deuxième catégorie peuvent jouer à la fois le rôle de « bâton » (pénalité à l'achat d'un véhicule polluant par exemple) ou celui de « carotte » (subvention à l'achat d'un véhicule électrique par exemple). Par ailleurs, il existe également des instruments de type « collaboratif » (tels que les partenariats publics privés ou les commandes publiques) ou « informatif » (tel que le label sur la consommation d'énergie et d'émissions de CO_2 des véhicules particuliers).

Compte tenu des caractéristiques du secteur des transports, de la diversité des instruments de politique publique s'appliquant à ce secteur et de la forte contribution des véhicules particuliers aux émissions de CO_2, la boite à outils du décideur public fait l'objet de multiples travaux de recherche et a d'ores et déjà été étudiée sous différentes perspectives. Cette Thèse s'intéresse également aux instruments de politique publique permettant de réduire les émissions de CO_2 des véhicules particuliers, à leur type, leur champ d'application et leur pertinence. Plus précisément, nous cherchons à déterminer quelle intervention publique est la plus efficace en tenant compte des décisions de production, d'achat et d'usage du véhicule.

1.3. Approche retenue pour répondre à la problématique

Pour répondre à notre problématique qui est de déterminer quelle est la meilleure intervention publique pour diminuer les émissions de CO_2 provenant de l'utilisation des voitures tout en tenant compte des étapes de production, d'achat et d'usage de ces dernières, notre approche consiste en une modélisation en équilibre partiel et statique du marché automobile. Ce choix est explicité dans les paragraphes suivants.

Notre approche permet premièrement d'examiner la complémentarité de divers outils de politique publique de façon plus approfondie qu'une approche empirique. Cela est particulièrement intéressant compte tenu de la tentation des autorités publiques à combiner plusieurs instruments étant donné d'une part l'importante boite à outils dont elles disposent, et d'autre part la taille de l'enjeu lié aux émissions de CO_2 des véhicules particuliers. Les effets de différentes politiques ne sont cependant pas nécessairement toujours additifs. Ces effets peuvent s'atténuer les uns les autres, ce qui réduit l'efficacité globale du système ; mais ils sont aussi susceptibles de s'auto-amplifier et l'efficacité globale s'en trouve dans ce cas renforcée. Déterminer dans quelle configuration nous sommes nécessite des informations quant aux effets des instruments mis en place isolément, mais également de façon combinée. Disposer de ces deux types d'information à la fois n'est pas possible dans le cadre d'une approche empirique, puisque cette dernière repose sur l'observation de données réelles ; autrement dit exclusivement sur l'observation des effets de la politique effectivement mise en place, qu'il s'agisse ou non d'une combinaison d'instruments.

La question de la complémentarité des instruments de politique publique est en effet abordée dans cette Thèse. Précisément, l'analyse de la complémentarité des instruments tarifaires portant sur l'achat et l'usage des véhicules fait l'objet du deuxième Chapitre. Cette problématique a d'ores et déjà été abordée dans la littérature économique. A tire d'illustration, De Borger (2001) perçoit la combinaison d'une taxe à l'achat et d'une taxe à l'usage comme étant un « tarif à double volet » et questionne l'impact de la nature de l'externalité[103] ainsi que celui de l'hétérogénéité des ménages sur la définition optimale de ce tarif à double volet. Notre contribution à la littérature diffère de celle de De Borger (2001) : l'accent est porté sur le lien existant entre la demande de véhicule et la demande de kilomètres – soient les deux décisions ciblées par les instruments de politique publique – en général, et sur la raison pour laquelle cette interdépendance entre ces deux décisions doit être prise en compte dans la conception de l'intervention publique en particulier. Comme nous l'expliquerons dans le Chapitre 2, la perte d'efficacité d'une taxe différenciée à l'achat d'un véhicule s'explique par le phénomène d'effet rebond ; cet effet justifiant alors la mise en place simultanée d'une taxe à l'usage (voir 2.2.).

[103] Toute sorte d'externalité ne s'accompagne pas nécessairement d'effet retour sur la demande de véhicules. La congestion et les risques d'accidents sont des externalités liées à l'usage des véhicules qui impactent la demande de véhicule, notamment sur le long terme, parce qu'elles influencent le désir de posséder un véhicule. A l'inverse, la pollution globale affecte le bien-être des automobilistes mais aussi celui des individus ne possédant pas de véhicules, et de ce fait n'aura surement pas d'impact sur la demande de véhicules et de kilomètres (De Borger, 2001).

Ensuite, avoir recours à une modélisation en équilibre partiel signifie que nous raisonnons à la fois sur le côté offre et le côté demande du marché automobile sans toutefois considérer les interactions entre ce marché et le reste de l'économie. Cette restriction s'explique en partie par notre intérêt pour uniquement deux des quatre leviers de réduction des émissions de CO_2 des activités de transport, à savoir la réduction de la consommation unitaire des véhicules et la diminution des distances parcourues en voiture. En effet, d'une part, l'étude de l'offre de véhicules nous permet de mettre l'accent sur le choix des performances énergétiques des nouveaux véhicules opéré par les membres de la filière automobile, alors que la réduction de l'intensité énergétique des différents modes de transport constitue précisément un levier important de réduction d'émissions du transport. Ce levier est également appréhendé à travers l'analyse de la demande de véhicules, dans la mesure où seuls les technologies et véhicules effectivement vendus composent le parc roulant ; soit celui qui détermine le montant total d'émissions. D'autre part, l'analyse de la demande permet de tenir compte du second levier de réduction des émissions du transport qu'est la réduction des distances parcourues.

