Technology Choices under Emissions Policy and Technology Diffusion constraints: the case of Passenger Vehicles

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Thèse de doctorat

UNIVERSITÉ PARIS SACLAY

DOCTORAL THESIS

Technology Choices under Emissions Policy and Technology Diffusion constraints: the case of Passenger Vehicles

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Pour Pepe, Paco et Fanny.

"Mucha gente pequeña en lugares pequeños, haciendo cosas pequeñas, pueden cambiar el mundo. "

Eduardo Galeano

"Climate change is the single biggest thing that humans have ever done on this planet. The one thing that needs to be bigger is our movement to stop it. "

Bill McKibben

Abstract

Technology Choices under Emissions Policy and Technology Diffusion constraints: the case of Passenger Vehicles

Policy instruments on passenger vehicle emissions aim at reducing negative environmental externalities from vehicles use. To regulate CO_2 emissions, fuel economy standards have been put in place in Europe and in the US, among others. These standards are made more stringent over time. This thesis analyzes how automotive firms anticipate and prepare their future technology portfolio to comply with expected future standards. To do so, we develop a model of optimal technology choice that captures technology diffusion constraints.

With this framework, this thesis investigates three policy questions. First, we ask how the form of anticipation can affect near- and long-term technology choices. We find that focusing solely on near-term objectives can lead to failure to comply with a long-term target. In fact, meeting the near-term target is not a necessary nor a sufficient condition to satisfy long-term compliance. Moreover, when there is partial anticipation, as in a myopic view of the future, technology choices will be stuck with low abatement technologies creating a path dependency that limits long-term abatement potential.

Second, we ask how much indexing fuel economy standard to mass (as in Europe or China) changes the optimal technology. We show that, for the same emission target, there is no significant difference in the social cost of mobility for an average vehicle with and without mass index. Thus a heavier vehicle fleet has the same cost than a lighter one. However, the technology choices are different, and mass indexed fuel economy standards lead to sidestepping lightweight technologies despite being cost effective from a CO_2 emissions abatement point of view.

Third, we ask how technology choices change when policies with multiple objectives overlap. We focus on two externalities associated with mobility: CO_2 emissions and local air pollution. We show three type of effects of overlapping policies. First, a technology specific policy such as the Zero Emission Vehicle Mandate in combination with a fuel economy standard induces carmakers to develop more expensive green technologies and prevents cheap, dirty technologies from disappearing compared to the case of a fuel economy standard alone. Second, the combination of policies can lead to very high costs when technologies adapted to each policy are very different. Third, we find an ambiguous effect of overlapping policies relative to single-objective policy in terms of emissions performance.

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AFV	**A**lternative **F**uel **V**ehicle
BEV	**B**attery **E**lectric **V**ehicle
CAC	**C**harge **A**ir **C**ooler
CAFE	**C**orporate **A**verage **F**uel **E**conomy
CFZ	**C**ar **F**ree **Z**one
DOC	**D**iesel **O**xidation **C**atalyst
DPF	**D**iesel **P**article **F**ilter
EV	**E**lectric **V**ehicle
EGR	**E**xhaust **G**as **R**ecirculation
FCHEV	**F**uel **C**ell **H**ybrid **E**lectric **V**ehicle
GPF	**G**asoline **P**article **F**ilter
HEV	**H**ybrid **E**lectric **V**ehicle
ICE	**I**nternal **C**ombustion **E**ngine
ICEV	**I**nternal **C**ombustion **E**ngine **V**ehicle
LDV	**L**ight **D**uty **V**ehicle
LEZ	**L**ow **E**mission **Z**one
LNT	**L**ean **N**Ox **T**rap
NEDC	**N**ew **E**uropean **D**riving **C**ycle
NOx	**N**itrogen **O**xides
OEM	**O**riginal **E**quipment **M**anufacturer
PHEV	**P**lug-in **H**ybrid **E**lectric **V**ehicle
PM	**P**article **M**atter
RDE	**R**eal **D**riving **E**missions
SCR	**S**elective **C**atalytic **R**eduction
SUV	**S**port **U**tility **V**ehicle
ULEZ	**U**ltra **L**ow **E**mission **Z**one
VGT	**V**ariable **G**eometry **T**urbocharger
WLTP	**W**orld harmonized **L**ight vehicles **T**est **P**rocedure
ZEV	**Z**ero **E**missions **V**ehicle

Résumé de la Thèse

Le secteur des transports est un des principaux contributeurs de gaz à effet de serre (GES). Les véhicules légers (VL) et lourds sont responsables de la plupart de ces émissions. La tendance à une plus forte motorisation des pays émergents fait que ce secteur va être d'autant plus important dans les émissions de GES dans le futur.

De nombreux leviers d'actions existent pour réduire les émissions du secteur des transports. Les solutions sont différentes dans le type d'acteurs engagés, le temps d'implémentation et le potentiel d'abattement. Dans ce secteur, il y a eu un accent pus important aux solutions de type offre comme l'amélioration de l'efficacité énergétique des modes de transport ou l'usage de combustibles bas carbone. La majorité des efforts de mitigation se concentrent sur un changement technologique.

Cette thèse se centre sur la transition des VL à des technologies qui améliore la consommation de carburant.

Les externalités générées par les véhicules à combustibles fossiles ne sont pas limitées au réchauffement climatique. Elles impactent aussi la pollution de l'air, le bruit sonore, la sécurité routière et la congestion. Les niveaux actuels de pollution de l'air dans les grandes aires urbaines de la planète dépassent les niveaux acceptables pour une qualité d'air propre pour la santé des habitants. Des villes comme Paris, Madrid, Beijing, New Delhi, Santiago de Chile et beaucoup d'autres souffrent de nombreux décès liés à la pollution de l'air. Les décideurs publics à l'échelle locale et nationale, inquiets par la qualité de l'air, prennent des actions pour introduire des mesures pour limiter la pollution de l'air. L'attention principale de cette thèse porte sur l'externalité liée au réchauffement climatique mais elle couvre aussi l' externalité liée à la pollution de l'air dans le Chapitre 5.

Cette thèse étudie les instruments politiques "push" qui agissent sur l'offre de véhicules des constructeurs automobiles. Le centre d'attention de cette thèse est la réglementation des émissions CO_2 (CAFE dans la littérature en anglais) qui régulent la moyenne des émissions CO_2 des ventes de nouveaux véhicules d'un constructeur automobile à ne dépasser une cible réglementaire. Les plus grandes économies mondiales ont toutes adoptées une version de la réglementation CAFE, notamment la Chine, les Etats-Unis, l'UE et le Japon. Dans tous les cas, ces politiques imposent une cible des émissions CO_2 qui donnent un certain temps d'anticipation aux sociétés automobiles pour adapter leur portefeuille.

Pour répondre à des cibles réglementaires contraignantes dans le futur, les constructeurs automobiles doivent déployer des technologies bas carbone pour réduire les émissions de dioxyde de carbone. Cependant l'adoption de nouvelles technologies fait face à plusieurs défis socio-techniques qui se traduisent par de l'inertie économique. Par exemple, l'introduction de véhicules électriques a besoin d'un changement de l'écosystème du véhicule qui va au-delà des technologies à l'intérieur du véhicule. La transition du vecteur d'énergie qui passe des combustibles fossiles à l'électricité a démontré d'être plus difficile que prévue à cause d'un écosystème dominant basé sur les énergies fossiles qui a formé le comportement du consommateur, l'infrastructure et les moyens de production qui prennent du temps pour développer l'environnement du véhicule électrique. Ce processus est similaire à des transitions socio-techniques vues dans le passé dans le secteur des transports telles que la diffusion des automobiles pour remplacer les carrosses à cheval (GEELS, 2012). Notre approche est compatible avec les stratégies des sociétés qui ne font pas souvent le pari d'investir massivement mais elles étalent les investissements dans le temps pour développer une technologie d'une façon progressive.

L'objectif principal de cette thèse est d'analyser le choix du portefeuille de technologies d'un constructeur automobile qui anticipe les futures cible réglementaires plus contraignantes. La première question de recherche est comment représenter l'inertie économique ? L'estimation de la vitesse de pénétration des technologies est la clé pour déterminer à quelle vitesse un secteur peut se transformer. Dans cette thèse, nous proposons un nouveau type de contrainte de diffusion qui limite la croissance des parts de ventes d'une technologie en fonction des part des ventes passées et d'une courbe de diffusion en "S". Nous traitons des scénarios de politiques environnementales sur les émissions de VL d'un point de vue de l'offre où un constructeur choisit un mix technologique parmi un ensemble de technologies disponibles pour répondre aux contraintes réglementaires de chaque scénario dans un environnement où la demande résiste au changement.

Sur cette base, cette thèse examine l'effet de trois caractéristiques de la réglementation CO_2 sur la transformation du portefeuille technologique. Premièrement, nous analysons l'impact de cibles réglementaires consécutives et la sévérité de la contrainte sur les sentiers technologiques. Les cibles à court terme sont typiquement connues, alors que les cibles à long terme sont souvent incertaines ou inconnues. Un constructeur peut choisir d'anticiper parfaitement la cible à long terme, ou de procéder pas-à-pas en préparant seulement le court terme. Nous posons deux questions : quelles sont les implications de différents types de stratégies pour préparer une réglementation CO_2 future ? Et, une stratégie d'anticipation est-elle un facteur limitant sur le potentiel d'abattement futur ?

Nous montrons qu'une anticipation du futur focalisée sur les objectifs de court terme peut empêcher l'atteinte de la cible à long terme. Respecter la cible à court terme n'est une condition ni nécessaire ni suffisante pour permettre le niveau d'émissions requis par la cible à long terme. De plus si l'anticipation du futur n'est pas parfaite, les choix technologiques vont être verrouillés dans des technologies à faible potentiel d'abattement créant ainsi une dépendance au sentier qui limite l'abattement potentiel à long terme.

Deuxièmement, nous augmentons le détail de représentation de la réglementation CO_2 avec l'introduction du paramètre d'indexation. Un paramètre d'indexation donne un niveau d'exigence différent de la cible réglementaire selon une caractéristique physique du véhicule telle que la masse ou l'emprunte au sol. L'objectif de cette partie est de quantifier l'effet sur le portefeuille de technologies et le coût économique d'une telle politique si elle n'est pas technologiquement neutre. Nous nous interrogeons : Comment l'introduction du paramètre d'indexation impacte les choix technologiques ? Et, quelles sont les implications d'une réglementation CO_2 basée sur le mécanisme d'indexation sur la réduction des émissions ?

Nous montrons qu'il n'existe pas de différence significative dans le coût social de la mobilité entre les deux mécanismes de réglementation CO_2 avec et sans indexation sur la masse pour une même cible d'émissions. Cependant les choix technologiques entre ces mécanismes sont différents, la réglementation CO_2 indexée à la masse ne développe en aucun cas les technologies d'allègement.

Troisièmement, nous élargissons le périmètre de l'ensemble des instruments politiques de cette étude pour inclure différents instruments qui régulent les externalités de réchauffement climatique et de pollution de l'air. Mise à part la réglementation CO_2, nous modélisons quatre autres politiques sur les VL pour montrer la diversité des mécanismes : un mandat de véhicule à zéro émissions (ZEV Mandate en anglais), une réglementation sur les polluants locaux et deux types de zones à faible émissions (LEZ en anglais). L'objectif est de montrer les interactions entre les politiques pour identifier l'effet indépendant et combiné de l'application des politiques. Nous insistons sur : Quel est l'impact de la superposition de politiques sur les choix technologiques ? Comment l'interaction entre les politiques s'expriment et dans quelle direction le portefeuille de technologies va-t-il évoluer ? Quel est la performance de l'ensemble de politiques sur deux dimensions des externalités des VL ?

Nous montrons trois types d'impacts de la superposition de politiques. Premièrement, une politique technologiquement spécifique tel que le Mandat de Véhicule à Zéro Émission en combinaison avec la réglementation CO_2 provoque le développement de technologies vertes coûteuses et empêche les technologies sales et peu coûteuses de disparaître. Dans le cas de l'application de la réglementation CO_2 seule nous n'observons pas ce comportement. Deuxièmement, la superposition de politiques peut mener à un coût élevé quand les technologies adaptées à chacune des politiques sont très différentes. Troisièmement, nous trouvons un effet ambigu de la superposition de politiques relative à l'application d'une politique seule sur la performance environnementale.

La réglementation CO_2 joue le rôle central de cette thèse mais sous des perspectives différentes pour montrer les implications de l'anticipation des cibles, les failles du mécanisme de la réglementation et l'effet sur d'autres politiques dans l'automobile. Chaque application de cette thèse partage deux aspects : elles traitent toutes la réglementation CO_2 et elles sont toutes basées sur le même modèle.

Le modèle de cette thèse n'est pas construit pour prédire comment un constructeur doit choisir les technologies, le modèle veut mettre en garde sur les aspects de certains mécanismes des politiques qui peuvent mener une société à choisir une mauvaise stratégie bas carbone.

La communauté scientifique a longtemps étudié les politiques bas carbone appliquées aux VL, nous contribuons à cette littérature en traitant trois points qui ont été moins étudiés. Premièrement, la dynamique du choix technologique nous donne les clefs pour identifier quand une solution technologique n'est pas assez compétitive pour être développer et va être abandonner à posteriori. La sévérité et le timing des politiques sont déterminants au moment de donner un signal fort aux sociétés à agir. Deuxièmement, la création de réglementations automobiles est le résultat des discussions entre l'industrie, les autorités réglementaires et le public, cette discussion aboutie parfois en des instruments politiques imparfaits. L'indexation de la réglementation CO_2 est un exemple d'une telle imperfection, les régulateurs ont besoin de suivre de près l'application de cette politique afin d'éviter des impacts négatifs à propos de l'objectif politique. Troisièmement, les décideurs publics ont créé des instruments politiques pour réguler les impacts des émissions des véhicules séparément, chaque type d'externalité se traduit par un instrument politique différent. Quand les constructeurs préparent un futur mix technologique, ils prennent en compte toutes les contraintes réglementaires à la fois pour obtenir un produit adaptés aux besoins.

Tout en reconnaissant la nature stylisée de l'approche pour représenter les mécanismes de choix technologiques sous des contraintes des scénarios politiques et de diffusions des technologies, nous pouvons élaborer quelques implications de nos résultats pour les constructeurs automobiles et les décideurs publics.

Implications pour un constructeur automobile

L'optimisation de chaque composant du véhicule pour réduire le coût afin d'augmenter le profit a dictée le développement des savoir-faire de chaque sous-système. Cette structure en silos favorise les améliorations incrémentales de la technologie dominante qui visent à retravailler une architecture existante. Les technologies disruptives qui changent la manière dont un constructeur est structuré créent une discontinuité et nécessitent plus d'efforts pour se diffuser. Il n'existe pas de solution unique pour résoudre tous les besoins, un compromis est toujours nécessaire pour obtenir un produit final compétitif et adapté au contexte réglementaire. Malgré le succès de l'industrie sur le développement du véhicule thermique, elle fait face à d'importants défis pour engager une transition bas carbone. L'évidence du passé sur les transitions technologiques montre que les technologies disruptives se développe rarement à l'intérieur du système dominant, elles se développent à l'extérieur dans des niches qui vont trouver des applications dans le système dominant plus tard. Quand nous étudions le potentiel d'une technologie bas carbone, la contrainte sur la diffusion technologique est aussi une mesure de la vitesse de changement de la structure existante du constructeur pour développer des véhicules bas carbones pour le grand public.

Une société automobile développe un plan de business qui définit le portefeuille de technologies pour les cinq années à venir en général, avec une vision plus précise pour les trois prochaines années. Cette anticipation court terme contraste avec une ambition long terme des décideurs publics qui planifient une transition bas carbone qui visent à limiter le réchauffement climatique à un maximum de 2^oC à la fin du siècle. Malgré ces signaux de long terme, la planification du futur du constructeur automobile ne se passe que dans le court terme. Quand le contexte de long terme n'est pas clair, un constructeur peut difficilement préparer le chemin. Ce qui pourrais être un plan rentable pour la cible à court terme peut déboucher en un portefeuille de technologies inadapté pour des cibles plus contraignantes qui vont apparaître plus tard dans le futur. Un constructeur automobile a le choix de décider si il prend en compte les signaux faibles de la politique à long terme pour anticiper le changement technologique. Ou bien il peut attendre et voir comment le lobby évolue et défendre un objectif moins ambitieux dans le futur. Le résultat de la première application de cette étude, sur l'anticipation des cibles consécutives, met en évidence le risque d'un verrou sur la stratégie qui ne prend pas en compte la cible à long terme.

La réglementation CO_2 indexée à la masse produit une incitation à développer des technologies plus lourdes. L'allégement est le champ de technologie le plus pénalisé. Le paramètre d'indexation peut créer un avantage, un obstacle ou être sans effet sur les technologies de réduction des émissions. Quand un constructeur décide d'exploiter les bénéfices de cette incitation, il risque de modifier la cible réglementaire spécifique au lieu de réduire les émissions réelles des véhicules. Dans le cas d'un changement réglementaire le constructeur qui a suivit le mécanisme d'incitation sera en difficulté pour s'adapter à un nouvel cadre politique. L'indexation à la masse de cette réglementation bénéficie les véhicules électriques qui émettent moins et sont plus lourds, cependant au niveau du portefeuille on observe une décroissance du développement des technologies incrémentales de véhicules thermiques. Un constructeur qui développe une stratégie de commercialisation massive de véhicules électriques va être favoriser par le cadre réglementaire à condition que les consommateurs adoptent des véhicules électriques en masse. Par contre un constructeur qui ciblent un développement incrémental des véhicules thermiques ne dépend pas de l'adoption de véhicules électriques mais peut souffrir une cible réglementaire plus sévère.

Nous avons identifié un effet similaire avec deux autres types de politiques, le ZEV Mandate et une LEZ, elles sont deux politiques qui incitent aussi la diffusion des véhicules électriques. La différence avec l'effet de l'indexation de la réglementation à la masse est qu'il y a plusieurs chemins pour réduire les émissions au lieu de développer une seule option qui est un quota minimum de véhicules à zéro émission. Ces deux politiques de véhicules à zéro émissions envoient un signal fort au développement de véhicules à zéro émissions, l'indexation de la réglementation n'est pas un signal clair, les véhicules électriques sont favorisés dans le mécanisme d'indexation parce qu'ils contribuent à une réduction des émissions et de la cible réglementaire.

Quand différents instruments politiques se superposent pour réguler les émissions de véhicules, les constructeurs doivent analyser quelles sont les solutions adaptées pour un cadre réglementaire multi-objectif. Il existe des technologies qui sont plus ou moins adaptées pour répondre à un type d'externalité. La technologie qui semble adaptée à une large source d'externalités est le véhicule électrique qui ne produit pas des émissions à l'usage. Il n'existe pas encore des politiques automobiles qui prennent en compte les émissions du puits à la roue à l'exception de la taxe au carburant. Il y a des combinaisons de politiques qui ont besoin de technologies coûteuses pour respecter le cadre politique. C'est le cas de la réglementation sur les émissions polluantes combinée avec avec la réglementation CO_2. Pour respecter le double enjeu sur les émissions des véhicules le mix de technologie actuel doit profondément changer . Aujourd'hui on observe un changement rapide dans le marché automobile, en France la part des ventes du diesel a chuté de 70% en 2010 à 39% en 2018.

Implications pour les décideurs publics

Les politiques sur les émissions des véhicules ont le rôle de pousser les constructeurs à développer des technologies bas carbones et moins polluantes. Elles ont aussi le rôle pour inciter les consommateurs à adopter ce type de technologie. Cette thèse peut donner quelques implications sur ce premier rôle des politiques.

Déterminer les cibles réglementaires a besoin d'un analyse des trajectoires bas carbone pour évaluer comment partager les efforts d'abattement parmis les secteurs d'énergies. L'ambition politique de l'abattement des VL dépend de la vitesse de changement du système énergétique dans l'ensemble de l'écosystème. L'objectif à long terme peut être estimé par contre la vitesse de la transition du secteur est un sujet de débat. Un décideur public doit proposer des cibles intermédiaires pour orienter le changement technologique dans le futur proche, l'industrie a besoin d'un signal qui peut être interprété dans le contexte actuel. Etablir ces cibles intermédiaires doit équilibrer entre un changement technologique faisable à court terme et une trajectoire compatible avec un objectif à long terme. En outre, dans les secteurs énergétiques qui risquent d'avoir des technologies qui provoquent des verrous à forte intensité de carbone il y a deux éléments qui ont besoin d'être contrôlés : le respect de la cible réglementaire et comment ce secteur choisit les technologies pour réduire les émissions. Ces deux élélements de contrôle sont nécessaires pour éviter la création de verrous de technologies à forte intensité carbone.

Pour déterminer la cible intermédiaire le régulateur doit prendre en compte les conséquences des choix technologiques à court terme sur les futurs choix technologiques à long terme. Déterminer la cible à court terme est une tâche difficile qui a besoin d'une évaluation fine du potentiel d'abattement des technologies. Or cette information appartient à l'industrie automobile ainsi le régulateur a seulement une information partielle du potentiel technologique. De ce fait, la cible intermédiaire peut être sous-estimé pour éviter une cible long terme trop ambitieuse selon des estimations trop conservatrices des constructeurs. Du point de vue du monitorage, nous alertons sur le fait de se centrer seulement sur la cible réglementaire qui peut être un indicateur insuffisant pour suivre le changement structurel nécessaire pour être amène à répondre à la cible de long terme. Ceci appelle à d'autres indicateurs qui soient capables de suivre ces changements structurels.

Souvent les instruments politiques visent la neutralité technologique afin d'être une politique économique efficace en laissant les sociétés choisir les technologies mieux adaptés pour répondre à un objectif réglementaire. Cependant, le mécanisme de la politique peut en pratique provoquer un biais pour une famille de technologies. Dans le cas de la réglementation CO_2 indexée à la masse nous montrons ce biais pour des technologies qui augmentent la masse du véhicule. Un instrument peut ainsi fermer la porte prématurément à des technologies bas carbone prometteuses. Un équilibre entre des instruments politiques efficaces qui sont neutres et des incitations en R&D sur des technologies spécifiques pour développer des niches de marché est nécessaire dans les étapes initiales d'une transition bas carbone.

La superposition d'instruments politiques, avec différents objectifs, peut créer des conséquences non désirées. Par exemple, nous avons montré que la combinaison de la réglementation CO_2 avec le ZEV Mandate peut provoquer une polarisation des réduction des émissions en créant une flotte de nouveaux véhicules divisée en des véhicules à zéro ou faibles émissions et des véhicules fortement émetteurs. En raison d'une réglementation CO_2 qui régule les émissions des véhicules neufs sous cycle homologué qui ne reflète pas la condition réelle d'usage, il y a un risque d'obtenir des émissions plus élevées que prévue. De plus, une telle polarisation peut causer des inégalités entre les ménages et territoires qui ont un facilité d'achat différente de véhicules à faible émissions.

Le contexte politique dans l'automobile est une combinaison de différents instruments qui ont des mécanismes distincts. Dans le cas des externalités du réchauffement climatique et de la pollution de l'air, les acteurs impliqués pour chaque politique sont différents et peuvent avoir des intérêts divergents. Certains acteurs sont communs comme le constructeur automobile et les propriétaires de véhicules mais les décideurs publics changent. De nombreux régulateurs et autorités publiques mettent en place des politiques qui impactent les technologies des véhicules. La superposition d'instruments politiques produit un effet sur le portefeuille de technologies mais la superposition de décideurs publics est aussi un défi qui produit des multiples débats simultanés sur différentes externalités. L'effort de coordination du réseau d'acteurs est difficile pour corriger l'ensemble des défaillances du marché.

Chapter 1

Introduction

1.1 Motivation and Research Questions

Modern transportation has created a highly connected world that allows individuals to move and trade wherever they want. The current means of transportation, however, are mostly based on fossil fuels which produce severe environmental challenges such as global climate change.

Road transportation is one of the main contributors of the transport sector to Greenhouse Gas (GHG) emissions, 72% of worldwide transport emissions originate by Heavy-Duty Vehicles (HDV) and Light-Duty Vehicles (LDV) (Sims et al., 2014). The current trend of rapid motorization in developed countries (International Organization of Motor Vehicle Manufacturers (OICA), 2015) can increase the contribution of road transportation to climate change in the absence of mitigation efforts.

There are many levers of action to reduce emissions from transportation. The solutions differ in the type of actors involved, the time needed for implementation and the abatement potential. In road transportation, there has been more emphasis on supply-side solutions such as improvements of energy efficiency of transportation or the use of low carbon fuels. Most current mitigation efforts in road transportation mitigation rely on technological change.

This thesis focuses on the transition of LDV to technologies that improve fuel economy.

The externalities generated by fossil-fuel vehicles are not limited to climate change. They also include air pollution, noise, road safety and traffic congestion. Current levels of air pollution in highly populated areas all over the world exceed the safe limits for clean air and are causing premature deaths in cities such as Paris, Madrid, Beijing, New Delhi, Santiago de Chile and others. Local and national policymakers, worried about air quality, take action to introduce measures to limit air pollution. Though, the main focus of this thesis is the climate externality, we also address the air pollution externality in Chapter 5.

This thesis investigates "push" policy instruments that act on the supply of vehicles provided by car manufacturers. The main focus of this thesis is on the Corporate Average Fuel Economy (CAFE) standard which requires a minimum level of average fuel economy of new vehicle sales from car manufacturers. Major economies have all adopted a version of a CAFE policy, including China, the USA, the EU and Japan. In all cases, these policies impose a future fuel economy target that gives some anticipation time for automotive firms to adapt their portfolio accordingly (see section 1.2.4 for more details).

To meet a more stringent fuel economy target in the future, carmakers must deploy low carbon technology to improve fuel economy. However, the adoption of new technologies faces several socio-technical challenges that translate into economic inertia. For example, the introduction of plug-in vehicles requires a change in the vehicle ecosystem that goes beyond the on-board technology of a vehicle. The change in fuel from fossil-fuels to electricity has proven to be more difficult than expected, since the incumbent ecosystem of fossil-fuel based vehicles has shaped consumer behavior, infrastructure and manufacturing capabilities that take time to transition to the plug-in vehicle environment. Thus the transition process is similar to socio-technical transitions seen in the past in the transportation sector such as the diffusion of automobiles to replace horse-carriages (Geels, 2012).

The main goal of this thesis is to analyze the choice of the technology portfolio for an automotive firm when required to anticipate future and more stringent fuel economy standards. The first research question is how to represent economic inertia? Estimating the rate of penetration of technologies is key to determine how fast a sector can transform. In this thesis, we propose a novel type of diffusion constraint that limits the sales share growth of a technology according to past sales share and a S-curve diffusion function.

On this basis, this thesis examines the effect of three characteristics of the fuel economy standard on the transformation of the technology portfolio. First, we analyze the impact of consecutive fuel economy targets and their relative degree of stringency on technology paths. Near-term targets are typically certain, while the long-term targets are often uncertain or unknown. A firm can choose to fully anticipate the long-term target, or to proceed in a step-wise fashion by focusing only on the near-term target. We ask: what are the implications of the different anticipation strategies to prepare for a fuel economy standard? Is the anticipation strategy a limiting factor for future abatement potential?

Second, we increase the detail of representation of the fuel economy standard to include the index parameter. An index parameter sets a different level of stringency of the target according to a physical characteristic of the vehicle such as vehicle mass or footprint. The objective is to quantify the effect on the portfolio of technologies and the economic cost of such a policy when the policy is not neutral.

We ask: how does the introduction of an index parameter affects technology choices? What are the implications for emission reduction of an indexed based fuel economy standard?

Third, we widen the scope of the policy package of this study to include multiple policies that regulate the climate change and air pollution externalities. The goal is to show the interactions of policies to identify the effect of single and combined policy applications. We ask: what is the impact of overlapping policies on technology choices? How does the interaction between policies occur and in what direction does the portfolio evolve? How does a policy package perform on the two dimension of LDV externalities?

The goal of the present Chapter is threefold. First, it presents the environmental impacts of road transportation, the key issues related to fuel economy standards and the literature review (Section 1.2). Second, Section 1.3 focuses on three selected policy issues that are successively addressed in this thesis: path dependency, policy neutrality and superposition of policies. Last, this Chapter describes the method adopted on the thesis, the institutional framework within which it was written, and the other related academic and non academic work done during this Research (Section 1.4).

1.2 Passenger Vehicle Externalities, Technical Solutions and Mitigation Policies

This section provides an overview of the externalities associated with passenger vehicles, of the technical solutions available, and of the mitigation policies. We begin by describing the climate change implications of vehicle emissions. The negative consequences of road transportation however are not limited to climate change, as described in section 1.2.1. A brief overview of mitigation options in the transport sector is provided in section 1.2.3, before focusing in the technologies that improve fuel economy in LDV. The policy instruments to improve fuel efficiency in LDV are described in section 1.2.4. We conclude this section by mapping the literature gap on policy studies in the automotive market that this thesis tries to fill.

1.2.1 Climate Change and the other externalities associated with Road Transport

The indisputable increase of earth's temperature is caused by human activity emitting Greenhouse Gases (GHG) into the atmosphere. Without any change climate change might lead to an increase in temperature of a range of 2.5 to 8ºC from pre-industrial temperatures. The main sectors that contribute to GHG emissions are Electricity and heat production, Agriculture, forestry and other land use (AFOLU), Industry and Transport. The transport sector accounted for 14 % of total GHG emissions in 2010 according to the IPCC, 2014. The contribution of the transport sector to GHG emissions varies depending on the region, in Western Europe the weight of the transport sector is about 20% and in France in particular is 28.5% in 2014 (Ministère de la Transition Écologique et Solidaire, 2018). The share of transport in GHG is growing especially in non-OECD countries where motorization grows every year (Sims et al., 2014) (Fig. 1.1). Motorization is still increasing in OECD countries despite the fact that levels of motorization are already high.

The main contribution to climate change comes from carbon dioxide (CO_2) emissions caused by combustion of fossil fuels. All modes of transportation are source of CO_2 emissions with road transportation representing 72% of a total of 7 $GtCO_2eq$ of direct and indirect emissions in 2010 worldwide (Sims et al., 2014). Most of road transportation is powered by fossil fuels such as gasoline, diesel and gas. LDV are the most common mode of transportation in developed countries (Schafer, 1998; Schafer and David G Victor, 2000; Sims et al., 2014) and the most consuming of fossil fuels among passenger transportation. At the same time, the worldwide fleet of LDV is increasing as developing countries use more LDV in a context of population and economic growth. We focus our research on this transportation mode.

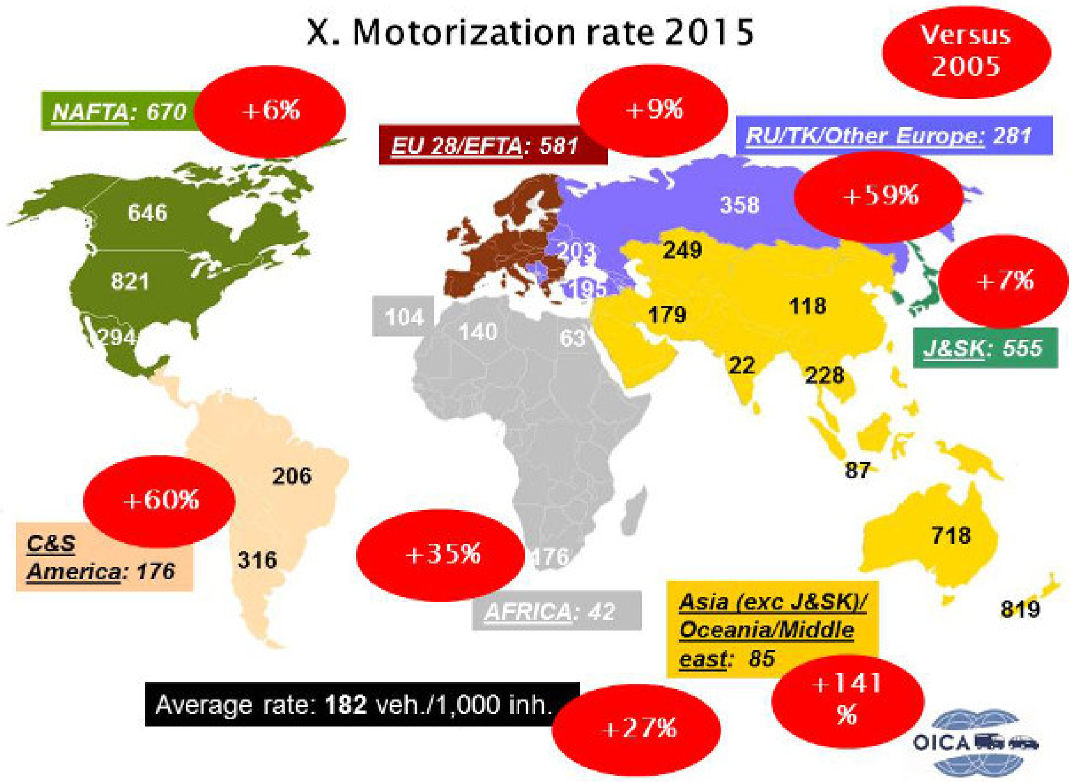

FIGURE 1.1 – Motorization rate in 2015 and increase from 2005 worldwide. Source: OICA,2015.

We briefly discuss the other externalities associated with road transport. The origin of these externalities is due to the intensive use of vehicles and the large volume of LDV on roads (Ian W. H Parry, Walls, and Harrington, 2007; Santos et al., 2010).

— Traffic congestion causes delays on urban trips and wasted productive time. Traffic congestion is highest during peak hours and is a major problem of highly motorized cities such as Los Angeles or Sao Paulo. A high number of idle vehicles during peak hours in large urban roads are also a major source of local air pollutants. Some urban shapes can produce bottlenecks that make traffic congestion worse.
— Despite many safety improvements on board and in roads, traffic accidents are still responsible for fatalities and injuries. In many developing countries where vehicles are less secure and road infrastructure for safe travel is not guaranteed, road accidents are among the top reasons of fatalities. The road transport related fatalities affect passenger vehicles, two- and three-wheelers, buses, taxis, bicycles and pedestrians.
— Noise from road traffic is a nuisance due to engine acceleration, tire contact and braking. It affects pedestrians and other road users (Lemp and Kockelman, 2008; Calthrop and Proost, 1998). Noise is proportional to the traffic density, speed and type of road. Some highways near urban areas have sound barriers to decrease noise affecting those living close to the road.
— Space allocation to parking and road infrastructure can be an externality if it leads to urban sprawl and if this space could be used for green-space and buildings (Lemp and Kockelman, 2008). Passenger vehicles can monopolize the use of urban space to the point of making urban areas vehicle dependent. In some cases, road vehicle becomes the only mean of transportation possible.
— Fossil fueled vehicles rely on oil imports when the local supply is not sufficient or not existent. This energy dependence on oil might translate into an energy security issue thus causing an externality on energy provision.
— Other environmental externalities can be associated to LDV if the entire life cycle is considered. For instance, the manufacturing process of vehicles can lead to damages on natural resources such as water and soil pollution from disposal of pollutants. Other sources of environmental damages exist at the oil extraction process.
— Local air pollution externality is due to vehicle emissions from vehicle engines or vehicle tires. Nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC) and particle matter (PM) emissions cause a health risk when a person is exposed to high concentrations of these gases during long periods. In urban areas that have a large vehicle fleet in a small geographical area air pollutant concentrations tend to rise beyond safe limits of exposure. Unlike carbon dioxide, local air pollutants produce immediate effects in peak emissions events when local conditions such as weather,

topography and urban traffic change the natural diffusion of these gases.

Local air pollution causes premature deaths and respiratory diseases, thereby cutting lives short, increasing medical costs and reducing productivity through working days lost across the economy. Overall, PM with a diameter of 2.5 μm or less ($PM_{2.5}$) were responsible for about 391 000 premature deaths in the EU-28 (Guerreiro et al., 2018). Road transport's contribution to local air pollution is significant: 39 % of NO_x, 10 % of PM_{10} and 11 % of $PM_{2.5}$ in EU-28 in 2016 (Guerreiro et al., 2018).

The literature on LDV air pollution is recent. It has increased after the so-called Dieselgate in 2015. Assessments on tail-pipe emissions agree that on-road emissions are several times higher than emissions registered by type approval procedures, which regulate the market, especially for diesel cars (Weiss et al., 2012; Tietge et al., 2017; Baldino et al., 2017). A general evaluation of the impact of vehicle's emissions on air pollution is difficult since pollution is higher where the concentration of gases is higher (unlike carbon emissions that act globally). Although there are local measurements of air pollutants in urban areas and non urban areas, a separate assessment by source is more difficult. Recent literature is trying to fill this gap, Degraeuwe et al., 2017 analyze the impact of NO_x car emissions on 8 European cities finding that impact of LDV on NO_X emissions depend on diesel share, road traffic intensity and other sources of pollution and S. Zhang et al., 2014 on Beijing that studies the trend of vehicle emissions to show that heavy-duty diesel vehicles have partly offset the reduction of NO_X emissions from light-duty gasoline vehicles.

In this thesis we focus for the most part on the climate externality.

1.2.2 Overview of Mitigation Options in the Transport Sector

To limit climate change, GHG emissions need to be reduced from all sectors. Most nations in the world have committed to the Paris Climate agreement to keep temperature increase below 2ºC compared to pre-industrial times. Mitigation actions can be classified in three main categories: avoid, shift and improve (F. Creutzig, Roy, et al., 2018) (Table 1.1).

In the context of transport mitigation policies (first row of Table 1.1), this classification translates into measures that aim at (i) avoiding the need of travel, (ii) shifting travel to lowest-carbon mode, and (iii) improving vehicles to be more energy-efficient and fuels to be less carbon-intensive. Another classification of mitigation solutions distinguishes supply-side solutions, that involve technological change to low carbon innovations, and demand side solutions that require consumers to change their behavior. Demand-side solutions have high potential but have not gathered the same level of attention from the scientific community as technological supply-side solutions (F. Creutzig, Fernandez, et al., 2016).

Sector	Service	Avoid	Shift	Improve
Transport	Accessibility Mobility	Integrate transport and land-use planning Smart logistics Teleworking Compact cities	Mode shift from car to cycling, walking or public transit	Electric two, three and four-wheelers Eco-driving Smaller, light-weight vehicles
Building	Shelter	Passive house or retrofit (avoiding demand for heating/cooling) Change temperature set-points	Heat pumps, district heating and cooling Combined heat and power Invertor air conditioning	Condensing boiler Incremental insulation options Energy-efficient appliances.
Manufactured products ans services	Clothing Appliances	Long-lasting fabric, appliances, sharing economy Eco-industrial parks, circular economy	Shift to recycled materials, low-carbon materials for buildings and infrastructure	Use of low-carbon fabrics New manufacturing processes and equipment use
Food	Nutrition	Calories in line with daily needs Food waste reduction	Shift from ruminant meat to other protein sources where appropriate	Reuse food waste Smaller, efficient fridges Healthy fresh food to replace processed food

TABLE 1.1 – Illustrative "avoid-shift-improve" options in different sectors and services. Source: F. Creutzig, Roy, et al., 2018
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In a more practical perspective, transport mitigation can be achieved by reducing (i) mobility demand, (ii) the amount of energy needed for propelling a vehicle over a given distance, or (iii) the carbon intensity of transport fuels or (iv) by shifting to less carbon-intensive modes (B. F. Creutzig et al., 2015) (Fig. 1.2 and eq. 1.1).

$$Total\ GHG\ Emissions = \sum_{Modal\ Shares} \sum_{Fuels} [Fuel\ Carbon\ Intensity * Energy\ Intensity * Activity] \tag{1.1}$$

The different types of modal shares include road transport, rail, air and sea. These modes of transportation depend on the urban form, the transport infrastructure and the behavioral choice between modes. The available fuels vary in their carbon content, direct and indirect emissions of fuels should be taken into account to access the carbon emissions per unit of energy delivered. Energy intensity depends on the mean of transportation and the occupation rate. Finally, road transport emissions account for all type of activities: passenger and freight. This thesis will focus on the Energy Intensity and Fuel Switching levers of Light Duty Vehicles.

1.2.3 Technical options for limiting Light Duty Vehicles emissions: An Overview

So far, the mitigation solutions to reduce carbon emissions from vehicles have been focused on fuel economy technologies. All main components of a passenger

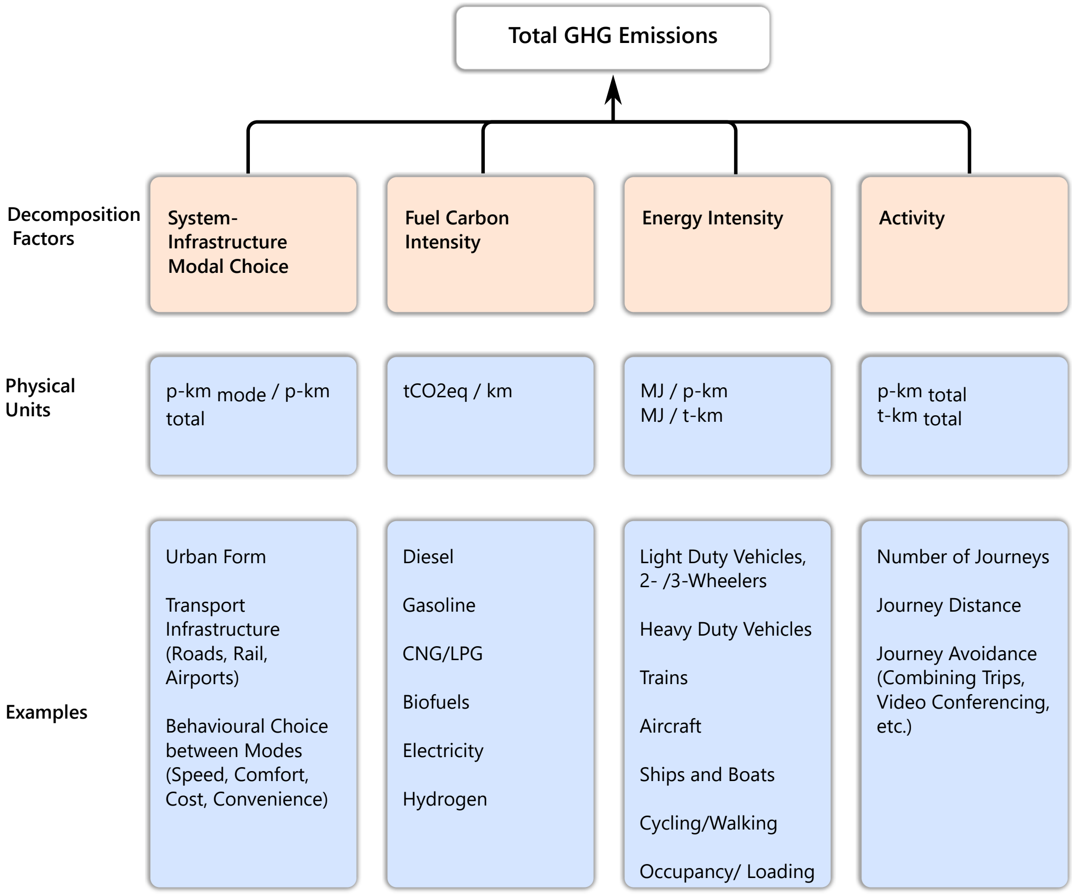

FIGURE 1.2 – Direct transport GHG emission reduction for each mode and fuel type options decomposed into activity, energy intensity, fuel carbon intensity and system infrastructure and modal choice. Source: Sims et al., 2014
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vehicle consume some energy, thus energy efficiency has steered technology innovation since the first fuel economy policies. In parallel, average modern vehicles have become more powerful than their predecessors therefore vehicles are today more energy efficient but also more powerful. To achieve this double objective, carmakers have explored solutions in all vehicle components from tires to engine friction. Every category of energy consumption has experienced some improvement: the average mass of vehicle has been reduced or optimized to get a higher power to mass ratio, the aerodynamic drag coefficient has been reduced through better design and lower profile vehicles, the tire rolling resistance has been improved to get better traction and less energy losses at the point of contact with the road, engines have introduced all kind of improvements to the energy cycle to obtain the maximum energy from combustion, new low carbon fuels have been introduced and new engine configurations with battery powered vehicles are an alternative to traditional powertrain configurations. All other appliances on board have experienced an improved energy efficiency to reduce energy demand as well.

The Internal Combustion Engine (ICE) has been the foundation stone of the car industry since the first car introduced in the XIX^{th} century. Today, the main engine types are the spark ignition engine based on gasoline or a mixture of gasoline with ethanol and the self ignition engine based on diesel or bio-diesels. Other alternatives of ICE are available replacing gasoline and diesel with compressed natural gas or liquefied petroleum gas. Despite the long history of ICE, the technology has progressively evolved and today there are improvements in the process of combustion of fuels with better design for ignition, exhaust control and improved air fuel mixture for better combustion. One of the many developments is the use of a turbocharger that uses engine's exhaust gas force to deliver compressed air to the combustion chamber. New materials and electronic controls are capable of adapting to different regimes and reducing fuel combustion. Current developments on ICE are still improving the thermodynamic efficiency of the engine with electric turbo, cylinder deactivation and direct injection. The energy efficiency frontier is being pushed beyond limits. We show in Figure 1.3 the different powertrain configurations that have been created to reduce carbon emissions. As illustrated, the baseline ICE (top left) is progressively equipped with an electric motor and battery, each step down in the figure representing a step further to full electrification of the powertrain.

The key limitation of ICE is that is only capable of storing and recuperating energy in the form of kinetic energy in the engine free wheel. This potential is small, and limited to certain conditions. To improve energy efficiency, the driving patterns are the center of electrified ICE that include a conventional ICE with a small electric motor and battery. This innovation is based on the electric start conveyor belt system that uses a battery and a electric motor to start all ICE and charge the battery. Electrified ICE go a step forward, the brake energy that would have been lost is converted to electricity by the electric motor that acts as a generator and stores energy in a battery for later use. There are many different possible architectures that vary in electric power, type of electric motor, store capacity, in line or parallel configuration. The applications to the driving patterns are diverse, and we only cite two here: a stop-start functionality that allows a vehicle to turn off the engine when the vehicle is stopped and start the engine back on to continue the ride, and a coasting functionality that allows a vehicle to operate at constant speed with an electric motor.

Today all ICE technologies are combined with advanced transmission technologies that improve efficiency by moving the fuel consumption to the best performance regime of the engine according to the engine map (Fig. 1.3, first row). To improve how power is delivered to wheels, transmission technologies focus on avoiding torque losses when shifting gears and being responsive when more power is needed. To do so engineers have improved the transmission mechanism to decrease energy losses and have also increased the number of gears to deliver more torque to wheels. Some of the recent developments are dual-clutch transmission, continuous variable transmission, automatic transmissions including more than 6 gears and electric transmissions that reduce torque loss when changing gears with

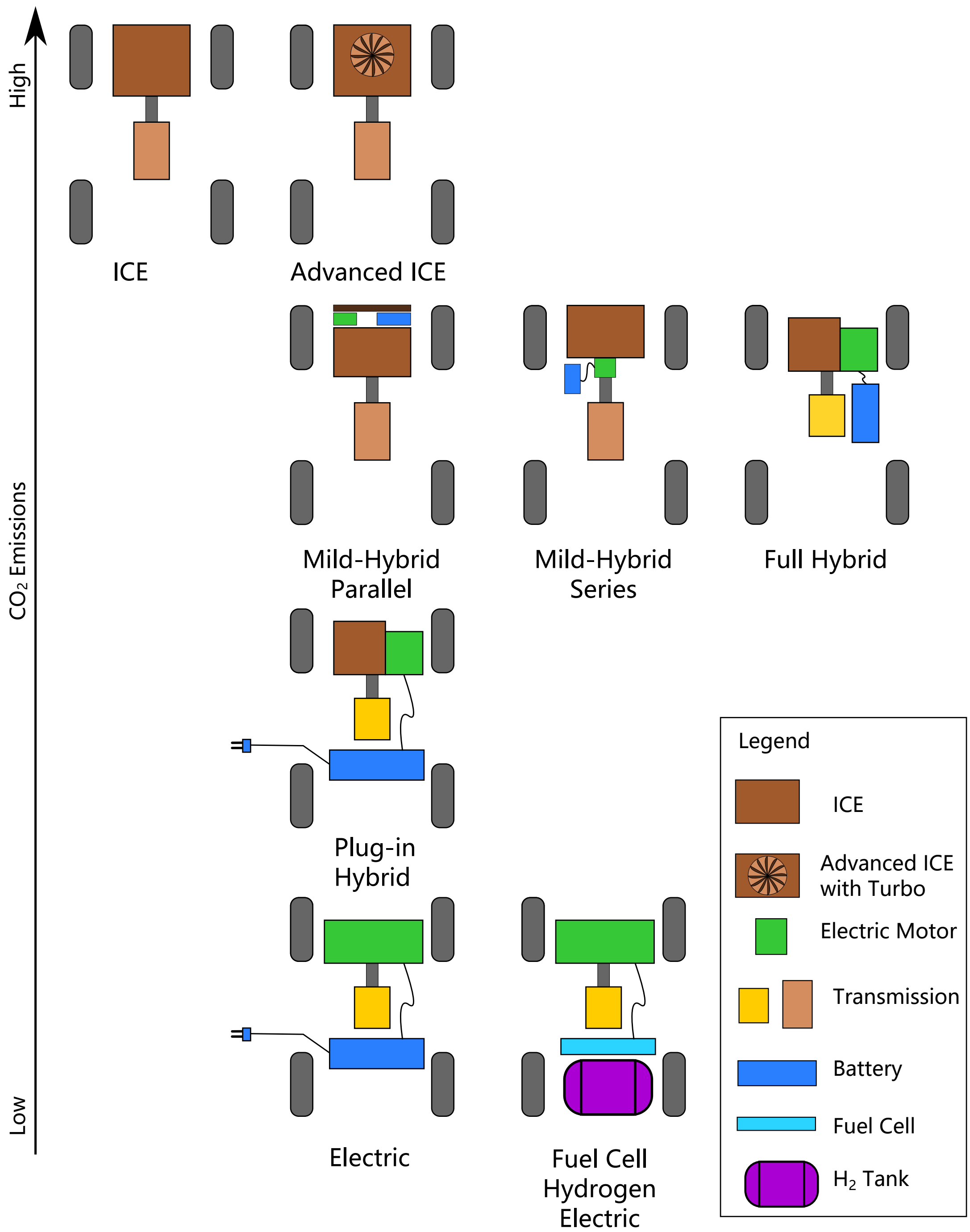

FIGURE 1.3 – Powertrain configuration of Automotive technologies to reduce CO_2 emissions. The CO_2 tail-pipe emissions order of each configuration is shown on the Y-axis. Source: The Author.

an electric motor.

The increasing storing and regenerating capacity of ICE that works on 12-Volts or 48-Volts create a new family of engines called mild-hybrids, seen as a transition stage in the electrification of engines (Fig. 1.3, second row). The 12V and 48V families of engines can have the following configurations: parallel or series [1]. A full-hybrid or Hybrid Electric Vehicle (HEV) has a new function that allows all electric drive under certain conditions. This type of engine is no longer in R&D phase, Toyota has been selling the Prius HEV since 1997. The limitation of an HEV is battery capacity. In order to increase the potential of the electric motor, electric power and battery storage capacity had to be improved. With new battery technology that allows an increase in energy density that converts to higher energy capacity at the same weight, car manufacturers were able to produce Plug-in Hybrid Electric Vehicles (PHEV) (Fig.1.3, third row). Some PHEV are optimized for an all electric use that will have an electric motor with an equivalent ICE of approximately the same power thus producing higher energy efficiency. However the architecture of a PHEV is more complex since it will integrate all ICE parts and all the Electric motor system.

The technological frontier on low carbon vehicles contains two solutions that have zero tail pipe emissions: Battery powered Electric Vehicles (BEV) and Fuel Cell Hydrogen Electric Vehicles (FCEV) (Fig. 1.3, bottom row). Both technologies use electric motors and electric energy to move the vehicle however the energy storage physics is different. In a BEV battery cells are combined to store a large electrochemical potential that can be charged or used to drive the electric motor. The FCEV has a hydrogen tank that is combined to a fuel-cell that converts hydrogen gas to electricity which produces only water and heat. While a BEV can be compatible with the existing electric network with the installation of public and private charging points, the FCEV can not, it requires a new hydrogen infrastructure to be deployed which is the main challenge of this technology. Today only a few car manufacturers are commercializing FCEV with limited models whereas BEV are commercialized by many car manufacturers and an increasing number of models is available. The battle of new BEVs focuses mostly on speed of charge: how much time to fully charge the battery? and the autonomy of the vehicle: how many km can a vehicle be driven with a full battery? The new technology solutions develop batteries with more energy storage and capable of charging at higher power input.

With the commercialization of BEV new possibilities to further explore mitigation solutions have emerged. From a power energy distribution point of view a BEV is an energy consumer that can move to different charging points. However it can also store energy in batteries to be transferred to the grid for later use, when the energy transfer is limited to home appliances this system is named Vehicle to Home (V2H) and when the energy transfer is directed to the entire grid this is named Vehicle to Grid (V2G). In a context where energy demand is predictable but renewable

1. A parallel configuration means that power output from the ICE engine and the electric motor is combined through a belt or gear whereas a series configuration means that output from the the ICE engine and the electric motor are added on the same shaft

energies are intermittent, BEV could store energy when renewable energy production is high and vice-versa they could provide energy when the electricity production is low. With the recent and future developments of battery cells and network systems, V2G and V2H become less costly and more efficient to manage the energy demand and supply dynamics.

The BEV has suffered critics that the Life-Cycle Emissions are higher than conventional engines due to indirect emissions of electric generation (J. R. Woo, Choi, and Ahn, 2017). This critic holds when the electric mix relies mostly on fossil fuels and coal which is the case in India and China but in regions where the carbon content of electricity is low: Brazil, EU and Japan an electric vehicle can effectively reduce emissions (Audoly et al., 2018). If the electric mix reduces its carbon intensity where it is still high then an electric vehicle becomes suited for sustainable low carbon transportation. Thus the benefits of a BEV can only be enhanced if the vehicle is integrated to the grid nonetheless location and time of charge are two elements to consider when deploying a BEV (Archsmith, Kendall, and Rapson, 2015). The BEV has also been pointed to have two more environmental impacts: metal depletion (specific chemical elements used in batteries) and water pollution (C. Bauer et al., 2015; Hawkins et al., 2012).

Technology solutions developed by Original Equipment Manufacturers (OEM) and suppliers are important to increase energy efficiency of vehicles. All R&D efforts require costly investments that are executed when the industry sees a clear future in a technology. More generally speaking, to provide the suitable conditions for R&D investments that correct market failures of road transportation, policymakers incentivize the industry to seek technology improvements that reduce vehicle's externalities. Next section describes the policy instruments that have been implemented so far in various jurisdictions.

1.2.4 Policy Instruments for Sustainable Passenger Vehicles Transportation

The negative externalities described above have inspired policymakers to both push carmakers to produce vehicles causing less environmental harm and pull public to adopt low carbon means of transportation. Policy instruments to regulate environmental externalities are traditionally classified into two main groups: command-and-control policies such as fuel economy standards and incentive policies such as fiscal policy instruments. We focus on the set of policy instruments that regulate vehicle's emissions. Policy instruments based on vehicle emissions are summarized in Table 1.2.

Incentive policies can be divided into two groups: incentives on vehicle purchase and incentives on vehicle usage. Vehicle purchase can be oriented via a feebate scheme, meaning fees + rebates based on the vehicle emissions level (Soren T Anderson, Ian W H Parry, and James M Sallee, 2011; Greene, Patterson, et al., 2005; Fischer, Harrington, and Ian W H Parry, 2007; Liu, Greene, and Bunch, 2014; Haan, Mueller, and Scholz, 2009). This incentive encourages manufacturers to build more efficient vehicles, by rewarding consumers who purchase more efficient vehicles. The essential elements of a feebate are: a pivot point that divides the vehicles charged with a fee from those receiving a rebate and a rate of fee or rebate depending on vehicle's emissions. In France, it is named "bonus-malus". It appeared in 2008, it has been adapted through the years by moving the pivot point, changing the configuration of fees and rebates according to the CO_2 emissions based categories and changing the maximum penalty and subsidy. More than 16 European countries have some form of CO_2 or fuel consumption tax on LDV (Mahlia, Tohno, and Tezuka, 2013). One of the characteristic of a feebate program is that it can be autonomous from the national budget if the subvention on low emission vehicles is founded by the tax revenue on high emission vehicles.

Sometimes government incentives for low carbon vehicles are present without an equivalent dedicated fuel consumption purchase fee for high carbon vehicles (Sen, Noori, and Tatari, 2017; Hardman et al., 2017). Conversely, there can be only a penalty for high carbon vehicles, with a gas guzzler tax (Greene, Patterson, et al., 2005; James M Sallee and Slemrod, 2012; Mahlia, Tohno, and Tezuka, 2013). To incentivize vehicle renewal with new and more efficient vehicles some countries have scrapping incentives, for example the UK (Brand, Anable, and Tran, 2013), France, Australia, California, China, Italy, Japan, Turkey, Germany and other countries (Mahlia, Tohno, and Tezuka, 2013). Scrappage schemes typically focus on vehicles that are more than a decade old or lack emission control technology such as the first generation of Diesel vehicles.

On a vehicle's lifetime, there are several policy instruments that regulate vehicle's usage: fuel taxes (Soren T Anderson, Ian W H Parry, and James M Sallee, 2011; Aghion et al., 2016; Tscharaktschiew, 2015) paid each time the vehicle consumes a liter/gallon of fuel [2], vehicle ownership taxes (ACEA, 2017) paid once a year or every other year where a tax is based on the carbon emissions and/or emission standard of a vehicle and vehicle km travelled taxation.

Command-and-control policies in the transport sector often come in the form of regulatory standards. This instrument takes the form of a technical rule imposed on firms, and characterized by a mandatory policy target or norm. To reduce fuel carbon intensity, low carbon fuel standards (LCFS) promote the use of biofuels (Ian W. H Parry, Walls, and Harrington, 2007; Santos et al., 2010). For example, Brazil has based its low carbon fuel strategy on a mandatory blend of gasoline and bio ethanol obtained from sugar cane plantations and promoted the use of flex-fuel vehicles

2. More stringent fuel tax can cause political resistance from consumers as seen in France where an increase in oil price coincided with an increase in tax that resulted in protests.

Policy	Type	Scale	Mechanism	Technology Specific / Neutral
Low carbon fuel standard	Command-and-control	National	Applied to fuel suppliers: lowering carbon intensity of fuel	Neutral
CAFE	Command-and-control	National	Applied to car manufacturers: increasing energy efficiency of vehicles	Partially Neutral*
ZEV Mandate	Command-and-control	National	Minimum quota of ZEV for car manufacturers	Technology Specific
Emission Standard	Command-and-control	National	Minimum requirement of emission limits for all vehicles	Neutral **
Feebate	Incentive-based	National	Fees and Rebates of vehicle price for high and low emitting vehicles respectively	Neutral
Scrapping scheme	Incentive-based	National	Subvention on new vehicle purchase when scrapping an old vehicle	Neutral
Fuel tax	Incentive-based	National	Tax on fuel suppliers	Neutral ***
Ownership tax	Incentive-based	National	Tax on vehicle owners paid once a year based on vehicle's emissions	Neutral
LEZ	Command-and-control	Local	Circulation restriction of high emitters from city-centers or urban areas	Technology Specific

TABLE 1.2 – Summary of Main Policy Instruments based on vehicle's emissions. *When the fuel economy standard is indexed to a parameter there is an incentive to comply with the target by changing the vehicle characteristic according to the index parameter.**The EURO standard has treated Diesel and Gasoline vehicles differently with less severe standards for Diesel vehicles. In latest standards this gap is reducing and the policy goal is to eliminate this gap.***Some countries have different fuel tax level for Gasoline and Diesel. In France Diesel had a lower tax than Gasoline. Source: The Author.

adapted to accept gasoline or ethanol (Stattman, Hospes, and Mol, 2013). LCFS require the average lifecycle fuel carbon intensity to improve over the years. The goal of the policy is to introduce low carbon fuels instead of traditional fuels. Lepitzki and Axsen, 2018 show that when combined with other vehicle standards it has an additive effect which is higher in the freight sector.

The Corporate Average Fuel Economy (CAFE) standard first implemented in the USA after the oil crisis in the 1970's is applied to car manufacturers. A firm is required to have new vehicle sales with an average fuel economy above the enacted target. If a firm fails to comply, it is subject to monetary fines. A CAFE standard is set between 5 to 10 years in advance to allow carmakers to develop low carbon vehicles and be compliant with more stringent targets. There is an increasing number of markets that are implementing a CAFE policy and the stringency of the policy is also growing in time. However there is still a wide gap between the leaders in fuel economy in 2015 such as Japan and the EU and India, and the back of the pack with countries such as China, South Africa and the US see Fig.1.4. The historic trend tell us that countries with poor fuel economy in the past are capable to catch up with others for example South Korea has done it in the past and plans to become one of the leaders.

The mechanism of CAFE has little variations such as (i) the base driving test

TABLE 1.3 – Fuel Economy Standards for Passenger Vehicles main vehicle markets. *JC08: Japanese test Cycle. Source: ICCT, 2017

Country or Region	Index Parameter	Unadjusted Target	Target Year	Test Cycle
Brazil	Mass	1.82 MJ/km	2017	U.S. Combined
Canada	Footprint	217 gCO_2/km	2016	U.S. Combined
China	Mass	5 L/100km	2020	NEDC
EU	Mass	95 gCO_2/km	2021	NEDC to WLTP
India	Mass	113 gCO_2/km	2022	NEDC
Japan	Mass	20.3 km/L	2020	JC08* to WLTP
Mexico	Footprint	39.3 mpg or 140 gCO_2/km	2016	U.S. Combined
Saudi Arabia	Footprint	17km/L	2020	U.S. Combined
South Korea	Mass	24km/L or 97 gCO_2/km	2020	U.S. Combined
U.S.	Footprint	55.2 mpg or 146 gCO_2/mi	2015	U.S. Combined

cycle, supposed to represent the typical usage of a car with a standard driving profile, (ii) the credits for off cycle technologies that are not fully captured in the emission test such as LED lights, (iii) the supercredits for low carbon vehicles allowing to count a zero emission vehicle more times on the average emissions of a firm, (iv) the metrics of the standard: fuel economy (mpg) , energy intensity (MJ/km) or carbon emissions (gCO_2/km) and the index parameter: vehicle mass or footprint. In Table 4.1 we show the differences in CAFE policies around the world.

Most of the literature on fuel economy standards is based on the U.S. case where it was introduced after the oil crisis in the 1970's.

The main specificity of the U.S. CAFE standard is that it determines fuel-economy target based on the footprint (wheelbase by track width) of vehicles, such that larger vehicles have less stringent fuel-economy target. This design of the policy introduces what some authors flag as a "loophole", because it creates a manufacturer incentive to increase vehicle size in place of implementing fuel-saving technology features to their vehicles; therefore reducing the stringency of the target and resulting in increased fleet-wide gasoline consumption and emissions. One of the key question explored in the literature has been to assess how much the CAFE leads to modify vehicle dimensions, implement fuel-saving technology features in internal combustion engine vehicles (ICEV) or increase the market share of alternative fuel vehicles, in particular electric vehicles. Using an agent-based model, Sen, Noori, and Tatari, 2017 showed that manufacturers tend to comply with the CAFE standards by changing the design of ICEV. With a representation of detailed vehicle specifications and wide ranges of scenarios for consumer preferences, Ullman, 2016, Whitefoot and Skerlos, 2012 and Shiau, Michalek, and Hendrickson, 2009 show that the footprint-based standards create an incentive to increase vehicle size. The order of magnitude of the resulting increased emissions is 5-15% compared to a standard with no indexation on the footprint. Klier and Linn, 2016b and Whitefoot, Fowlie, and Skerlos, 2017 add an additional dimension to the analysis, considering design trade off with other vehicles attributes (horsepower, torque, acceleration) implied by CAFE standards.

They provide empirical evidence that the standards have affected the direction of technology adoption and that producers reduced horsepower, torque and acceleration to achieve compliance. This effect mitigated incentives to shift sales toward larger vehicles.

On the issue of size increase, implied by footprint based targets, some authors explored the security implications (Bento, Gillingham, and Roth, 2017; Jacobsen, 2013). They find empirical evidence that CAFE standards reduced the mean weight of vehicles, while increasing the dispersion of weights in the fleet. The lowered mean weight dominated the effect on security, such that CAFE standards have reduced accident fatalities.

A few studies focus on other specificities in the design of the CAFE standard, in particular bonuses associated with certain technologies that allow automakers to meet less stringent target. Jenn, Azevedo, and Michalek, 2016 analyzed the effect of bonuses that give incentives to sell alternative fuel vehicles (AFV). They quantify the additional emissions associated with this bonus, amounting to up to 60 tons of CO2 per AVF sold, compared to a case without the bonus. Soren T. Anderson and James M. Sallee, 2011 exploit another "loophole", as they call it, in the standards to estimate cost of compliance. Automakers get a bonus when they equip vehicles with flexible-fuel capacity. Soren T. Anderson and James M. Sallee, 2011 assume that profit-maximizing firms will equate the marginal cost of compliance with the standard using the bonus, which is observable, with the unobservable costs of technologies to improve fuel economy. They estimate compliance costs between $9 and $27 per vehicle in years just before 2011.

Finally, some studies adopt a prospective approach and project the effect of tightening CAFE standard at the 2025 horizon (Xie and Lin, 2017; Nicholas Lutsey, 2012; Liu, Greene, and Bunch, 2014; Luk, Saville, and Maclean, 2016). They find that the technology adoption (of fuel efficiency technologies and alternative fuel vehicles) is likely to play a larger role with the increased stringency in the standard.

There are also studies on CAFE standards in other countries and regions: in Europe (German and Nic Lutsey, 2010; Thiel et al., 2016; Skeete, 2017; Klier and Linn, 2016a; Klier and Linn, 2016b; Yeh, Witcover, et al., 2016), in Japan (Ito and James M Sallee, 2017), in China (Wang et al., 2018; X. Zhang and Bai, 2017), in South Korea (J. Woo et al., 2017), in Brazil (Augustus et al., 2018), in ASEAN countries (Silitonga, Atabani, and Mahlia, 2012) and a review of passenger car emission standards and taxation measures in G20 countries by Yang, Mock, et al., 2017.

The Zero Emission Vehicle (ZEV) Mandate is an air pollution measure that the state California put in place to deploy low emission vehicles (Sykes and Axsen, 2017; Sierzchula and Nemet, 2015; Greene, Park, and Liu, 2014; Wesseling, Farla, and Hekkert, 2015; Collantes and Sperling, 2008). The policy requires manufacturers to deliver a mandatory share of ZEVs per year registered as ZEV credits. These credits

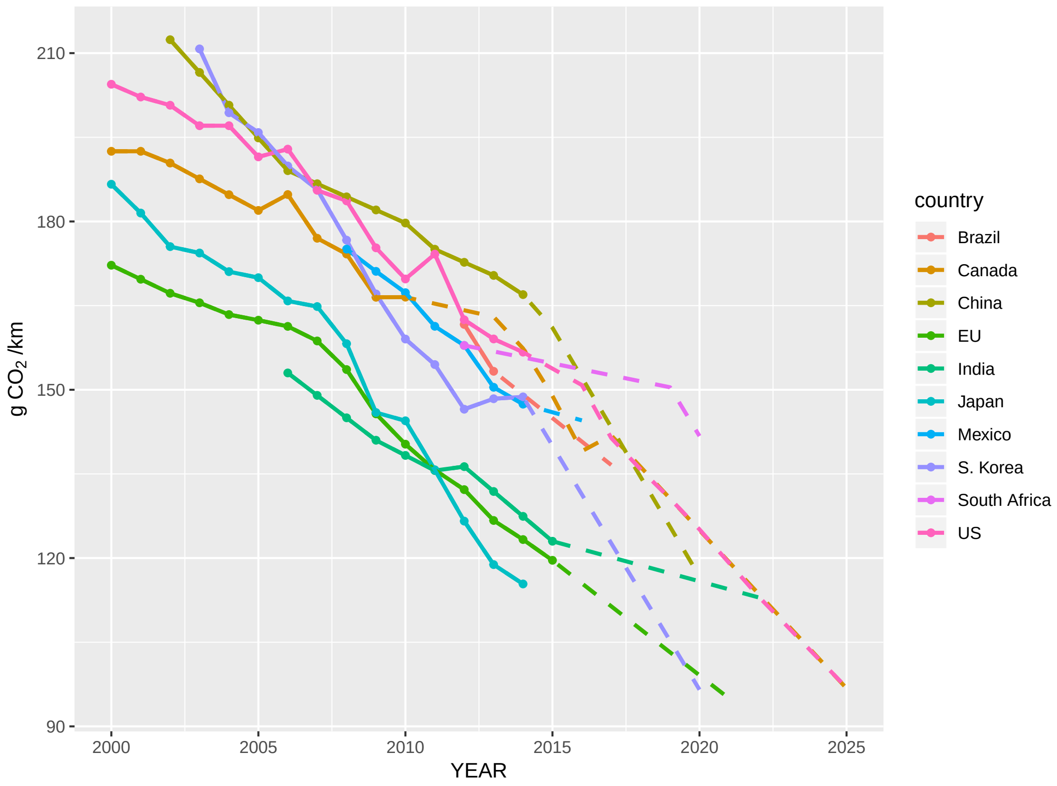

FIGURE 1.4 – Historical fleet CO_2 emissions performance, and current standards targets in dashed lines (gCO_2/km normalized to NEDC) for passenger cars. Source: Yang and Bandivadekar, 2017.

work like a bank system where a car manufacturer can owe, lend and distribute the credits with other OEM firms. The system includes also a possible conversion of ZEV credits to fuel economy compliance to incentive ZEV. This technology specific policy is only implemented in California, Quebec and China. This policy instrument fosters innovation on zero emission vehicle but can also be a risky bet on battery electric vehicles if the technology fails to deliver.

Air pollution is a major concern for policymakers. The EU has agreed on maximum concentrations levels of pollutants. For LDV this limits translate to emission standards called EURO norms first introduced in 1992. In practice, firms need to pass the emission test to receive approval for commercialization of a vehicle thus new vehicles need to adapt when limits are more severe. Today EURO 6 standard is integrating progressively Real Driving Emissions (RDE) to reduce the gap between test-cycle and on road emissions.

The rapid motorization in the United States led to smog becoming a major health issue during the 1950s and 1960s. Due to weather conditions and high volume of traffic, the Los Angeles basin suffered more from this problem. California decided to pass a Clean Air Act in 1965 that became later the federal rule for the nation (Klier and Linn, 2016a). The first nationwide emission standards were implemented in 1968, Today they are known as Tier 3 standards that were implemented in 2017, they differ from European standards in their approach to be "fuel neutral" having the same emission limits for all vehicles. The large majority of the vehicle market is regulated by some variant of the US or EU type emission standard [3].

Vehicle labeling is a policy instrument that can be used as a complement to fuel economy standards (Silitonga, Atabani, and Mahlia, 2012). The effectiveness of fuel economy label depends upon supportive retail staff, advertisement and consumer awareness of the label (Mahlia, Tohno, and Tezuka, 2013). The vehicle label program works best when a grading system provides the consumer with the information about the efficiency level.

There is a group of instruments that can be command-and-control or incentive-based but that are applied locally to urban areas (Ajanovic and Haas, 2016) that also regulate the vehicle market such as: tolls, high occupancy lanes or car pool lanes, vehicle restriction or Low Emission Zones (LEZ) (Wolff, 2014; Ellison, Greaves, and Hensher, 2013; Holman, R. Harrison, and Querol, 2015; Jiang et al., 2017; Morton, Lovelace, and Anable, 2017) and parking restriction. The aim of local policies is that they solve a local pollution or congestion problem to do so the mechanism can vary. They can be technology neutral when based on the occupancy of a vehicle or the registration plate number as oppose to technology specific policies that penalize high emitting vehicles by restricting access to city centers or prohibiting the use of such vehicles during peak emissions in french cities. Some services can be targeted for low emission vehicles only for instance allowing access to Ultra Low Emission Zones only (ULEZ) or access to reserved parking spaces. For developing the BEV there are additional measures that can be implemented concerning infrastructure to avoid having a chicken and the egg problem (G. Harrison and Thiel, 2017; Broadbent and Drozdzewski, 2017; Querini and Benetto, 2014).

Today, many European cities have implemented LEZ or are planning to do so. Before introducing the examples of applications, we can note that the strength of LEZ policies can be measured by what is the share of the vehicle fleet that will be left out of the restricted area. Figure 1.5 represents the type of LEZ from a policy affecting old and polluting light and heavy duty vehicles to a policy allowing ZEV only or no cars at all. Some LEZ are combined with car-restrict centers where only vehicles of special purpose are allowed. In Milan, a urban toll labeled Ecopass was implemented in 2009 and charges a fee proportional to PM emissions to enter an area in the center of Milan. The policy today is called Area-C and charges a daily fee for all vehicles except low emission vehicles: HEV, PHEV and BEV. The policy includes a ban on Diesel vehicles registered with an Euro standard 1 to 4. In London, the London Congestion Charge scheme, introduced in 2003, is also a system of fee levels for different types of vehicles. Today the area covers the Greater London and only Ultra Low Emission vehicles are exempt of the fee (Morton, Lovelace, and Anable,

3. More detail on limits and evolution of emission standards worldwide can be found in TransportPolicy.net

2017). In Paris, vehicle labels Crit'Air that identify vehicles in a note from zero emission (0) to high polluters (5) guide the LEZ. Since 2015, in case of peak emissions the government can decide to ban the most polluting class of vehicles. The policy also bans the highest class of labels from the city of Paris during weekdays permanently. In the future, the major of Paris has plans to ban Diesel vehicles by 2024 and Gasoline vehicles by 2030. The area of the LEZ will expand next year to cover the outer circulation rim delimiting the Greater Paris.

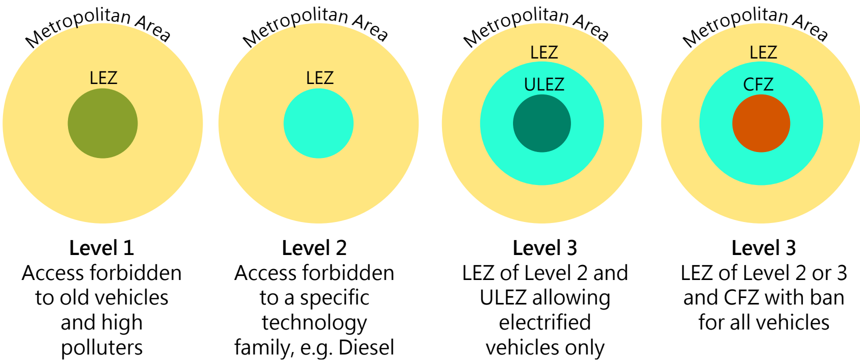

FIGURE 1.5 – Four different levels of Low Emission Zones (LEZ) that are currently implemented or planned by cities. An Ultra Low Emission Zone (ULEZ) only allows very low emission vehicles to circulate in city centers. A Car Free Zone (CFZ) bans vehicles from city centers. Source: The Author.

1.3 Position of the Thesis

Developed economies have based their growth in better connecting economic hubs, this led to a high dependence on the automobile ecosystem: roads, fueling stations and manufacturing. The economic benefits of a highly connected economy have allowed countries to create wealth. However the economy has failed to solve important damages to the environment and health threads from vehicle's emissions. This thesis is focused on a small part of sustainable transportation, we center our attention on the low carbon technologies choices made by automotive firms. We cover two externalities: climate change and air pollution.

There are multiple pathways to reduce emissions from road transportation, we focus on passenger vehicles. We concentrate on energy efficient solutions to reduce fuel consumption or increase the use of low carbon fuels. Thus we look closely at powertrain technologies in all applications. We are also interested on a different family of low carbon solutions, lightweight technologies in the aim of testing how a fuel economy standard mass-index parameter treats a technology that reduces vehicle's mass, see Chapter 4.

The policy tools created in the LDV market are necessary but their efforts are not sufficient, carbon dioxide concentration on the atmosphere is still on the rise and air pollution is still above safe limits in many cities from developed countries and the situation is worse in developed countries. It is urgent to act on all possible levers to reduce vehicle's emissions. We pick the fuel economy standard to drive the discussion of this thesis for three reasons. First, it is a worldwide policy that have already been tested thus we know how the automotive market has reacted to this policy. Second, it is a policy that gives short term vision and a more stable long term sight than other policies giving policy targets for firms. Therefore the fuel economy standard gives strong signals to develop a future technology portfolio. Third, the literature is large but there are still key policy issues that need to be explored.

We focus on three policy issues related to fuel economy standards in this Thesis. First, we study the intertemporal effects of fuel economy targets and how a firm perception of future policies could lead to lock-in technologies that have low abatement potential (1.3.1). Second, we zoom in the fuel economy standard to show how the mass-indexation works and how it affects technology choices and compliance costs (1.3.2). Third, we incorporate air pollution policies on LDV to the analysis, an emission standard, two types of LEZ (Level 2 and 3 in Fig. 1.5) and a Zero Emission mandate. Air pollution is receiving more attention due the growing vehicle fleet worldwide and the extreme pollutants concentrations in developing countries that have highly populated urban areas with an increasing demand for motorized vehicles. We evaluate the effect of overlapping policies with different policy objectives (1.3.3).

1.3.1 Fuel Economy Standard and Path Dependency of vehicle technology choices

Energy efficiency solutions to reduce carbon emissions require a R& D to market process than can be long until cost and performance can compete with current technologies. Moreover, technology adoption of innovative products is slow because only a small niche of consumers is willing to adopt new technology at first. Passenger vehicle technology show this behavior for new low carbon technologies as we will describe in section 1.4. Therefore the response that an automotive firm can produce to reduce emissions depends not only on the knowledge and experience to deliver a safe and reliable vehicle but also on the rate of adoption of new technologies.

These market limitations are key to preparing a mix of solutions adapted to future fuel economy standards. The challenge for a firm is to prepare technology solutions in advance to allow for consumer adoption with the final goal being compliant when the standard comes into effect. In a competitive industry where market strategy pushes firms to make profits in the short term, long term policies are often a second priority. The perception of future policy objectives is key along two dimensions: time and stringency.

A fuel economy policy is determined several years in advance, in most markets ten years. This horizon needs to be large enough to allow technology development. Time also relates to the diffusion of new technologies that is slow especially when the replacement technology does not provide exactly the same performance as the incumbent technology. This is case of the EV, which is not yet capable of fully replacing an ICEV for all purposes. Conversely, when a technology diffuses in a market and a car manufacturer has already committed to this technology, the firm will be less likely to change for another technology in the near term. This is economic inertia.

The stringency of the fuel economy standard determines the amount of low carbon technology in the technology portfolio. An stringent policy means that it is more likely to have a high share of low carbon technologies rather than a scenario where stringency is low and compliance is possible with little change in the current mix. The stringency of the policy increases in time as seen in Fig.1.4 thus a car manufacturer knows that if the trend of increasing stringency continues, it will be required to develop or diffuse more low carbon technology in the future.

How does an automotive firm prepares for near term and longer term policy targets? A firm can take two approaches: It can take all available information on future policy targets to develop a foresight strategy to adapt for the near and the longer term, or it can weight in more the near term policy input and prepare for the longer term target later on in a myopic view of the future. What is the impact of a myopic view of the future on technology choices? These questions will be treated in Chapter 3.

When addressing the same question for energy supply technologies under emissions constraint, Integrated Assessment Models (IAM) show carbon lock-in on coal generation when there is lack of policy ambition (Bertram et al., 2015; Vuuren and Riahi, 2011; N. Bauer et al., 2015) that is caused by a failure to anticipate long-term targets.