Les deux autres leviers de réduction des émissions du transport que nous n'abordons pas ici sont « un changement de répartition modale en faveur des modes bas carbone » et « une baisse du contenu CO_2 de l'énergie » des différents modes de transport.

La non prise en compte du levier « répartition modale » se justifie par notre souhait de centrer notre analyse exclusivement sur les véhicules particuliers et le marché automobile, sans tenir compte de la diversité des autres modes de transport, et par conséquent de la multiplicité des autres acteurs du système de transport. De plus, nous centrons notre analyse sur les automobilistes faisant l'achat d'un nouveau véhicule (cf. 2.2.). Cela implique qu'une seule partie de la population est étudiée ici. Par conséquent, les hypothèses généralement utilisées dans les modélisations en équilibre général – selon lesquelles par exemple l'instauration d'une nouvelle subvention se traduit par une hausse des taxes sur les ménages – n'ont pas lieu d'être[104].

En ce qui concerne notre non prise en compte du levier « contenu CO_2 de l'énergie », cela signifie que la question des effets de substitution entre énergies (notamment entre diesel et pétrole) n'est pas abordée ici. Aussi, une modélisation précise du secteur de l'énergie ne présente pas un intérêt marqué dans ce travail. En réalité, dans l'analyse de l'industrie automobile proposée dans le premier Chapitre de cette Thèse, nous ne développons pas un

[104] Clairement, puisqu'une subvention introduite dans notre modélisation ne concerne qu'une partie de la population (par exemple un Bonus à l'achat d'un véhicule), alors que sa charge est supportée par l'ensemble de la population, la charge au niveau individuel reste faible et peut donc être négligée dans notre travail.

modèle précis en termes d'innovations technologiques. L'accent est davantage porté sur l'impact d'une décision d'un producteur sur la décision des autres producteurs de la filière. Le principal argument est que là aussi les comportements sont tout aussi importants que les technologies dans la poursuite d'une mobilité bas-carbone ; si ce n'est pas plus, compte tenu du fait que les nouvelles technologies ne permettront de réduire les émissions que si elles sont effectivement adoptées par les industriels en aval de la filière ou par les consommateurs finaux.

Finalement, le fait de ne considérer qu'un type de véhicule (en fait, une seule motorisation) et qu'une seule partie de la population (les individus achetant un nouveau véhicule) met clairement en évidence le fait que cette Thèse n'a pas pour ambition de dessiner des scénarios en termes de réductions d'émissions de CO_2 liées à l'usage des véhicules particuliers. C'est pour cette raison que notre modélisation reste statique. Raisonner en dynamique aurait introduit une certaine complexité à la fois dans la modélisation et dans l'interprétation des résultats, sans pour autant permettre de proposer de tels scénarios.

Les choix de modélisation seront discutés plus précisément dans la partie suivante, qui présente la structure de la Thèse ainsi que ses principaux messages.

2. Structure de la Thèse et principaux messages

Cette Thèse est composée de trois Chapitres. Le premier Chapitre porte sur le côté offre du système automobile, c'est-à-dire sur les constructeurs automobiles et leurs équipementiers. Le deuxième Chapitre traite de la demande, c'est-à-dire des consommateurs finaux, et plus précisément des automobilistes. Enfin, le troisième et dernier Chapitre étudie le système automobile à son équilibre. Dans chaque Chapitre, divers instruments de politique publique permettant de réduire les émissions de CO_2 liées à l'usage des véhicules particuliers sont discutés.

Les motivations de chaque Chapitre, ainsi que les choix de modélisation et les principaux résultats sont exposés dans les trois sous-parties ci-dessous.

2.1. Dans quelle mesure une coopération entre membres de la filière automobile est un substitut à une intervention publique pour assurer la production des véhicules les plus efficients sur le plan énergétique ?

Le premier Chapitre est consacré à l'analyse côté offre du système automobile. Son originalité tient à la prise en compte de l'existence de divers acteurs industriels pouvant influer sur la performance énergétique des nouveaux véhicules (*i.e.* constructeurs automobiles et équipementiers divers).

Un véhicule particulier est en effet le résultat de l'assemblage d'environ 50 modules (Frigant, 2013), résultant eux-mêmes de l'assemblage d'environ 15 000 voire 20 000 composants selon les modèles (Frigant et Talbot, 2004). Une multitude d'acteurs industriels participe donc à la production d'un véhicule. De plus, la part des achats dans le prix de revient de fabrication d'un véhicule est de nos jours de l'ordre de 75 à 80% (Frigant, 2007). Ainsi, les constructeurs automobiles ne sont plus que des « acheteurs de technologies », et les équipementiers ont un rôle de plus en plus important dans la définition du véhicule. Cela est d'autant plus vrai en raison du transfert de responsabilités vers un nombre de plus en plus restreint d'équipementiers, qui résulte du développement de la modularisation dans le secteur automobile. Parmi les équipementiers, plusieurs d'entre eux peuvent agir sur la performance énergétique (c.-à-d. la consommation unitaire) des nouveaux véhicules ; notamment parce qu'il existe plusieurs forces de résistance à l'avancement d'un véhicule. On distingue la résistance aérodynamique, la résistance liée à la masse, la résistance au roulement des pneumatiques, et les frottements internes. Les efforts accomplis pour réduire chacune de ces forces de résistance participent par conséquent à l'atteinte d'un même objectif, *i.e.* réduire la consommation unitaire des nouveaux véhicules.

Toutefois, les externalités environnementale et de connaissance expliquent qu'en l'absence d'intervention publique, les investissements privés permettant de réduire les émissions de CO_2 au kilomètre des nouveaux véhicules des équipementiers et constructeurs automobiles sont sous-optimaux !
La connaissance est en effet une externalité en raison de ses propriétés de non-rivalité (*i.e.* reproduire la connaissance n'entraine pas de coût supplémentaire) et de non-exclusion (*i.e.* priver quelqu'un de la connaissance serait trop coûteux). Ces deux propriétés sous-tendent le *dilemme de la connaissance* qui peut être résumé de la façon suivante :

« *Puisque les agents s'attendent à bénéficier des connaissances accumulées par les autres agents grâce aux externalités de connaissance, ils ne s'engagent pas eux-mêmes dans la création de nouvelles connaissances. Dans le même temps, l'absence de coût de reproduction de la connaissance se traduit par un prix de la connaissance égal à zéro. Le paradoxe apparait dès lors que les entreprises, étant à la recherche de profit, exigent un prix positif pour investir en recherche et développement (R&D)* » (traduit par l'auteur, à partir de Bonnet et Renner, à paraitre ; p5).

Dit autrement, l'externalité de connaissance signifie que le taux de retour sur investissement social est supérieur au taux de retour sur investissement privé. Cet écart explique précisément pourquoi les investissements privés sont sous-optimaux.

Par ailleurs, l'environnement souffre lui aussi d'externalités ; négatives cette-fois. La pollution est l'un des exemples d'externalités environnementales les plus discutés. En raison d'une mauvaise voire d'une absence de tarification de la pollution, le coût social associé à la production ou à la consommation de biens polluants (tenant compte des effets néfastes de la pollution sur l'environnement, le bâti, la santé, etc.) est plus élevé que le coût privé associé.

Finalement, selon Nordhaus (2011) :

« *La double externalité associée aux technologies permettant de lutter contre le réchauffement climatique résulte du fait que les taux de retour sur investissement sociaux sont bien au-delà des taux de retours privés, et les taux de retours privés sont limités parce que le prix de marché du carbone est bien en-deçà de son vrai coût social* » (traduit de l'auteur, p667).

En ce qui concerne l'enjeu environnemental, c'est la diversité des acteurs à même de pouvoir participer aux efforts de réduction de la consommation unitaire des véhicules qui pose la question de l'intérêt ou non d'une coopération entre acteurs industriels au sein d'une filière automobile qui se doit de participer aux efforts de lutte contre le réchauffement climatique. Précisément, la question de recherche de ce premier Chapitre est de déterminer si une coopération entre constructeur automobile d'une part et divers équipementiers d'autre part conduit à la production de véhicules plus économes en carburant qu'en l'absence de coopération. Dans une certaine mesure, l'analyse proposée dans ce Chapitre permet également de déterminer si cette coopération est un substitut ou non à l'intervention publique.

D'une part, l'analyse est inspirée de la théorie des coalitions, et plus précisément de la branche de cette théorie dans laquelle la décision individuelle de coopérer ou non repose sur la maximisation du profit individuel. Dans ce cas, la coopération n‘est envisageable uniquement dès lors qu'il existe un gain (en termes de profit) à la coopération. Cela implique que la somme des profits des membres de la coopération ne doit pas être inférieure à la somme des profits de ces acteurs lorsqu'ils ne coopèrent pas (c'est la propriété de super-additivité). D'autre part, l'analyse repose sur la modélisation du comportement d'un constructeur automobile et de deux équipementiers, pour qui la performance énergétique des biens qu'ils produisent (véhicules ou technologies) est une variable de décision importante. Cette modélisation est propre à l'auteur et n'est pas tirée de travaux existants. Enfin, la présentation du modèle est accompagnée d'un exercice de simulation, facilitant l'interprétation des résultats.

Les résultats montrent qu'en l'absence d'intervention publique, le libre jeu des constructeurs et fournisseurs automobiles ne conduit pas toujours à la production du véhicule le plus économe en carburant étant donné les technologies disponibles. Il est en effet mis en évidence, dans ce premier Chapitre, que l'incitation du constructeur à équiper ses véhicules d'équipements performants sur le plan énergétique dépend de la demande de véhicules économes en carburant à laquelle il fait face. Schématiquement, nous pouvons distinguer deux cas :

- Lorsque cette demande est relativement faible, seule une coopération totale entre membres de la filière automobile en ce qui concerne le choix des performances énergétiques des équipements garantit la production du véhicule le plus économe en carburant. Toutefois, le fait que chaque producteur ait intérêt à coopérer n'est pas certain. En réalité, pour certains niveaux de demande, la coopération n'est pas stable, dans la mesure où il existe au moins un producteur pour lequel il n'est pas rentable de coopérer. Ce résultat justifie l'intervention des pouvoirs publics, telle que la mise en place d'instruments de type « *technology push* ». Ces instruments agissent sur le processus d'innovation à l'origine de l'amélioration des technologies et prennent notamment la forme d'aides à la Recherche & Développement, de brevets ou encore de pôle de compétitivité. La modification des signaux prix dans les programmes de maximisation de profit des différents producteurs peut alors permettre soit de rendre la coopération stable, soit d'assurer la production du véhicule le plus efficient, y compris en l'absence de coopération. Ce résultat amène par conséquent à la conclusion selon laquelle la coopération entre membres de la filière automobile n'est pas un substitut crédible à l'intervention publique.