Applying a similar approach, we focus in Chapter 3 on the impact in the automotive industry of consecutive fuel economy policies with increasing stringency. This problem has been overlooked in the previous fuel economy literature in which a single policy target is often considered, thus neglecting the path dependency of technology choices. In a macro scale, Vogt-schilb, Meunier, and Hallegatte, 2018 suggest that investments should be optimally directed to sectors with higher mitigation cost if they are also characterized by higher inertia. We will develop the concepts of path dependency, technology lock-in and inertia in section 1.4.

Specifically, Chapter 3 will explore the different conditions under which the near term efforts are sufficient to allow long term compliance in a myopic scenario and ask when near term target compliance is a sufficient condition, or not, to guarantee longer term compliance.

1.3.2 Mass-index fuel economy standard implications on technology selection

Automotive regulations such as fuel economy standards are made to correct market failures. However, they can produce unintended consequences, such as vehicles using conventional fuels instead of renewable fuels for flex-fuel vehicles (Marchant, 2009). Consumers that bought flex-fuel vehicles refuel with gasoline, thus the government objective of reducing emissions is not achieved. In the corporate fuel economy standard, studies show that automakers have adapted a vehicle parameter or vehicle segment to have less stringent targets (Knittel, 2011; Ullman, 2016; Luk, Saville, and Maclean, 2016). For example, in the USA there are two LDV fuel economy standards: one for small to medium vehicles that is stringent and another one for pick-ups and SUV segment that is less stringent, thus the segment distribution of some manufactures has evolved to develop more of the high carbon emission segment of pick-up and SUV.

Does the fuel economy standard has any loophole and if any what are the implications? Two main kinds of fuel economy standard exist: one based on vehicle footprint, a measure of vehicle size: wheelbase x track width, and the other based on vehicle mass, also a measure an indirect measure of vehicle size. Both have been studied closely to check if there was any incentive to change the policy parameter instead of introducing better fuel economy vehicles. Studies in the US (footprint indexation) (Ullman, 2016; Whitefoot and Skerlos, 2012; Shiau, Michalek, and Hendrickson, 2009; Ito and James M Sallee, 2017) and in Europe (mass indexation) (Luk, Saville, and Maclean, 2016; German and Nic Lutsey, 2010; Kollamthodi et al., 2015) have found evidence of an incentive to change the indexation parameter. This thesis investigates the neutrality of fuel economy standard indexed to vehicle's mass and discusses the implications of such technology choices in Chapter 4. Our approach shows the bias on technology choice in theory and in compliance application that includes lightweight technologies. To do so we isolate the effect of mass indexation by modeling two scenarios with the same fuel economy target but with a fuel economy standard with and without indexation. We show the differences between the two mechanisms in terms of vehicle's mass, technology cost and cost of ownership.

We found that when preparing for a future CAFE policy target indexed to mass a car manufacturer does not have an incentive to introduce lightweight technologies instead it develops BEV that have zero emissions in the context of CAFE and are heavy. Besides this difference in technology choice, we find only limited difference in overall costs between a CAFE standard with and without indexation.

1.3.3 Overlapping of Environmental Policies to address a double objective: air pollution and climate change

The automotive industry needs to produce vehicles that correspond to local government ambitions that push for less emitting vehicles. The technology portfolio of current technologies needs to evolve if the aim of local policies is to have a zero emitting fleet. Furthermore, the time horizon of zero emission policies of cities through local policies is closer than national or regional scale policies. Therefore the technology solutions need to be prepared in advance and there is a more severe stringency on technology choices. The problem arises when policymakers create policies meant to reduce GHG emissions and policies meant to reduce local pollution in urban traffic, these are two different objectives and an automotive firm faces both.

The combination of two policies in the automotive sector one local and the other global is the subject of Chapter 5. How the overlapping of policy instruments affects technology choice? To study the effects of the combination of two policies we use two concepts: synergy and trade-off to describe the interaction of policies. We can describe these effects at three different levels, described below: a single technology choice, a portfolio of technologies selection and a policymaker ambition to reduce vehicle's externalities.

When a firm is confronted with different objectives, it will analyze if an objective prevails over the others. Likewise, when preparing a future technology portfolio a firm strategy will look for technology solutions that can answer to multiple policy objectives, in this case the policy effect is synergy. In the case that such a technology does not exist or is too expensive, a car manufacturer will have to trade-off between the optimal solution for a policy objective and a second-best solution that complies with multiple objectives. Are synergy and tradeoff effects seen when combining two passenger vehicles policies? We check for the gap at the technology choice level to understand how overlapping of policies changes the preferred technology.

To prepare a future technology portfolio, a firm finds a least cost solution to answer a policy objective. When two objectives are considered, there can be three situations. First, the second policy does not change the first choice of technologies because the policy is not severe enough to constraint technology choice. Second, the stringency of the second policy is high enough to affect technology choice but both policies share some compatible technologies thus creating synergy. Thus there will be differences between the first choice and the second choice with overlapping policies but it will be small. Third, when there is incompatibility between the requirements for the two policies, the technology portfolio optimal for each of the policies will be different when combined with the other policy and a trade-off emerge to create a mix suitable for both policies.

For policymakers aiming to reduce different sorts of externalities, they face a challenge to create a policy package that is efficient meaning that it will be be cost-beneficial for society. Finding the ideal combination of policies is difficult because synergies reduce the cost of overlapping policy compliance but some objectives do not produce synergy therefore a policymaker decision is based on a balance between trade-off and synergies within a policy package. The challenge is double because most often policies for different externalities are prepared by different actors.

We have combined a fuel economy standard with a local policy to see the interaction between these policies. We have also modeled a Zero Emission Vehicle (ZEV) Mandate that is a mandatory quota of low zero emission or very low carbon vehicles that a car manufacturer needs to comply at a national scale in the same fashion than the Chinese and Californian ZEV Mandates. There are three policies that are technology specific the two types of LEZ and the ZEV Mandate, nevertheless the actors engaged on each of the LEZ policies and the ZEV Mandate are entirely different: one is developed by local authorities and is subject to local context and the other is a national enacted target that has been created by national governments. The mechanism is different where a ZEV Mandate does not require to sell low emission vehicles in cities, a LEZ policy only restricts vehicles of urban areas meaning that in rural areas or cities that do not adopt LEZ policies there is no constraint on the type of technology. Therefore we modeled both policies to compare it effects.

The ZEV Mandate pushes for very low carbon vehicles which puts more constraints on technology choices and develops a mix that has very low emissions vehicles and high emissions vehicles. This compensating effect seen in other policies and described as the green promotes the dirtiest (Böhringer and Rosendahl, 2010) is an undesired effect of the ZEV Mandate.

We explore various scenarios of policy applications: first we identify the effects of application of a single passenger policy and second we combine a fuel economy standard with one of the policies described above to identify a difference in technology choice, CO_2 emission reduction and costs. A prevailing policy exist when it is more difficult to comply with a policy than others. The strength of a policy can be modified by a change in stringency. For this reason and to model a range of policy outcomes to represent the policy target uncertainty we have changed the stringency of each of the policies. For the purpose of this Chapter, the analysis is focused on prevailing policies rather than the uncertainty of the target. The aim of Chapter 5 is to study the effect of overlapping policies.

1.3.4 Summary

The fuel economy standard has the spotlight of this thesis but it is seen from different perspectives to show implications on the anticipation of targets, the loophole in the mechanism of compliance and the effect on other automotive policies.

Every application of this thesis shares two aspects: they all treat the fuel economy standard and they are all based on the same model that we introduce in section 1.4.

The research community has long studied low carbon policies that apply to passenger vehicles, we contribute to this literature by focusing on three aspects that have been less studied. First, the dynamics of how technologies are selected gives us the clues to detect when a technology solution is not competitive enough to be developed and is consequently abandoned. The stringency and timing of policies are crucial to give a strong signal to firms to take action. Second, the creation of automotive policies is the result of discussions between firms, policymakers and public, this sometimes leads to imperfect policy instruments. The CO_2 emission standard indexed to vehicle's mass is one example of such policies, regulators need to keep an eye on the application of this policy to avoid negative impacts on the policy goal. Third, policymakers have created policy instruments to regulate vehicle's emissions impacts separately, meaning that the policy objective is focused on solving one type of externality. When preparing a future technology mix, a firm will need to take into account all of policy constraints jointly to deliver an adapted product. All of these aspects on vehicle's emission policy will be treated from a supply side approach where a firm will choose the technology options to respond to a policy framework and a demand that resist to change. The next section will describe this approach.

1.4 Methodological Approach: Technology Choice under inertia and policy constraints

To address the questions outlined in Section 1.3, we develop a stylized model of technology choice for an automotive firm with policy and market constraints. This section describes the gap that the model tries to fill. Two branches of literature have inspired the development of the model: the diffusion of technologies literature that has observed past technological transitions and characterized them (1.4.1) and the passenger vehicle technology models that have multiple forms but all are related in the sense that they study the same market relations between policymakers, firms and consumers (1.4.2).

1.4.1 Economic inertia as a constraint on Technology Diffusion

The wider context of economic and social changes in which the transport sector evolves is a lengthy process of energy demand and supply transition that is changing the current system. This large transformation is referred to as the low carbon transition and is comparable with past energy transitions that have also deeply changed the energy systems. In short, an energy transition can been defined as the period of major changes from a established and functional energy system to a new and different system (Geels, 2002; Geels, 2012). Thus the adoption of a new energy system requires changes not only on the end-use technology but also on the ecosystem as a whole (Kemp and Pontoglio, 2011). In terms of automotive technology, the low carbon transition means developing less fossil fuel consuming technologies. The internal combustion engine is the incumbent technology that is the established ecosystem and alternative fuel vehicles (AFV) are the low carbon solution. Once that the transition takes place, the incumbent technology will try to resist and will develop further to avoid been replaced, this is called the sailing ship or last gap effect (Grübler, Nakićenović, and David G. Victor, 1999; Fouquet, 2016; Sick et al., 2016).

Past transitions in the transport sector have been analyzed and give valuable information about how future transition might occur. Two examples that have radically changed the means of transportation are the evolution from horse carriage to steam engines and railways and the diffusion of petrol engines and roads replacing steam engines and railways (Grübler, Nakićenović, and David G. Victor, 1999; Wilson and Grubler, 2011). The change in the energy vector from oil to electricity in transport is a sign that the future transition to electric powered vehicles will radically change the energy system as it is conceived today. The technological improvements have been accelerating in recent years with the main markets demanding for low carbon solutions from the industry (Dechezleprêtre, Neumayer, and Perkins, 2015).

The concept of path dependency was first elaborated to describe how a product spreads and becomes a standard despite not being the optimal solution for everyone. The QWERTY keyboard system was develop to avoid typewriters to type fast in machines that tend to jam. This change in design stuck through decades despite losing its purpose to avoid fast-typing when technology improvements solve the jamming problem. The reasons for keeping with this design were technical interrelatedness, economies of scale and quasi-irreversibility of investment (David, 1985).

Economists have applied the concept of path dependency to describe the way in which a small, historically contingent events can trigger self-reinforcing mechanisms and processes that "lock-in" particular structures and pathways of development (Martin and Sunley, 2006). In the automotive industry path dependency occurs when technical choices dictated by historical developments due to scale and learning economies, technical compatibility, and industrial networks, result in lock-in in technologies that are less competitive for future's requirements (Åhman and Nilsson, 2008). In the climate change community, the concept of carbon lock-in defines the interlocking technological, institutional and social forces that led industrial economies become locked into fossil fuel-based technological systems (Unruh, 2000).

In a complex and large energy system where different end-use technologies coexist, clustering and network effects form between energy conversion technologies and energy supply infrastructure (Wilson and Grubler, 2011). The dominant system benefits from an adapted network and infrastructure that are difficult to change. On top on the energy system, institutions, behavioral routines and practices enhance the system mechanisms (Wilson and Grubler, 2011; Li, Trutnevyte, and Strachan, 2015). These definitions describe the system dynamics and forces that create lock-in and the dynamics of this process are described as path dependency. To replace the dominant technology, the entire system needs to adapt too, this dynamic is slow because of lock-ins where the incomer technology finds a niche market to develop but finds resistance to spread to a larger market.

To integrate how a technology can become more competitive through cost reductions and performance improvements, economists introduce learning effects. The specific mechanisms driving learning are listed below, taken from Kahouli-brahmi, 2008:

— Learning-by-doing: repetitive manufacturing tasks involve an improvement of the production process.
— Learning-by-researching: improvements related to the innovation process and creation of knowledge.
— Learning-by-using: user's experience and feedback effects that follow introduction to the market are source of technology learning.
— Learning-by-interacting: interactions between the various actors like the research laboratories, the industry, the end-users and the political decision-makers enhance the diffusion of knowledge.
— Economies of scale: at the mass production stage, as the output increases the unit cost curve drives costs down.

Learning is one of the mechanism that can explain technology lock-in (Mattauch, F. Creutzig, and Edenhofer, 2015). A dedicated literature has focused on estimating the learning rate of technologies: in the energy sector (Mcdonald and Schrattenholzer, 2001) and in vehicle technology (Weiss et al., 2012). The implementation of learning in models allowed to take into account some of the dynamics driving path dependency, when a technology spreads in a market it will reduce costs following a learning curve (Grübler and Messner, 1998; Berglund and Söderholm, 2006; Kahouli-brahmi, 2008). Although our model does not include any type of learning but, we are able to capture the effects of path dependency by focusing on inertia and diffusion constraints.

Past diffusion of technologies have shown a defined S shape of market share where the initial rate of diffusion is slow when the market share is low in the first stage of diffusion then the rate of diffusion peaks when half of the potential market has been covered and finally is slow again to diffuse on the most incompatible or unwilling consumers to adopt the technology. A large freight cargo ship requires several kms to fully stop because of mechanical inertia. In economy, an energy system also have a difficulty to change direction and speed. To capture this dynamic we can use economic inertia that acts as an upper limit on technology diffusion (Vogt-schilb, Meunier, and Hallegatte, 2018).

The approach that we have developed is different from (Vogt-schilb, Meunier, and Hallegatte, 2018) in the way that we treat the diffusion constraint. We obtain the limits on speed of diffusion from the sales share of technologies. By doing so we solve the estimation problem of being too optimistic or pessimistic on the rate of diffusion of technologies when modeling an exogenous constant diffusion limit. The seminal research on optimal abatement from Vogt-Schilb and Hallegatte, 2014 inspired the model that is presented in the next section. We propose a different mechanism to represent technology diffusion and apply this to the optimal choice of car manufacturer.

Government agencies and the scientific community have studied the diffusion of automobile technologies since the oil crisis in the 1970's. The trend of technology evolution is key to understand how fast a market can adopt a technology. We contribute to this literature of estimation of diffusion speed by analyzing recent data in the US market(Zoepf and Heywood, 2012). In terms of technology adoption behavior our model relies on the diffusion speed estimations to limit technology adoption when low carbon technologies will progressively enter the market. Thus, the diffusion of technologies follows a "S-shape" curve where the initial take-off is slow then the diffusion process gains momentum, peaks and then slows when the technology is close to the saturation point. How this mechanism is integrated in an optimization model of low carbon technologies is a main contribution of this research.

1.4.2 An Optimization Model of Low Carbon Technologies

The economic literature has studied road transport with different approaches in a spectrum of geographical and temporal scales represented in Fig. 1.6. The main families of models that are developed to answer questions about the environmental impacts of the road transport are: traffic network models, behavioural models, agent-based modelling, system dynamics modelling, techno-economic models and Integrated Assessment Models (IAM) (Linton, Grant-Muller, and Gale, 2015). These categories represent the various scales from local to global and from the near-term future to long-term horizons of 2100 (Fig. 1.6). In the case of the automotive sector, the representation of a vehicle passenger to assess the environmental impacts depends on the focus on the study.

Traffic networks studies are local-based and produce the impact of road transportation in urban areas. Behavioral models are based on the consumer choice theory that describes individual and collective decision making (Al-alawi and Bradley, 2013). Agent-based models focus on the action and interaction of each agent in a virtual environment where they are characterized by their demographics and preferences (Al-alawi and Bradley, 2013). System dynamics modelling uses a high level of aggregation to model a system by breaking it into its major components and interactions Shafiei et al., 2012. Techno-economics models uses expert judgment, policy makers ambitions and consumer surveys to forecast the trends on the automobile sector (FEV, 2015; Hill et al., 2016; National Rearch Council Board on Energy and Environmental, 2015). IAM are economy-wide models that develop specific packages for the transport sector and link the transport environment to a macro-scale economy (Yeh, Shankar, et al., 2016). To do so they often model transport based on four factors: technological: intensity of fuels, energy intensity of mobility and behavioural: modal structure and volume of mobility (Linton, Grant-Muller, and Gale, 2015).

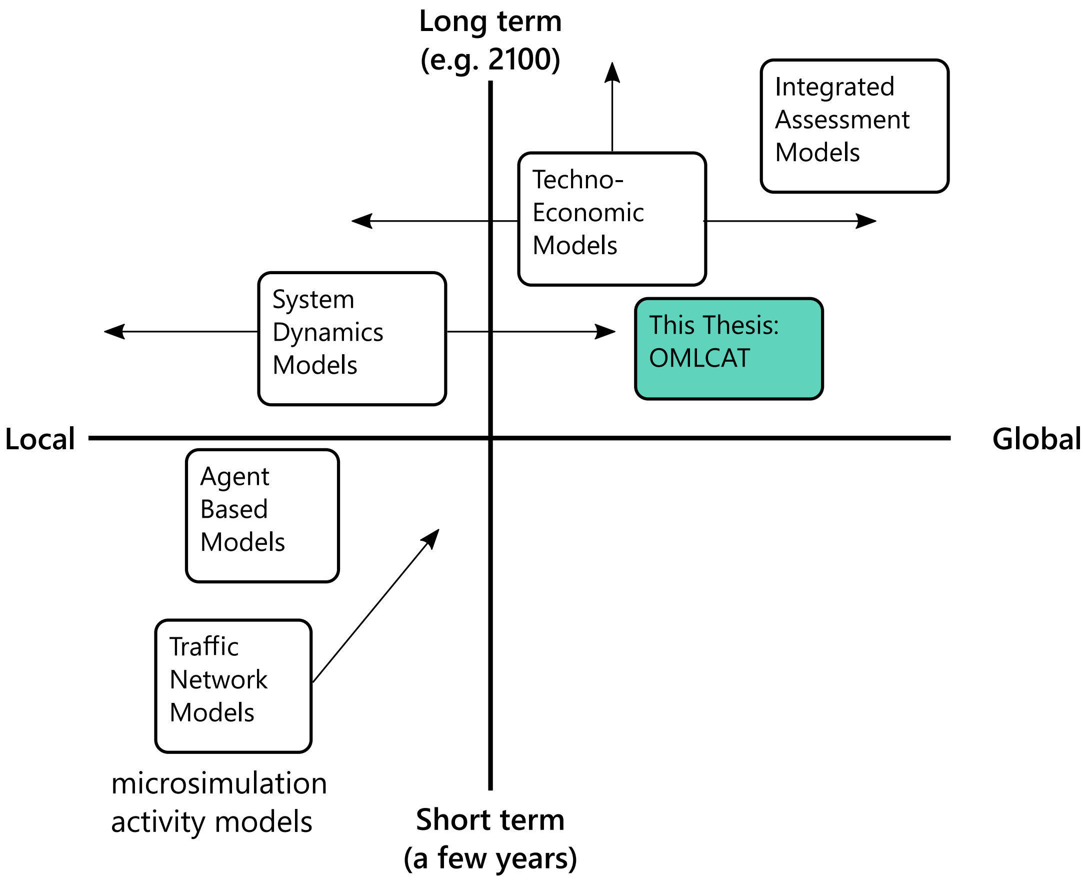

FIGURE 1.6 – Spatial and temporal scales for Road Transport Models.
Source: Linton, Grant-Muller, and Gale, 2015.

The model that is developed in this thesis is based on Techno-Economic Models. The methodology of the model is suited to represent long term horizon to show the dynamics in play, the technology diffusion constraint makes sense in a large scale context such that aggregate market trends are dominant (Fig. 1.6).

Applied to energy systems, marginal abatement cost curves (MACC) are graphical representations of the relationship between abatement costs and emission levels to determine the appropiate set of measures to reach the desired carbon reduction target (Tomaschek, 2015; Kesicki, 2013; Kesicki and Strachan, 2011). The model of this thesis shares the same foundations to build a MACC but it introduces a constraint to limit technology diffusion to take into account the economic inertia of each option as seen in Vogt-schilb, Meunier, and Hallegatte, 2018. Most of the models in automotive studies are agent-based, econometric models of policy impacts and consumer behavior that are static, thus portraying a future of technology landscape without actually detailing the roadmap. Our goal is to fill this gap and propose a model that is dynamic to take into account the yearly change of the technology mix.

The objective is to obtain the optimal technology choices that a car manufacturer makes to prepare for environmental policies. The logic behind the optimization problem is that a firm will seek to obtain the maximum profits from a product portfolio. To do so they apply pricing strategies to different vehicles to obtain more or less profit for a particular type of vehicles. We do not treat pricing strategies instead we focus on the choice of the technology portfolio. To allow for maximum profit we assume a base price equal for a vehicle segment and find the technology mix that has minimal cost. Thus we search for the technology mix that has the lowest cost over the entire simulation period. We have selected the CAFE standard to be central to the model because it is targeted on the industry and requires a change in the technology portfolio to comply with more stringent targets in the future. This thesis uses this model through out the entire length but selects key topics on environmental policy modeling to develop insights on the impacts of policy applications on technology choices. Chapter 2 describes the assumptions, mechanism and methodology of the model.

1.4.3 Summary

Low carbon technologies are considerably different than the traditional automobile technologies that firms produce. The consumer experience is also different because an electric motor does not behave the same way as an ICE. Moreover, the electric vehicle or hydrogen vehicle ecosystem are not compatible with the existing automobile infrastructure. The adoption of low carbon technologies has started in a niche market that is supported by policymakers but it has not spread to the mass market yet. The mass adoption of these technologies will require effort from all actors to develop the ecosystem. This is the reason why we limit growth of technologies with a diffusion constraint. This approach is compatible with a firm's strategy that can not gamble its future which implies that a firm will be more likely to invest on low carbon technologies in an incremental fashion. Our model is not built to predict how a firm should actually pick technologies, the model is made to show what are the implications of some policy caveats and rise concern on the aspects that can lead to a firm to choose a better low carbon strategy.

1.4.4 Institutional Framework of the Thesis

This research was conducted thanks to a CIFRE fellowship, a program that allows private firms to research on a promising field with the help of a academic partner. The partnership was established between the automotive firm Groupe Renault and Ecole des Ponts ParisTech, and more specifically its affiliated research institute CIRED. The project was formulated in collaboration between the environmental strategic team in Groupe Renault and CIRED, following prior research projects conducted within the frame of the Sustainable Mobility Institute (Institut de la Mobilité Durable, IMD). IMD is a partnership between Groupe Renault Foundation for Research and ParisTech, and Ecole des Ponts ParisTech. In particular, IMD contributed to finance previous work from Adrien Vogt-Schilb (()Vogt-Schilb2014), within an research program on the global vision on raw materials, climate and health. The thesis was conducted half-time in the environmental strategic team in Groupe Renault and half-time at CIRED research institute.

In terms of non research work, I was involved in several workgroups that discussed the challenges of low carbon mobility. Next, I briefly present these workgroups:

— MoMo IEA: This was a large workgroup of different actors in the transportation and energy sector that talk about the future of low carbon technologies: powertrain and fuels in a worldwide perspective. The group was lead by IEA who manages the MoMo model. Groupe Renault participated in reviewing and commenting technology, policy and LDV mobility assumptions.

— UC Davis Institute of Transportation Studies: Groupe Renault is an industry partner of the research projects conducted by this institute. Groupe Renault gives feedback on ongoing research projects. I had a main interest and exchanged with STEPS program coordinator Lew Fulton in four projects: Transportation Transition Scenarios to Meet Climate Change Goals for CA and the US, International Electric Vehicle Modeling and Scenarios and Near-term Transitions to AF Vehicles Using a Regional Consumer Choice and Fueling Infrastructure Model.

— BIPE: Groupe Renault commands ad hoc studies to consulting group BIPE about many subjects on low carbon mobility. Their strength is a Total Cost of Ownership model with a detailed mobility demand analysis. I contributed in this group to learn how Renault and BIPE interact and provide a different type of analysis in this thesis. BIPE also lead a workgroup in Plateforme Automobile (PFA) that is composed of several automotive industry actors in France. This latter workgroup develops a worldwide view of the evolution of the automotive industry. They base their work on their World Automotive Powertrain Outlook.

— CO_2 Public Policy team in Environmental Planning: I contributed to followup of ongoing public policy discussions and evaluations. I was in charge of one part of the literature review, focusing on ICCT publications, on low carbon policies in the automotive sector. This close contact with Groupe Renault managers in charge of planning future compliance of climate change objectives was crucial to apprehend the challenges of the low carbon mobility for an automotive firm.

During the meetings of these workgroups, there were different approaches to study the low carbon mobility challenge. These studies varied in scope: space and time horizon, methodology and ad hoc questions. This thesis is inspired by many of the discussions conducted during these meetings. The automotive firm vision on low carbon mobility was made clear during these discussions which feeds this research that shows the industry technology choices. Data on automotive technologies was provided by Groupe Renault.

Concerning non academic research, I participated in different internal Seminars of different topics concerning the automotive markets that helped me understand how the industry works. The topics of such conferences were consumer behavior and needs, vehicle design, autonomous vehicles, vehicle charge infrastructure, regional market characteristics. I was also in contact with interns that conducted their project in the environmental planning team where I learn about the other areas of the department: air quality, life cycle assessment, circular economy and raw materials.

1.5 Structure of Thesis

This thesis is organized as follows. Chapter 2 describes the optimization model of low carbon technology choices under inertia and policy instruments constraints. This model is the foundation for the applications that follow. Chapter 3 looks at the impact of consecutive fuel economy targets on vehicle technology choices. Chapter 4 uses a more refined model of the fuel economy standard to study how technology choices are influenced by mass indexation of the policy. Chapter 5 expands the spectrum of policy instruments from climate change to air pollution to consider a combination of policies answering both challenges. There we analyze the implications on the technology mix when the fuel economy standard is combined with another local or global policy. Chapter 6 concludes and discusses the implications of our findings for automotive firms and for policymakers.

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Chapter 2

Optimal Technology choice under policy and inertia constraints: Model description

2.1 Introduction

Industries from all sectors face a difficult challenge to change the fossil-fuel based economy to a low carbon economy that limits climate change. The development of low emission technologies requires time and resources. In the automotive industry, the technological challenge can be briefly summarized to the transition from Internal Combustion Engines Vehicles (ICEVs) to Alternative Fuel Vehicles (AFVs). There is no silver-bullet solution and there is a consensus that a technology mix between various AFVs is needed to replace ICEVs (González Palencia et al., 2015; Yang et al., 2009). How this transition unfolds depends on the mix of policies that steer the technology pathway.

This thesis evaluates economic outcomes for economy sectors based on assumptions about technology development, policy scenarios and market dynamics (Al-alawi and Bradley, 2013; Li and Strachan, 2016). The technology rich family of models and technical-economy assessment are close to what is developed in this thesis (Miotti et al., 2016; Mcdowall, 2014; Dodds and Mcdowall, 2013). However instead of searching for the more cost beneficial solution to reduce emissions from a sector we reduce the scale of the analysis to the firm to find out what is the least cost technology choices that a firm has to make to comply with a fuel economy policy. To answer this we look for the technology mix that has the minimum technology costs thus creating an optimization problem.

Policy makers have different options to push car manufactures to reduce carbon emissions from passenger vehicles that vary on mechanisms, stringency and time horizons. Car manufacturers are directly regulated by fuel economy standards and are indirectly impacted by incentives and taxes on different vehicles classes. All policy instruments have an effect on technology selection in the automotive industry. Here, we focus on the corporate average fuel economy standard (CAFE) for three reasons: it is applied in main automotive markets, it is a main concern for car manufacturers and it has near term and mid term signals for future abatement requirements.

Replacing a mainstream technology with a new technology faces resistance from the established socio-technical system (Frank W Geels, 2002). Thus, the potential growth of a technology is limited in the initial phase where only a niche market adopts new technology. In latter phases of diffusion the speed of diffusion can be greater. A car manufacturer that responds to an ambitious CAFE target needs to consider this lag on the technology deployment to anticipate commercialization of new products. We use a S-shape curve to limit the dynamics of a technology in a similar fashion that the literature has characterized the diffusion dynamics of past technology transitions (S. M. Zoepf, 2011; EPA, 2016; ICCT, 2015).

The novelty of our modelisation is how inertia is integrated as a diffusion constraint independent of time. It is based on previous works from Vogt-schilb, Meunier, and Hallegatte, 2018; Vogt-Schilb and Hallegatte, 2014 on technology selection for abatement objectives under limiting factors such as availability of the abatement potential. This seminal research uses a simplified model to show that investments should be directed early to technology with high abatement potential but with low speed of diffusion. Their approach limits the diffusion of abatement technologies with a constraint on the available potential that can be introduced in a given year. Thus only a part of total abatement potential can be implemented each year because an increase in the abatement technology requires time and resources. This inertia constraint acts on every abatement option in the market limiting the diffusion speed to a constant maximum.

Based on the same principle of limited diffusion of abatement technologies seen in Vogt-schilb, Meunier, and Hallegatte, 2018 we propose a new variation of the diffusion constraint where the diffusion constraint, based on a S-shape curve, changes the speed of diffusion according to the sales share of a technology. The diffusion of technologies in the past has seen different speeds according to the diffusion stage of the technology. Our contribution to modeling of technology diffusion is the mechanism of the constraint. Our model does not have a constant speed of diffusion anymore, we replicate a form of diffusion seen in the past in the shape of S-curve. A new technology will face a change in diffusion speed from low speed at market entry to maximum speed at mass market adoption to low speed again when the diffusion saturates.

This Chapter describes the model developed to represent technology portfolio choices in a policy context where CAFE regulation pushes for low carbon solutions. The model has three main forces that interact to produce an optimal solution: the overall goal that searches for the least cost technology mix, the policy context that mandates a minimal requirement on technology fuel economy and a limiting change in technology subject to diffusion limits.

The model is used in the subsequent Chapters of this thesis to answer the following questions about firm policy: Is an emission target feasible? What does it take and how much does it cost to comply with a CAFE target? How will the technology pathway evolve? To answer these questions we describe the mechanics of the model applied to the case of a lower medium vehicle segment in an automotive firm. We aim at isolating the effects of the fuel economy standard with the limited scope of a single vehicle segment.

This Chapter is structured as follows, Section 2.2 presents an overview of the model and its components. Section 2.3 describes the main assumptions on how an automotive technology is treated and the associated policies that affect a firm's choice. Section 2.4 presents the governing equations, explains how the model works and discusses its limitations. Section 2.5 presents the applications and variations of the model used in this thesis.

2.2 Overview of the Model

The Optimization Model of Low Carbon Automotive Technologies (OMLCAT) developed in this thesis analyzes the impact of regulations that affect fleet emissions on the choice of technology made by the industry. The model is a supply-side car manufacturer perspective, which would seek to minimize the total production costs of vehicles sold, discounted over the time horizon considered. To do so the optimization algorithm finds the least cost technology mix that complies with a given policy target.

The model has three main blocks, in Fig.2.1: a *technology input* block that defines the technology cost & other attributes, a *policy package* block that defines the external constraint that steers the technology mix in the direction to adapt to a policy and an *optimization algorithm* that is built on an endogenous model of inertia that interacts with the sales share of a technology to determine where a technology is on S-shape curves (see Section 2.4.2 below).

The structure of the model is generic meaning that the application to a different automotive firm, a different vehicle segment and a different market is possible. In the automotive industry there are two different categories of vehicles: Light-Duty Vehicles and Heavy-Duty Vehicles. Light-Duty Vehicles are composed of passenger vehicles and commercial vehicles. We focus on a particular segment of passenger vehicles: lower-medium segment. In Europe this segment is the largest segment and contains many different models. For generalist car manufacturers such as Renault it is one of the core segments of their market. Thus we adapt the generic structure to fit the case of technology choice in the lower medium vehicle segment, we detail the assumptions made below in Section 2.3.

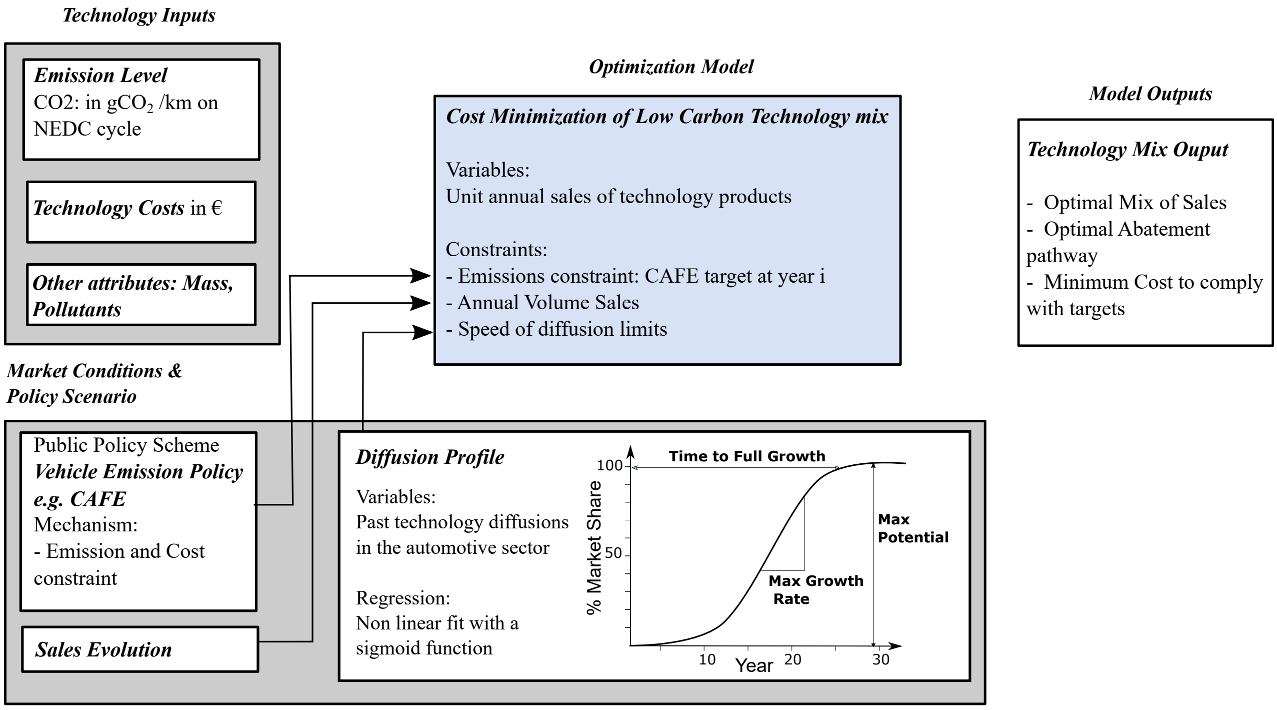


FIGURE 2.1 – Overview of Optimization Model of Low Carbon Technologies for the study of the fuel economy standard. Source: The Author.

In the following sections we describe each block of the model.

2.3 Technology assumptions for a lower medium vehicle segment

A vehicle is today full of different components that give a unique mechanical performance and consumer experience. In terms of energy consumption, some components play a more important role than others, in Fig. 2.2 we show the main technology bricks that play a key role on energy consumption. There are many fields that have the potential to increase energy efficiency. Some have been explored since the birth of automobiles such as powertrain technologies but some are new, such as electric appliances of low consumption. From these technology bricks we construct a few vehicle variants focused mainly on powertrain technologies which define our technology inputs. For a vehicle segment we have a limited number of vehicle models but they are representative of the different powertrain options available.

The other technology bricks are also developed to reduce vehicle's emissions but are not studied in this Chapter. Aerodynamics develops technologies aiming at reducing the aerodynamic drag of the vehicle such as low profile vehicles to reduce

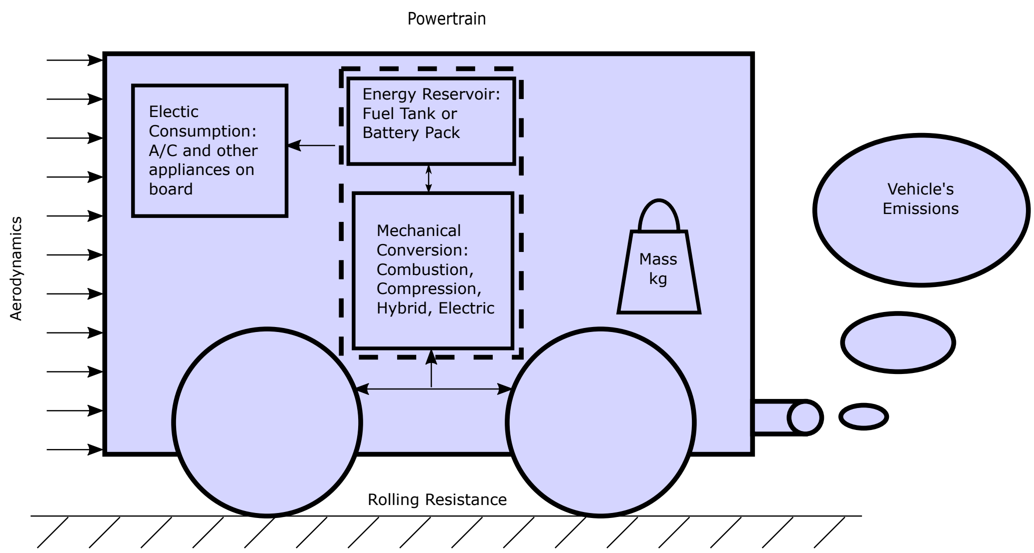


FIGURE 2.2 – Main low carbon technology bricks in a vehicle. Source: The Author.

energy demand. Tires are the point of contact with the road, they convert the rotational motion into linear motion, but they oppose a rolling resistance that causes energy losses. Tire suppliers search for new materials and architectures to reduce this resistance. The overall mass of the vehicle is essential to determine the energy demand of the vehicle, with a light mass a vehicle will require less energy to move. Lightweight technologies are thus an important vector for low carbon technologies and are explored in Chapter 4.

We can consider a modern passenger car as an energy conversion system where a reservoir, a mechanical conversion system or powertrain and a mechanical transfer component interact to allow movement. The energy conversion system can be divided into different blocks with a main process that converts chemical energy into kinetic energy. Today there are three common conversion systems. The first type converts the chemical energy potential of a fossil fuel into kinetic energy in an internal combustion engine by a compression (CI) or spark-ignition (SI). The second type uses electricity to stock electrochemical potential into a battery that will supply electric energy to an electric machine (EM) thus obtaining kinetic energy. The third type transforms hydrogen gas to produce electricity in a fuel cell that connects with an electric machine. This definition of a vehicle system does not describe the energy supply methods for passenger cars, e.g. the means to produce electricity and fossil fuel extraction. The boundary of the technology system is consistent with the scope of the CAFE policy that is based on tank-to-wheel emissions in Europe.

There are many different alternatives that can be chosen to produce a low carbon vehicle. Some options might have a high abatement potential and others might have a lower potential. The blocks used to build a powertrain option are fuel type, energy conversion system and transmission type. Some models use two fuel types:

electricity and fossil-fuels. These are a 12-V mild-hybrid engine, a 48-V mild-hybrid engine, a full hybrid engine or a plug-in hybrid system: fossil-fuel engine and electric engine. There are different kinds of transmissions that are available, from low to high efficiency: Manual, Automated Transmission, Double-Clutch Transmission and Continuous Variable Transmission. A Gas Vehicle works with variation of a SI Engine and uses Liquefied Petroleum Gas or Compressed Natural Gas.

The model does not explore all solutions, to build the set of feasible vehicles that defines the future technology mix we choose technologies based on three rules: an engineering criteria of feasibility, an automotive firm compatibility criteria and a reduction of technology choices to only have one option per powertrain. The engineering criteria selects which options are feasible from the combination of a Powertrain Type with a Transmission type. For example for a BEV architecture there are only two options: an automated transmission or no transmission at all. From an engineering perspective a BEV with a manual transmission is not possible. We applied the same criteria to all options. We aggregate the technology contribution of different blocks into one single technology option that is named after its powertrain unit. The reduced number of technology families is presented in Table 2.1 which has already passed the engineering criteria filter.

A second criteria based on automotive firm compatibility depends on a firm strategy. For example a car manufacturer that has not invested in Hydrogen vehicles will not consider this option for the near-term thus we do not include this option in the model for that particular manufacturer. In reality a firm faces only a limited flexibility when it comes to technology diversity due to limited resources to develop a portfolio of engine variations. Thus product strategy, manufacturing facilities and consumer needs define how an automotive firm selects a reduced number powertrain units. Our selected technology portfolio is similar to the available choices of french car manufacturer Renault which contributed to this thesis [1]. The shortlist of technologies is compatible with a European market.

For each technology package we define three main features: the cost of the technology, the CO_2 emissions level measured in New European Driving Cycle (NEDC), the mass of vehicle and the air quality compliance level according to the EURO standards of the vehicle. The cost, emission, mass and air quality compliance estimation is obtained via estimates from Renault and data from ICCT (Meszler et al., 2016) for a lower medium vehicle segment in the European market. The cost of the technology is the sum of cost of production of each component of the powertrain technology family for a lower medium vehicle segment. The cost does not represent the total

1. This thesis was developed under the CIFRE fellowship that is an Industrial Agreement of Training through Research between CIRED and Renault. This research is thus fundamentally applied to an industry need of understanding policy impacts in a more challenging context of low carbon mobility to do so the fellowship gathers academic researchers and industrial managers to develop a research program that contributes to the scientific research and provides key elements of understanding the given topic.

TABLE 2.1 – Powertrain Technology Families for Passenger Vehicles

Powertrain Type	Fuel	Energy Conversion	Transmission
Gasoline	Gasoline	SI Engine	Manual, AT, CVT or DCT
Gasoline Next Gen	Gasoline	SI Engine with 12V or 48V	Manual, AT, CVT or DCT
Diesel	Diesel	CI Engine	Manual, AT, CVT or DCT
Diesel Next Gen	Diesel	CI Engine with 12V or 48V	Manual, AT, CVT or DCT
Hybrid (HEV)	Gasoline or Diesel	CI or SI with EM	AT, CVT
Plug-in Hybrid (PHEV)	Gasoline or Diesel and Electricity	CI or SI with EM	AT, CVT
Battery Electric (BEV)	Electricity	EM	AT or None
Hydrogen (FCHEV)	Hydrogen	EM	AT or None
Gas (GV)	LPG or CNG	SI Engines	Manual, AT, CVT or DCT

cost of production of the vehicle. For technological assumptions used for each application, refer to Table 3.1 in Chapter 3, Table 4.2 in Chapter 4 and Table 5.5 in Chapter 5.

To develop low carbon technologies, manufacturing, research and marketing efforts are needed. Thus an automotive firm best interest is to share the risk of investment in a new promising technology with a competitor. Allowing for market influence might change the preferred choices for a firm. Further research might look into the automotive firm's dynamics in terms of technology choices. Some information is available from patent data: where firms that historically develop alternative fuel vehicles tend to spread these technologies to others in the same market (Aghion et al., 2016). At a single firm level, the technology cost can integrate a component of R&D cost in an exogenous manner which can not vary as function of the sales share.

The technology inputs are used by the global objective function and the model constraints based on policies and inertia limits described in the next Section.

2.4 Core Optimization Algorithm

2.4.1 Governing Equations

A firm's profit maximization problem can be simplified to eq.2.1 which indicates that a firm can change vehicle price, number of vehicles sold or cost of production. Assuming that low carbon technologies are the main component of abatement technology cost we can consider that cost of production is determined by low carbon technology costs. The type of low carbon technologies in a vehicle is in turn determined by policy ambitions.

$$max_{x_j} \quad \sum_{j=1}^{n} x_j * (P_j - C_j) \tag{2.1}$$

where x_j is the number of vehicles sold with powertrain technology j, P_j is the price of a vehicle with powertrain technology j and C_j is the cost of production of a vehicle with powertrain technology j.

Vehicle price is not a variable of optimization in our model. We do not integrate the mechanism of pricing different vehicle technologies to adjust for profitability margin. The vehicle price of expensive low carbon technology is in practice higher than the vehicle price of fossil-fuel based technologies. We do not investigate how the vehicle margin varies according to the type of technology.

The model is limited to find the least low carbon technology cost solution to comply with a policy ambition. The technology cost is determined in a vehicle unit basis, it does not take into account the resources necessary to increase or launch production of low carbon vehicles. Plug-in vehicles require a new type of assembly lines of electric motors which in turn requires a new type of labor and knowledge. The cost assumptions used in this thesis are limited to marginal cost of producing a powertrain with a specific technology type. The cost of all other technologies of the vehicle is considered the same for all powertrain types.

The simplifying assumption of cost minimization gives information of what is the cheapest technology mix to comply with a policy target limited by inertia constraints. The solution of the model can not be interpreted as the optimal technology mix to maximize profit margins. However the mechanism of policy instruments and technology diffusion constraints are applicable to a profit maximization problem.

The result of a given run of the model is the optimal technology mix output, or *technologies portfolio*, i.e. the share of each technology in the total vehicle sale every year along the time horizon considered. From the optimal technology mix of sales over the entire period, the optimal emissions pathway and the production costs can be calculated. Thus a firm following the optimal technology choices of the model would respect the policy regulations and can potentially maximize its revenue.

The model accounts for two type of constraints. The first type corresponds to the regulatory constraint imposed by corporate average fuel economy standards described in this Section below. The second type are dynamic constraints, or *inertia constraints*, on the maximum speed at which each technology can be diffused. This dynamic model acts on the yearly sales of new vehicles.

The model searches the mix of technologies with the minimum cost while respecting inertia and policy constraints. The governing equations are the objective function, a set of constraints and auxiliary functions (eq.2.2, 2.3, 2.4 and 2.17)[2].

$$min \quad \sum_{i=1}^{m} \frac{1}{(1+r)^{(i-1)}} \sum_{j=1}^{n} x_{ij} * C_j \tag{2.2}$$

$$\forall years\ i \sum_{j=1}^{n} x_{ij} = SALES_i \tag{2.3}$$

2. The optimization algorithm uses Interior Point Optimizer (IPOPT) (Wächter and Biegler, 2006) with the Scilab library Sci-IPOpt. All runs of the model are made with the same optimization solver.

$$for\ target\ year\ i^* \frac{\sum_{j=1}^{n} x_{i^*j} E_{i^*j}}{SALES} \leq TARGET \tag{2.4}$$

where x_{ij} are the sales of technology j at year i, m is the number of years in the model, n is the number of technologies, r is the discount rate, E_i is the emission level in gCO_2/km, C_j is the cost of technology of j in €, $SALES_i$ are unit sales in a year i and TARGET is the CAFE target in gCO_2/km.

The objective function in eq. 2.2 aims at reducing costs, there are two ways to do so: reducing the number of vehicles sold or reducing the cost of vehicles sold. The first option is not allowed by constraining the volume of sales each year in eq. 2.3. The second and only option is to reduce costs, therefore the objective function looks for the least cost technology mix. However the fuel economy policy constraint in eq. 2.4 sets a maximum requirement of average CO_2 emissions. Thus the model selects the least cost low carbon technologies adapted to the policy ambition.

The volume constraint presented in eq.2.3 sets an exogenous trajectory of total vehicle sales in number of vehicles sold each year. An automotive firm has a sales volume goal for future years determined for the strategic plan that guides labor and manufacturing needs. In order to commit to a strategic change in the number of vehicles sold, an automotive firm also prepares for future policy constraints. Our approach is a policy assessment of the impact of CAFE that is made before setting volume targets. For the purpose of this thesis, we keep the sales volume constraint constant and refer to sales share instead of number vehicles. The volume constraint can be interpreted as a guarantee that the sum of sales share of the technology portfolio is always 100 %.

In practice, the volume constraint requires a high level of the cheapest solution in the near future until low carbon alternatives become available due to the limiting constraint of inertia in the initial phases of diffusion. There is no upper limit on volume sales which is not needed given the minimization objective function. The volume constraint acts as a dam, all units sold must fill a sales minimum but any additional unit over this limit is not profitable since the dam was designed to a fixed volume. A feature that is not used in this thesis is that the volume constraint can be used to test volume growth with a sales forecast.

The automotive policy that is central to this thesis and common for all applications is the fuel economy standard. The model described in this Chapter has only the CAFE policy. Four more policies studied later in this thesis are presented in section 2.5.3. The model of CAFE shown in eq. 2.4 is a simplified version of the policy, we force the firm to comply with the fuel economy standard without allowing the firm to pay fines. Also, we have not taken into account the following elements of the European policy:

— Supercredits on low emission vehicles that make low emission vehicles count more times in the corporate average to promote the deployment of low carbon vehicles and help OEMs meet their target (European Parliament and European Council, 2009).

- Eco innovation or off-cycle technology credits that reduce stringency of the target up to 7 gCO_2/km if vehicles are equipped with technologies that allow energy savings not captured by the test-cycle (European Parliament and European Council, 2009; Fontaras, Zacharof, and Ciuffo, 2017).
- Pooling strategies where car manufacturers can regroup their vehicles sales from different brands to have a joint corporate average.
- Phase-in of the target which requires an increasing share of new passenger vehicle registrations of car manufacturers to be compliant with the policy target before the enacted year of the policy.

Eq.2.4 could be modified in future exercises to accommodate some of these elements. Mass indexation, for instance is introduced in Ch.4 and 5.

The CAFE constraint makes sure that the automotive firm complies with the emissions reduction target. The CAFE acts on the average emissions of vehicles therefore some vehicles having higher emissions than the target are still in the technology mix. These high emitting vehicles are compensated by low emissions vehicles. This is seen in practice where automotive firms produce low emitting vehicles to keep high emitting vehicles in their offer. This is one caveat of the CAFE policy that has been already identified, the model reproduces the same behavior. The abatement pathway of the technology mix, meaning how fast the emission reduction rate occurs is subject to the diffusion constraint. Since the CAFE policy final objective is a low carbon automotive fleet, the constraint is applied on the final year of simulation. Intermediate targets may be applied as well.

The Policy package is limited to a selection of policies nevertheless other policies affecting technology choice might be interesting to study (Anderson et al., 2011). For instance, a feebate scheme that will penalize high emitting technologies and incentive low emitting technologies (Anderson et al., 2011; Carley et al., 2016; Haan, Mueller, and Scholz, 2009; Greene et al., 2005). This and other policies have been studied for policy efficiency purposes. The OMLCAT can be compatible with all of these applications and can be extended to such analysis. A road tax or fuel tax (Klier and Linn, 2013) are beyond the scope of OLMCAT and can not be treated with its current form.

The model is a linear optimization problem which in the absence of diffusion constraints, would create a bang-bang solution. In this non-dynamic case it would only change in the year of compliance creating a discontinuity or step in the technology pathway, choosing 100% of the cheapest technology to comply with the target. We present below several methods to correct this. We introduce the last constraint of the model that limits technology in the following Section 2.4.2 to describe the novel approach that we use to constraint technology growth.

2.4.2 Modeling the constraint on the Speed of Diffusion of new technologies

Here, we develop the principle and mechanism of the diffusion constraint. Technological change is time consuming and extends over decades (Rogers, 2003), the success of technology diffusion depends on the dynamics of supply and demand. A technology that enters a market might experience all or one part of the following phases: innovation, diffusion, stabilization and decay. We are interested in the diffusion phase that occurs after innovation when sales share show a growth from zero sales share meaning that the technology is commercially available.

At the consumer level the reasons explaining the limitations of technology diffusion are consumer awareness, consumer willingness to buy and consumer preferences. At the automotive firm level, technology change is limited by capital inertia of the assets of the firm to produce a specific technology. When a firm plans to develop a new technology it requires adapted manufacturing and labor resources than can be new to the firm and costly. A more radical technological change demands a deeper change in the firm business structure.

The technological change in a firm is the supply-side transition in a diffusion process. This transition integrates a build up in capacity to produce the new technology. In economy models it is represented by learning effects or how a technology can become more competitive through cost reductions and performance improvements. The specific mechanisms driving learning are listed below, taken from Kahouli-brahmi, 2008:

- — Learning-by-doing: repetitive manufacturing tasks involve an improvement of the production process.
- — Learning-by-researching: improvements related to the innovation process and creation of knowledge.
- — Learning-by-using: user's experience and feedback effects that follow introduction to the market are source of technology learning.
- — Learning-by-interacting: interactions between the various actors like the research laboratories, the industry, the end-users and the political decision-makers enhance the diffusion of knowledge.
- — Economies of scale: at the mass production stage, as the output increases the unit cost curve drives costs down.

In the automotive sector, technology learning is one of the key methods to acquire knowledge, capabilities and experience. The process of learning requires time thus it is a limiting factor in the diffusion of new technologies. The learning rate of technologies has been estimated in vehicle technology (Weiss et al., 2012). The implementation of learning in models follows a learning curve where each additional unit produced or each additional investment builds up the knowledge and experience stock (Grübler and Messner, 1998; Berglund and Söderholm, 2006; Kahouli-brahmi, 2008). Although our model does not include any type of explicit learning we are able to capture the effects of limiting supply-side inertia and market diffusion through the S-curve.

From a technology perspective, the model does not describe the complex mechanisms of neither adoption of a given technology (consumer dynamics) nor capital inertia of a the technology (industry dynamics), it uses a more comprehensive approach. A technology is subject to market inertia that represents both consumer and supply dynamics of technology diffusion. At market level, products that are broadly used like vehicles have been analyzed in literature to understand how does the diffusion of a technology has occurred in the past.

Empirical research on past technology diffusion has found that S-shaped curves are useful for analyzing technology diffusion where two simple processes: diffusion and substitution are observed (Grübler, Nakićenović, and Victor, 1999). Diffusion occurs whenever a technology becomes widely adopted starting from a market niche. Substitution occurs when a technology replaces an incumbent technology such as the replacement of horses by cars in transportation. The storyline, the history of facts defining the direction of technology development, that accompanies the diffusion of technology is key to understand its limitations, success and failure (Charlie Wilson, 2012; Charlie Wilson and Grubler, 2011; Rogers, 2003). The drivers of technology diffusion are described in socio-technical studies of technological change (Frank W Geels, 2012; Frank W. Geels, Berkhout, and Vuuren, 2016). We are interested in how empirical research has modeled technology diffusion.

The profile of growth has a consistent shape where technologies go from low to high market shares. For cumulative sales or stock of technology, this shape is known as the S-curve (Rogers, 2003; Peres, Muller, and Mahajan, 2010; Geroski, 2000). This S-curve can be divided into 5 phases: Niche Market, Early Adoption, Early Majority, Late Majority and Laggards seen in Fig.2.3. The initial phase of Innovators refers to the more complex and unstable phase that is critical for new technology development (Bento and Charlie Wilson, 2016; Charlie Wilson, 2012). The other phases are commonly seen on diffusion literature and define the type of consumer that adopts the technology. The Niche Market contains consumers that are eager to buy new technology and are willing to pay for an additional cost in technology whereas Laggards are consumers that are not compatible with the technology services and will adopt it only when neighbors have done the change. The properties that define the diffusion profile are the total time to reach to full growth, the maximum growth rate and the maximum potential or saturation of a technology (S. Zoepf and Heywood, 2012) shown in Fig.2.3.

The sigmoid or logistic function has been used to fit past technology diffusion (Grübler, 1991; Wilson et al., 2013; S. Zoepf and Heywood, 2012). We apply this

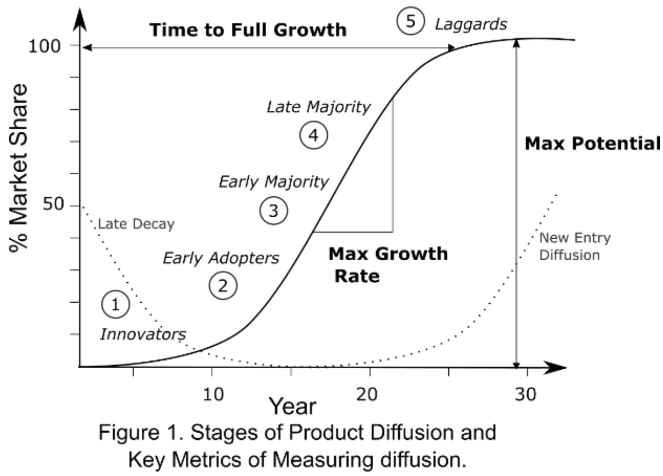


FIGURE 2.3 – Schematics of the stages of diffusion of a technology from innovation to full deployment. Source: The Author.

sigmoid function to model future technology diffusion:

$$Growth: \ SS(t) = \frac{a}{1 + be^{-ct}} \tag{2.5}$$

where a is the saturation point, c is the speed of diffusion, b is the translation parameter of the function in time and SS is the resulting sales share.

To model the technology pathway of an economic sector a hypothesis on the diffusion of technologies is needed, there are different ways used on classical families of models to treat diffusion: "While diffusion is clearly a distinct area of empirical work, climate models diverge in their treatment of diffusion: top-down models without technology detail typically subsume diffusion into trends in sectoral productivity, while technology-rich bottom-up models typically include more ad hoc assumptions to constrain the penetration of new technologies."(Pizer and Popp, 2008). Our approach is technology rich and fixes limits on diffusion from the basis of technology inertia.

In energy systems models, there are limits on the diffusion of technologies where growth constraints set the limit on the expansion of a technology. In bottom-up models, technology growth is expressed with a maximum growth rate(Leibowicz, Krey, and Grubler, 2016). The MARKAL family of models (Fishbone and Abilok, 1981) puts a constraint on the cumulative sales of a technology:

$$\forall \ years \ i > 0 \ \forall technology \ j \quad S_{ij} - (1 + g_{i-1j})^i S_{i-1j} \leq S_{0j} \tag{2.6}$$

where S is the cumulative sales of a technology, g is the annual growth rate and S_0 is an initial constant to allow growth from zero.

The MESSAGE family of models (Schrattenholzer, 1981) also defines limit on technology growth based on the added capacity of the technology.

$$\forall\, years\ i > 0\ \forall technology\ j \quad X_{ij} \leq \gamma X_{i-1j} + g \tag{2.7}$$

where X is the number of annual sales of a technology, γ is the matrix of growth parameters and g is a vector of start-up values allowing X to reach positive values after having zero before.

Both of these expressions of technology diffusion translate into an exponential constraint with a constant or variable growth rate. Other cases where technology diffusion is modeled are marginal abatement cost curve (MACCs) where technology options are launched if the cost of abatement is lower than the carbon tax/price. The growth of an abatement technology comes with a marginal cost increase necessary to produce the additional unit of abatement. In a classic MACC (Enkvist, Nauclér, and Rosander, 2007) there is no constraint on growth thus in this form they fail to capture the dynamics of diffusion (Kesicki, 2012; Vogt-Schilb and Hallegatte, 2014). In other words, the potential of a technology is assumed to be fully available at any point in time. To capture the slow take-off on abatement solutions, economic inertia of an investment is defined as the availability of the abatement potential of an option at a period of time. A technical inertia is used to include the resources and tools needed to favor the spread of the technology: labor, manufacturing, R&D, logistics (Vogt-Schilb and Hallegatte, 2014).

With economic inertia, only a fraction of the total abatement potential is available, the logic of this concept is that it takes time to achieve full abatement potential. A constraint on inertia can limit the amount of a technology as defined in eq. 2.8.

$$\forall\, year\ i > 0\ \forall\ technology\ j\ Maximumpotential\ a_{ij} = a_{i-1j} + \beta_j(t_i - t_{i-1}) \tag{2.8}$$

$$a_{ij} - a_{i-1j} \leq a_{maxj} \tag{2.9}$$

Where a is the abatement of a technology, β is the speed of abatement of a technology and a_{max} is the maximum number of abatement for a technology

When the maximum abatement potential constraint is considered, the short term solution to achieve emission reduction in the future is not limited to those investments that are cheaper to the target but also includes more expensive measures because it will take time to spread a high inertia technology. If we consider that additional abatement capacity is due to the deployment of new units in the market, we can express eq.2.9 in terms of units of technology and maximal technology units per year.

$$X_{ij} - X_{i-1j} \leq X_{maxj} \tag{2.10}$$

To describe the complex dynamics behind inertia, energy models have used learning effects. OMLCAT does not have learning effects but has a constraint on diffusion that is inspired on the inertia constraint on abatement technologies. When including learning there is a component of increasing knowledge based on the cumulative size of a technology that reduces investment cost and technology cost in time (Goulder and Mathai, 2000). With learning there is a more refined mechanism to analyze the mechanism of path dependency however they require more data and estimations on the sector's learning curve. For macro trends on the automotive market and to consider market effects beyond learning such as consumer behavior a constraint on diffusion is enough. In Vogt-schilb, Meunier, and Hallegatte, 2018 there is no learning either, only a part of abatement potential is available at a point in time thus making an abatement solution not instantaneous as in a classic MACC.

The approach of learning in Goulder and Mathai, 2000 requires a learning curve that produce a change in costs of options when knowledge stock changes. In the exogenous model of inertia of Vogt-schilb, Meunier, and Hallegatte, 2018 there is a constant exogenous limit on diffusion that does not evolve in time. The constant speed of diffusion fails to capture the change in diffusion dynamics of an S-curve. Our approach shows that we can produce a limiting inertia that evolves in time if we replicate a S-curve behavior from the history of the economic sector.

Our model is related to limited availability of abatement potential form of diffusion constraint but the difference lies in the limits on growth. The model in eq. 2.8 can change the limits of speed by increasing or decreasing the exogenous limits with time, β_j. Diffusion limits that are too optimistic, a high β_j will result in a share of low carbon technologies that is too high inconsistent with a pace that can be followed. In contrast diffusion limits that are too pessimistic, a low β_j will reduce the chance of penetration of low carbon technologies. To follow a S-shape diffusion, this type of constraint would have to modulate speed limits in time. However this modified constraint would still be ex-ante meaning that diffusion limits are fixed before simulation. The limitation would be that the model assumes some diffusion is already happening which creates a bias to artificially change the speed of diffusion.

In a near term perspective an ex-ante approach is not an issue because the diffusion limit potential error when a technology under-performs is small. In a long term perspective if the technology does not diffuse in the early period, the diffusion limits will still grow and the technology might be picked only when the diffusion limit is highest. Thus the technology might benefit from an artificial diffusion process that reduces growth constraints in the future. The inconvenient is that a technology might develop only because the model enables the technology to diffuse instead of being the adapted abatement technology for the model settings. The overall consequence is that a model might reserve high abatement options to be developed at the time when the ex-ante defined S-shaped diffusion exhibits its faster growth.

Thus we propose an endogenous function that limits growth for each technology that is constructed from a sigmoid function. We modified the function to take the sales share at year i as input and return the maximum growth or maximum speed of diffusion that is possible for that technology. By doing so we limit the diffusion profile of a technology to the S-curve profile. The following equations explain the intermediate steps to obtain the diffusion constraint.

$$f: \; SS(t) = \frac{a}{1 + be^{-ct}} \tag{2.11}$$

$$g: \; t(SS) = -\frac{1}{c} ln(\frac{1}{b}(\frac{a}{SS} - 1)) \tag{2.12}$$

where SS is the sales share of a technology, a,b and c are the coefficients of the sigmoid function of diffusion: saturation point, translation parameter and speed parameter respectively. f is a function of time of the sales share. We want a function of the rate of change of the sales share respect to the sales share at any given time. Therefore we perform a time derivative of function f and then we replace t by g.

$$\frac{df}{dt} = \frac{abce^{-ct}}{(1 + be^{-ct})^2} \tag{2.13}$$

$$\frac{df}{dt} = \frac{abce^{-cg}}{(1 + be^{-cg})^2} \tag{2.14}$$

$$\frac{df}{dt} = \frac{cSS(a - SS)}{a} \tag{2.15}$$

$$\forall year\ i > i_0\ and\ \forall technology\ j : SS_{ij} - SS_{i-1j} \leq \frac{df(SS_{i-1j})}{dt} \tag{2.16}$$

$$\forall year\ i > i_0\ and\ \forall technology\ j : SS_{ij} - SS_{i-1j} \leq \frac{cSS_{i-1j}(a - SS_{i-1j})}{a} \tag{2.17}$$

To allow possible full diffusion of any technology we have set $a = 1$ for all technologies. There are some technologies that are not perfect substitutes of fossil-fuel based engines, plug-in vehicles for example are not fit for consumers that do not have access to a charging infrastructure or those that do very long trips. Thus having a lower a saturation point reduces the maximum sales share of a technology and limit the emission reduction potential of this technology. For the purpose of this thesis, we do not change the saturation point. For distant time horizons, a change in the saturation parameter is key to determine which technologies are necessary to develop once that the least cost technologies have reached their maximum potential. For $a = 1$ and for short time horizons, c is the only parameter constraining the speed of diffusion as in eq. 2.18.

$$\forall year\ i > i_0\ and\ \forall technology\ j : \frac{SS_{ij} - SS_{i-1j}}{SS_{i-1j}} \leq c(1 - SS_{i-1j}) \tag{2.18}$$

where SS is the sales share of a technology, and c is the speed parameter of the sigmoid function of diffusion. The constraint on diffusion is a convex function and all other constraints are linear, therefore the solution is unique.

The diffusion constraint fixes the growth limits on technologies with a recursive limit obtained with the year n-1 sales share. The diffusion constraint is strong for low and high sales share of technologies because it does not let a rapid growth. For a CAFE policy the most profitable solution is the one with the lowest marginal abatement cost, the technology that satisfies this condition will be likely to be fully deployed by a firm. In our applications we can test when OMLCAT saturates the technology diffusion constraint by comparing the sales share of a technology with the hypothetical saturation profile that simulates the maximum deployment capacity of a technology. When the two curves are identical, the technology is fully saturated and can not be further deployed.

The function in eq. 2.15 gives a low speed limit for sales shares that are low, it peaks when sales share are at 50% of a and then decreases until sales shares reach the value a. The difference from other models relies on two aspects: first, the diffusion constraint is based on the sales share meaning that if sales remain stable for several years the speed limits will not change and second it considers both the slow take off characteristic of an exponential growth and also the reduction on diffusion speed when the market faces those consumers that are more resistant to adopt new technology. The model represents the inertia of low carbon technologies to diffuse in a market that starts from a low sales share and then takes time to diffuse.

The type of constraint proposed in eq.2.18 is different from the exponential growth rates of MARKAL and MESSAGE families in eq.2.6 and 2.7 because the growth rate is not constant it will decrease when the market share is high. This produces a technology adoption in the shape of an S-curve instead of an exponential growth seen in the other families. Calibrating the diffusion constraint in an exogenous and constant manner as in MARKAL and MESSAGE can result in overestimating the potential growth if the exponential constant is high or underestimating the potential growth if the exponential constant is low. In OMLCAT overestimation and underestimation issues are reduced but there needs to be available data on past diffusions to obtain the sigmoid function profiles of an economic sector. If the model is assessing the technology diffusion of a new economic sector or when there are no estimates of the diffusion of technologies, OMLCAT can test different diffusion speeds.

The difference of the diffusion constraint in OMLCAT with the model presented in eq.2.9 is that the gap in abatement potential from one year to the other is always limited to the same exogenous constant. For initial market adoption this limit will not constraint technology deployment on the contrary if the abatement speed is too high, low carbon technologies will move too fast. Conversely if the limit is too low, it will delay the deployment of low carbon technologies to a mass market. In

OMLCAT this gap depends on the market share of the previous year it can increase meaning that the technology can grow faster if the market share is below 50% or it can decrease when the market share is above 50%.

Moreover, the same differences in speed are observed in the geographical location of the market (Barreto, 2008; Grübler, 2012). A core market is the one that first adopts the technology and a periphery market is the one that follows. The choice of the region of the model in our case Europe also determines the diffusion rate. Europe is a core automotive market thus using estimates from USA diffusion another core market is not problematic in terms of speed.

The diffusion constraint is different from what is found in literature because it does not fixes constant growth limits at a given year, the constraint acts according to the sales share evolution of a technology. This constraint is more adapted to model long periods of a technology mix because the time to full diffusion of a technology under this constraint in the case of LOW diffusion profile is 25 years. With a long time horizon one should be able to see the change in speed of technology diffusion and identify the peak in speed of diffusion at half of the saturation sales share.

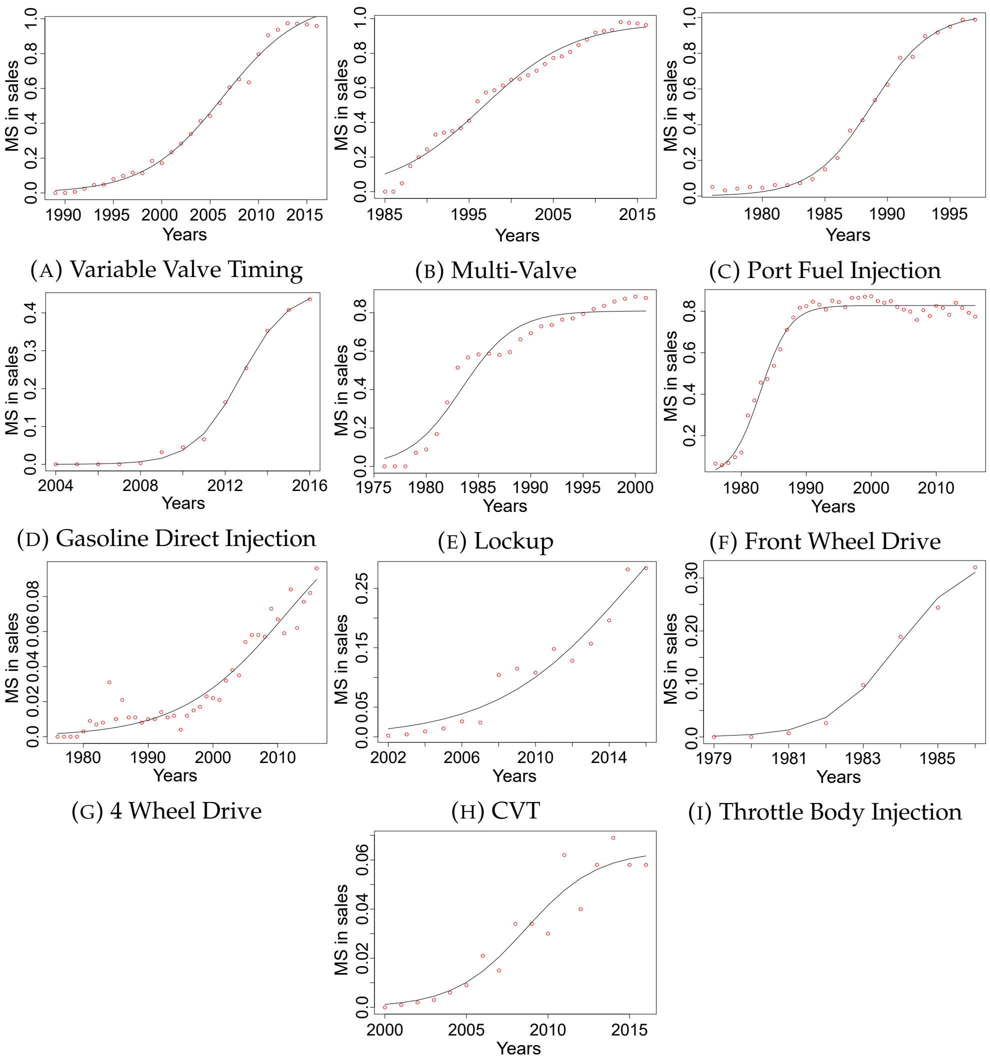
The recursive nature of the diffusion constraint implies that the technology diffusion depends on the start point of sales share of the technology. The calibration of initial technology sale shares is made on data of the sales share of the lower vehicle segment. However, some technologies are not commercialized so the real sales shares are zero. Our model can not develop a technology from a zero sales share, therefore we simulate an introduction of commercialization of a technology with a 2% sales share. Costs on the first years are expected to be high until the model reduces the number of options of technologies. This is a limitation of the model and results on potentially sensitivity to initial value chosen for technologies with small sales shares. A sensitivity test should be applied to check for robustness of results with variations of initial conditions.

Keeping in mind that comparable technology diffusion makes sense in a large market and with a large scale of time (Grubler, Charlie Wilson, and Nemet, 2016) we look at USA market. The data that was used to determine the parameters of the diffusion constraint are extracted from the dynamics of USA automobile technology historic from 1975 to 2015 from national agencies Environmental Protection Agency (EPA, 2016) and Oak Ridge National Laboratory (Davis et al., 2016).

From the database on historical trends (EPA, 2016; Davis et al., 2016) we have performed a non linear least square regression with the fitted function defined in eq. 2.5 on technologies with a penetration of more than 50% [3]. We isolated the diffusion phase from the first growth phase to where growth trend is stable or is reversed to a decay phase. The fitted curves on the database can be seen in Fig. 2.4. We obtain the

3. The diffusion profiles of technologies in the automotive sectors were obtained using non linear regression in R.

speed of diffusion from parameter c in Table 2.2. There are different types of technologies in the database: gasoline engine technologies that reduce fuel consumption such as Port Fuel Injection, Multi-Valve and Variable Valve Timing, transmission technologies: CVT and Lockup and drive type technology: Front Wheel Drive.



(A) Variable Valve Timing (B) Multi-Valve (C) Port Fuel Injection

(D) Gasoline Direct Injection (E) Lockup (F) Front Wheel Drive

(G) 4 Wheel Drive (H) CVT (I) Throttle Body Injection

(J) Hybrid

FIGURE 2.4 – Plots of historical automotive diffusion technologies in the USA with fitted sigmoid function. Technologies are in the engine or transmission components. The start year is the beginning of the diffusion phase and the end year is the end of the diffusion phase or the end of the time series in 2015. Red circles are historical data and black line is the fitted function. CVT: Continuous Variable Transmission. Source: EPA, 2016; Davis et al., 2016.

What we learn from these time series is that in the trajectory of sales share, there are moments were growth occurs faster and others when it slows down. As new technology replaces the older alternatives, the growth of the newcomer increases and the decay of the mainstream technology accelerates, sometimes there is a symmetry. For example as seen in the replacement of Carburetor by Port Fuel Injection in the USA. In this case the newcomer is a perfect replacement. In general, most diffusions take time to penetrate to the mass market. Some technologies fail and do not diffuse in a market, this is the case of diesel in the USA for passenger cars. The analysis of the historical trends will allow us to understand how the diffusion process works and characterize it. We define the rhythm at which consumers buy the newcomer technology and the capacity of the industry to deliver products at competitive price. Our approach is empirical, we test a diffusion model into historical data. The diffusion model comes from the S-shape curve.

From the historic trends of diffusion, we have some technologies that have a low saturation point $a < 50\%$. These technologies did not successfully diffuse in the market and, were ruled out of the estimation of parameters. The fitted function shows different estimates for its parameters. The saturation parameter a changes with the maximum sales share of past technology, we have not constrained a to be lower than 1 although the diffusion is theoretically limited to 1. The translation b parameter indicates when the S curve profile will begin, it can vary due to the difference between the trimmed data and a theoretical diffusion starting at year 0, b is a measure of this delay. The speed of diffusion c parameter is of most interest to this research and shows that there is not a single dynamic of diffusion in the automotive market, different speeds define technology diffusion as seen on Table 2.2. The residuals from the regression are low, this means that the sigmoid function was a good fit.

Technology	**a**	**b**	**c**	**RSE**	**Δt**
Front Wheel Drive	0.886	27.67	-0.394	0.040	11.2
Lockup	0.809	28.30	-0.398	0.069	11.0
CVT	0.515	48.77	-0.274	0.025	16.0
Port Fuel Injection	1.024	341.03	-0.423	0.026	10.4
Multi-Valve	0.979	10.27	-0.184	0.049	23.8
Variable Valve Timing	1.107	95.36	-0.248	0.032	17.7

TABLE 2.2 – Summary of regression estimates of diffusion technologies in the USA. Those technologies with parameter a less than 0.5 mean that they have not diffused in the entire market and thus are not example of a fully successful diffusion. RSE is the Residual Standard Error of the fitted function and Δt is the time period over which market share grows from 10% to 90% of a, thus $\Delta t = \frac{ln(81)}{c}$.

Table 2.3 is a compilation of large technology diffusions in the past, the examples cover the transport and energy sectors and represent infrastructure and end-use technologies. A review of diffusion processes from Grübler, Nakićenović, and Victor, 1999 shows that the mean value of time constants is 41 years, with a standard deviation of about equal size and half of the diffusion processes have Δt, defined in Table 2.2, of less than 30 years. Nonetheless this study includes infrastructure and energy generation processes that take a long time to diffuse. The more end-user technologies such as passenger vehicles diffuse faster. From these regression estimates,

Technology Description	Region	Δt in years	Source
Steamships	Worldwide	55	(Grübler, 1991)
Railway networks	Worldwide	56.9	(Grübler, 1991)
Canals	USA	30	(Grübler, 1991)
Length of surface roads	USA	64	(Grübler, 1991)
Motor vehicles (cars, taxis and motorcycles)	UK	16	(Grübler, 1991)
Air conditioning	USA	18	(Grübler, 1991)
Nuclear power	OECD	20	(Wilson et al., 2013)
Natural gas power	OECD	28	(Wilson et al., 2013)
Compact fluorescent light Bulbs	OECD	15	(Wilson et al., 2013)

TABLE 2.3 – Summary of diffusion time periods from different technology in transport and energy sectors from historic data.

we created three diffusion profiles: LOW, MEDIUM, HIGH and VERY HIGH that represent the lower bound and intermediate speed and a higher speed presented in Table 2.4 and Fig. 2.5.

The powertrain technologies with an electric motor have a more difficult challenge to diffuse in a market due to a change in the energy supply ecosystem (charging infrastructure) but also a change in the consumer behavior (vehicle's autonomy limited to battery size and driving behavior) therefore we took the conservative diffusion profile of LOW for all technologies. Two reasons from a diffusion perspective are important to be conservative about the speed of diffusion. First an electrification of passenger vehicles is a novel diffusion process that will affect core regions where conventional vehicles are deeply adopted and dominate the market. Second electrification of vehicles is not the only technology at disposal to develop a low carbon transport. It is today competing with other technologies vs. only replacing the incumbent technology, e.g. motor vehicles and horse carriages, which makes diffusion process slower.

The LOW diffusion profile is used to limit diffusion of all technologies in Chapter 3 and 4. In Chapter 5 we have changed the diffusion profiles of emission control technologies that diffuse faster than powertrain technologies. The change in the diffusion profiles is shown in Table 5.5.

The above mentioned technology diffusion model of a S-curve looks at market wide changes containing all firms in a sector. Our model is focused on one firm technology choice. The difference relies on whether the firm is a first mover or a follower (Wesseling, Farla, and Hekkert, 2015). If the firm is a first-mover, i.e. the first to develop a technology, it will have a slower diffusion rate than those that come after and benefit from technology spillovers (EPA, 2016; S. Zoepf and Heywood, 2012). A firm that prepares a future technology portfolio can push the boundaries of diffusion of a technology if they find a competitive advantage to attract more consumers,

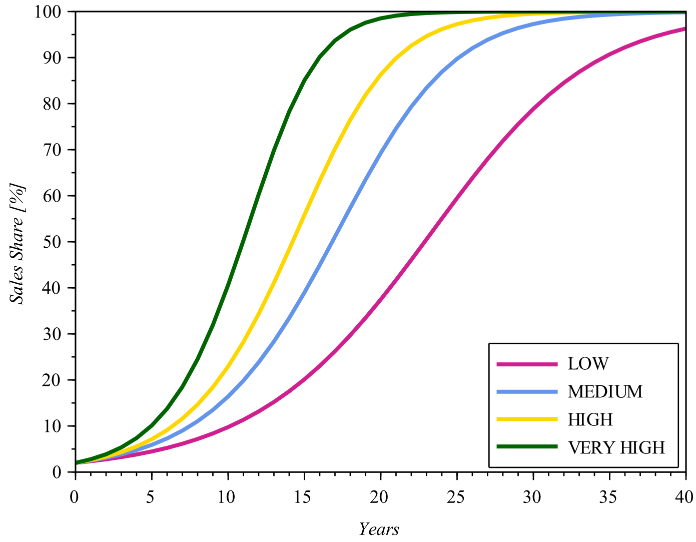


FIGURE 2.5 – Example of Technology diffusion limited by three diffusion profiles: LOW, MEDIUM, HIGH and VERY HIGH from an initial share of 2 %. LOW means also slow and HIGH means fast.