- En revanche, lorsque la demande de véhicules économes en carburant est élevée, le véhicule le plus performant sur le plan énergétique est produit, et ce quel que soit le niveau de coopération entre acteurs de la filière automobile. Aussi, l'instauration d'instruments de type « *market pull* » est justifiée, ne serait-ce que de manière temporaire pour stimuler la demande, et ainsi créer un marché de taille suffisante. En effet, ces instruments visent plus spécifiquement à assurer une diffusion efficiente des technologies. Les automobilistes sont le plus souvent la cible de ces instruments. Il peut s'agir d'instruments incitatifs portant sur l'achat ou l'usage des véhicules, (*e.g.* Bonus-malus, taxe carbone, etc.), d'instruments réglementaires (*e.g.* zones à faibles émissions), d'instruments « informatifs » (*e.g.* labels sur les véhicules, campagnes de sensibilisation aux enjeux du réchauffement climatique, etc.), ou encore d'instruments dits « collaboratifs » (*e.g.* commandes publiques).

Pour estimer l'efficacité de ces instruments de type « *market pull* », une analyse plus fine de la demande de véhicule et de kilomètres est nécessaire. Cet exercice fait précisément l'objet du deuxième Chapitre.

2.2. Quelle est la pertinence des instruments tarifaires portant sur l'achat et l'usage des véhicules particuliers compte tenu du phénomène d'effet rebond ?

Le deuxième Chapitre est consacré à l'analyse de la demande de véhicules et de kilomètres. L'accent est mis sur l'interdépendance entre ces deux demandes, et sur l'impact que celle-ci peut avoir sur l'efficacité des taxes à l'achat et à l'usage des véhicules.

Un véhicule particulier est l'exemple type du bien durable pour lequel on distingue généralement quatre types de décision, à savoir :

- La décision de possession du bien (*i.e.* est-ce que j'achète un véhicule ?) ;
- La décision d'achat du bien (quel véhicule j'achète ?) ;
- La décision d'usage du bien (combien de kilomètre je parcours avec le véhicule ?) ;
- La décision de remplacement du bien (est-ce que je remplace mon véhicule ?).

Dans cette Thèse, nous nous intéressons tout particulièrement aux décisions d'achat et d'usage du véhicule. En effet, compte tenu de notre intérêt pour l'impact environnemental des véhicules, le taux de motorisation des ménages (*i.e.* décision de possession d'un véhicule) n'est pas une information suffisante dès lors que les véhicules diffèrent en termes de consommation d'énergie au kilomètre d'une part ; et que le total d'émissions est *in fine* fonction des distances parcourues par les véhicules d'autre part. Il faut noter toutefois que le choix de n'étudier que ces deux décisions implique que nous raisonnons sur des individus achetant effectivement un nouveau véhicule.

Les décisions d'achat et d'usage du véhicule sont par ailleurs liées. Certaines variables explicatives des décisions d'achat et d'usage du véhicule – propres à l'individu (lieu de résidence, âge, structure du ménage, revenu, etc.) ou relatives au contexte (densité, qualité du réseau de transport en commun, prix du carburant, etc.) – sont en effet communes aux deux décisions. De plus, au-delà de l'existence de variables explicatives communes aux décisions d'achat et d'usage du véhicule, il est communément admis que ces deux décisions sont interdépendantes. En effet, certaines caractéristiques du véhicule telles que sa consommation unitaire ou son prix d'achat (et donc la décision d'achat) jouent sur l'usage du véhicule. Mais l'inverse est aussi vrai : l'usage – plus précisément l'usage attendu du véhicule – influence le choix du véhicule. A titre d'exemple, un usage intensif du véhicule (pour de longs trajets domicile-travail par exemple) incitera l'automobiliste à acheter un véhicule plus confortable.

L'approche retenue dans ce Chapitre consiste en une analyse statique comparative basée sur un modèle de maximisation de l'utilité indirecte. Plus explicitement, comme pour tout bien durable, c'est le service fourni par le bien qui entre dans la fonction d'utilité directe ; à savoir ici la consommation de kilomètres. L'utilité retirée de la possession du bien durable en lui-même entre, quant à elle, dans l'utilité dite indirecte, dans la mesure où l'utilité retirée de la possession est simplement fonction des caractéristiques du bien durable et ne dépend pas de son usage. Dans le cas de l'automobile, il est en effet admis que le fait de posséder un véhicule procure de l'utilité indépendamment de l'usage qui est fait du véhicule, et ce en raison du statut procuré par le véhicule et des valeurs qui y sont associées telles que la liberté, l'indépendance, etc. Précisément, le comportement de l'automobiliste est composé de deux étapes : le choix du véhicule et la décision d'usage de ce véhicule. Pour chacune de ces deux étapes, l'automobiliste doit tenir compte de sa contrainte budgétaire. Aussi, l'utilité retirée de l'usage du véhicule est conditionnelle au type de véhicule ; et l'utilité retirée de la possession du véhicule est conditionnelle à l'usage que l'automobiliste fera de son véhicule. Le modèle proposé par Dubin et McFadden (1984) est particulièrement adapté pour tenir compte de ces interdépendances. Ce cadre théorique consiste à :

- maximiser l'utilité directe du ménage pour déterminer le niveau optimal de consommation du service fourni par le bien durable (ici, le nombre de kilomètres à parcourir avec le véhicule) d'une part ;
- et à maximiser l'utilité indirecte pour déterminer le type de bien durable qu'il est optimal d'acheter (ici, le type de véhicule) d'autre part. Nous « augmentons » l'utilité indirecte en ajoutant un terme reflétant les préférences des ménages pour les caractéristiques du véhicule jouant sur la décision d'achat sans affecter pour autant la décision d'usage (par exemple la couleur du véhicule, le nombre de portes, etc.). Ce terme, aléatoire dans notre modèle, explique l'existence d'une catégorie de ménages achetant un véhicule qui serait plus cher à l'achat et à l'usage.