Diffusion Profile	**c**	**Δt (in years)**
LOW	0.18	24.4
MEDIUM	0.25	17.6
HIGH	0.30	14.6
VERY HIGH	0.40	11

TABLE 2.4 – Four diffusion profiles representing the different dynamics in automotive technologies. Summary of c parameter and time period defining the speed of diffusion. LOW represents the lower bound of technology diffusion, MEDIUM is an intermediate speed seen in all markets, HIGH is a fast diffusion and VERY HIGH represents the upper bound of family of fast diffusion.

lower the prices of vehicles or increase the technology exposure. However on average the supply-side dynamics is limited to the market speed. The last firm to change technology has often the fastest rate of change. Our model does not distinguish the position of a firm if it a first mover or a follower therefore our estimate on diffusion is based on the market average. This thesis is based on a large car manufacturer in Europe therefore we can assume that it moves at an average speed compared to the market.

The discount rate value is presented on each application of the model, we have taken a low estimate that is close to a social discount rate. In the automotive industry, we can distinguish three different values of discount rates where a firm discounts the investments in technology, an end-user discounts the price and use of a vehicle and a policymaker discounts the social cost of a policy. Although modeling a firm technology choice, we want to evaluate the social implications of the technology portfolio therefore our estimate is lower than the industry discount rate.

2.4.3 Model Output

The OMLCAT is a dynamic model of optimization, it can show the technology pathway or the static technology mix profile at a point in time. The results can be interpreted on a yearly basis with the status of the mix at one point in time or as an indicator of the dynamics of a technology. The variables that are obtained to monitor the emission reduction of the technology portfolio focus on the abatement pathway, the content and cost of the mix. The abatement pathway is the yearly average emissions that is compared to the CO_2 emissions target. Technology choices are shown in the sales share decomposition of the mix. The overall cost of the portfolio of technologies is the objective function of the model, shown in eq.2.2, and can also be analyzed dynamically to see how the cost evolves. We describe the methodology to include the cost of using the technology mix in Chapter 4.

2.5 Variants of the Model used to study specific Research Questions

The OMLCAT is used in three different applications in this thesis to study different policy issues with a fuel economy standard. These applications are described in full in each of the following chapters. Chapter 3 explores the impacts of a firm strategy when it prepares future consecutive policy targets. Chapter 4 focuses on the implications on technology selection caused by the nature of the fuel economy standard that is indexed to vehicle's mass. Chapter 5 enlarges the policy scope of the model to treat both local and global policies in two dimensions: air pollutants and CO_2 emissions in order to understand how different policies interact with each other. Here we describe the model variations, change in technology assumptions and key elements used for each application.

2.5.1 Chapter 3: Path Dependency of technology choices

In this first application of OMLCAT, we introduce 9 powertrain technologies of the lower medium vehicle segment listed in Table 2.5. The fuel economy standard constraint is modeled in two steps of increasing stringency in 2020 and 2030. The CAFE constraint is the same simplified mechanism presented in section 2.4. What we change in this application is the strategy to anticipate future targets, in terms of modeling application the effect is three different variants of time horizon and number of constraints.

— A single CAFE constraint in 2030

— Two CAFE constraints in 2020 and 2030 in one single run

— Two CAFE constraints in 2020 and 2030 a first run up to 2020 and a second run starting in 2020 up to 2030.

Technology Name	Description
Gasoline	Baseline Gasoline engine
Gasoline 12V	Gasoline engine with a small 12-V electric motor and battery
Gasoline 48V	Gasoline engine with a 48-V electric motor and battery
Gasoline HEV	Hybrid engine with gasoline ICE, an electric motor and a battery
Gasoline PHEV	Plug-in Hybrid engine with gasoline ICE, and electric motor and a battery capable of charge from the grid
Diesel	Baseline Diesel engine
Diesel 12V	Diesel engine with a small 12-V electric motor and battery
Diesel 48V	Diesel engine with a 48-V electric motor and battery
BEV	Electric motor and large battery capable of charge from the grid

TABLE 2.5 – Nine powertrain technologies common to all applications in this thesis. These technologies were selected to represent the portfolio selection a car manufacturer with limited choices.

The key element that is analyzed here is the fuel economy constraint and the timing of abatement technology deployment.

2.5.2 Chapter 4: Implications of CO_2 vehicle's emission regulation indexed to mass

A second application focuses on the mechanism of the policy to distribute abatement efforts. Chapter 2 has presented a simplified version of the CAFE constraint, eq.2.4 does not include any vehicle's parameter to distinguish between vehicle categories. In practice there are two parameters: mass and footprint that are used to differentiate vehicles and correct fuel economy targets as a function of this parameter. Chapter 4 introduces the vehicle mass parameter and modifies the fuel economy constraint in 2030 to the form applied in Europe with a mass index seen in eq.2.19.

$$CAFE_i = TARGET_i + a\left(M_{corporate} - M_0\right) \tag{2.19}$$

where $TARGET_i$ is the enacted European target in $gCO_2/km$for year i
$a = 0.0457 \quad gCO_2/km/kg$ in 2015 and 0.0333 from 2020 is the mass index coefficient

$M_{corporate}$ is the average mass in kg of corporate sales for year i M_0 is the estimated average mass in kg of all new vehicles by the regulator

To test this constraint we introduce one additional technology variant to a Gasoline technology called Gasoline Light including weight reduction at different levels to see which scenarios choose this technology. In order to show the gap of indexing the fuel economy standard to mass we use four scenarios with variations of the fuel economy standard.

— A CAFE constraint in 2030 without mass indexation
— A CAFE constraint in 2030 with mass indexation based on the initial average vehicle's mass
— A CAFE constraint in 2030 with mass indexation based on yearly average vehicle's mass
— A CAFE constraint in 2030 with the same target of the scenario above but without mass indexation

The key element that is analyzed here is vehicle's mass and the second part of the fuel economy expression related to vehicle's mass.

2.5.3 Chapter 5: Overlapping of CO_2 and Air Quality Policies

The third and last application of OMLCAT expands the policy package limited in all other application to the fuel economy standard. This Chapter explores 5 more policies, listed below: 2 national policies and 3 local policies concerning both GHG emissions and air pollutants. To simulate the impact of local policies we develop in Chapter 5 a model of propagation of LEZ policy in urban areas that affects a larger share of vehicle sales.

— National: EURO Emission standard applied on pollutant vehicle's emissions for each vehicle
— National: Zero Emission Vehicle (ZEV) Mandate that requires a minimum share of ZEV
— Local: Low Emission Zones (LEZ) with a progressive ban on ICE
— Local: LEZ with a hard ban on ICE to force entry of ZEV

Automotive technologies in this section are further divided into emission technology categories where the Diesel and Gasoline families have three variants that change with compliance with more severe Emission Standards. The technology evolution includes better fuel combustion and after-treatment of vehicle's emissions improvements. In terms of mechanism, each policy affects the whole or a part of new vehicle sales, has its own time horizon and its own target. The key element of this Chapter is the inclusion of more policy constraints and how this additional limits change the baseline of fuel economy standard only scenario.

Table 2.6 is a landscape view of the Scenarios developed in this thesis which explore the mechanism of the CAFE constraint, the time horizon and the combination with other policies. We leave the discussion of the results of each application to

Application	Scenarios	Fuel Economy Policy	Horizon	Other Policies
Path Dependency	Optimal Long term	no mass index	2030	None
	Foresight	no mass index	2020 & 2030	None
	Myopic	no mass index	2020 then 2030	None
Mass Index	Simplified	no mass index	2030	None
	Initial Mass correction	target corrected by initial mass	2030	None
	Mass correction endogenous	target corrected by yearly average mass	2030	None
	Target correction from Scenario mass-index	target equal to Scenario mass-index	2030	None
Vehicle's Emissions Policies	CO_2 only	w & w/o mass index	2030	None
	CO_2 & Air Pollution regulation	w & w/o mass index	2030	EURO standard:6dFull and 7 in 2020 and 2025
	CO_2 & ZEV Mandate	w & w/o mass index	2030	Quota for NEV: 25-37 credits in 2030
	CO_2 & LEZ ICE ban	w & w/o mass index	2030	tech restriction in cities starts in 2022 with Diesel
	CO_2 & LEZ ZEV force	w & w/o mass index	2030	tech restriction in cities starts in 2027

TABLE 2.6 – Scenarios of Vehicle's Emissions Policies for Passenger Vehicles for each application in this thesis.

the corresponding Chapters. Throughout this thesis we have tested each of the components blocks: changing the technology assumptions, changing the policy package and changing the time horizon of the simulation.

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Chapter 3

Path Dependency of vehicle technology choices with consecutive fuel economy targets

3.1 Introduction

The objective to limit climate change below a 2°C, or a 1.5°C, increase compared to preindustrial times, as agreed in the Paris Agreement, require meeting an ambitious target of net zero CO_2 emissions in the course of the 21^{st} century (Masson-Delmotte et al., 2018). Triggering and amplifying mitigation efforts along a pathway compatible with such long-term target necessitates the implementation of policy instruments to guide investment, consumption and R&D decisions. Because the credibility of long-term targets and policy instruments is problematic, shorter-term targets are enacted. For example, at the national level, short-term carbon budgets are defined along national low-carbon strategies and in the framework of the Paris Agreement countries announce Nationally Determined Contributions at the 2030 horizon. At the sectoral level, several examples of short-term targets also exist: for instance targets on the share of renewable energy in power generation or targets on average fuel efficiency in car manufacturing. The question is therefore how shorter-term targets can be chosen to enable the transformations required to be triggered, or how the choice of short-term targets influences the attainability of long-term targets.

Recent studies on the dynamics of mitigation pathways, at an economy-wide global level, have highlighted the risk of carbon lock-in implied when short-term targets are not stringent enough and thus compromise long-term abatement solutions (Bertram et al., 2015; Bauer et al., 2015; Vuuren and Riahi, 2011). With a more methodological approach, Vogt-Schilb and Hallegatte, 2014 have shown that the optimal strategy to reach a short-term target depends on longer-term targets, and that the best strategy might not be to implement the cheapest abatement options first. The reason for this result lies in the inertia, or limited speed, at which abatement options can be deployed: in the presence of inertia, it may be optimal to start early implementing expensive but high-potential and long-to-implement options. Vogt-Schilb, Hallegatte, and De Gouvello, 2015 applies this reasoning to the case of Brazil 2030 mitigation target, and show that optimal mitigation for each sector at the 2030 horizon depends on the long-term target.

But these studies remain at an aggregated and relatively abstract level, and fail to connect directly with existing policy instrument. This chapter aims to bridge this gap. It focuses on a specific sector, car manufacturing, and a specific policy instrument, Corporate Average Fuel Efficiency (CAFE) Standards, which are the main instrument in place to reduce CO_2 emissions from the new fleet of vehicles sold. It aims to study how consecutive fuel economy standard influences vehicles technology choices, and how reaching short-term CAFE targets enables or hinders the attainment of long-term targets.

CAFE standards apply to car manufacturers requiring a performance limit on the average fuel economy of their yearly sales. They are announced some years in advance, and are designed to become more stringent over time. The economic literature on CAFE standards has evaluated the cost of meeting the standard in a static approach (Luk, Saville, and Maclean, 2016; Hill et al., 2016; Krause, Donati, and Thiel, 2017; Pasaoglu, Honselaar, and Thiel, 2012; NHTSA, 2010; NHTSA, 2011) in two main markets: USA and Europe. There are also studies that compare the CAFE standard with other policy instruments to determine policy efficiency (Karplus et al., 2013; Damert and Rudolph, 2018; Yang et al., 2017; Anderson and Sallee, 2016; Yang et al., 2017; Anderson, Parry, and Sallee, 2011; Brand, Anable, and Tran, 2013; Damert and Rudolph, 2018; Fox, Axsen, and Jaccard, 2017). The literature agrees that a fuel tax is the most efficient policy but it has the highest political risk. But the literature on CAFE standards has mainly taken a static perspective and neglected to study the dynamics of technology choices implied by consecutive targets that tighten over time.

Our goal is to bridge the gap between climate policy assessment of long-term and near-term targets with a sector specific policy instrument dynamics. Our aim is to show an illustrative case of a CAFE policy with two targets in the future to study the interaction between a near-term target and a longer term target.

To do so, we build an optimization model of vehicle technology portfolio choices, and use it to analyze two polar cases of anticipation of policy targets. The first case is a myopic scenario where only a short-term target is accounted for. The other is a case of perfect information and foresight of both short-term and long-term targets. We show how the different types of anticipation have an impact on policy feasibility, technology choices and compliance costs. We illustrate the analysis with a given set of technologies from which the car manufacturer can choose a portfolio, a given short-term target and a range of long-term targets. We study how emission pathways and technology choices pathways differ depending on the type of anticipation, with foresight or myopic, and exhibit cases of path-dependency of technology choices.

The remainder of this chapter is organized as follows. Section 3.2 describes the methods, data and scenarios used for the analysis. Section 3.3 describes and analyzes the results. Section 3.4 discusses the implications of the results for the anticipation of a fuel economy standard policy and concludes the chapter.

3.2 Methodology

We use an optimization model of the technologies portfolio choices. The complete model description is presented in Chapter 2. The assumptions and data used to represent technologies are described in section 3.2.2. The representation of fuel economy standards in the model are given and discussed in section 3.2.3. The scenarios constructed with this modeling framework are detailed in section 3.2.4.

3.2.1 Model of Optimization for Low Carbon Technologies

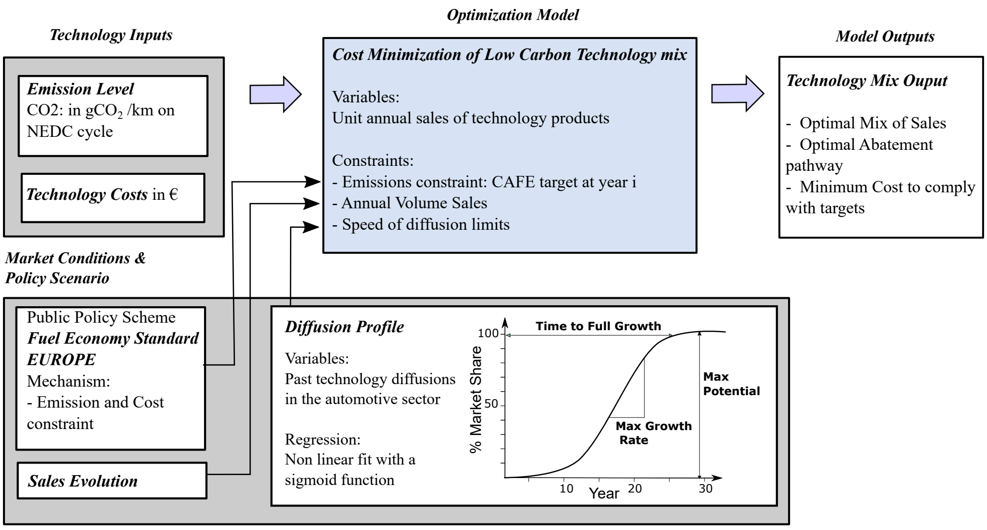


FIGURE 3.1 – Overview of the version of the Model of of Optimization of Cost of Low Carbon Technologies for this article. Source: The Author.

The model, described in Fig.3.1 adopts a supply-side car manufacturer perspective, which would seek to minimize the total production costs of vehicles sold, discounted over the time horizon considered. A firm's profit maximization problem can be simplified to eq. 3.1 which indicates that a firm can change vehicle price, number of vehicles or cost of production. In the context of abatement solutions in the automotive industry, we assume that low carbon technologies are the main driver of technology cost and consider that cost of production corresponds to low carbon powertrain technology costs. The type of low carbon technologies in a vehicle is determined by policy ambitions.

$$max \quad \sum_{j=1}^{n} x_j * (P_j - C_j) \tag{3.1}$$

where x_j is the number of vehicles sold with powertrain technology j, P_j is the selling price of a vehicle with powertrain technology j and C_j is the production cost of a vehicle with powertrain technology j.

Vehicle price is not a variable of optimization in our model. We do not integrate the mechanism of pricing different vehicle technologies to adjust for profitability margin, and therefore neglect that the selling price of low carbon technology is in practice higher than the vehicle price of fossil-fuel based technologies. Instead, the model finds the least cost solution among low carbon technologies to comply with a policy ambition.

In addition, we assume technologies unit cost to be constant and independent of the number of units produced. The model does not take into account the resources necessary to increase or launch production of low carbon vehicles. Plug-in vehicles require new type of assembly lines of electric motors and batteries which in turn requires new type of knowledge and skills. The cost assumptions used in this article are limited to marginal cost of producing a powertrain unit with a specific technology type. The cost of all other technologies of the vehicle is considered the same for all powertrain types.

The simplifying assumption of costs minimization gives information of what is the cheapest technology mix to comply with a policy target limited by inertia constraints. The solution of the model could be interpreted as the optimal technology mix to maximize profit margins, under the simplifying assumptions of constant selling prices and constant unit production cost independent of the number of units produced.

Here, *technology* is used to describe a complete vehicle product that includes all the required technologies to satisfy customer needs in a given vehicle segment. It is different from the definition of a *single technology* application e.g. automated transmission. For example, a technology can refer to a gasoline-powered vehicle and a different technology would be an electric vehicle.

The inputs to the model are the characteristics of the available technologies: their production costs and the associated emissions levels. See section 3.2.2 for a description of these inputs.

The result of a given run of the model is the optimal technology mix output, or "technologies portfolio", i.e. the share of each technology in total vehicle sales every year though the time horizon considered. From the optimal technology mix of sales over the entire period, the associated emissions pathway and the production costs can be calculated.

The model accounts for two types of constraints. The first type corresponds to the regulatory constraint imposed by corporate average fuel economy standards. The second type are dynamic constraints, or "inertia constraints", on the maximum speed at which each technology can be diffused. These dynamic constraints act on the yearly sales of new vehicles.

The objective function and constraints are defined as follows:

$$min_{x_{ij}} \quad \sum_{i=1}^{m} \frac{1}{(1+r)^{i-1}} \sum_{j=1}^{n} x_{ij} * C_j \tag{3.2}$$

$$\forall years\ i \sum_{j=1}^{n} x_{ij} = SALES_i \tag{3.3}$$

$$for\ target\ year\ i^* \frac{\sum_{j=1}^{n} x_{i^*j} E_j}{SALES_{i^*}} \leq TARGET_{i^*} \tag{3.4}$$

where x_{ij} is the number of vehicles sold corresponding to a technology j on year i, m is the time horizon considered (in years), r is the discount rate, n is the number of technologies considered, C_j is the cost of technology j in €, $SALES_i$ is the total number of vehicles sold at the year i, E_j is the CO_2 emissions of technology j in gCO_2/km, and $TARGET_{i^*}$ is the corporate average fuel economy standard imposed at the compliance year i^*.

The sales volume constraint presented in eq. 3.3 sets an exogenous trajectory of number of vehicles sold each year. An automotive firm has a sales volume goal for future years that guides the labor and manufacturing needs. In order to commit to a strategic change in the number of vehicles sold, an automotive firm also prepares for future policy constraints. Our approach is a policy assessment of the impact of CAFE that is made after setting volume targets. For the purpose of this article, we keep the sales volume constraint constant and refer to sales share instead of number of vehicles. The volume constraint can be interpreted as a guarantee that the sum of sales share of the technology portfolio is always 100%.

The corporate average fuel economy standard introduced in our modelling framework is described in section 3.2.3.

The application of the model presented in this article is calibrated to year 2014 and the time horizon considered is 2030. The time step is annual, such that $m = 17$ is the number of years. The number of technology options is $n = 9$ (see section 3.2.2). The discount rate r is set at 4%.

The inertia constraints introduced aim at accounting for stylized facts about the dynamics of technology diffusion. Both supply and demand barriers to diffusion are complex to model. Historical evidence on automotive technologies in the European and North American markets (EPA, 2016; Davis et al., 2016; ICCT, 2015) shows that technology diffusion tends to follow an 'S' shaped curve where diffusion rates first rise and then fall over time. The stages of diffusion under this curve are defined as: Innovation, Early Adoption, Early Majority, Late Majority and Laggards (Fouquet, 2016; Charlie Wilson and Grubler, 2011; Grubler, Charlie Wilson, and Nemet, 2016). To represent the shape of diffusion, the literature suggest that a sigmoid function captures the different stages of diffusion (Grübler, 1991; Wilson et al., 2013; Zoepf and Heywood, 2012).

$$SS(t) = \frac{a}{1 + be^{-ct}} \tag{3.5}$$

where $SS(t)$ is the share of a technology in total sales at time t, a,b and c are the coefficients of the sigmoid function of diffusion: saturation point, translation parameter and speed parameter respectively.

To replicate the S-curve dynamics on our model, we limit the sales share of year i as a function of the sales share of year $i-1$. We use a sigmoid function (eq.3.5) to derive the constraint on speed of diffusion from the sales share of a technology (see Chapter 2). We obtain the inertia constraint, eq. 3.6, which produces an upper limit to the speed of diffusion of each technology, i.e. the maximum yearly change of sales share of a technology as a function of the previous year sales share.

$$\forall year\ i > i_0\ and\ \forall technology\ j : \frac{SS_{ij} - SS_{i-1j}}{SS_{i-1j}} \leq c(1 - SS_{i-1j}) \tag{3.6}$$

where SS_{ij} is the share of a technology j in total sales at year i, SS_{i-1j} the share of the same technology at the previous year $i-1$, and c the speed parameter coefficients of the sigmoid function of diffusion.

Based on this modelling framework of diffusion, we analyze data of past diffusion dynamics of engine and transmission technologies from the USA market (EPA, 2016; Davis et al., 2016). We perform a non linear regression to obtain the dynamics parameters of past diffusion. We obtain three "archetypes" of diffusion profiles based on past dynamics: LOW, MEDIUM, HIGH and VERY HIGH, depending on the speed of the diffusion. Supplementary Material gives further details on the data used and the analysis performed.

In the application of the model presented here, we retain the same diffusion constraint for all technologies. It is set to LOW which corresponds to a slow diffusion process of high inertia. The values of the sigmoid function coefficients are: $a = 1, b = 300\ and\ c = 0.18$. In such condition, the increase from 10% market share to 90% of full adoption would take 24 years. We choose this conservative estimate of inertia because our technology assumptions include electric-powered vehicles that are more difficult to diffuse. Compared to past fossil fuel technologies, plug-in vehicles demand infrastructure deployment and consumer behavior change. Therefore a conservative diffusion profile seems more compatible with the deep changes required to the vehicle ecosystem. Although the dynamics on diffusion vary among car manufacturers and locations, we estimate that the car manufacturer size and location in a core automotive market justifies the estimate of a diffusion speed calibrated to the average of the market.

The model does not include learning-by-doing effects but has a constraint on diffusion that is inspired on the inertia constraint on abatement technologies. When including learning there is a component of increasing knowledge based on the cumulative size of a technology that reduces investment cost and technology cost in time (Goulder and Mathai, 2000). With learning there is a more refine mechanism to analyze the mechanism of path dependency however they require more data and estimations on the sector's technologies learning curve. For macro trends on the automotive market and to consider market effects beyond learning such as consumer behavior a constraint on diffusion is enough.

3.2.2 Technology Assumptions

The set of technologies considered in the application presented here is constructed to represent a medium vehicle segment with powertrain options to comply with the fuel economy standard in Europe. Our model does not take into account all low carbon technology options as opposed to (Krause, Donati, and Thiel, 2017; Hill et al., 2016; Sanchez, Bandivadekar, and German, 2012) where they explore a large set of technologies, but focuses on the main powertrain solutions that are available in the market. The baseline engine technologies are a Gasoline Engine and a Diesel Engine, from which incremental electrification of the powertrain improves vehicle's emissions but it increases the technology cost. There are two options of mild-hybrids at 12 and 48 V for Gasoline and Diesel. These hybrid technologies work most the time in ICE mode but they allow some energy recovery to assist the ICE in specific conditions and include a stop & start capacity. There is one single full-hybrid and plug-in hybrid configuration with a gasoline engine. There is a battery-electric vehicle that is the best option in terms of tailpipe emissions but it is also the most costly (BEV).

Table 3.1 gathers the numerical assumptions for the emission levels and costs of the technologies considered. These assumptions were discussed with technology experts from Renault, a french car manufacturer, and are meant to be consistent with a medium vehicle segment case. The emissions data correspond to emissions over the New European Driving Cycle (NEDC), given that the upgrade to measurement of emissions over the World harmonized Light vehicles Test Procedure (WTLP) cycle is currently on going.

The initial shares of technologies in total sales for the year of calibration, 2014, are indicative. They are not meant to represent exactly the sales of a real car manufacturer. Instead, they represent the case of an hypothetical firm that would have already introduced in the market all types of technologies for the medium vehicle segment. Otherwise, having a zero market share in 2014 for a given technology would prevent the diffusion of this technology over the entire time horizon, given the representation of the inertia constraint chosen. This is a limitation of the methodology, and obviously results are sensitive to initial market shares for technologies that have small initial shares. But the objective of the application presented in this paper is not to reproduce a real case, but rather to exhibit illustrative cases of path dependency in technology choices.

Technology	**Emissions (gCO_2/km)**	**Powertrain Cost (€)**	**Share (% 2014)**
Gasoline	105	1950	45
Gasoline 12V	98	2350	3
Gasoline 48V	91	3150	2
Diesel	95	2950	40
Diesel 12V	89	3350	3
Diesel 48V	83	4150	2
Gasoline HEV	80	4650	1
Gasoline PHEV	40	5950	1
BEV	0	7950	3

TABLE 3.1 – Assumption of Powertrain Technologies for a lower vehicle segment.

Traditionally in energy models, technology learning is the mechanism to represent how a technology can become more competitive through cost reductions and technological improvements (Kahouli-brahmi, 2008). The accumulation of know-hows in a technology is progressive and follows a diffusion process of its own. For simplicity, we abstract from learning-by-doing mechanisms and costs are kept constant over time.

3.2.3 Future of Fuel Economy Targets

We aim to test how technology choices for reducing carbon dioxide emissions made in the short term affect the abatement potential and composition of the technology mix in a future where fuel economy policy will be more stringent. We analyze the fuel economy policy in Europe.

The European Fuel Economy Standard is defined as a mandatory upper limit of Corporate Average CO_2 emissions that is calculated as the arithmetic mean of the emissions level of all new vehicles sold in a given year as in eq.3.7, measured in gCO_2/km. The target for passenger vehicles is set every 5 years with an increasing stringency to reduce vehicle emission of the overall fleet.

$$\forall \quad year \quad i \quad CAFE_i = \frac{\sum_{j=1}^{n} X_{ij} E_j}{SALES_i} \tag{3.7}$$

where E_j is the emission level for technology j in gCO_2/km,
$SALES_i$ is the total vehicle sales of the manufacturer at year i,
X_{ij} is the units of sales of vehicles with technology j at year i,
and n is the total number of vehicle technology options.

The regulatory constraint imposed by CAFE standards is thus represented as:

$$CAFE_i \leq TARGET_i \tag{3.8}$$

where $TARGET_i$ is the enacted European target in gCO_2/km.

For the purpose of this Chapter, we make a number of simplifications and neglect some details of the CAFE standard enacted regulation, that would not change our overall results. In particular, the fuel economy standard in current European regulation is indexed on the average mass of vehicles, such that heavier vehicles contribute to lowering the overall standard (European Parliament and European Council, 2009). Here, we do not account for this indexation of the standard on the mass of vehicles. Also, the regulation provision includes an economic fine that non-complying manufacturers would pay. In our modeling choices here, we do not consider this possibility to pay the fine, and the firm has to comply whatever the cost.

The economic literature on Corporate Average Fuel Economy standards has evaluated the cost of meeting the standard looking at different aspects that limit the technology pathways, such as consumer preferences on vehicle characteristics: acceleration, size, price, weight (Whitefoot and Skerlos, 2012; Whitefoot, Fowlie, and Skerlos, 2017; Klier and Linn, 2012; Knittel, 2011), car manufacturers competition (Whitefoot and Skerlos, 2012). Techno-Economic models have produced an assessment of the technology potential of current solutions (Luk, Saville, and Maclean, 2016; Hill et al., 2016; Krause, Donati, and Thiel, 2017; Pasaoglu, Honselaar, and Thiel, 2012; NHTSA, 2010; NHTSA, 2011) in two main markets: USA and Europe. Previous studies produce a static picture of the future technology mix complying with a given target (Karplus et al., 2013; Damert and Rudolph, 2018; Yang et al., 2017; Anderson and Sallee, 2016) but few studies are interested in the technology dynamics under CAFE standards, the implications of short-term technology choices on long-term technology choices. We bridge this gap in this chapter.

3.2.4 Scenarios

Our aim is twofold: first, test the impact of different levels of stringency of long term targets that are still uncertain on the technology mix and second, investigate the implications of complying with a short term target for the attainment of a longer term target.

The time horizon considered covers 2015-2030, and includes two fuel economy targets - a short-term target for 2020 and a long-term target for 2030. The short-term target is fixed at the enacted target from European Commission of 95 gCO_2/km in 2020. For the long-term target, we explored the range between 60 and 80 gCO_2/km comprising a 15% and 30% reduction of the target from the 2020 target level which correspond to the possible target which is not yet definitive at the time of publication. Four Scenarios are considered:

— The 2020 only Scenario corresponds to a strategy aiming to respect the 2020 target only. For this Scenario, the time horizon is limited to 2015-2020.

— The 2030 only Scenario corresponds to a strategy aiming to respect the 2030 target only. It optimizes technology choices over the time horizon to minimize the overall discounted compliance cost for the 2030 target, without considering the 2020 target. The resulting average emissions of the fleet sold in 2020 may in this scenario be higher or lower than the 2020 target of 95 gCO_2/km.

— The Foresight Scenario corresponds to a strategy optimizing technology choices over the time horizon to minimize the overall discounted compliance cost to respect both the 2020 and the 2030 target. It represents a case where the manufacturer would have perfect information and perfect anticipation of both the short-term and the long-term target.

— The Myopic Scenario corresponds to a sequential strategy that would optimize technology choices first over 2015-2020 to minimize discounted compliance costs over the period to respect the 2020 target, and then over 2020-2030. The choices over 2015-2020 do not take into account the 2030 target, they are identical to those from the 2020 only scenario. Technology shares are re-calibrated in 2020 to the results of the first period optimization, and the 2030 target is only prepared in the strategy starting in 2020. This Scenario represent a manufacturer that would focus solely on the closest target, without anticipating the potential tightening of longer-term targets.

A Myopic Scenario would illustrate a case where a car manufacturer would have no information on future targets or would not anticipate beyond the short-term target. In Supplementary Material we present a variant of the Myopic Scenario where the first technology choice is made on the 2014-2030 period but without considering the 2030 target, keeping the 2020 target constant from 2020 to 2030 and a second technology choice is made for a 2020-2030 with a 2030 target from the mix in 2020 of the first run.

Table 3.2 summarizes the scenarios and fuel economy targets considered.

Target years	**2020**	**2030**
CAFE targets (gCO_2/km)	95	60-80
2020 only	$\star$	
2030 only		$\star$
Foresight Scenario	$\star$	$\star$
Myopic Scenario	$\star$	$\circ$

TABLE 3.2 – Scenarios of Fuel Economy Standards for Passenger Vehicles Targets. For each Scenario, the CAFE target constraints accounted for are defined by a $\star$. The 2030 target $\circ$ in the *Myopic Scenario* is not anticipated from the start of the horizon, it is prepared from the 2020 mix that complies with a 2020 target.

3.3 Results

We first compare average emissions level in 2020 for the four scenarios considered. Figure 3.2 shows the difference in emission levels in 2020 between the 2020 CAFE target of 95 gCO_2/km and two Scenarios - the 2030 Only Scenario and the Foresight Scenario - as a function of the 2030 target. Note that for the two other scenarios - the 2020 only Scenario and the Myopic Scenario - the emissions in 2020 are trivially strictly equal to the 2020 target. In the 2030 Only Scenario, emissions in 2020 are below 95 gCO_2/km if the 2030 target is stringent (below 67 gCO_2/km in our case), and above if the 2030 target is less stringent. It means that it is optimal to outperform the short-term target when the long-term target is stringent, and that when the long-term target is less stringent it is not necessary nor optimal to meet the short-term target when the only objective is to meet the long-term target at minimal compliance cost. In the Foresight Scenario, if the 2030 target is stringent (below 67 gCO_2/km in our case), it is the real constraint and it is optimal to outperform the 2020 target as in the 2030 Only Scenario. When the 2030 target is less stringent, the constraint on the short-term is the 2020 target, and the emissions in 2020 in the Foresight Scenario are strictly equal to the target.

The Myopic Scenario becomes unfeasible for long-term targets below a certain threshold. The inertia constraints on the diffusion of new technologies is more limiting when technologies deployment starts in 2020. For 2030 CAFE targets below 69 gCO_2/km, the portfolio of technologies fails to comply with the 2030 target. It is remarkable that in our case this unfeasibility threshold is above the value (67 gCO_2/km) for which it becomes optimal in the Foresight Scenario to outperform the 2020 target. The two values determine a range of 2030 targets for which it is neither necessary nor sufficient to comply with the 2020 target to guarantee the ability to meet the 2030 target.

Within this range, the Myopic Scenario and the Foresight Scenario have identical average emissions over the vehicles sales. However, the composition of the

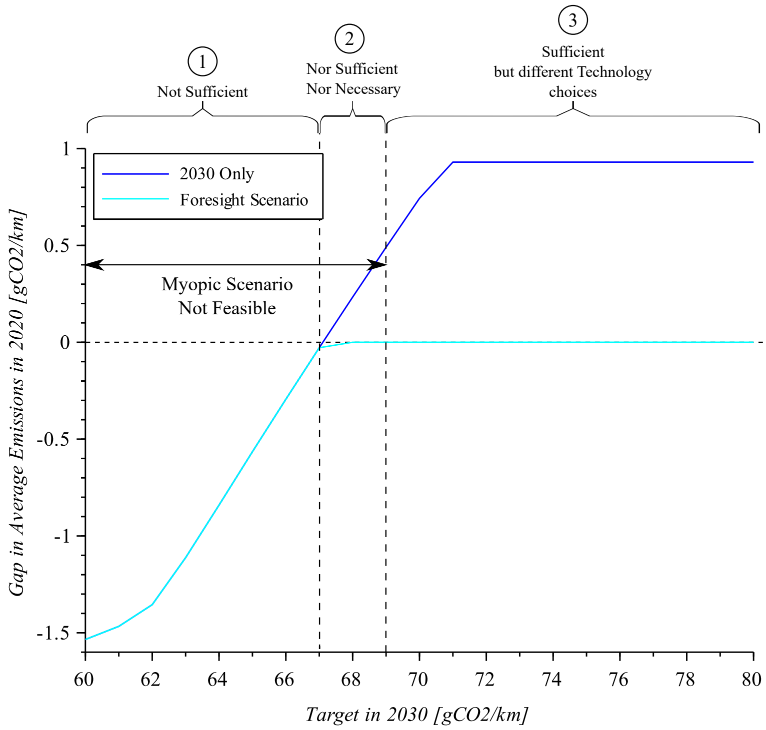


FIGURE 3.2 – CO_2 emissions gap in 2020 between the 2020 CAFE Target of 95 gCO_2/km and two Scenarios - the 2030 Only Scenario and the Foresight Scenario - as a function of the 2030 target. A positive gap means that emissions in the scenario considered are higher in 2020 than the CAFE Target, a negative gap means that the scenario over-complies with the target in 2020.

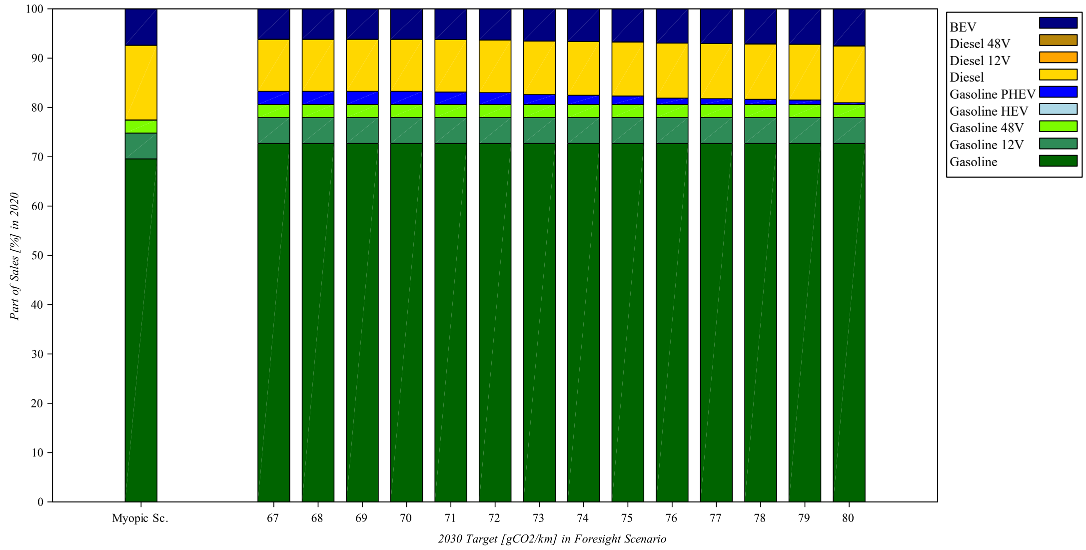
sales is different in terms of technology shares. For long-term targets above the feasibility threshold for the Myopic Scenario, technologies shares remain different from the Foresight Scenario. Figures 3.3 and 3.4 detail this point by comparing the technologies shares in 2020 and in 2030 between the Myopic Scenario and the Foresight Scenario.

We can define the 2030 compliance conditions from the comparison between the short-term average emissions and the 2020 target. The 2020 emissions target level is said sufficient when a short-term target compliance enables a latter target compliance. It is not sufficient when a short-term target is not enough to comply with a long-term target. And, it is not necessary when the compliance of the long-term can be achieved without a short-term target, the emissions level may be higher than the target in the short-term.

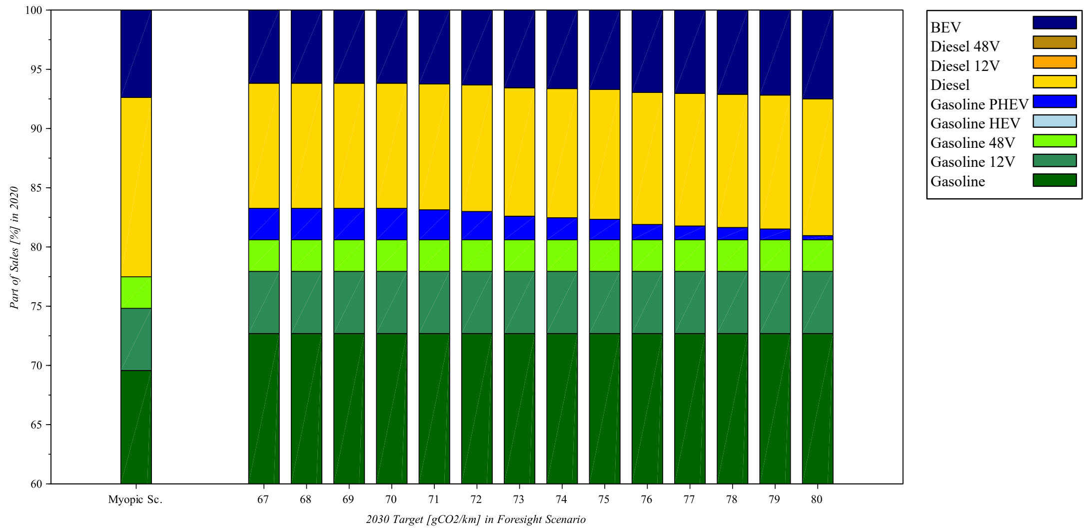
- Not Sufficient Region: To comply with a 2030 target, the average emissions in 2020 needs to be below the 2020 target. The Myopic Scenario is not feasible in this region. It is Region 1 in Fig. 3.2.
- Nor Necessary nor Sufficient Region: To comply with a 2030 target, the average emissions in 2020 may be at the 2020 target but the optimal compliance in 2030 is obtained with an average emissions higher than the target in 2020. The Myopic Scenario is not yet feasible in this region. It is Region 2 in Fig.3.2
- Sufficient but Different Choices Region: The same conditions as in Nor Necessary nor Sufficient Region but the Myopic Scenario is feasible. However the technology choices between Myopic and Foresight Scenarios are different.

To further analyze the dynamics at play, we compare the technology choices in the Myopic Scenarios and in the Foresight Scenarios. In Figure 3.3 the share of technology in new vehicles sales in 2020 is compared between the Myopic Scenario and different Foresight Scenarios ranging from a 68 to 80 gCO_2/km CAFE target in 2030. There is only one single case for the Myopic Scenario in 2020 since the first period from 2014 to 2020 is independent from the 2030 target by construction. In contrast, the Foresight Scenario where the 2030 target has impact on the 2020 technology choices produces a different 2020 technology mix for each 2030 target.

The main difference between the Myopic and Foresight Scenario technology mixes is the absence of Gasoline PHEV in the Myopic Scenario. This technology can achieve high reduction of CO_2 emissions when fully deployed, thus the absence of Gasoline PHEV removes the option of reducing emissions with this technology in the longer term in the Myopic Scenario. Furthermore, in Foresight scenarios when the 2030 target becomes less stringent, the share of PHEV in the 2020 technology mixes decreases while the share of Gasoline increases. The share of Diesel is slightly higher in the Myopic Scenario than in all the Foresight Scenarios. Since the Myopic Scenario minimizes technology costs in a sequential manner, the 2020 technology



(A) Mix in 2020



(B) Zoom in Mix 2020

FIGURE 3.3 – Technology mix in 2020 of Foresight Scenario for different 2030 targets and Myopic Scenario for a common 95 gCO_2/km target in 2020. Myopic Scenario only sees the 2020 target up to 2020.

mix of the Myopic Scenario is the optimal mix in 2020. Therefore, the introduction of Gasoline PHEV is not optimal for a 2020 CAFE compliance but it is present in 2020 in the optimal pathway to comply with both 2020 and 2030 targets.

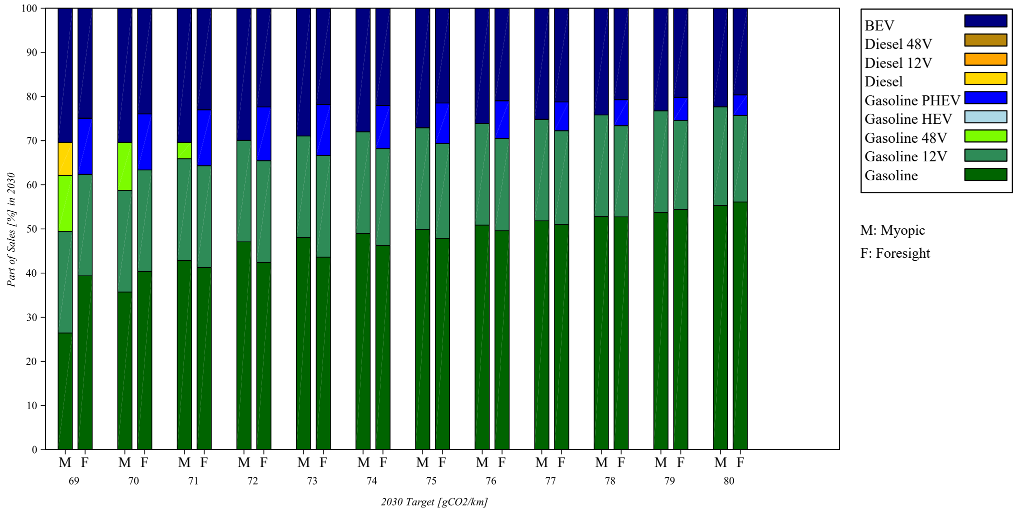


FIGURE 3.4 – Technology mix in 2030 of Myopic Scenario (left) and Foresight Scenario (right) for each 2030 target from 69 to 74 gCO_2/km.

The technology mix of new vehicle sales in 2030 of the Myopic and Foresight Scenarios in Fig. 3.4 indicates how each Scenario makes different technology choices to achieve each of the 2030 emission objectives. There are two main difference. First, Myopic Scenarios, on the left of each 2030 target, do not deploy any Gasoline PHEV which is consistent with the technology choices made for the 2020 technology mix. Second, the Myopic Scenario searches the highest abatement technology: BEV to compensate the lack of Gasoline PHEV, thus the share of BEV is higher in Myopic Scenarios for stringent CAFE targets. In Foresight scenarios, the response to a 2030 target uses a mixture of Gasoline PHEV and BEV, and only adapts the sales share of low carbon technologies to the stringency of the 2030 target. In contrast the Myopic Scenario produces a technology mix with a high dependence on BEV that requires an additional abatement technology: Gasoline 48V to comply with more stringent targets in 2030. When the 2030 target is not stringent, Foresight and Myopic Scenarios produce an identical technology mix in 2030, as seen on the right of Fig.3.3.

The technology choices made have locked out a potential low carbon technology such as Gasoline PHEV and have locked-in Diesel that produces little abatement only. These 2030 technology choices are the consequence of the 2020 technology mix where the Myopic Scenario has to choose from fewer low carbon technologies and thus pushes BEV to the diffusion limit. When this diffusion limit is reached, Myopic Scenario resort to other technologies such as Gasoline 48V. Gasoline 48V plays a role of an intermediate technology that is used to comply with a short-term target but then is abandoned in favor of technologies with higher abatement in the longer term in the Foresight Scenario.

Next, we compare the total discounted vehicle production cost in Scenarios Myopic and Foresight. We show the relative difference in costs between Myopic and Foresight to the 2030 only Scenario as a function of the 2030 target in Fig.3.5. The 2030 only Scenario is the optimal pathway to comply with a 2030 CAFE target. Thus all gaps are positive which is consistent with the construction of the 2030 only Scenario that has less policy constraints. Foresight Scenario has a better anticipation of the 2030 target than Myopic Scenario by construction thus the relative difference in cost with 2030 only Scenario is higher in the Myopic Scenario. However we find that the cost difference between Myopic and Foresight Scenarios remains small in all cases.

We show that the Foresight Scenario is more expensive than the 2030 only Scenario for less stringent 2030 targets and this gap increases. The pivot point is the change between Region 1 and Region 2 defined in Fig. 3.2. For CAFE targets in Region 1, the Foresight Scenario needs to have an emission level lower than the 2020 target in order to comply with the 2030 target. In Region 1 technology choices between Foresight and 2030 only Scenarios are identical because the near term CAFE constraint is not binding. In Region 2, the 2030 only Scenario has a higher emission level in 2020 than the target in 2020. Thus the 2030 Only scenario is free to choose less expensive solutions for year 2020 which results in a less expensive solution overall.

The Myopic Scenario is not feasible for 2030 targets less than 69 gCO_2/km. However, the Myopic Scenario is the least expensive scenario until 2020 by construction. After 2020, the Myopic Scenario has to re-adapt the technology mix for 2030. This second step in the Myopic Scenario is costly for stringent targets in 2030. For less stringent 2030 CAFE target we should expect Myopic and Foresight Scenarios having the same cost, this is not case because the first step of the Myopic Scenario does not anticipate the 2020-2030 thus choices are only optimal until 2020. In Supplementary Material we show that the variant of the Myopic Scenario which anticipates the 2020-2030 period with a constant target at the 2020 level, has the same cost than Foresight scenario for low stringency 2030 targets.

We have studied the case of a single 2020 target, because the near-term target is less uncertain. We have explored a range of 2030 targets, which are more uncertain. In the last part of this results section, we conduct a sensitivity analysis of the results to the level of the 2020 target. Fig.3.6 shows the three Regions defined above and the explored area of the 2020 and 2030 targets.

Due to the diffusion constraint on low carbon technologies, the abatement potential in the near-term and longer term is limited. We explore the maximal abatement that could be obtained with the current diffusion speed settings. First, from left to right, 2020 targets that are lower than 86 gCO_2/km are not feasible because the near-term target is too stringent. Second, from bottom to top, 2030 targets lower than 53 gCO_2/km are not feasible because they are too stringent.

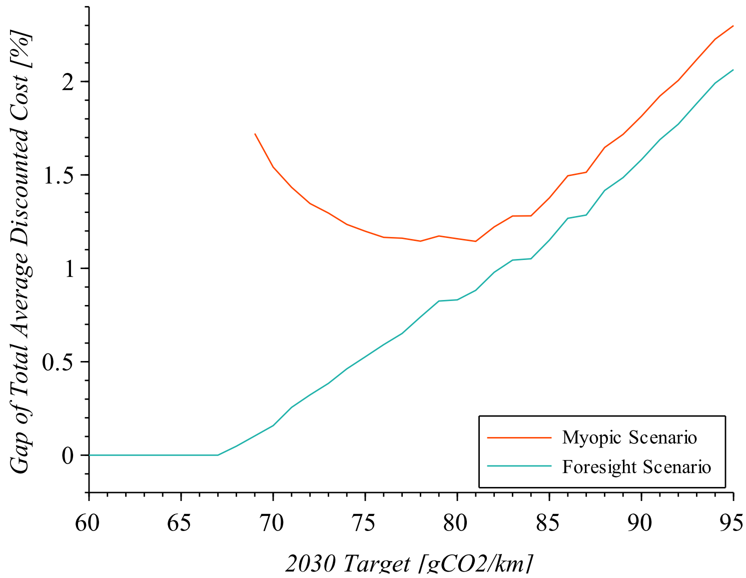


FIGURE 3.5 – Gap of Total Discounted Cost of technologies between Scenarios Myopic and Foresight to Scenario 2030 Only. The gap is the relative difference of cost of Myopic and Foresight Scenarios to 2030 only Scenario for a range of 2030 CAFE targets.

Targets that are higher than 96 gCO_2/km in 2020 are not interesting and are not explored because they would imply that the target is less stringent than average initial in 2014 emission level of 96 gCO_2/km. We also left aside, a 2030 target that is less stringent than the 2020 ambition thus the line on top of compliance box represents cases where the near-term and long-term targets are equal.

Region 1 is the "‘not sufficient"’ region, region 2 the "‘nor sufficient nor necessary"’ and region 3 the "‘sufficient but different choices"’ region. Regions 1 & 2 are the regions where Myopic scenarios are unfeasible. The Foresight Scenario is feasible for all cases inside the delimited zone in Fig. 3.6. However Regions 2 & 3 are the regions where the Foresight Scenario is feasible and does not need to have a lower emission level in 2020 than the target. Region 1 requires a more stringent intermediate point in 2020 than the target for the Foresight Scenario. We show that when the 2020 target is stringent all 2030 targets are feasible for Myopic Scenario. As the 2020 target becomes less stringent, some stringent targets in 2030 are not feasible for the Myopic Scenario: there is an increase in the size of the combination of Regions 1 and 2. When the 2020 Target is not stringent on the right of the box, the Myopic Scenario is unable to comply with almost half of the 2030 targets.

B shows the results of the variant of the Myopic Scenario for the 2020 and 2030 technology mixes. When taking into account the 2020-2030 period in a the first optimization step of the Myopic Scenario the 2020 technology mix converges with a Foresight Scenario with a low stringent target in 2030.

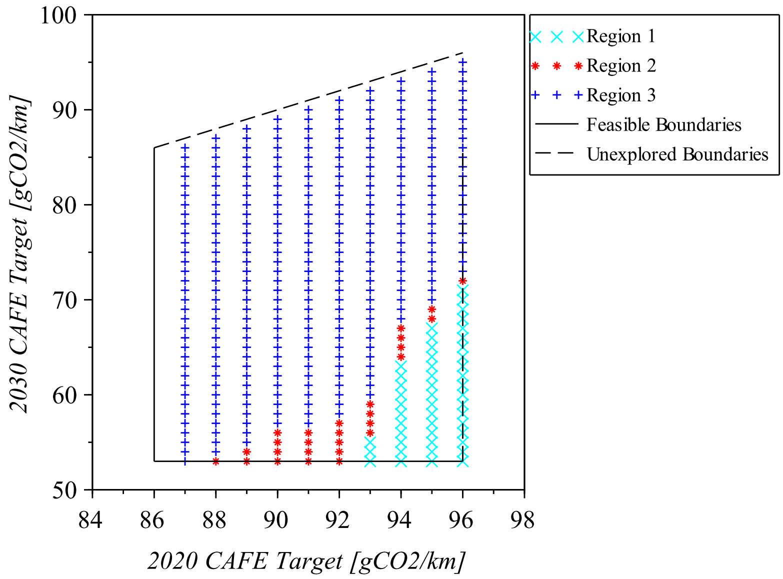


FIGURE 3.6 – Change in the conditions of compliance of the 2030 target for a range of 2020 and 2030 targets. The three regions identified are described above in Fig. 3.2 which describes in detail the case for 95 gCO_2/km target.

3.4 Discussion and Conclusion

We showed how consecutive CAFE targets affect technology choices with two different types of anticipation. A limited foresight means that a firm optimizes technology choices for the closest target and then repeats the same process for the next target. On the contrary, a perfect foresight corresponds to a firm optimizing technology choices knowing and considering all upcoming targets.

We illustrated how near-term target compliance influences long-term targets attainment. We identified three regions, depending on the stringency of the long-term target, where a myopic strategy focusing on the 2020 CAFE target can be: not sufficient, nor sufficient nor necessary or sufficient but leading technology choices are different. When meeting the 2020 target is "'not sufficient"' or "'nor sufficient nor necessary"', Myopic scenario is unable to comply with a 2030 target. For less stringent 2030 targets, the Myopic scenario is able to meet the long-term target, but technology choices remain different to the optimal choices with foresight. The lack of anticipation creates technology choice lock-ins that are optimal for a near-term compliance but not adapted for stringent long-term targets.

Preparing an intermediate target might develop technologies that are not suitable for a long-term abatement trajectory. Thus, there is a risk of not complying with long-term targets because a near-term technology mix might not be well prepared or not adapted for ambitious reductions in the long-term despite complying the near-term target. The results are illustrative, they show the effect of the consecutive CAFE targets instead of a complete assessment on how to comply with the upcoming targets. Some of the limitations are that we consider only a limited set of technologies and a single vehicle segment, that we do not account for learning-by-doing mechanisms and that representation of the CAFE policy instrument is simplified and neglects mass-indexation of targets for instance. Therefore, our contribution remains of an illustrative nature and cannot provide precise quantitative elements for policy design or firm strategy to comply with policy.

Furthermore, we have only considered a horizon limited to 2030, although the mitigation objective are in fact going further in time with net zero objectives along the 21^{st} century. Considering even longer-term targets may change the picture. In particular a strategy that develops early very low emissions technologies or zero emissions technologies may in fact be in better place to be compatible with the net zero emissions target. However, at this time horizon, it would be necessary to consider mechanisms of learning-by-doing, as well as types of technologies that are essentially not yet deployed, such as fuel cell technologies.

Notwithstanding these limitations, our results have implications for both policy makers and car manufacturers. The potential risks of a myopic strategy highlighted in this article, call for regulators to announce targets as early as possible, with credibility and stability. When policymakers prepare long-term policies there is a need to give more tangible objectives to firms on the near-term. A near-term point of passage can effectively steer change in firms but it can mislead to think the mix of technologies developed for the near-term plan is compatible with very low carbon reductions. There are two challenges on the near-term objective: first the stringency of the target needs to be compatible with the long-term ambition and second the share of low carbon technologies needs to be monitored to allow deeper reductions for a more stringent long-term target. Beyond the illustrative case on CAFE standards developped in the article, our results indicate that monitoring only the aggregate emissions results along a low-carbon transition pathway might not be sufficient to indicate whether the trends are adequate to reach long-term targets. Indicators to track the structural change and technology change at finer levels are also necessary.

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Chapter 4

Technology choices under a mass-indexed CO_2 emission standard

4.1 Introduction

The passenger vehicle market is composed of different segments that vary in aspects such as price, performance, comfort, occupancy capacity, utility, size and mass. A key question for carmakers and regulators alike is how to distribute emission reductions across segments? In the first version of the CAFE standard, the fuel economy target was the same for all passenger vehicles, but less stringent for light-trucks and Sport Utility Vehicles (SUV). In order to equally distribute the emission reduction efforts across all vehicle segments, a vehicle characteristic was introduced to differentiate the different segments.

At the time of creation of the standard, the choice of the index parameter [1] was a matter of debate. Two parameters seemed suitable to capture the differences between segments: mass and footprint: the wheelbase x the track width. In both cases, the purpose is to distribute fuel economy efforts by allowing heavier or larger vehicles to have a less stringent fuel economy limit and increasing the stringency for smaller or lighter vehicles. The USA chose footprint to "facilitate the use of promising lightweight materials for current and future policy targets to enhance both vehicle safety and fuel economy" (National Highway Traffic Safety Administration, 2006). In Europe, where the standard was created later, an assessment on the nature of the index concluded that both mass and footprint are suitable for the CO_2 regulation but finally mass was chosen (Commision of the European Communities, 2007). In 2009 the first mandatory standard was introduced. It was applied to vehicle's emissions measured in gCO_2/km and was mass-indexed meaning that size was not a direct parameter (European Parliament and European Council, 2009).

1. The index parameter is often called utility parameter in legislation but it is not to be confused with economic utility. To avoid any confusion we will use the term index parameter.

This work treats the impact of the mechanism of technology choice for optimal compliance with a mass-indexed CAFE standard for a car manufacturer and the implications for society. We investigate how mass evolution of the technology mix determines the stringency of future targets. For a 2030 target compliance we quantify how much does the mix change when we consider a mass index coefficient. This lead us to our main research question: how does the technology mix with a mass indexed fuel economy standard change and what are the implications for society? In order to answer this question, we compare different mechanisms of modeling a CO_2 emissions regulation with and without mass indexation in a car manufacturer technology model that finds the least cost compliance conditions. The model explores the dynamics of technology diffusion and focuses on the minimal cost solution of technology choices. We complete the study with an insight of the cost benefit of the mass-indexed CAFE for society with the implications on the usage of the vehicle: mobility cost, road safety, air pollutants and energy demand.

The policy analysis in this Chapter relates with other studies that have taken a closer look at the CAFE standard in the US (Shiau, Michalek, and Hendrickson, 2009; Whitefoot and Skerlos, 2012; Whitefoot, Fowlie, and Skerlos, 2017; Klier and Linn, 2012; Klier and Linn, 2016). We focus on the European region where the fuel economy standard is mass indexed and has risen concern on potential drawbacks that were already identified by policymakers: "this system (utility based standard) which reflects better the diversity of cars and car makers, would provide more realistic targets for individual manufacturers, but could be the source of perverse incentives (e.g. if car makers chose to increase utility instead of decreasing CO_2)" (Commision of the European Communities, 2007). We contribute to the literature that has studied the market evidence of the fuel economy standard impact on vehicle's features (Martin et al., 2015; Luk, Saville, and Maclean, 2016; Fontaras and Samaras, 2010) and why the CAFE is not a technology neutral standard (Ito and Sallee, 2017; Fox, Axsen, and Jaccard, 2017).

Our contribution shows the implications of the mass indexed policy, we quantify the difference in the optimal portfolio of technologies of the bias induced by mass indexation. We highlight these differences by focusing on technology choices and the resulting vehicle characteristics of the optimal compliance for two scenarios whit and without mass indexation. We investigate the consequences of this bias in terms of technology and usage costs to assess the economic benefits or impacts of mass indexation.

Our approach centered on OEM low carbon technology choices under a fuel economy standard is novel because we focus on the implication of the policy at the manufacturer level. We use an ex-ante dynamic approach of technology choices. In addition, we have included lightweight technology options to identify which scenarios pick these technologies for CAFE compliance. We model different mechanisms of compliance of a fuel economy standard indexed to mass with an endogenous and exogenous evolution of mass and compare them with a fuel economy standard without a mass index.

The mechanism to comply with a fuel economy standard indexed to mass excludes technologies that make vehicles lighter consequently this type of policy is not technology neutral: there is a preference for heavier technologies for the same abatement cost. Our results show that the index factor of the fuel economy standard is key to determine the mass impact on the technology choice, a low index factor of the fuel economy standard reduces the regulation bias. We introduce a lightweight cost curve to explore different technology options of mass reduction. We identify the mass reduction potential that delivers optimal cost for a given abatement goal. We can see as expected that when the fuel economy standard is indexed to mass, the optimal output does not pick lightweight technologies and thus limits the technology choices to reduce emissions.

When considering the production cost and the cost of usage of a vehicle we obtain a non significant difference between a scenario preparing a technology mix for a CAFE target with mass indexation and scenario aiming at the same emission target without mass indexation. This is counter-intuitive since one should expect that a heavier vehicle mix, preferred by a CAFE with mass index, will consume more fuel thus having a higher cost of usage. However, BEV play an important role in countering this effect, they are heavy, expensive to produce but cheap to use. There is a significant difference in cost of usage of BEVs compared to all other technologies, they are the least costly technology in usage. In addition, not developing lightweight technologies in a mass indexed policy compensates the difference in cost with the scenario that does but has lower BEV sales share.

The remainder of the Chapter is organized as follows. Section 4.2 describes the data and methodology used for analyzing the fuel economy standard impact on technology choice. Section 4.3 compares and shows the impact of the fuel economy standard constraint on a full vehicle segment and a broader technology availability of options with lightweighting for the same vehicle segment. Section 4.4 discusses the implications of the results for fuel economy standard policy and concludes the chapter.

4.2 Modeling the Mechanism of the CO_2 Regulation in Europe

4.2.1 Indexing a Fuel Economy Standard

The main goal of fuel economy standard is to regulate the environmental performance of supply of new vehicles at the OEM level. The policy is applied to the average environmental performance of all vehicles sold in a year. Vehicle metrics can be measured in fuel economy (distance traveled with an amount of fuel), fuel consumption (amount of fuel to travel a given distance) or CO_2 emissions to drive a given distance [2]. The OEM fuel economy mean of vehicles is compared with a country or region compliance target. Fuel economy standards are mandatory and imply fines for those OEMs that do not comply with the target. In Chapter 1 in Table 4.1 we present the fuel economy standard variations in the main vehicle markets. We can see that the differences come from the index parameter: mass or footprint. On the stringency and year of compliance of the target: given that the latest fuel economy standards are currently been defined by policymakers we refer to the International Council of Clean Transportation (ICCT) publications for the latest targets and discussion (Yang and Bandivadekar, 2017).

The test cycle used to test vehicles under the same conditions is different from one region to the other which is partially explained by the different driving conditions of each country or the unherited market regulations from the main market supplier. Although test cycles do not represent real driving conditions [3] they allow a comparison between low carbon vehicle technologies. Further differences between CAFE standards in two major markets: EU and USA have been studied in German and Lutsey, 2010. Mass-indexed CAFE is wide-spread, we focus on the European fuel economy standard but the policy analysis in this chapter is relevant for other markets.

The Fuel Economy Standard in Europe works as a mandatory upper limit of Corporate Average CO_2 emissions that are calculated as the arithmetic mean of the emissions level of all new vehicles sold in a given year eq.4.2. The target is set in a 5 year step fashion, lowering the emissions target at each step. OEMs that fail to comply are subject to economic fines. There is a target that applies to passenger vehicles and a different target for commercial vehicles that is not treated in this Chapter. The fuel economy in Europe is measured in the equivalent gCO_2/km emissions from a vehicle under the NEDC test that simulates an specific driving behavior. In 2017, the World harmonized Light duty Vehicle Test Procedure (WLTP) has been adopted to better capture real driving conditions (Fontaras, Ciuffo, et al., 2017).

The policy introduces three flexibilities to comply with the final target. First, the target is introduced progressively in a phase-in mechanism where only a part of an OEM sales must comply with the target. Second, supercredits on zero emission vehicles are introduced to promote the deployment of AFVs and to help OEM to meet the target (European Parliament and European Council, 2009). Third, vehicles equipped with eco innovation or off-cycle technologies that allow energy savings but are not captured by the New European Driving Cycle (NEDC) test (Fontaras, Zacharof, and Ciuffo, 2017) benefit of an emissions reduction to comply with CAFE.

2. Brazil uses a different unit: MJ/km to account for differences in energy content in fuels: ethanol vs petrol and is expressed as energy efficiency.

3. For a discussion on the differences between in use driving emissions and type-approval test cycle emissions see Fontaras, Ciuffo, et al., 2017; Fontaras, Zacharof, and Ciuffo, 2017; Tsokolis et al., 2016

TABLE 4.1 – Fuel Economy Standards for Passenger Vehicles main vehicle markets. *JC08: Japanese test Cycle. Source: ICCT,2017

Country or Region	Index Parameter	Unadjusted Target	Target Year	Test Cycle
Brazil	Mass	1.82 MJ/km	2017	U.S. Combined
Canada	Footprint	217 gCO_2/km	2016	U.S. Combined
China	Mass	5 L/100km	2020	NEDC
EU	Mass	95 gCO_2/km	2021	NEDC to WLTP
India	Mass	113 gCO_2/km	2022	NEDC
Japan	Mass	20.3 km/L	2020	JC08* to WLTP
Mexico	Footprint	39.3 mpg or 140 gCO_2/km	2016	U.S. Combined
Saudi Arabia	Footprint	17km/L	2020	U.S. Combined
South Korea	Mass	24km/L or 97 gCO_2/km	2020	U.S. Combined
U.S.	Footprint	55.2 mpg or 146 gCO_2/mi	2015	U.S. Combined

The EU fixes one target but, in practice the abatement efforts are distributed according to the gap between the corporate average and the compliance line as seen in Fig.4.1. The logic behind is that carmakers with a low average vehicle mass considered as *light* have low emissions and thus will have a lower target, as opposed to carmakers with a high average vehicle mass considered as *heavy* that have high emissions and a higher target.

The mass-index standard is a continuous linear function of the homologated vehicle mass and the allowed gCO_2/km emissions for a manufacturer as explained below eq.4.1.

$$CAFE_i = TARGET_i + a\left(M_{corporate} - M_0\right) \tag{4.1}$$

where $TARGET_i$ is the enacted European target in $gCO_2/km$for year i
$a = 0.0457 \quad gCO_2/km/kg$ in 2015 and 0.0333 from 2020 is the mass index coefficient
$M_{corporate}$ is the average mass in kg of corporate sales for year i $M_{corporate} = \frac{\sum_{j=1}^{n} X_{ij} M_{ij}}{SALES_i}$
M_0 is the estimated average mass in kg of all new vehicles by the regulator M_{ij} is the mass of technology [4] j for year i in kg. X_{ij} is the unit sales of vehicle with technology j for year i and n is the total number of vehicle technology options. The arithmetic mean of CO_2 emissions of a car manufacturer is obtained below.

$$\forall \quad year \quad i \quad CAFE_i = \frac{\sum_{j=1}^{n} X_{ij} E_{ij}}{SALES_i} \tag{4.2}$$

where E_{ij} is the emission level for technology j at year i in gCO_2/km
$SALES_i$ is the Vehicle Sales of the manufacturer at year i

Equation 4.1 is the full expression of the fuel economy standard, the average

4. We use *technology* to describe a complete vehicle product that includes all the required technologies to satisfy customer need in a given segment. Therefore, it is different from the definition of a *single technology* application e.g. automated transmission. The mass of a *technology* is defined as the mass of a vehicle equipped with that technology.

mass of the manufacturer and the a slope parameter define the stringency of the specific target. The slope of the linear regression of the weighted sales for curb weight and emissions as seen in Fig. 4.1 is slightly higher than the index factor of the regulation, $a_{fitted} = 0.8 \quad a_{policy}$ in 2015. To promote lighter cars, the regulator uses a smaller slope (Commision of the European Communities, 2007) this pushes heavier manufacturers to do more efforts to comply with the policy.

In order to understand how the mass-indexed compliance works, the first step is to define OEM's target. An OEM that produces lighter than the average mass vehicles (determined by M_0) will have a more stringent target than an OEM that is heavier than average. In Fig. 4.1 the positioning of several OEM in Europe is compared with the 2015 and 2020 compliance target lines. More on the trends of size and mass evolution can be found in Cuenot, 2017. The fuel economy standard has a more stringent target in 2020, the slope of the line will be reduced and the average mass has been slightly corrected in 2016. The progression of the main OEMs from 2011 shows three behaviors: OEMs that reduce emissions and increase mass: Ford, OEMs that reduce emissions and mass: Peugeot and GM and OEMS that reduce emissions and keep mass constant: Renault, Volkswagen, BMW [5]. In Fig. 4.2 we detail these different approaches of compliance. We can see that from a given initial condition the strategy that requires the minimum emission reduction efforts is to increase vehicle mass and decreasing vehicle emissions for a less stringent target.

In summary, in order to reduce emissions of an OEM, there are three mechanisms that can be combined or not when choosing the strategy to comply with a fuel economy standard as is described in Kollamthodi et al. (2015) and German and Lutsey (2010). For example a powertrain that emits less CO_2 and has an equivalent mass than the traditional technology allows a vehicle to move down the y-axis in Fig. 4.2. A new vehicle that includes a crossover appearance is heavier and allows a vehicle to move right the x-axis. Some technologies can have a combined effect like HEV vehicles (clean + heavy) or a low weight chassis with downsized engine (clean + light). In the upcoming section we will detail the impact on technology choice of a mass attribute.

4.2.2 From the simplified constraint to an emission and mass constraint

Without any complexity on the Fuel Economy standard, the first model of a fuel economy standard that is intuitive is a limit on the emissions goal only. This approach is straight forward, the fuel economy standard can be converted to an upper limit on the average emissions of the manufacturer eq.4.3. This simplification allows to focus only on the potential of abatement technologies and does not consider any

5. Fiat shows an increase of mass and emissions, this is not due to technology choices, it is caused by the acquisition of the heavier and more emitting firm Chrysler.

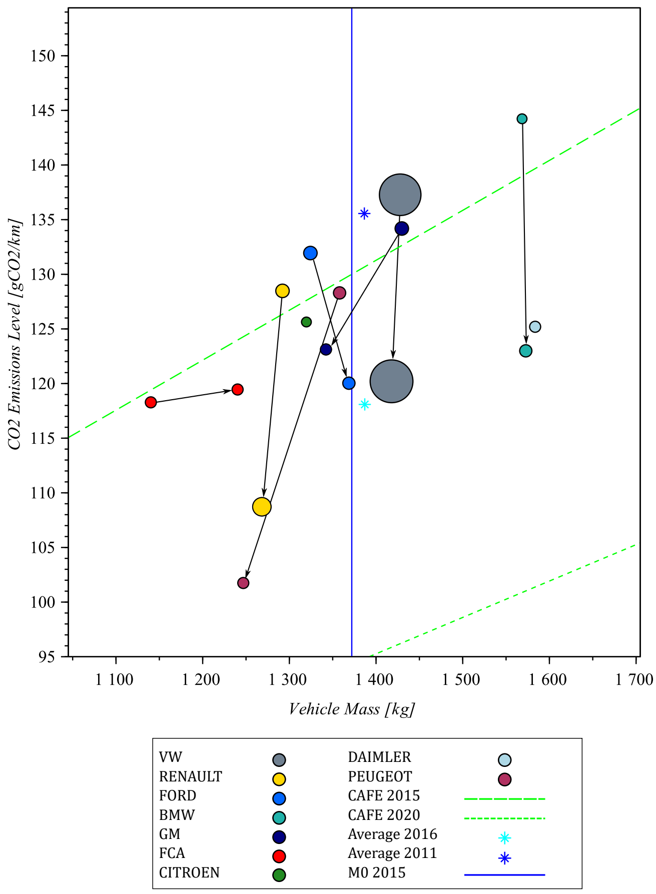

FIGURE 4.1 – Sales-weighted fuel economy of main OEMs in Europe indexed to the average mass in 2011 and 2016 and fuel economy standard compliance lines in 2015 and 2020. Source: ICCT, 2017.

difference between OEMs.

$$\forall \quad year \quad i \quad CAFE_i = \frac{\sum_{j=1}^{n} X_{ij} E_{ij}}{SALES_i} \leq TARGET_i \tag{4.3}$$

where $TARGET_i$ is the enacted European target.

In order to show the differences in the optimal choice of technologies whether the CAFE constraint takes the mass into account or not, we modify eq.4.3 to account for the CAFE policy with a mass index parameter. The objective is to show how the optimal conditions change and how does the mass impacts the final result,

$$\frac{\sum_{j=1}^{n} x_j (E_j - a M_j)}{SALES} \leq TARGET - a M_0 \tag{4.4}$$

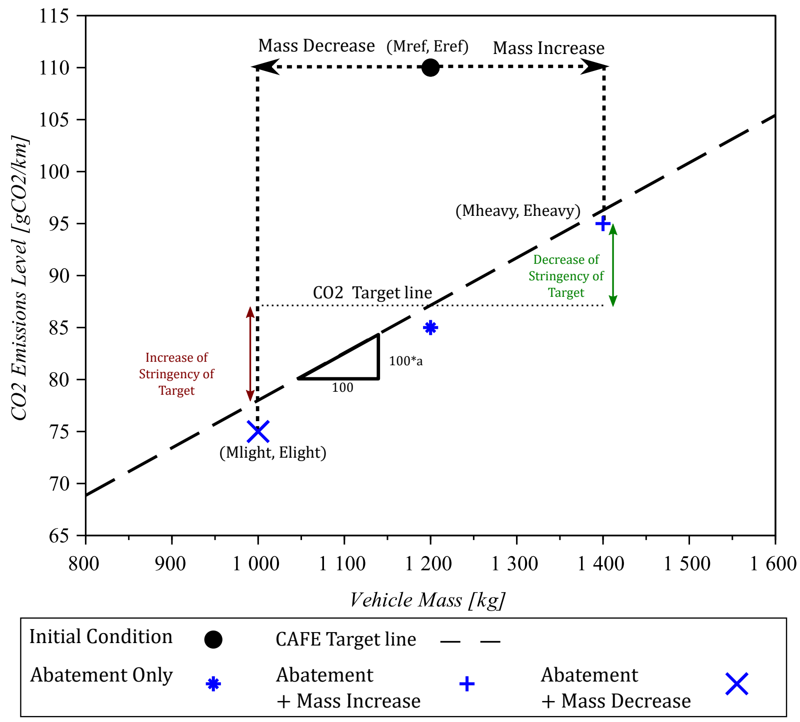

FIGURE 4.2 – Detail on the technology options for abatement: from an initial condition the different options to comply. Every technology that is placed below a given target line is compliant. Source: The Author.

where M_j is the vehicle mass in kg with technology j, a is the index factor in $gCO_2/km/kg$ and M_0 the reference mass of the standard in kg.

If we compare all technology options to a baseline, we obtain an Abatement ratio in eq.4.5 that is used to rank potential solutions according to their abatement costs and potential emission reduction. This ratio is a comparative measure of the abatement cost to identify technologies that are less costly in terms of CO_2 emissions. A low ratio means that the technology is either cheaper, less emitting or both.

$$Abatement \quad Ratio_i = \frac{C_{baseline} - C_{abat_i}}{E_{abat_i} - E_{baseline}} \tag{4.5}$$

where E_{abat_i} defines the emission of technology i and Baseline defines the reference technology. The abatement of technology i is the difference in the numerator of eq. 4.5.

The optimal choice in the case of a mass-indexed CAFE changes from an optimal abatement cost (cost/emission) to a modified optimal cost by the mass (cost/(emission-mass)). The best option now depends on cost and technology attributes: mass and emissions and a regulatory parameter a. If we compare all technologies with a reference we can obtain the CAFE ratio that is used in the same way than the Abatement ratio. The aim is to rank abatement technologies according to their abatement costs under a mass indexed fuel economy standard defined in eq.4.6.

$$CAFE \quad Ratio_i = \frac{C_{baseline} - C_{abat_i}}{E_{abat_i} - E_{baseline} + a(M_{baseline} - M_{abat_i})} \tag{4.6}$$

Appendix C develops the mathematical difference of a fuel economy standard with and without mass indexation in optimal conditions. This difference results in the different rankings presented in Table 4.2 and obtained with the Abatement and CAFE ratio in eqs. 4.5 and 4.6.

4.2.3 Modeling the mass-indexed CO_2 emission regulation in the OMLCAT framework

The technology choices that a car manufacturer makes to prepare a CAFE target depend on the state of the technology mix on the previous years. Therefore a dynamic approach of this policy compliance is needed to consider how the technology mix evolves in time whereas other assessments of cost curves use a static approach (Hill et al., 2016; Krause, Donati, and Thiel, 2017; FEV, 2015; Singh, 2012).

In the remaining of this chapter we will use a version of Optimization Model of Low Carbon Automotive Technologies (OMLCAT). This model is basically a supply model of the powertrain technologies that a manufacturer can develop in a market constrained by public policies and diffusion of technology limits on technology growth. The focus of the model is on powertrain technologies because they have the largest abatement potential. It is based on data of the emission level, the cost and mass of the main powertrain solutions that are available in the market from advanced ICE engines to EVs.

The model does not represent endogenous technological improvements nor cost reductions. Every technology diffusion is limited by an endogenous diffusion function in the shape of sigmoid curve that was constructed using historical evidence on automotive technologies diffusion in the European and North American markets and is calibrated initially to 2014 conditions and sales shares from data found in International Council of Clean Transportation (ICCT) (ICCT, 2015) and Environmental Protection Agency (EPA) (EPA, 2016) technology diffusion reports. Every year the diffusion constraint sets the limit of growth for a given technology for that year according to the sales share of the past year of that technology. The constraint then covers all the entire time spam except for the initial year and applies to all technologies. The diffusion profiles of every technology in the model can be calibrated to the closest historical parent of the same technology family. In this application of the model all diffusion profiles are calibrated to a lower diffusion profile: LOW, defined in Chapter 2, meaning that a technology has high inertia so that it diffuses slowly. The complete description of the model can be found in Chapter 2.

The optimization algorithm of the model is summarized in the following governing equations: the objective function and the constraints of the model are described below.

$$min \quad \sum_{i=1}^{m} \frac{1}{(1+r)^{(i-1)}} \sum_{j=1}^{n} X_{ij} * C_{ij}$$

$$s.t. \; \forall \; year \quad i > i_0 \sum_{j=1}^{n} x_j = SALES \tag{4.7}$$

$$s.t. \forall year \quad i > i_0 \quad and \quad \forall technology \quad j : SS_{ij} - SS_{i-1j} \leq Diffusion\ limit(SS_{i-1,j-1}) \tag{4.8}$$

where r is the discount rate equal to 4%, SS is the sales share of a technology.

The policy package of the model includes a fuel economy standard constraint as seen in eqs.4.2 and 4.4. The Volume of sales for a manufacturer is defined exogenously which is held constant through out the simulation in eq. 4.7. The optimization algorithm is a minimization of discounted costs of compliance with the CAFE objective under constraints. In this Chapter, the focus is on the fuel economy standard brick and the related technology attributes: Cost, Emissions and Mass. For more details about the Model of Optimization of Cost of Low Carbon Technologies refer to Chapter 2.

We use the OMLCAT for a lower medium vehicle segment. The following section presents the data on this vehicle segment in Europe to study the impact of the diffusion constraint in the optimization of powertrain technologies.

4.2.4 Technology Assumptions: Focus on Lightweight Technologies

The application of the OMLCAT considers a realistic case of choice of technologies: a medium vehicle segment with powertrain options to comply with the fuel economy standard. First we define a representative medium car segment in Europe in Table 4.2 and second we include light-weighting options. We do not include the 5 year step-wise condition of the fuel economy standard in Europe, which increases complexity, refer to Chapter 3 for the study of intermediate targets. Our focus is the mass index impact on the choice of technologies so we model only a single CAFE target in 2030, since the final target is yet to be known we take a range of possible targets from 70 to 84 gCO_2/km in NEDC. This estimate of the range of possible targets should be higher than the actual target, since there is no other technology component other than powertrain to lower emissions (5-10 gCO_2/km potential depending on efforts on rolling resistance, electric energy consumption, aerodynamics and lightweight engineering).