Le lien entre décisions d'achat et d'usage du véhicule est par ailleurs précisément à la base de l'effet rebond. De façon générale, cet effet est défini comme « *une augmentation de la consommation liée à la réduction des limites à l'utilisation d'une technologie ; ces limites pouvant être monétaires, temporelles, sociales, physiques, liées à l'effort, au danger, à l'organisation* ». Dans le cas de la mobilité, l'effet rebond fait référence à la hausse des distances parcourues en réponse à une réduction de la consommation de carburant au kilomètre du véhicule ; cette dernière se traduisant par une réduction du coût au kilomètre. Précisément, il s'agit ici de l'effet *direct.* L'effet *indirect* fait référence à la hausse de la consommation d'autres biens (consommateurs d'énergie) permise par une augmentation du revenu réel à la suite d'une diminution des dépenses en carburant. Nous nous intéressons uniquement à l'effet *direct* ici. Le changement de comportement des automobilistes sous-tendant cet effet *direct* implique que les économies de carburant (et donc d'émissions de CO_2) obtenues grâce à l'utilisation de véhicules plus économes en carburant sont finalement plus faibles que celles espérées initialement. Une large littérature s'attache à mesurer l'ampleur de cet effet rebond pour le cas particulier qui nous intéresse ici ; celui de l'usage des véhicules particuliers à faible consommation de carburant. A titre d'illustration, Small et Van Dender (2007) estime que l'effet rebond lié à l'usage de véhicules plus économes sur la période 1966-2001 aux Etats Unis s'élève en moyenne à hauteur de 4.5% sur le court terme et à 22.2% sur le long terme[105] ; cet effet fluctuant avec le revenu, le degré d'urbanisation ou encore le coût au kilomètre.

[105] Aide à la lecture : un effet rebond de 4.5% signifie que la réduction des émissions de CO_2 ne s'élève qu'à 95.5% du potentiel de réduction d'émissions associé à l'usage de véhicules plus économes. La perte des 4.5% est due aux comportements d'adaptation des automobilistes qui parcourent plus de kilomètres avec un véhicule plus économe.

Dans la très grande majorité des travaux, l'amélioration des performances énergétiques des véhicules est observée au niveau individuel (*i.e.* à l'échelle d'un véhicule), et résulte de progrès technologiques. Il est d'ailleurs admis que l'existence d'un effet rebond limite l'efficacité des normes d'émissions de CO_2. En effet, ces normes contraignent les constructeurs automobiles à produire des véhicules moins consommateurs de carburant sans pour autant contrôler l'usage qui sera fait de ces véhicules plus économes. Dans un autre ordre d'idées, dès lors que la répartition des véhicules au sein du parc évolue en faveur des véhicules les plus économes en carburant, on peut observer une amélioration de la performance énergétique moyenne du parc sans que les performances individuelles des véhicules ne soient modifiées. Ce changement dans la composition du parc est précisément l'objet d'instruments de politique publique tels que les instruments tarifaires portant sur l'achat des véhicules et différenciés en fonction des performances environnementales du véhicule (Bonus-Malus par exemple).

Dans ce travail, un intérêt particulier est porté aux effets d'une taxe à l'achat différenciée en fonction des émissions de CO_2 (de type Malus). L'instauration de cet instrument tarifaire se traduit en effet par une amélioration de la performance énergétique moyenne du parc automobile et peut donc s'accompagner d'un effet rebond. L'objet de ce Chapitre est alors de réévaluer la pertinence de l'instauration de taxes à l'achat différenciées en fonction des émissions de CO_2 en tenant compte de l'existence de cet effet rebond d'une part, et d'estimer l'intérêt de la mise en place d'une taxe à l'usage dans un tel contexte d'autre part.

Notre analyse montre que l'existence ou non d'un effet rebond lié à l'instauration d'une taxe différenciée à l'achat des véhicules dépend des écarts de prix d'achat et de consommations unitaires entre les différents véhicules proposés à la vente. En effet, l'effet rebond apparait dès lors que l'écart de consommation unitaire entre le véhicule acheté en présence du Malus et celui qui aurait été acheté en l'absence de Malus est relativement élevé comparé à l'écart de prix d'achat de ces deux véhicules. Le résultat intéressant réside toutefois dans l'augmentation de l'effet rebond – dès lors que celui-ci existe – avec le montant de la taxe à l'achat. Autrement dit, la perte d'efficacité de la taxe différenciée à l'achat, due à l'effet rebond, croit avec le niveau de la taxe. Ce résultat est dû à la plus forte propension d'individus basculant vers un véhicule plus économe en carburant du fait du Malus plus élevé. Dans un tel contexte, l'instauration d'une taxe sur le carburant est intéressante, puisqu'elle permet de limiter l'effet rebond causé par le premier instrument (en jouant directement sur les distances parcourues), et permet donc d'accroitre la réduction d'émissions.

Par ailleurs, la capacité d'une taxe sur le carburant (d'un montant raisonnable) à atteindre, seule, la réduction d'émissions permise avec la combinaison d'une taxe sur le carburant et d'un Malus est démontrée dans ce deuxième Chapitre, ce qui témoigne de son efficacité. Toutefois, la réduction d'émissions de CO_2 ne doit pas être le seul critère de décision retenu par les décideurs publics lorsqu'ils arbitrent entre plusieurs instruments de politique publique. Cela est d'autant plus vrai dans le secteur des transports, comme expliqué dans le troisième et dernier Chapitre.

2.3. Quelle est la politique optimale de régulation du CO_2 compte tenu des objectifs plus larges du décideur public en termes de bien-être de la population et de profit du secteur automobile ?