TABLE 4.2 – Assumption of Powertrain Technologies for a lower vehicle segment and ratios for optimal choices

Technology	Emissions $\frac{gCO_2}{km}$	Powertrain Cost €	Mass kg	Sales Share %2014	Abatement c. r. $\frac{€km}{gCO_2}$	CAFE c. r. $\frac{€km}{gCO_2}$
Gasoline	105	1950	1000	45		
Gasoline 12V	98	2350	1020	3	57.14	52.18
Gasoline 48V	91	3150	1040	2	85.71	78.27
Diesel	95	2950	1070	40	100.00	81.10
Diesel 12V	89	3350	1090	3	87.50	73.70
Diesel 48V	83	4150	1110	2	100.00	85.73
Gasoline HEV	80	4650	1130	1	108.00	92.06
Gasoline PHEV	40	5950	1230	1	61.54	55.05
BEV	0	7950	1450	3	64.52	50.01

Our model does take into account all low carbon technology options as opposed to (Krause, Donati, and Thiel, 2017; Hill et al., 2016; FEV, 2015) and it does not take into account supercredits and off cycle technology credits. Therefore the actual target should be lower. Giving that the WLTP upgrade is currently on going we treat emissions measures in NEDC. Moreover, we include the Abatement choice ratio and CAFE choice ratio of an abatement only fuel economy standard and a mass indexed fuel economy standard respectively calibrated to Europe .

The assumptions on lightweight technologies are obtained in three steps. First we obtain the relationship between fuel consumption and mass reduction. Second we estimate the cost of the lightweight technology to achieve a given mass reduction. And third we combine both assumptions to obtain the cost of abatement of applying a lightweight technology. We describe below each one of these steps.

The first step aims at relating how a change in mass saves fuel consumption. There is a physical relationship between mass and energy demand that determines fuel consumption(González Palencia et al., 2015; Wilhelm et al., 2012; Palencia et al., 2017). The basic principle is that a heavy vehicle requires more energy to move which translates in an increase in fuel consumption. We approximate the physical relationship with a linear function based on data provided by experts and literature estimates (FEV, 2015; Kollamthodi et al., 2015; Singh, 2012; Krause, Donati, and Thiel, 2017). The resulting equation of Abatement in percentage and mass reduction in percentage is presented in eq. 4.9 with primary and secondary effects [6]. Our estimates include secondary mass-reduction because we include an engine tuning where we allow maximum potential of the lightweight technology with a change in the number of transmission gear ratios for medium weight reductions and a downsized engine for high weight reductions. Both adaptations move down the curve to allow more abatement reduction.

6. As defined by Kollamthodi et al., 2015 primary mass-reductions are those that are achieved by reducing the mass of vehicle's components and secondary mass-reductions are those that are achieved by redefining components specifications due to a lighter body for example suspensions specs and downsizing.

The second step is a cost assessment of the different lightweight technologies. There are many combinations of lightweight technologies to produce a mass reduction, it is difficult to select bundles of lightweight solutions to provide a mass reduction. When we name *lightweight* technology we are describing a family of solutions from light materials: high strength steel, aluminum, composite materials and carbon fiber, to redesigning architecture. The cost estimates were based on the curve of cost from expert estimate of Renault to obtain the marginal mass reduction cost and eq. 4.10 is the fitted curve of these estimates that are more costly than what is found in ITF (International Transport Forum), 2017; Singh, 2012; Kollamthodi et al., 2015. We obtain the cost of mass reduction in €from a given mass reduction in kg, shown in eq. 4.10.

The third step is to combine the function of abatement potential and mass reduction in eq. 4.9 and the cost of mass reduction in eq. 4.10 to obtain the abatement cost curve of lightweight technologies in eq. 4.11. The Gasoline Light technology can have a range of mass reduction up to a technical limit of 15% , we explore all the range of possible mass reduction.

$$Emission\ Reduction = a_1 Mass\ Reduction^{c_1} + b_1 \tag{4.9}$$

Where Emission Reduction is in % of fuel economy reduction [gCO_2/km], Mass Reduction is also in % of [kg] and a_1, b_1 and c_1 are the function coefficients.

$$Cost\ of\ Mass\ Reduction = a_2 Mass\ Reduction^{c_2} + b_2 \tag{4.10}$$

Where Cost of Mass Reduction is in €, Mass Reduction is in kg and a_2, b_2 and c_2 are the function coefficients.

$$Cost\ of\ Emission\ Reduction = a_2(M_{ref}(\frac{Emission\ Reduction + b_1}{a_1})^{1/c_1})^{c_2} - b_2 \tag{4.11}$$

Where M_{ref} is the Mass of the baseline technology.

Mass reduction is applied in an incremental manner, we have explored the mass reduction range from 1% to 15%. To create a lightweight alternative from the technology assumptions, first we fix an amount of mass reduction of the reference technology: Gasoline. Second we use the cost curve to obtain both the incremental cost of lightweight technology and we use the mass reduction and the fuel economy performance curve to obtain the abatement cost of the introduction of lightweight. Third we introduce the lightweight technology option in the model as a competing technology of the Gasoline 12V: a less emitting version of standard Gasoline option but more expensive and heavy than Gasoline Light. We calibrate the same initial sales share to Gasoline Light and Gasoline 12V taking away a small share of Gasoline. Both abatement options are more expensive and less emitting than Gasoline option but Gasoline 12V increases mass and Gasoline Light decreases mass.

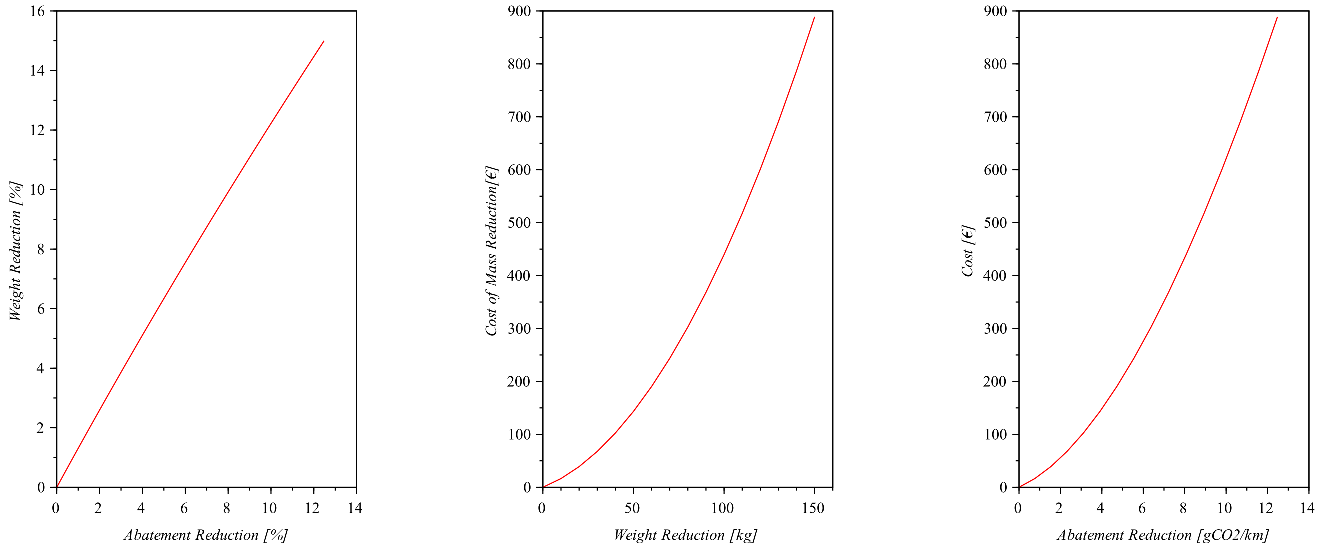

FIGURE 4.3 – From left to right, lightweight abatement potential, lightweight cost curve and lightweight abatement cost curve.

4.2.5 Scenarios

In order to isolate the effect of the CAFE constraint, we study 4 Scenarios of CAFE representation. First, *Scenario 1* is a climate change emission reduction type of constraint where the objective is to reduce carbon emissions only, this type of fuel economy standard constraint is only based on cost and emissions. It would be the only Scenario that one could simulate when data on mass is not available. Second, *Scenario 2* has the same type of constraint but it has been set to the initial position of a manufacturer in the mass axis. Third, *Scenario 3* is a CAFE Europe type of constraint where the attributes that contribute for a fuel economy standard compliance are cost, emission and mass. Fourth and final, *Scenario 4* has the same type of constraint of Scenario 1 and 2, no mass in the constraint, but instead of correcting the mass with the initial position we set the emission target at the final position to be equal to the mass-indexed emission target of *Scenario 3* at the final position. All Scenarios were tested under the same vehicle and diffusion market hypothesis and we are changing the mechanism of the fuel standard to test for change in stringency and change in the technology choices. For simplicity we can name the Scenarios as follows:

1. *Scenario 1*: Simplified CAFE constraint
   $CAFE_i \leq TARGET_i$
2. *Scenario 2*: Simplified CAFE constraint corrected target with initial average mass
   $CAFE_i \leq TARGET_i + a(M^{t=0}_{corporate} - M_0)$

3. *Scenario 3*: Mass Indexed CAFE constraint
   $CAFE_i \leq TARGET_i + a(M^{t=i}_{corporate} - M_0)$
4. *Scenario 4*: Simplified CAFE constraint with corrected final target from Scenario 3
   $CAFE_i \leq TARGET_{t=2030 fromSc.3}$

The following section presents the Results on the stylized medium vehicle segment and the lightweight alternative option.

4.3 Results of the mass indexed constraint on a vehicle segment

To show the difference on the technology mix when changing the mechanism of the constraint of the fuel economy standard, we use the results of our four Scenarios. We model a CO_2 emissions target of 75 gCO_2/km in 2030 and a Gasoline Light version at 10% of mass reduction.

We start by looking at the impact of the change in the type of constraint on the effective CO_2 target compared to the policy target. In all 4 Scenarios, we have interpreted the CO_2 target policy differently. Results show that this interpretation can lead to different technology choices.

The first difference is in the final fuel economy performance of the average vehicle at the year of compliance, 2030. If we neglect mass from the policy model as in Scenario 1, the average fuel economy in 2030 is equal to the CO_2 target in 2030 as can be seen in Table 4.3. Scenario 2 assumes that the average mass in 2030 will be equal to the mass in 2014. The policy model translates the CO_2 policy target of $75gCO_2/km$ to the mass indexed target using the reference average mass of 2014, the final target in 2030 is lower than the policy target because the reference average mass is below the M_0 market reference of the policy. It is also the more stringent target of all scenarios therefore the estimated target is more ambitious than what the real CO_2 target should be in 2030. The reverse would be true if $M_0 < M_{corporate}$ at $t = 0$.

Scenario 3 does not make an assumption on the evolution of the average mass of a vehicle, instead it optimizes the fuel economy of the mix taking mass as a component of the fuel economy constraint. The final target in 2030 of Scenario 3 is at 67.6 gCO_2/km which is the same target of Scenario 4 by construction. The emission level of Scenario 3 is between emission levels of Scenarios 1 and 2 which is expected because the target gives an incentive to increase mass and thus relax the emission constraint.

When comparing the average mass at every year in Table 4.3, all Scenarios have an increasing average mass. The less stringent target of Scenario 1 corresponds to the lowest average mass because there is no increase in stringency. The technology mix does not require to develop high potential low carbon technologies that are

TABLE 4.3 – Average Mass and Emissions Level in 2030 for all Scenarios at CAFE target of 75 gCO_2/km and Gasoline Light with a mass reduction of 10 %

Scenario	Average Mass (kg)	Average Emissions (gCO_2/km)
1	1090	75
2	1134	64.2
3	1150	67.6
4	1119	67.6

also the heaviest (EV and PHEV). Although Scenario 2 is the more ambitious, the average mass in this scenario is lower than Scenario 3 which shows that in order to achieve a more stringent target, Scenario 2 prefers lighter technologies. The same remark is obtain when comparing the average mass of Scenarios 3 and 4 although they are subject to the same compliance limit. This result is consistent with the fact that allowing the model to optimize the technology choices using vehicle's mass is an incentive to develop heavier technologies. For the same CO_2 emissions target in 2030 Scenario 3 has chosen more heavier technologies.

Considering the content of the technology mix, we are interested in the share of sales of each technology, specially at the end of period which is the year of compliance for our fuel economy constraint. In Fig.4.4 we can see that the share of sales in 2030 of Gasoline12V is identical in all Scenarios and Gasoline Light is almost identical among Scenario 1, 2 and 4. However Gasoline Light is absent in Scenario 3, this is an indicator that the mass index fuel economy standard has an incentive for heavier technologies. The upgrade to a lightweight technology is absent in Scenario 3, the share of Gasoline is highest in Scenario 3. Further details on the technology mix and the diffusion of technologies can be found on Appendix C for this same example.

The results of the model application in a stylized vehicle segment example confirm the impact of a mass indexed fuel economy standard in the choice of technologies as seen in eq.4.4. The incentive is to develop technologies that are heavier. First, the target has become more stringent when correcting the final objective with the initial mass (Scenario 1 to Scenario 2). Second, the optimization of technology choices considering both mass and abatement show that the target is less stringent (Scenario 2 to Scenario 3). And third, the only difference between Scenario 3 and 4 lies on the incentive to choose heavier technologies in Scenario 3 and thus eliminating the choice of light technologies.

When checking for the compliance with the policy framework in Europe in 2030, the technology mix in Scenario 3 is exactly at the compliance limit which is expected by construction it develops the least cost solution for this policy. In contrast Scenario 4 fails to comply with the policy in Europe because the lower average mass increases the target stringency. Two questions remain to be answered: first, does the difference between Scenario 3 and 4 hold for other cases of mass reduction and

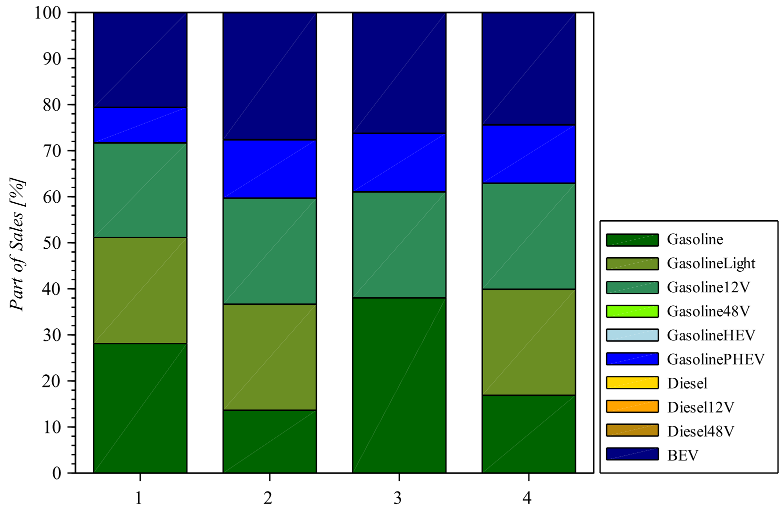

FIGURE 4.4 – Output of technology mix optimization with different Scenarios of fuel standard constraint with Light Tech: Technology Mix in 2030 for lower vehicle segment.

CAFE targets? and second, what is the economic impact on the social cost of the heavier average vehicle?

We have seen an example of application of our model for a given CO_2 emissions target and one type of lightweight option. In the remaining of this Chapter, we will focus on the difference between Scenario 3 and 4. Both achieve the same CO_2 emission target for corporate average in 2030. However, they do not have the same mechanism to comply with a fuel economy policy. One neglects mass of a vehicle (Scenario 4) and the other does not (Scenario 3). We will explore a broad range of fuel economy targets and mass reduction percentages. This allow us to highlight the cases where the technology choice is affected by looking at the lightweight version of Gasoline technology in our model. In Fig. 4.5 we show the difference on the share of sales of Gasoline Light between scenarios (Scenario 4 – Scenario 3) in absolute value in 2030.

For low percentage of mass reduction the difference between both scenarios is low. Likewise, for a mass reduction above 14% and not so stringent targets, the difference is also low. In both of these cases, the share of Gasoline Light is also low for both Scenarios. A low mass reduction is not optimal, the cost of reduction of CO_2 emissions with lightweight technologies is optimal for a range between 8 and 13 %. In this range the difference between the Scenarios is the highest. In this region the Gasoline Light technology is more than 20 points more present in Scenario 4 than Scenario 3. The maximum difference is equal to the saturation diffusion limit of Gasoline Light in 2030 at 23%. This difference has an impact on the average mass of the vehicle: in Fig.4.6 the average mass difference in 2030 (Scenario 3-Scenario 4) follows the trend seen for Gasoline Light Technology but the effect is small since average mass is the result of every technology contributions to the average mass. There is a particular region around 12 to 14 % of mass reduction and 70 to 78 gCO_2/km of CO_2 emission target where the difference in mass is at a maximum.

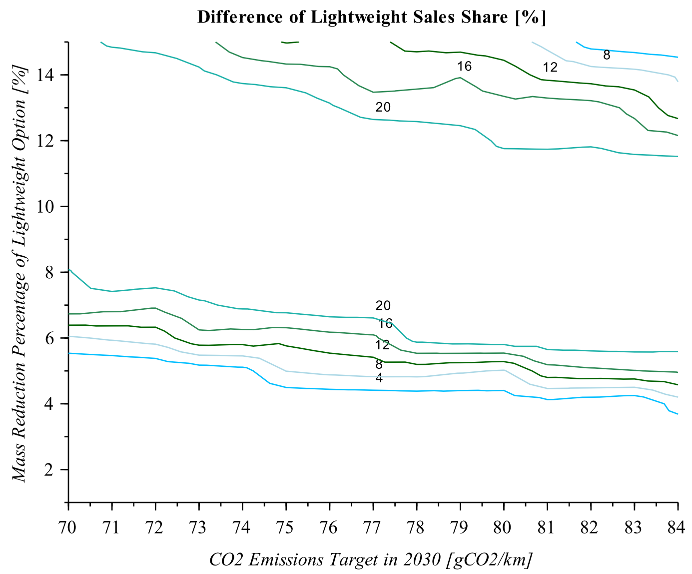

FIGURE 4.5 – Contour Plot of the Difference in Lightweight Share Technology in 2030 between Scenarios 3 and 4 in percentage of sales share for a range of CO_2 emissions target (70-84) and different amounts of mass reduction (0-15%) .

Thus, the change in the technology mix when preparing for a mass indexed fuel economy standard is not conditional to one case, it holds for a range of applications of lightweight technology and fuel economy targets. It is high for medium to high mass reduction percentages in most of CO_2 emission targets and specially for more stringent targets. We saw that we could achieve the same emission reductions by two different means. First, not using lightweight technologies and increasing the share of heavy technologies in the mix. Second, having a mix that uses lightweight technologies but fails to comply with the current policy because a lighter mix would mean a more stringent CO_2 target with the mass-indexed CAFE. In terms of the social impact of the mass indexed fuel economy standard, we assess the cost of both scenarios in the context of a mobility solution, we will look at the cost of having a technology mix on the road in France for both Scenarios 3 and 4. The social cost here is defined as the total mobility cost of a vehicle composed of the cost of the vehicle plus the cost of usage of the vehicle.

The cost of a vehicle is reduced to a simpler form of the cost of producing a low carbon technology. The cost of producing the technology mix in 2030 to comply with the fuel economy target is the average of the discounted cost to produce the

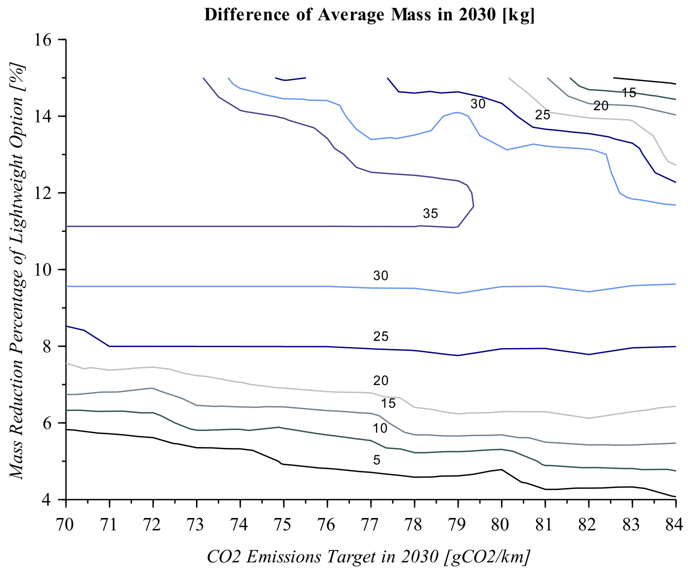

FIGURE 4.6 – Contour Plot of the Difference in Average Mass in 2030 between Scenarios 3 and 4 in percentage of sales share for a range of CO_2 emissions target (70-84) and different amounts of mass reduction (0-15%).

technology mix. The cost of usage of the vehicle is defined in Eq.4.12

$$Cost\ of\ Usage_i = \sum_{k=10}^{10} \frac{1}{(1+r)^k} \sum_{j=10}^{10} X_{ij} * Fuel\ Consumption_{ij} * Fuel\ Cost_{ij} * km_i \quad (4.12)$$

$$Mobility\ Cost_i = Production\ Cost_i + Cost\ of\ usage_i * \frac{1}{(1+r)^i} \quad (4.13)$$

$$Total\ Ownership\ Cost_{2030} = Production\ Cost_{2030} + Cost\ of\ usage_{2030} \quad (4.14)$$

where i is the year of simulation from 2014 to 2030, r is the social interest rate defined at 0.04 and km are the annual kilometers driven by an average user at 11000 km (CCFA, 2017) and the average possession period is 9 years (ACEA, 2017). Fuel Consumption is defined as the amount of fuel to drive one km in L/km [7]. Fuel Cost is defined as the cost of energy (fuel price or electricity price without taxes) in France. We obtain this by looking at current market prices and subtracting taxes for each fuel or electricity prices [8].

7. In order to convert CO2 emission per km to fuel consumption we apply the amount of carbon dioxide contained in a liter of Gasoline and a liter of Diesel: $CO_2 Diesel = 2640 g/L$ and $CO_2 Gasoline = 2392 g/L$ from ecoscore.be. For EV technology we have an equivalent to fuel consumption, the electric consumption is the amount of kWh to drive one km.

8. Taxes applied on Gasoline and Diesel demand are: VAT to the overall cost and TICPE ("Taxe Intérieur de Consommation sur les Produits Energétiques" applied on the consumption of Fossil Fuels. TCIPE has different tax level for Gasoline and Diesel in 2017. The reference Gasoline and Diesel prices with taxes in 2018 in France are respectively 1.462 and 1.374€/L (IEA, 2018). Taxes applied to Electricity demand are: VAT to the electricity cost, TCCFE and CSPE and a lower VAT to the subscription rate and CTA. TCCFE is a local tax fixed on electricity demand, CSPE is a national tax to contribute

We make the assumption that all car owners drive the same distance as would an average driver and that the average possession does not change depending on the type of technology. In practice, frequent drivers tend to own cars that have a lower usage cost. Car owners also keep their vehicle more or less time depending on powertrain technology, when BEV are frequently used they need a battery replacement that is not included in the model. The goal of this Chapter is to isolate the effect of the mass-indexed fuel economy standard thus we subtract taxes from energy prices. We also assume future energy prices are equal to current prices which is a limiting factor of this cost assessment because we are modeling future usage of passenger vehicles where energy prices might change.

We show the results for the example introduced at the beginning of this section, we found that the difference in cost of producing a technology under Scenario 4 is less than 6 €per vehicle compared to Scenario 3 in Fig.4.7. The inferior cost of Scenario 4 is expected since the fuel economy standard constraint with Scenario 4 is open to all solutions whereas Scenario 3 has the mass-index bias. The main result is that this difference is very small, therefore the technology bias does not have an impact on technology costs. This difference is also small for all mass reduction percentages and CAFE targets.

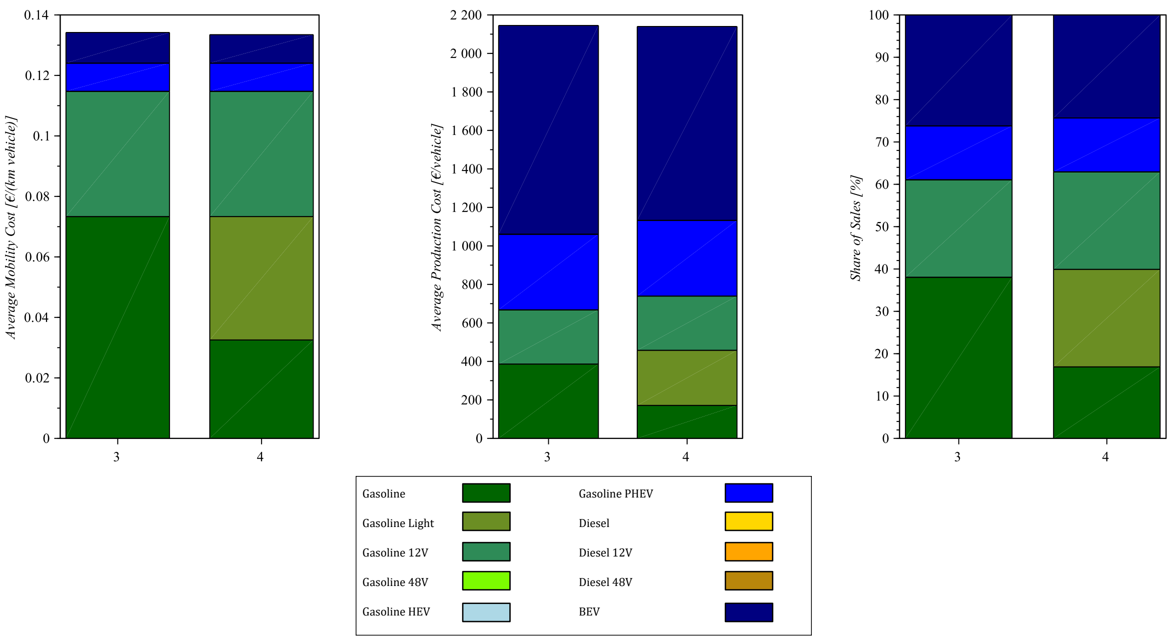

FIGURE 4.7 – Comparison of Mobility Cost: cost of usage, Production Cost and Share of Sales in 2030 between Scenarios 3 and 4 for 75 gCO_2/km emissions target and 10% of mass reduction.

to projects and equity on the electric sector and CTA is supplier fee that is different for an electric supplier profit. The reference electricity price with taxes for a household in France in 2018 is 0.1483 €/kWh from EDF standard rate

The cost of usage changes as the fuel mix and average consumption evolves with the technology choices for the CAFE standard but the difference between Scenarios is also small in Fig.4.7 we can see that they are almost equal in 2030. Despite the small differences in cost, we can see that the weight of each technology is not the same, BEV technology production cost is slightly higher in Scenario 3 and this compensates the increase in cost when chosing Gasoline Light instead of Gasoline in Scenario 4. In terms of mobility cost, a BEV has a very low cost of usage while the difference between Gasoline and Gasoline Light is small. The combination of costs of production and usage of a vehicle is the total cost of possession of a vehicle which is negligible under our assumptions from a consumer perspective. The JRC report (Krause, Donati, and Thiel, 2017) found that to comply with an emission regulation the cost to the end-user will be negligible over the entire lifetime of the vehicle because the technology cost is compensated by the fuel economy savings.

Appendix D shows the diffusion profiles compared with their speed limits, the dynamics of the technology mix, weighted distribution of technology choices in 2030 in two dimensions: CO_2 emissions and vehicle mass and the comparison of the ranking of technologies with and without mass indexation.

The mass-indexed fuel economy standard is an indirect constraint on the mass of the vehicle and therefore it does not allow to explore the whole optimum frontier. The mass of a vehicle plays a crucial role in determining the future target of the policy according to mass evolution it might increase or decrease the overall stringency of compliance. Lightweight technologies are not compatible with the mass-index fuel economy standard because they suffer of a policy penalty proportional to the mass reduction. When looking at the cost of the fuel economy standard with and without a mass indexation we see that the most expensive solution is the mass index fuel economy both in usage and production but this difference is small.

Here we have studied the effect of engine technologies and lightweight technologies but other vehicle attributes might be changed in order to increase fuel economy and not changing mass for example acceleration and horse power that have both an impact on powertrain and vehicle mass.

4.4 Discussion & Conclusion

The fuel economy standard based on an index parameter was set from present weight and fuel economy distribution of carmakers, in theory no assumption of the mass evolution of vehicles is done. This opens the door to comply with the fuel economy standard by increasing the index parameter, mass instead of reducing emissions. In practice we showed that if an OEM acts on its own and assumes that the competitors do not change mass, it will choose a heavier abatement solution instead of a light alternative. This is counter productive because in usage a lighter vehicle will be less expensive and will reduce emissions (ITF (International Transport Forum), 2017). Furthermore all low carbon powertrains solutions are heavier than the gasoline baseline, thus the final average mass will be higher than the initial mass if some abatement effort is performed. Not knowing the future average mass might lead to over-compliance (Scenario 2) or not compliance (Scenarios 1 and 4) at all of the standard because a change in average mass will change the OEM specific fuel economy target and it can lead to not choosing the required technology mix for compliance.

We highlight a caveat of this policy in the incentive to increase vehicle mass. Although adjustments on the reference mass are made on a three-year basis, there can be manufacturers that opt to increase mass. The M_0 adjustment is identified in Kollamthodi et al., 2015 as a policy weakness that can lead to push a manufacturer in or out of compliance depending on the direction of the adjustment. If the mass of our segment was continuing to increase with time up to M_0 then Scenario 1,3 and 4 will be equivalent in terms of the emissions target. The policy implications of the adjustment of M_0 can be studied in the context of game theory. First, there is a disincentive to be the first to introduce lightweight technologies because the emission reduction potential will be diminished by the policy mechanism so the first mover will certainly face higher costs at a smaller benefit to comply with the policy. Second, a manufacturer might choose to be a free rider in the case where it will benefit from the actions of its competitors without facing any investment risk (Kollamthodi et al., 2015). When a car manufacturer does not reduce weight and the remaining firms do, the average mass will decline and so does the reference mass M_0. Keeping the same mass in a market decreasing vehicle mass will reduce the stringency of the CO_2 emission target under a mass index policy, making policy compliance easier. In the case when the majority of firms increase mass, the policy incites a manufacturer to follow the mainstream trend of increasing mass because keeping the same mass would increase policy target stringency.

From a technology perspective, the optimal choices when preparing for an abatement only scenario and a mass indexed fuel economy standard are different. We proved that when choosing for the least cost solution the ranking of optimal solutions changes if the mass index mechanism is taken into account. Preparing for compliance (Scenario 3) includes heavier abatement technologies than preparing for abatement only (Scenario 4). For Scenarios of abatement only type of constraint, lightweight solutions are an effective and cheap way to increase fuel economy up to the point where it becomes too costly. There is only a small window of opportunity for lightweight technologies under a fuel economy standard that is limited by the index coefficient in Scenario 3. Today, despite a wide range of lightweight options, a manufacturer is more inclined to produce heavy vehicles and does not have an interest on investing on lightweight technologies because they are not cost effective from a fuel economy standard perspective. A decrease of the index coefficient is key to obtain a more technology neutral standard and discourage OEMs from changing the index parameter instead of reducing emissions.

We performed a cost assessment on the two mechanisms to apply a CO_2 regulation in the automotive industry: with and without a mass-index to show the economic impact of the different types of fuel economy standards for society. We have optimized the technology cost for each policy framework, the objective function of the model aims at reducing technology costs. Cost in usage are obtained from the technology mix of the model and energy prices assumed constant. We choose to focus on the 2030 technology mix instead of the total cost for every mix from 2014 to 2030 because the gap between Scenarios in terms of emissions and mass is low in the first period of simulation and is highest in 2030. We found that the gap in total cost to prepare for the two variants of the fuel economy standard is small. We saw that the difference in technology choices were significant but the difference in cost is not, this is not intuitive. There is a compensation effect in technology cost: the heavier variant of Gasoline technology is favored in a mass index policy and is less expensive. At the same time BEV is also favored by the mass indexed CAFE, it is heavier but more expensive thus creating no difference in technology cost from a policy without mass indexation. In terms of cost of usage, we also observe a compensation effect: the cost of usage of Gasoline Light is less expensive therefore a scenario without a mass index has lower cost of usage for fossil-fuel vehicles. However, plug-in vehicles have much lower cost of usage than fossil-fuels vehicles. Plug-in vehicles are more present in a policy with mass index thus reducing the cost in usage gap.

There are several limitations with this cost assessment, first energy prices are kept constant in our model. First, we assume that fuel cost in 2030 will be equal to those in 2017 neglecting any evolution of fossil fuels cost and electricity cost. If fossil-fuel prices were to rise the cost of usage for Gasoline and Diesel vehicles will also increase because there is a direct effect. For plug-in vehicles the effect is indirect, it depends on the carbon intensity of the electricity mix. If carbon intensity is high, it is probable that electricity prices will increase with an increase in fossil-fuel prices. If carbon intensity is low such as in France, with a high share of nuclear, fossil fuel prices will have a smaller impact on cost of usage of plug-in vehicles.

Second, the CO_2 emissions externality has two compounds: tail pipe emissions that are covered by the fuel economy standard and well to tank emissions that are not covered by the standard. Tank-to-wheel emissions are indirectly covered by the fuel economy standard, the policy limits the average carbon intensity of new vehicles but it does not target how many kilometers and in what conditions are those kilometers driven. Thus the fuel economy standard does not apply directly to tailpipe emissions. Well to tank emissions are potential negative externalities that might affect results since different ways of obtaining fuel and electricity are more or less emitting. The energy mix of electricity is different from one country to the other and further research is needed to assess this externality. We fail to consider the indirect emissions of the type of fuels used in the technology mix thus we can not tell which technology is better from well-to-wheel basis, we are limited in scope to tank-to-wheel analysis.

Third, on technology assumptions, we do not model learning effects or economies of scale, these would potentially decrease the cost of plug-in vehicles. Having less expensive plug-in vehicles in the technology mix will favor PHEV, BEV is already close to the saturation point. We have a limited set of technologies other technology families such as aerodynamics or rolling resistance have an emission reduction potential and further research should investigate if these technologies are also affected by a fuel economy standard indexed to mass.

Fourth, we assumed that all vehicles are driven the same yearly distance. However the technology choice of high mobility drivers is more influenced by fuel cost thus preferred technology choices might be sensitive to the type driver. We should expect long distance drivers choosing BEV however the driving range, charging infrastructure and upfront cost of a BEV keeps them out of choosing plug-in vehicles. Instead they are attracted by high fuel economy fossil-fuel vehicles such as Diesel. We did not weight more the technologies that might be favored by high mobility drivers in the evaluation of cost of usage.

Fifth, we assumed an average possession equal for all technologies. In practice, there might be technologies that can resist more to intensive use and last longer. Some fossil-fuel vehicles have been used for more than two decades, in contrast the first plug-in vehicles to enter the market have been sold less than a decade ago therefore we are not certain if drivers will keep their plug-in vehicles as long as fossil fuel vehicles.

Our approach includes different ways of modeling the fuel economy constraint to show how the mass indexed policy translates into a different mechanism of technology choice than an abatement technology rationale. We quantify the impact of the fuel economy standard in the automotive sector. On the first objective, we have judged the index parameter as a negative component of the fuel economy standard this is true for the mass index but other index parameters lead to different conclusions, in the USA the effects of the footprint parameter are not negative (Ullman, 2016) and public reports suggest that it might be a better index parameter (German and Lutsey, 2010; Kollamthodi et al., 2015). On the second objective, we showed that a mass indexed fuel economy standard can lead to a high share of plug-in vehicles that are key to achieve a low carbon mobility. Thus the fuel economy standard indexed can help develop plug-in vehicles however the reference mass must catch up to avoid failing to reach the European emission reduction objective for passenger vehicles.

We have used the OMLCAT to focus on the technology choice from a car manufacturer perspective when it is limited by a fuel economy policy and diffusion of new technologies in a market with some inertia. The features of the model presented in this analysis are fitted to study a simple vehicle segment for the purpose of studying the policy implications, further studies could extend the model to a vehicle fleet but for simplicity and comprehension we choose to reduce the model application to the minimum. One of the limits of the model is that it does not include market competition therefore there is no effect of what other competitors are doing in the choice of the technologies. Including other competitors might be useful to explore other policy implications. Another limitation is that the model does not include consumer choices that have different preferences according to type of vehicle technologies. There are many studies that have focused on consumer behavior to quantify the preference for plug-in vehicles (Plötz, Gnann, and Wietschel, 2014; Gnann and Plötz, 2015; Gnann, Stephens, et al., 2017; Al-alawi and Bradley, 2013; Coffman, Bernstein, and Wee, 2017).

The mechanism of modeling a fuel economy standard policy requires a level of technology detail that is very complex, we have neglected several aspects of the policy that might change the results.

First, supercredits multiply the sales of low or zero emissions vehicles by a factor on the CAFE calculation. They decrease the level of stringency of the policy but like the mass index they are not technology neutral because only very low carbon technology can benefit from this scheme. Nevertheless, the trend is to decrease the supercredit coefficient in the future so its role will become less important.

Second, eco innovation or off cycle technologies, as defined by the regulation are innovative technologies that help cut emissions, but in some cases it is not possible to demonstrate the CO_2 reducing effects during the test procedure used for vehicle type approval. They are key to enable compliance from OEMs when the compliance target is close but they are difficult to compare in terms of fuel economy performance to other technologies because they can not be fully captured by the test cycle [9]. This type of technologies must be treated separately since their applications differs from the other technologies treated in this article. Literature suggests that the potential benefit of use of off-cycle technologies should be revised specially if their use and eco-innovations permits tend to increase (Lutsey and Isenstadt, 2018).

Third, the compliance period of the fuel economy standard was simplified, instead of having three targets in 2020, 2025 and 2030 we chose to have a single target in 2030. Due to implications of the choice of a short term technology mix when preparing a long term target we do not want any bias introduced by a set of targets that might deformed an optimal response when preparing a long term abatement target.

9. Some examples from the list of eco-inovations from the European Comission are 12V motor generator, battery charging photo-voltaic roof, LEDs, coasting functions. The eco-innovation credit is capped at 7 gCO_2/km.

In practice the introduction of new technologies does not happen without drawbacks or unintended consequences, in the case of lightweight technology, studies have agreed on the potential on increasing fuel economy (Luk, Saville, and Maclean, 2016). Nevertheless, researchers have risen concern on road safety from two undesirable effects: a change in size might cause more road accidents because the size distribution of the overall fleet will change (Bento, Gillingham, and Roth, 2017), making driving conditions more dangerous; whereas a change in mass, will either reduce the amount of fatal accidents since the vehicle will have less kinetic energy making multiple car accidents less mortal or it will increase fatalities since a lighter vehicle is more vulnerable when it crashes with a heavier object (White, 2004; Anderson and Auffhammer, 2014). Road safety is not the main interest of this research and dedicated literature (Bento, Gillingham, and Roth, 2017) studies these effects. For lightweight technologies the report by Singh, 2012 requires the technology alternative to have the same crash-testing rating than the baseline technology, so the lightweight packages proposed in that studied do not have this externality.

Our results demonstrate that the CAFE indexed to mass does not lead to higher social costs to reduce carbon dioxide emissions. Nevertheless this result is conditional to the type of externalities that we included in the model. As stated above, a safety issue might imply that an increase in mass might have a negative externality when looking at an overall safety risk but it can be seen as positive externality when considering an individual safety risk. The cost gap between both policy mechanisms might be smaller if we consider that the cheapest alternative will suffer from a rebound effect due to lower mobility cost, we have not explored this effect but it can be a negative externality on the least social cost Scenario of the fuel economy standard without a mass index.