Dans le troisième Chapitre, le point de vue du décideur public est retenu. Plus précisément, nous revenons sur trois principales caractéristiques du secteur des transports qui expliquent d'une part que les décideurs publiques peuvent servir plusieurs objectifs à partir de la mise en place d'un seul instrument de politique publique, et d'autre part que plusieurs instruments peuvent servir à atteindre un unique objectif dans ce secteur.

Premièrement, les activités de transport génèrent des bénéfices pour les autres secteurs. Cette particularité vient de la nature même de l'activité de transport. En effet, l'activité de transport est un bien dérivé, en ce sens qu'elle n'est pas consommée pour elle-même, mais est associée à la consommation d'autres biens (Crozet et Lopez-Ruiz, 2013). Aussi, l'activité de transport contribue automatiquement à la croissance économique, en étant le support de toute autre activité (travail, éducation, achats, activités de soins, etc.). Cette contribution à la croissance économique se mesure également à travers des « économies de temps » qui participent à l'expansion des marchés, à la hausse de la productivité, etc. De plus, les infrastructures de transport génèrent des externalités positives, et notamment des économies d'agglomération[106]. Enfin, et dans un autre ordre d'idées, les politiques de transport constituent un élément central lorsqu'il s'agit pour les autorités publiques d'assurer un certain accès à la population au marché de l'emploi, à l'éducation, et aux diverses activités sociales. De ce point de vue, l'accès aux infrastructures de transport est un moyen d'éviter l'exclusion. Aussi, la mobilité est également un vecteur de bien-être. Pour toutes ces raisons, une politique de transport a des répercussions

[106] Les économies d'agglomération constituent des gains en termes de compétitivité et d'innovation résultant de la concentration spatiale d'activités économiques liée au développement des infrastructures de transport permettant ainsi aux activités de se situer proches les unes des autres.

sur d'autres secteurs, ce qui implique qu'il faille penser simultanément les différentes politiques sectorielles, en termes de transport, d'urbanisme, etc.

Deuxièmement, le transport routier génère une multitude d'externalités négatives ; telles que la pollution locale (particules fines principalement), la pollution globale (CO_2), l'insécurité, la congestion, le bruit, etc. Ces externalités sont interdépendantes ; ce qui implique qu'il est difficile de ne cibler qu'une externalité à la fois. A titre d'illustration, l'instauration d'une taxe carbone, dont l'objectif est de réduire la pollution globale, conduit également à une diminution de la pollution locale, des accidents, etc. dans la mesure où elle se traduit par une réduction des distances parcourues en véhicule particulier. Cet exemple illustre pleinement la capacité d'un outil de politique publique à servir plusieurs objectifs à la fois. Cette particularité est d'autant plus intéressante dans un contexte où les gains d'émissions de CO_2 sont faiblement valorisés dans les évaluations des projets publics, relativement aux autres externalités. A titre d'exemple, en urbain dense, le CO_2 est valorisé à hauteur de 0.54c€ par passager-kilomètre contre 16.6c€ pour la congestion (CGDD, 2013a, p19).

Troisièmement, il existe différents leviers de réduction des émissions de CO_2 du secteur des transports, comme d'ores et déjà mentionné en introduction (cf. 1.3.). Ces leviers sont identifiés à partir du schéma dit « ASIF »[107] (Schipper et al., 2000) qui décompose les émissions de gaz à effet de serre liées aux activités de transport de la façon suivante :

Emissions du transport = Activité **X** *Répartition modale* **X** *Intensité énergétique* **X** *Contenu CO_2 de l'énergie*

Les quatre leviers sont donc : a) une réduction de l'activité de transport ou encore des distances parcourues, b) un changement de répartition modale en faveur des modes bas carbone (tels que les transports en commun ou les modes actifs comme le vélo ou la marche à pied), c) une réduction de l'intensité énergétique des modes de transport et enfin d) une baisse du contenu CO_2 de l'énergie utilisée dans les différents modes. Dans le même ordre d'idées, on peut également identifier les trois leviers suivants : a) éviter de parcourir certaines distances, b) opter pour un mode de transport moins émetteur, et c) améliorer les performances énergétiques des différents modes (il s'agit du schéma ASI[108]). Ainsi, alors que l'objectif du décideur public est unique – soit une réduction des émissions – c'est l'existence de ces différents leviers qui justifie

[107] ASIF pour « **A**ctivity, modal **S**hare, energy **I**ntensity, carbon intensity of **F**uel » en anglais.
[108] ASI pour « **A**void, **S**hift and **I**mprove » en anglais.

que soient combinés plusieurs instruments de politique publique (dès lors qu'ils jouent sur des leviers différents), et cela afin qu'aucun potentiel de réduction d'émissions ne soit négligé.

En résumé, et en allant du plus détaillé au plus général :

- Les décideurs publics ont à leur disposition plusieurs types d'instruments de politique publique permettant de réduire les émissions de CO_2 liées à l'usage des véhicules particuliers parce que ces émissions peuvent être décomposées en plusieurs facteurs. Combiner les instruments est donc possible. Toutefois l'étude de l'additivité des effets des instruments est nécessaire.
- Une réduction des émissions de CO_2 liées à l'usage des véhicules particuliers peut s'accompagner d'une diminution des autres externalités du transport routier ; notamment lorsque la réduction d'émissions est permise par une baisse des distances parcourues.
- Une politique de transport a des effets sur d'autres secteurs, dans la mesure où les activités de transports ont la particularité d'être le support de toute autre activité. Cela implique qu'il existe des objectifs plus larges en termes de croissance économique et de bien-être de la population associés aux politiques de transport.

Dans ce travail, l'accent est porté sur les émissions de CO_2, et les autres externalités du transport routier ne sont pas considérées. Par ailleurs, en termes de bien-être et de croissance, accroitre l'utilité des ménages et le profit de la filière automobile constitue dans ce travail les deux objectifs poursuivis par le décideur public parallèlement à son objectif de réduction des émissions. La question de recherche posée dans ce dernier Chapitre est donc la suivante : A l'aide de quel(s) instrument(s) de politique publique, le décideur public peut-il à la fois réduire les émissions de CO_2 liées à l'usage des véhicules particuliers, tout en augmentant d'une part l'utilité des ménages et d'autre part le profit de la filière automobile ?

Deux approches complémentaires sont proposées. L'approche positive consiste à étudier les effets d'outils de politique publique dont les niveaux sont fixés de façon exogène. L'approche normative consiste à déterminer quelle est l'intervention publique optimale. Cette approche repose dans ce travail sur l'analyse de la complémentarité des effets de différents instruments (en réalité : complémentarité, additivité, synergie ou substituabilité). Les instruments étudiés sont au nombre de trois ; soient un Bonus à l'achat des véhicules propres[109], une taxe sur le

[109] Un Bonus à l'achat des véhicules « propres » est étudié dans ce dernier Chapitre, alors qu'il s'agissait d'étudier les effets d'un Malus à l'achat des véhicules les plus « polluants » dans le deuxième Chapitre. Notre choix de

carburant et une taxe à l'achat des technologies les moins performantes sur le plan énergétique. Ces trois instruments ont été choisis en fonction de leur cible, c'est-à-dire la décision d'achat du véhicule pour le premier instrument et la décision d'usage du véhicule pour le second du côté de la demande, et la conception du véhicule du côté de l'offre pour le troisième et dernier instrument.

L'analyse montre qu'instaurer une taxe sur le carburant permet de réduire les émissions de CO_2 mais dégrade dans le même temps les bénéfices retirés de l'usage du véhicule pour les ménages qui vont, du fait de la taxe, parcourir moins de kilomètres. En revanche, l'efficacité du Bonus à réduire les émissions est discutable en raison de l'effet rebond qu'il engendre. Cependant, cet instrument permet une hausse de l'utilité des ménages (en diminuant le coût d'achat du véhicule) et un accroissement du profit de la filière automobile (en augmentant le prix de vente des véhicules économes en carburant[110]). Par ailleurs, l'intérêt de cibler le côté offre de la filière automobile avec l'instauration d'une taxe à l'achat des technologies les moins performantes n'est pas confirmé. En effet, instauré seul, cet instrument provoque une baisse du profit de la filière automobile, et sa capacité à permettre une réduction des émissions de CO_2 est limitée, comme pour le Bonus, du fait de l'effet rebond engendré. C'est pourquoi finalement, il peut être recommandé d'instaurer simultanément une subvention différenciée à l'achat du véhicule (un Bonus) et une taxe sur le carburant. Cette combinaison d'instruments tarifaires portant sur l'achat et l'usage du véhicule semble d'autant plus efficace que ses effets en termes d'émissions de CO_2 sont synergiques, ce qui signifie que l'instauration simultanée des deux instruments procure un résultat plus élevé que la somme des effets des deux instruments pris isolément. Ce type de recommandations risque cependant de conduire à une économie subventionnée ; c'est là l'une des principales limites d'une approche en équilibre partiel.

changer d'instrument tarifaire portant sur l'achat du véhicule se justifie par le besoin de contrebalancer les effets négatifs (soit la baisse de l'utilité) de la taxe à l'usage qui reste utile pour limiter l'effet rebond accompagnant la mise en place d'un instrument tarifaire portant sur l'achat du véhicule qui soit fonction des émissions du véhicule (c'est-à-dire un Malus mais aussi un Bonus).

[110] La hausse du prix de vente du véhicule pour lequel l'acheteur bénéficie d'un Bonus à l'achat renvoie à la problématique de l'incidence fiscale, c'est-à-dire au partage des bénéfices (dans le cas d'une subvention) ou de la charge (dans le cas d'une taxe) entre l'offreur et le demandeur. L'exemple le plus discuté est celui de l'augmentation des loyers (qui bénéficie aux propriétaires) qui accompagne la mise en place d'aides aux logements (qui ont pour objectif de bénéficier aux locataires).

3. Problématiques liées et perspectives de recherche

Cette Thèse a permis de mettre en perspective les objectifs des décideurs publics ainsi que les instruments de politique publique à leur disposition pour réduire les émissions de CO_2 liées à l'usage des véhicules particuliers.

L'intérêt des taxes à l'usage a été mis en évidence, notamment pour limiter le phénomène bien connu d'effet rebond. Cet intérêt porté aux taxes à l'usage devrait être grandissant ces prochaines années si l'on tient compte de l'actuel changement de paradigme quant à notre relation avec le véhicule. Les préférences des ménages en termes de mobilité évoluent en effet de la voiture-objet à la voiture-service. Autrement dit, on observe un passage de la possession à l'usage du véhicule. Ce changement s'explique en partie par la hausse des coûts liés à la possession d'un véhicule. Dans un contexte où il est dorénavant possible – grâce au développement des services de location de voitures – de ne supporter que le coût d'usage du véhicule (carburant, stationnement, etc.), de plus en plus d'automobilistes considèrent le coût de possession (taxes à l'achat et à l'immatriculation, assurance, etc.) comme étant trop élevé. Cela est d'autant plus vrai que l'offre croissante de transports en commun et de multi-modalité conduit à une baisse de l'usage du véhicule particulier, ce qui diminue les possibilités de rentabiliser l'investissement initial que représente l'achat du véhicule. Ces changements de comportements de la part des usagers des véhicules ne sont pas sans conséquence pour les acteurs industriels de la filière automobile. En effet, dès lors qu'un véhicule est utilisé par plusieurs individus, autres que les membres d'une même famille, la conception du véhicule doit être adaptée. De plus, le comportement d'achat de véhicules par une société de location par exemple diffère du comportement d'achat d'un véhicule par un ménage : un ménage maximise son utilité, comme déjà explicité dans le deuxième Chapitre de cette Thèse, tandis qu'une entreprise cherche à minimiser le coût total de possession du véhicule (Total Cost of Ownership, en anglais)[111]. La prise en compte de cette différence de comportement d'achat de véhicules entre ménages et entreprises doit être considérée par les constructeurs automobiles dans la mesure où, de 25% au début des années 1990, la part des véhicules de flottes (véhicules de location, véhicules de service, véhicules de fonction) est d'ores et déjà passée à 43% en 2012 (OVE, 2012). Du côté des chercheurs, ce changement de répartition dans les immatriculations des véhicules nécessite également une modification de l'approche retenue dans les modèles de choix de véhicules. Précisément, en considérant les véhicules comme des actifs plus ou moins

[111] La décision d'achat de véhicules par une entreprise est discutée notamment dans Meurisse (2014).

risqués aux yeux des entreprises, les travaux portant sur les choix de portefeuille pourront être mobilisés (voir par exemple un premier travail de Ansaripoor and al. (2014) à ce sujet).

En lien avec ce qui vient d'être dit, si l'attention a d'abord été portée aux innovations technologiques, l'idée selon laquelle les modifications de comportements pouvaient participer aux efforts pour atteindre une mobilité bas-carbone se répand de plus en plus. Le développement du covoiturage et de l'auto-partage l'illustre clairement. Un autre changement de comportement réside dans l'accroissement de l'immobilité, qui est partiellement rendu possible par le développement d'activités « immobiles » (travail à domicile par exemple) comprenant notamment les *e-activités* (e-commerce, e-travail, etc.). L'émergence de ces activités n'est pas à négliger, compte tenu de son impact sur la mobilité considérée comme contrainte jusqu'il y a peu de temps. Toutefois, la capacité des *e-activités* à jouer un rôle dans l'atteinte des objectifs nationaux et européens en termes de réduction des émissions n'est pas garantie. Si les individus consomment moins de carburant en évitant de réaliser certains trajets, ils consomment cependant plus d'énergie pour l'utilisation d'Internet, de sorte que la consommation totale d'énergie ne se trouve pas nécessairement réduite. Il s'agit là d'une question d'effets de substitution entre différents usages ; tandis que la question plus généralement posée et traitée dans les travaux de recherche existants est celle des effets de substitution entre différentes sources d'énergie pour un même usage (par exemple diesel *versus* pétrole pour l'usage des véhicules particuliers). Ceci étant dit, raisonner à une échelle plus large que celle du secteur des transports serait pertinent. En termes de politique publique, la principale raison de ce changement d'échelle d'analyse réside dans le fait que tous les secteurs ne peuvent pas être subventionnés. Avoir recours à une modélisation en équilibre général présente, à cet égard, un avantage certain, en permettant de mettre en évidence les arbitrages à opérer entre les différents secteurs.

Qui plus est, l'apparition des nouveaux services (covoiturage, auto-partage, mais aussi *e-activités*) illustre le fait que, si les décideurs publics disposent actuellement d'instruments de régulation pour réduire les émissions de CO_2 du secteur du transport, il se trouve qu'en parallèle les acteurs privés du transport mais aussi d'autres secteurs (énergies, nouvelles technologies de l'information et de la communication, etc.) ont également la capacité de développer des outils de transition vers la mobilité bas-carbone. Toutefois, d'une part, le développement de certains outils par les acteurs privés nécessite l'intervention des décideurs publics (politique de soutien à l'innovation, encadrement juridique des nouveaux services tels que l'auto-partage ou le covoiturage, etc.). D'autre part, les décideurs publics, dans leur rôle d'acteurs de la mobilité durable (ex. collectivités territoriales), font de plus en plus souvent appel au financement et à l'expertise du secteur privé, à travers notamment des Partenariats Publics Privés. Par conséquent, dans le contexte actuel, acteurs publics et acteurs privés dessinent ensemble la transition vers la mobilité bas-carbone. L'un des enjeux principaux consiste à déterminer la façon avec laquelle ce processus de transition vers la mobilité bas-carbone peut être accéléré. En effet, au-delà de la difficulté à atteindre un consensus entre les différentes parties prenantes d'un système de transport complexe, le difficile accès à l'information dans le domaine de l'environnement (par exemple quantifier les émissions de CO_2) ralentit davantage la prise de décision. Augmenter la coopération entre acteurs est une façon de répondre à cet enjeu (*i.e.* accélérer le processus de décision), notamment à travers une participation davantage marquée des acteurs du transport à la conception des outils de politique publique. Cela est d'autant plus vrai que les acteurs privés ayant participé à la définition de ces outils seront sans doute mieux à même de faire de ces politiques publiques, non plus des contraintes, mais bien des opportunités économiques. Une autre perspective de recherche consiste par conséquent à analyser de façon plus approfondie le processus de décision à la base de la conception des politiques publiques, afin d'identifier des facteurs de réussite des politiques qui soient propres à leur processus même de construction.

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