Although we obtain a production cost of a vehicle we do not take into account the potential externality of the manufacturing process and raw materials. Studies focused on life cycle analysis examine the different energy inputs to extract all raw materials to produce a vehicle (Raugei et al., 2015; Lewis, Kelly, and Keoleian, 2014). The usage of key chemical elements such as rare earth elements in batteries has risen concern on the extraction process of these elements. Taking the end of life of the vehicle will also require to study the disposal of a vehicle. The externality in this domain comes from a supplementary CO_2 emissions and a potential pollution cost of those environments where the extraction and disposal if any of a vehicle occurs.

A different class of emissions, pollutants that cause an air quality concern are not addressed in this Chapter. They might affect the result because there is a high difference between pollutant emissions (NOx and particles) from a Diesel vehicle and a EV. A first guess is that the Scenario with the highest share of EV and lowest share of Diesel will have the lower externality from an air quality perspective. Finally, the noise from a vehicle is an externality that is not addressed in this Chapter.

Vehicles having a electrical driving mode: EV, PHEV and some HEV produce very little noise at low speeds and reduced noise at high speeds.

A fuel economy standard is interesting only if there is an incentive to lower emissions no matter where a manufacturer is positioned however Durrmeyer and Samano, 2018 showed that this is not the case when a manufacturer is already compliant it will not seek any further abatement efforts. In terms of the technology portfolio, the mass-indexed fuel economy standard does not allow to develop all potential abatement solutions, therefore it fails on its mission to be technology neutral. The incentive to develop heavier vehicles can have either a positive effect on emissions, when the technology alternative is an EV or a negative effect where an increase in mass and a marginal change in emissions is operated to comply with the target and allow for a change in segment: from sedan to SUV. Some countries are complementing a fuel economy standard with a ZEV mandate that creates a quota of low to zero emission vehicles (mostly EV) on the sales share of a carmaker. The emission credits assigned are avaialbre for trade either with absolute emissions or with ZEVs among other manufacturers, emission credits have been analyzed by Fischer, 2008. The ZEV mandate is integrated in the model in Chapter 5.

The mass-indexed fuel economy standard has several impacts on the abatement efforts that an OEM will do to comply with the enacted target. From a Climate Change perspective what matters the most is CO_2 emission cuts of new vehicle sales in order to have a cleaner vehicle fleet therefore all technologies that cut CO_2 emissions are interesting. The automotive sector is not composed of homogeneous vehicle products and thus some mechanism of sharing the reduction efforts among all OEMs needs to be created. The mass index standard effectively does the job of distributing the share of reduction between the manufacturers. It requires lighter OEMs do more efforts than their heavier peers and on average it can lead to a low average emissions from new vehicles. However, some caveats come from the mechanism of the regulation that do not allow to explore the full scope of abatement technologies for deeper reductions. Further research on the potential lock-in of the fuel economy standard on technologies that have low abatement potential but are heavy is important to understand the impacts of the mass based fuel economy standard. A reduction in mass from a low carbon technology is penalized by the compensating impact of a resulting more stringent target, therefore the standard is biased in detriment of those potentially cost-effective solutions that reduce weight. There are several ways to correct this bias as proposed by Kollamthodi et al., 2015 :

— Mass reduction credits for OEM demonstrating a downward trend in sales-weighted average mass
— Banking of CO2 emissions reductions where a downward sales-weighted average mass trend is demonstrated
— Link targets to mass by setting more stringent targets for heavier vehicles and more lenient target for smaller vehicles or setting a ceiling that affects

only the heavier vehicles and a floor for smaller vehicles

— Mass reduction credits and debits) for vehicles based on their density relative to the overall average density

The most promising option is mass reduction credit for vehicles based on their density relative to overall average density, this option include both footprint and mass into consideration but requires more investigation since it will introduce more complexity into the standard.

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Chapter 5

Overlapping Automotive Emissions Policies, a double challenge: CO_2 and Air Pollution

5.1 Introduction

Vehicles' emissions contain a mixture of different gases, including greenhouse gases (GHG) such as CO_2 and local pollutants such as nitrogen oxides NOx or Particle Matter (PM). The former contribute to global climate change, the latter to local air pollution. While the contribution of road transport to climate change is undeniable, its climate consequences are not directly experienced at the place of emission. By contrast, local air pollutants are directly affecting communities where there is a dense and intensive use of road vehicles, with clearly visible health impacts, causing premature deaths and illness (related to the exposure to high concentration of gases) (International Energy Agency, 2016). Tail-pipe emissions thus produce two different externalities. In this Chapter, we focus on the automakers and policymakers responses to these joint externalities.

Most vehicles today integrate an Internal Combustion Engine (ICE) that emits GHG and pollutant gases. Some technologies are fitted to reduce one type of emissions only. There are three types of emission reduction technologies. In the first case the technology acts on GHG emissions only and has no or a negative impact on local pollutants, e.g. Gasoline Direct Injection or Diesel engines. The second type acts on local pollutants only but has no or negative impact on GHG emissions, e.g. Selective Catalytic Reduction after-treatment technology. In the third type both types of emissions are positively impacted, for example Battery Electric Vehicles (BEVs). Since air pollution is a combination of harmful gases, reducing all emissions with a single technology is very difficult. The effect of a technology on air pollutants is more complex than the effect on GHG emissions because of the different performance on each type of gases. Therefore, we analyze a combination of technologies to respect a regulatory limit instead of focusing on a single air de-pollution technology. In this Chapter we focus on the distinction between two families of externalities: GHG emissions and air pollutants. The technology solutions developed for a climate change objective might differ from those developed for an air pollution objective.

The policy instruments that have been developed to regulate tail-pipe emissions are not sufficiently comprehensive to consider all emissions, with the exception of Zero Emission Programs. In terms of climate change policy, the low carbon pathways developed for mitigation show overall co-benefits in reducing local air pollution on the long term, only a small impact is observed in the short term (Takeshita, 2012). Some policy instruments such as fuel economy standards and energy efficiency standards focus on reducing the carbon intensity of the road transport sector but have failed to consider air pollutants. Local emissions have been regulated in two scales: national and local. National or regional emission standards, e.g. the Tier 1 emission standard introduced in California, are a minimum requirement for all new vehicles at a national level. Local governments have promoted the use of less polluting vehicles at the city level for example the London Congestion Charge. Today, local policies in cities act on the vehicle fleet with a few also acting on new vehicle sales. Policy tools for vehicle emissions have various mechanisms that can have positive or negative effects on the reduction of GHG emissions or air pollutants.

Our work offers a new combined assessment of policy analysis on the existing literature. Many previous studies examine the isolated effect of a policy implemented on the automotive sector (Klier and Linn, 2016; Whitefoot, Fowlie, and Skerlos, 2017; Luk, Saville, and Maclean, 2016). While a comparison of policies on GHG emissions exist, the literature focuses on policy efficiency and finding the best fit for carbon emissions reduction (Anderson, Parry, and Sallee, 2011; Liu, Greene, and Bunch, 2014; Fischer, Harrington, and Parry, 2007). However on a national scale few have gone beyond GHG emissions to expand the scope of vehicle emissions to air pollutants. There are two combined cost assessments of CO_2 and pollutants emission reduction technologies in Europe (FEV, 2015; Hill et al., 2016) and USA (National Rearch Council Board on Energy and Environmental, 2015) that address both type of emissions. We contribute to this technical-economic literature by introducing different policy scenarios requiring change in the technology portfolio.

We do not focus on a single shot examination of policies, we acknowledge future uncertainties of policy targets thus we analyze a range of possible outcomes and we also consider the pathways to reach such ambitions instead of restraining to a single picture of the future. This approach is common in the Climate Change community, as observed in the uncertainty of mitigation actions in Integrated Assessment Models (Bauer et al., 2015). We conduct an analysis of several possible outcomes for each automotive policy.

The literature is focusing on the local scale of the automotive market for two reasons: the electric vehicle transition requires a dedicated infrastructure that grows at the same pace than the market and policy instruments applied at a local scale try to incentivize low emission technology adoption. The electric vehicle transition has been described as a chicken or the egg problem (Leibowicz, 2018). This logic is that the electric charge infrastructure is deployed only if Plug-in Electric Vehicles (PEV) are adopted and vice-versa PEVs are adopted only when the infrastructure is deployed. A zero air pollution objective does not rely only on low emission vehicles, it has to reduce the impact of tyre use and other sources of pollution from household heating and industry activities (Hooftman et al., 2018). Our interest is on the literature treating emerging local policies at the city level, also known as Low Emission Zones.

Next, we briefly introduce the two type of policies new to this Thesis: Low Emission Zones and the Zero Emission Vehicle Mandate.

5.1.1 Low Emission Zones

One of the first application of Low Emission Zones (LEZ) was introduced in the city center of Stockholm in 1996 to diesel trucks and buses with a weight over 3.5 tonnes. A LEZ policy constraint is an area restricted to some categories of vehicles that do not exceed emissions limits (Pasquier and Andre, 2017). This translates to a technology ban that spreads over time due to the diffusion of local policies. The mechanism is a step change in normal fleet turnover, resulting in lower emissions than would have occurred without the LEZ (Holman, Harrison, and Querol, 2015). There are more than 200 LEZs in the EU with different applications and rules applied to different vehicle types, urban area coverage, vehicle emissions labels, restriction hours, penalties, enforcement instruments and national frameworks.

The impact of LEZ on the reduction of emissions has to be analyzed on the basis of local conditions. The urban landscape and activities in the urban area determine the type and efficiency of a LEZ. The London Congestion Charge (LCC) is not a ban on circulation but a circulation charge on high emitting vehicles, it has shown an increase share of HEV sales inside the LCC zone and its neighbor urban areas too (Morton, Lovelace, and Anable, 2017). The air quality in London has shown limited (Ellison, Greaves, and Hensher, 2013; Wolff, 2014) or no improvement in air quality (Hooftman et al., 2018) after the LCC application. However both studies highlight the difficulty to isolate the policy impact on air pollution. In Germany a study conducted on multiple cities shows that there is a more rapid decrease on certain pollutants: Particle matter concentration smaller than 10 μ m (PM_{10}) inside the LEZ compared to areas outside the LEZ (Jiang et al., 2017). Originally a LEZ is intended to reduce air pollution but the results of different LEZ are ambiguous. However, they have already changed the technology mix and reduced traffic in restricted areas.

5.1.2 Zero Emission Vehicle Mandate

We have based our analysis on the fuel economy standard that regulates carbon emissions because it is widely adopted in the automotive industry and it clearly affects technology choices. The policy based on a fuel economy standard has been combined with a Zero Emission Vehicle Mandate (ZEV). The ZEV Mandate was first implemented in California in 1990 as one of the policy instruments to reduce air pollution (Collantes and Sperling, 2008). It is a policy that sets a minimum quota of Zero Emission Vehicle for carmakers at a country or regional level. The quota in practice works as a credit system that can be transferred to a CAFE compliance, to others manufacturers or carried back and forward depending on construction. Although the first implementation occurred almost thirty years ago, only few regions have already applied it, namely the ZEV states in the US, the province of Quebec and China have implemented a ZEV Mandate (Lutsey et al., 2018). The EU is studying the potential introduction of a ZEV Mandate type requirement in the next carbon emissions regulations (European Commision, 2017).

The economic efficiency of the ZEV Mandate has been treated in literature, this technology specific policy is not the most efficient but it can be useful to incentive the construction of a zero emission vehicle ecosystem (Fox, Axsen, and Jaccard, 2017; Bergek and Berggren, 2014). This policy seems to have more political acceptability (Wesseling et al., 2014) and more importantly it gives a clear signal to automakers, fuel providers, and other stakeholders to progress on lowering adoption barriers that may be difficult for regional governments to influence directly (Sykes and Axsen, 2017; Bergek and Berggren, 2014; Greene, Park, and Liu, 2014). Fox, Axsen, and Jaccard, 2017 discuss the application of two types of technology specific standards: a standard based on low emission vehicles and a standard based on a single technology (plug-in vehicles). The study finds that the more technology selective standard is more efficient but some risks emerge on the uncertainty of cost reductions and the path dependency of a policymaker choosing the "winner" technology. If the policymaker assessment of a technology is wrong it can lead to higher costs. The introduction of a ZEV Mandate in California has forced the deployment of EV, the patent count shows an increase in ZEV technology (Sierzchula and Nemet, 2015) but it can led to a path dependent low carbon trajectory (Contestabile, Alajaji, and Almubarak, 2017) if the EV ecosystem fails to deliver.

5.1.3 Method

To identify the effect of policy combination we have modeled the isolated effect of a policy and the combined effect of the fuel economy standard with the other policies. The national policies such as standards and the ZEV Mandate affect all vehicles sold in a region. In contrast, local policies such as LEZ affect the acquisition of a vehicle in urban areas only, therefore the policy effect applies to a part of all vehicles sold in a region. For that purpose, we modeled the policy coverage of local policies in France. A cost analysis of the total cost of the mobility service: technology cost and mobility cost is used to compare how the cost evolves with changes in the portfolio of technologies when policies are combined together.

This Chapter explores the implications of applying two policies that answer two problems found in the same product: local air pollution and global warming. The main question is how to assess the effects of overlapping policies under three different perspectives. First, we look at the difference in technology choice to see what are the preferred technology requirements for each policy and then what is the effect when they are combined. Second, we study the overcost that a policy and the combination of policies would imply for society from a baseline without policies. Third, we investigate how policies perform on the two dimensions of vehicle emissions: GHG emissions and air pollutants. Based on these two externalities of vehicle emissions we study the relationship between a change in stringency in the policy package and the performance on these two dimensions. This Chapter examines the impact on technology choices when a car manufacturer is constrained by a policy framework of various combinations of environmental policies. Since technology choices are strategic decisions that require time to be mass-diffused in a market we develop a model that includes economic inertia to take into account the dynamics of low emitting technologies.

A technology can be adapted for multiple policy objectives which allows a firm to solve various externalities with a single solution, however when there is no such technology or when the potential of this technology is limited a car manufacturer will develop other technologies that are not fit for all policy ambitions. For the comparison of policy impacts on technology choices, we start by identifying the change in sales share from a case where a policy is applied alone and a case where two policies are combined. We show the gap in technology sales share of the single policy scenario and the combined policy scenario. We identify how the preferred technology changes when overlapping policies.

In a technology portfolio the effect is similar, whilst some combination of policies do not require a change in mix, others alter the portfolio of technologies. When the technology content required for a policy is similar to another policy or when a policy is already compliant with another policy objective, the change in the portfolio to prepare for the combination of these policies is small. In other cases when policies show little common technology choices, the combination of policies shows different technology choices than the single case scenario. We can identify which technologies suffered from the introduction of a combined two-policy package and which have not. We check if the behavior of interaction between policies holds when we vary the stringency of the targets.

A policy framework implies a new constraint for the technology mix which can increase cost if the policy is binding. We identify the technology cost of application of each single policy analyzed in this Chapter and then we compare with the combination with a fuel economy standard. We obtain the overcost of the two policy package from the baseline of a Scenario without policies to check when policies are binding and how is this cost compared with the single policy scenarios.

Policies have multiple objectives when considering different externalities. Thus building a policy package is complex when different levels of performance are expected in each of the regulated externalities. In the case of automotive emission externality, multiple policymakers, (e.g. in France: international: EU, national: french government and local: major of Paris,) create different mechanisms to correct each externality thus a coherent policy package is difficult to obtain with diverse actors having different visions. The climate change and air pollution externalities are targeted by different policies in various mechanisms. We focus on the impact of a single policy and a combination of two policies on two dimensions: CO_2 emissions and air pollutant emissions. To check for this impact we vary policy goals and observe how does the environmental performance changes on these two dimensions.

5.1.4 Summary of Results

Our results show that the application of two policies, in some cases deviates the technology mix from its optimal response to a single policy. For low stringent fuel economy standards, the other policy has a stronger effect and decreases CO_2 emissions below the fuel economy target. We found a range of CAFE targets, where there is a similar response in technology choices of the CAFE policy, the LEZ policies and the ZEV Mandate.

A LEZ that forces ZEV in city centers and a ZEV Mandate will favor EV which is in line with the policy objective, however they will also produce the higher share of the most polluting technology category. The ZEV Mandate has modified the rationale of a fuel economy standard, ZEVs count more under this scheme thus the distribution of abatement efforts is also different. We find that there are two opposite effects: when the share of ZEV increases, the share of non-abatement technologies also increases. This means that the car manufacturer has directed all efforts on ZEV solutions and chooses to keep the share of profitable cheap technologies with high emissions. We will see that this problem resembles to the results found for renewable quotas combined with a Emissions Trading System (ETS) in the energy sector (Böhringer and Rosendahl, 2010) however the scope of the policy in the energy sector is different.

Concerning the interaction between the two dimensions of vehicle emissions externalities: air pollution and climate change, we can define a positive relationship between both dimensions of environmental performance when an increase in policy stringency improves the environmental performance of a vehicle in the two dimensions. A negative relationship implies that an increase in policy stringency only improves the environmental performance on one of the two dimensions. For most of policy applications we observe a positive relationship with our model assumptions. For an improvement in CO_2 emissions, there is an improvement in air pollutant emissions too. The only exception is the air emission standard that seems to have no effect on improving CO_2 emissions. In this latter case, there is only an improvement on air pollutants performance.

The total cost of the mobility service is lowest for the CO_2 only Scenario. When analyzing both components of this cost: technology cost and usage cost, the combined policy scenarios having a high share of EVs are less costly in usage but are more expensive in technology cost. Focusing on technology costs we compare the overcost of different policy packages from the baseline No Policy Scenario, we find that overall the gap in cost between single and combined policy scenarios is small except for the emissions standard where the overcost of the two policy scenario is higher than the sum of the overcost of each policy applied independently.

The remainder of the Chapter is organized as follows. Section 5.2 describes the methods, data and scenarios used for the analysis. Section 5.3 describes and analyses the results. Section 5.4 discusses the limitations of the study and the implications of the results for the anticipation of a fuel economy standard policy and concludes the Chapter.

5.2 Methodology

The technology choice that a carmaker does to prepare the adapted solutions for policy constraints is determined by stringency and timing of policy targets. The industry is looking for least cost solutions to guarantee maximum profit of vehicle sales in a competitive market. We use OMLCAT that will be enriched with a broad policy package to study more applications and completed with technology solutions for air pollution. The baseline version of OMLCAT presented in Chapter 2 will be modified to address a broader scope of vehicle's emissions. The policy package will incorporate three types of policies, described in section 5.2.4 that are not included in the other Chapters: an emissions standard (air pollutants), a Zero Emission Vehicle (ZEV) Mandate and a city restriction in the form of Low Emission Zones (LEZ). The CAFE policy, treated in fully in Chapter 4 is modeled without mass indexation with a single target in 2030 and with mass indexation in Appendix E. The technology options available in this model include the basis of low carbon technologies that are combined with de-pollution technologies described in section 5.2.3.

5.2.1 Modeling Local Policies on passenger vehicles

The impact of a local policy in overall emissions of vehicles of a country is limited to vehicles entering the boundaries of an urban area defined by the policy. In comparison the fuel economy standard is an average corporate fuel economy regulation that is calculated on a region or country basis. Our goal is to estimate the share of total vehicles sales that is affected by local policies and model the implementation of local policies in a country.

First, we define the share of vehicle sales that will be concerned by the city policy. We assume that city policies on new vehicle sales affect both internal and external sales that are close to the city. Daily usage of vehicles often experience inter-departmental trips as seen in Île De France. We assume that all vehicles sold in a department where a city adopting a local policy is will have to comply with the restriction. In the case that urban areas expand to more than one department, we consider all vehicles sales from all departments involved. This approximation does not require community level data on vehicle sales, it requires car registrations on a department basis. The assumption of a city policy affecting the entire department means that the weight in mobility demand of a city in a department concentrates most of passenger vehicle demand thus affecting all vehicle department sales. To refine this assumptions a more precise study on mobility patterns is required, we will discuss this in section 5.4.

Based in France we will model where local policies will be implemented to simulate the coverage of policies applied at a city-scale for future sales. We define four criteria to decide the share of new car registrations affected by a local policy: we choose two criteria based on the city size (100k or 150k inhabitants) and two criteria based on urban area size (300k or 500k inhabitants). We have gathered two sets of information from INSEE: first the population of cities above 100 000 and 150 000 inhabitants and the population of urban areas above 300 000 and 500 000 inhabitants, second the new car registrations in each of the departments where a city or urban area is established according with the previous criteria, this data is shown in Table 5.1. For each criteria we collect the new car registrations of the department where the city/urban area is and divide this by total registrations to obtain the maximum coverage of an urban policy if all cities where to apply a local policy as seen in eq.5.1.

Second, the other main assumption is that we consider that a local policy is implemented first in larger cities before smaller cities. We model the implementation of local policies in France starting at the city of Paris and then spreading to other large cities that satisfy the size criteria. We assume that cities or urban areas smaller than the size criteria will not implement a LEZ. The rate of spread of the LEZ policy is an increment of 10% of total new vehicle sales. The diffusion is capped at the maximum policy coverage defined in Table 5.1.

$$Max_{coverage} = \frac{\sum_{p=1}^{n} Sales_p in\ department^{\star}}{\sum_{p=1}^{n} Sales_p} \tag{5.1}$$

where n is the total number of departments in France, $Sales_p in\ deparment^{\star}$ is the number of new vehicles registered in the department satisfying the city/urban area size criteria and $Sales_p$ is the number of new vehicles registered in department p.

Population Size criteria	French Population Share %	New Car Registration Share %
City >100k	15.2	54.8
City >150k	10.9	35.7
Urban area >300k	51.2	61.1
Urban area >500k	42.0	50.8

TABLE 5.1 – Definition of urban criteria: Population Size of cities and urban areas under the four criteria for local policies as share of total French population and share of total new car registrations in departments affected by the same criteria.

In Table 5.1 we compare the population share of each of the urban criteria and the coverage size in vehicle sales. The relationship between the French population and new car registrations does not coincide because the geographical limits are different from one criteria to the other. A larger share population should have a large coverage in vehicle sales but the assumption of taking new vehicle sales at the department scale instead of urban area/city scale creates this distortion. The difference lies on the fact that some urban areas touch more than one department, e.g. IDF. The maximum coverage for city criteria are: 35.7% for 150k inhabitants and 54.8% for 100k inhabitants and for urban areas: 50.8% for 500k inhabitatns and 61.1% for 300k inhabitants. The start coverage is IDF with 18.2% of new car registrations that increases with the propagation of the policy. The incremental change is constant and represents a rapid progression meaning that many cities or urban areas follow Paris example. Each year an additional 10% of total new car registrations will be concerned by a LEZ policy until reaching maximum coverage or until the model stops which ever comes first. In section 5.3 we will model the more severe case that corresponds to urban areas of more than 300k inhabitants or a maximum coverage of 61.1 % of new car registrations.

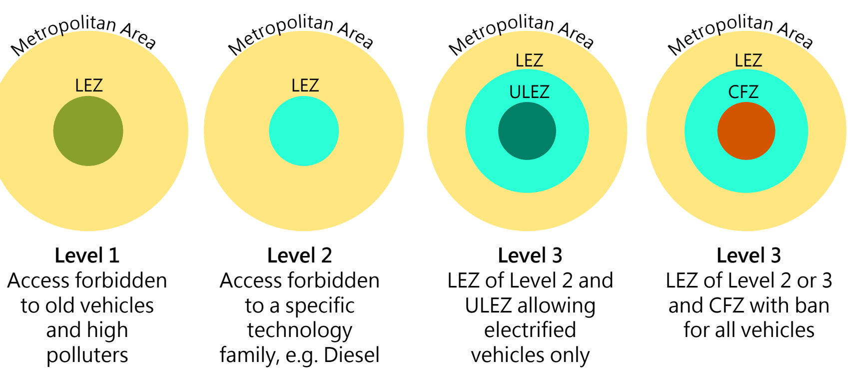


FIGURE 5.1 – Four different levels of LEZ that are currently implemented or planned by cities. An Ultra Low Emission Zone (ULEZ) only allows very low emission vehicles to circulate in city centers. A Car Free Zone (CFZ) bans vehicles from city centers. Source: The Author.

There are many types of LEZ that change in stringency and mechanism to charge or ban vehicles from city centers. We can however draw four levels of LEZ based on the impact on the vehicle fleet, shown in Fig. 5.1. The first level of LEZ only limits the existing fleet and forbids access to the zone to polluting vehicles [1]. The last level of LEZ bans all vehicle types in Car Free Zones (CFZ). We simulate two models of LEZ policy based on our profiles: the second level of LEZ model is a city that will progressively ban ICE engines which starts with a Diesel ban first and then continues with an all ICE ban eq.5.2 and the third level of LEZ model where only Ultra Low Emission Vehicles are allowed in city center which means only Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) are allowed all other technologies are excluded eq.5.4.

The first LEZ model is called a LEZ ICE ban and the expansion of this policy starts in the city of Paris and then spreads, therefore the model will increase the Urban exposition of the policy until maximum coverage of the urban area criteria described above. The share of restricted vehicles is the sum of all technologies banned by the policy and can not be greater than the rural exposition (1-urban exposition) of the mix. Thus, the constraint guarantees that only non-polluting vehicles can be sold in cities and their influence area.

$$MS(family)_i \leq (1 - min(Urbanexpo(family)_i, Max_{coverage})) \tag{5.2}$$

$$\forall i > year\ start\ Urbanexpo_i = Urbanexpo_{i-1} + 10\% \tag{5.3}$$

The second LEZ model is called LEZ ZEV force and it will have the same progression in policy coverage. In contrast to the our first model of LEZ, the share of allowed ZEV by the policy must be greater than the urban exposition of the mix. Thus, the constraint guarantees that only ZEV are sold in cities and their influence area.

$$min(Urbanexpo(family)_i, max_{coverage}) \leq SS(family)_i \tag{5.4}$$

where $SS(family)_i$ is the sales share of the family at year i, $Urbanexpo(family)_i$ is the urban exposure of a family to sales in cities with local policies and $Max_{coverage}$ is the maximum coverage of urban policies in new car registrations. This constraint only applies for technologies affected by the policy.

1. Polluting vehicles are often classified by two criteria age and the emission standard if it is applied. Thus a prohibition can take the form of a ban of vehicles with an standard less stringent than a limit or a ban of vehicles produced before a given year.

5.2.2 Variation of OMLCAT

ZEV mandate constraint

We will model a ZEV Mandate with a credit system without trading with other car manufacturers and without banking mechanisms of credits [2] as follows:

$$\sum_{j=1}^{n} MS_{ij} Creditscore_j \geq ZEV_{targeti} \tag{5.5}$$

where $Creditscore_{ij}$ is the credit associated to technology j at year i: 1 for BEV 1/2 for PHEV and 0 for all others and $ZEV_{targeti}$ is the ZEV Mandate target at year i. The year of the target is intended to begin at the end of the period or a few years early, it will not be applied at the start of the simulation. Today the credits given for ZEV under the Chinese scheme depend on the range of the battery. In California they depend on drivetrain type and electric range. The policy trend is to reduce the advantage of some EV that can earn as much as 4 credits. For simplicity our BEV technology counts as 1.

Air Quality Emission Standard constraint

The Emission standard works as a technology ban over new vehicle sales: at the time of application a technology that is not compliant is banned from the technology mix. The policy modeled by the air quality emission standard constraint is the EURO emission standard regulating European passenger vehicles since 1992. The policy regulates pollutants from tail-pipe emissions of the following gases: carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxydes (NOx), particle matter (PM) and particle number (PN) (Nesbit et al., 2016). This policy had different limits for diesel and gasoline engines, with less stringent limits for diesel vehicles. Today this gap is reducing and both NOx and PM limits of all ICE engines are becoming more stringent.

In our model we will base the emission standard compliance on two steps. A first step will introduce the last Real Driving Emissions package of the EURO 6 RDE policy. This policy called Air Quality 1 is intended to consider real driving conditions to reduce the gap between tested and on road emissions. A second step will introduce a more stringent policy such as a future EURO 7 standard that we call Air Quality 2 that will require state-of-the art emission control technologies from gasoline and diesel engines.

The constraint in the model is modeled as follows, a technology in the mix is identified according to the compliance with the EURO Standard. The ban acts on

2. Trading between manufacturers allows a car manufacturer that has an excess of ZEV sales to sell the credits earned from its production to other companies. Banking is the mechanism of saving or owing a part of ZEV credits if the car manufacturer is over-compliant or under-compliant respectively. The saving or debt of credits can be used in future years for compliance.

technologies that are not compliant, therefore the mix will have to compensate with technologies that can be commercialized.

$$\forall\ j\ technologies\ X_{ij} \leq Compliance\ pollution_{ij} * SALES \tag{5.6}$$

where X_{ij} is the number of units of technology j at year i and $Compliance\ pollution_{ij}$ is 1 when the technology is compliant with the Air Quality emission standard at year i and 0 otherwise.

We do not check for compliance for each pollutant separately. Instead we produce a technology option that is compliant with the limits of standard for all pollutants.

5.2.3 Technology Assumptions

Air quality policies have shaped emissions control technology vehicles since its first introduction. This section will detail the areas of technology development to reduce vehicle emissions and the estimates that we consider for our simulation. The emission reduction technologies have a carbon emission component that is the same set of vehicle technologies used in previous chapters and a pollutant emission component that will be coupled with the previous package. Technology to reduce pollution from tail pipe emissions, described in Table 5.2 can be divided in two families: Gasoline and Diesel technologies.

The cost of emission reduction technologies is obtained from Sanchez, Bandivadekar, and German (2012) and resumed in Table 5.3.

The pollution reduction technologies where applied in Gasoline and Diesel vehicles in two levels: a first level that is compliant with EURO 6D Full Standard and a second level compliant with a potential EURO 7 standard from a basis that is compliant with EURO 6 c. Table 5.5 summarizes all technology hypothesis. More detail on the emission control technologies used in this study and the requirements for each policy can be found in Sanchez, Bandivadekar, and German, 2012. In Table 5.4 we describe the standard requirement for EURO 6 since 2016. Integrating a new technology component has an impact on the environmental performance and an increase of vehicle's mass. The impact on the environmental performance and mass is overall small or has no impact and was obtained from FEV, 2015.

The emission control technologies are a particular type of technology that is sometimes retrofitted into existing engines. Most emission technologies are capable of diffusing faster because they are based on the core engines of the segment and are only an incremental innovation. They can be deployed much faster than low carbon technologies that are more radical innovations. Therefore we change the diffusion profiles in this section, introduced in Chapter 2, the last column in Table

Technology	Description
	Gasoline Technologies
	Gasoline Vehicle In-cylinder emission control
Air-fuel management system	Deliver a specific amount of fuel according to the amount of air that is being drawn into the engine. Different injection systems have been developed Throttle Body Injection (TBI), Multi-point Injection systems and more recently Direction Injection (GDI).
Improved fuel burning	Variable Valve Timing (VVT) reduces NOx by improving mixture circulation.
Exhaust Gas Re-circulation (EGR)	Traps NOx emissions on the combustion chamber.
O_2 sensor	Hardware required for in-cylinder control. They are part of the On-Board Diagnosis (OBD) systems required since Euro3 standard.
Low thermal capacity manifold	Keeps exhaust gases hot during cold starts to reduce the catalyst activation time.
Water Charge Air Cooler (Water CAC)	Air-to-liquid intercooler that transfer intake char heat to a fluid, usually water which finally reject heat to the air. through a radiator.
	Gasoline Aftertreatment Systems
Catalytic Converter	Reduces HC, CO and NOx by a Three-way Catalytic Converter (TWC).
Gasoline Particle Filter (GPF)	Wall flow PM filter for Gasoline Engines necessary with GDI.
Heating Grid	Used to warm up air flow input of the engine used in cold-start.
	Diesel Technologies
	Diesel In-cylinder emission control
Variable Geometry Turbocharger (VGT)	Change the geometry of either the nozzle or the turbine ring area to account for changes in engine speed.
Intercooler	Required to reduce the intake air temperature for better performance and to reduce combustion temperature for lower NOx.
EGR	In Diesel engines, requires fuel sulfur level below 500 ppm to avoid pipe corrosion with sulfur compounds.
High Pressure Fuel Injection	Increases in fuel injection pressure to improve fuel penetration and atomization, and mixing of air and fuel near the nozzle. High pressure fuel pump and fuel sytem at 1800 bar.
	Diesel Aftertreatment Systems
Selective Catalytic Reduction (SCR)	Uses ammonia (known as AdBlue in Europe) to reduce the exhaust NOx on a catalytic surface. High conversion efficiencies regardless of the engine-out NOx and tolerance for sulfur content.
Diesel Oxidation Catalyst (DOC)	Uses precious metals such as platinum and platinum-palladium to oxidize HC, CO and the soluble organic fraction of PM. Effective at low temperature %50 reduction of PM. DOCs are in many cases an integral part of DPF.
Diesel Particle Filter (DPF)	Traps the solid fraction of PM, including soot. Two types: flow through PM filters: free of maintenance and reduction efficiency of 40-70 % and Wall-flow PM filters with efficiency higher than 95% but the accumulation of PM solid fraction needs to be carefully monitored to avoid increasing exhaust backpressure, which directly reduces engine performance.
Lean NOx Trap (LNT)	Used in lean-burn engines, based on materials that can absorb NOx during periods of low temperature, or lean periods, and then release them during minimal periods of rich operation to be reduced in a TWC function.

TABLE 5.2 – Description of Emission Control Technologies in Gasoline and Diesel Engines. Gasoline Vehicle engine technology try to set conditions for stoechiometric combustion (ideal mix of air and fuel in the combustion chamber) and Diesel engine technology try to increase fuel pressure to improve mixture of air and fuel in the fuel intake. Source:(Sanchez, Bandivadekar, and German, 2012)

Technology	Cost in USD	Cost in €
Gasoline Technologies		
Engine Modifications	20	15.6
EGR	39	30.4
O_2 Sensor set	40	31.2
Low thermal capacity Manifold	45	35.1
Water CAC	45	35.1
TWC	82	64.0
GPF stand alone	88	68.6
GPF + TWC	121	94.4
Heating Grid	100	78
Diesel Technologies		
Turbocharger	128	99.8
Intercooler	30	23.4
EGR	92	71.8
Fuel System High Pressure	399	311
SCR	508	396
DOC	68	53
DPF	323	252
LNT	388	303

TABLE 5.3 – Technology Cost of pollutant emission reduction technologies for a lower-medium segment.

Pollutant	Euro 6 Light-Duty	
	Gasoline	Diesel
CO	1.0	0.5
HC	0.1	
HC+NO_X		0.17
NO_X	0.06	0.08
PM	0.005[a]	0.005
PN (#/km)	6.0 e11[b]	6.0e11

TABLE 5.4 – Light-duty Euro 6 vehicle emission standards on the New European Driving Cycle (NEDC). [a] applicable only to Direction Injection engines, 0.0045 g/km using the PMP measurement procedure. [b] applicable only to Direct Injection engines, 6 e12 #/km within the first three years of Euro 6 effective dates. Source: Williams and Minjares (2016)

5.5 shows that all Baseline ICE Engines and their emission control variants have a HIGH diffusion profile meaning that they can diffuse faster.

Technology	Description	Cost in €	CO_2 Emissions in gCO_2/km	Mass in kg	Initial Share %	Diffusion Profile
Gasoline	O_2 sensor set + TWC	1950	105	1000	22	HIGH
Gasoline EURO 6d Full	+ GPF + TWC underfloor	2044	105	1010	23	HIGH
Gasoline EURO 7	+ e-Water CAC + enhanced EGR + GDI + Heating Grid	2204	100	1020	2	HIGH
Gasoline 12V	Euro 7 Compatible	2350	98	1020	2	MED
Gasoline 48V	Euro 7 Compatible	3150	91	1040	1	MED
Gasoline HEV	Euro 7 Compatible	4650	80	1130	1	LOW
Gasoline PHEV	Euro 7 Compatible	5950	40	1230	1	LOW
Diesel	EGR + High Pressure Injection + DOC + SCR	2950	95	1070	25	LOW
Diesel Euro 6d Full	+ LNT + SCR underfloor + enhanced EGR *	3300	94	1095	15	HIGH
Diesel Euro 7	EGR enhanced + CR lower **	3315	93	1095	2	HIGH
Diesel 12V	Euro 6dFull Compatible	3350	89	1090	2	MED
Diesel 48V	Euro 7 Compatible	4150	83	1110	1	MED
BEV	Zero emissions	7950	0	1450	3	LOW

TABLE 5.5 – Summary of Cost, Emissions, Mass, Initial Share and Diffusion Profile of vehicle technologies for a lower-medium segment. The hypothesis of Gasoline and Diesel variants of emission control technologies are build as follows: Baseline + Technologies for first compliance + Technologies for second compliance. *In Diesel engines there are existing elements of the first compliance that are enlarged or enhanced for the next target. Underfloor means that the aftertreatment element is bigger and is located under the cabin. In this case cost increases by 10% of elements that were already present.**CR means Compression ratio and is an engine modification to improve combustion.

To compare the Air quality performance of a technology portfolio, we define an pollution emission note for each technology. To relate to the emission standard we took the same categories and assigned a note from 0 to 4, shown in Table 5.6. The total note for a portfolio is the average note of the technology portfolio. It is high for a more polluting mix and low for a more clean mix.

5.2.4 Scenarios of CO_2 and Air Quality Policies

The objective of building different scenarios is to test different combinations of environmental policies and show the impact on technology mixes. In terms of

Technology	Pollutant Emission Note
Euro 6 Technologies	4
Euro 6d Full Technologies	2
Euro 7	1
BEV	0

TABLE 5.6 – Pollution Emission Note depends on the EURO emission compliance shown in Table 5.5 for each Technology. A high note means that the technology is a high pollutant.

comparison of policies we want to see how the combination of policies changes technology choices. These changes are visible in terms of the CO_2 emission level of the mix, the type of technologies favored by a policy, the cost of the mix and the emission performance on the two dimensions of vehicle's emissions. The fuel economy standard serves as a common policy that is combined with other policies to test its effects from a common basis.

At the technology level, we can identify which technologies are preferred under different policies. For example, the analysis of a Diesel vehicle from the perspective of policy compliance of multiple objectives shows that it will probably be absent from the technology portfolio in 2030. It is not among the most cost-efficient solutions to reduce CO_2 emissions, this technology is restricted from both types of LEZ, it does not provide ZEV credits and it can not be certified with the more stringent Air Quality emission standard. The opposite case is seen with BEV, it is compatible with all policies and produces an improvement from incumbent technologies. We will see what happens for more technology choices in section 5.3.

The trend at the portfolio level is less obvious, the policy conditions require different technology mix adapted to each of the policy specifications. When a policy is applied alone, a technology mix will evolve to the least cost solution adapted to the policy objective. When we compare the technology mix of the application of policies independently we expect to find different mixes or similar mixes if the policy objectives are similar. However when policies are overlapped the expected results are less obvious because the policy package has more conditions that limit choices. We wish to quantify the difference between cases of application of a single policy and cases of application of two policies at the portfolio level. We only check for a policy package containing a CAFE policy, we do not study other combinations. In section 5.3 we will see how the technology mix evolves in each scenario.

From a policymaker perspective the objective is to create a policy package with the least cost to society to solve passenger vehicles externalities. There are combination of policies that perform better: they have a better carbon and pollutant emission levels and they cost less. This type of optimal combinations are a suitable policy instrument.

Since environmental policies are not yet established in the long term we explore a range of possible values for each policy. Each Scenario is a possible policy framework that is based on existing policies. There are 5 types of policies: CAFE, ZEV Mandate, LEZ ICE ban, LEZ ZEV force and Air Quality Standard. Scenarios of application of single policies are analyzed to test the technology choice when there was a choice only with the policy mechanism independently. To assess overlapping policies we construct Scenarios that have a two policy package that try to identify the effect of policy when combined with a common CO_2 constraint. A Baseline Scenario called No Policy without policy efforts is also modeled to see the cost gap between the base Scenario and the Policy Scenarios.

— The CO_2 only scenario corresponds to a strategy aiming to respect a fuel economy standard in 2030. For this scenario, the range of possible targets is 60 to 80 gCO_2/km. The model of CO_2 emissions constraint and targets is common to all Scenarios.

— The CO_2 and Air Quality emission regulation scenario corresponds to a strategy aiming to respect the 2030 target and a vehicle emissions regulation that does not allow registration of non compliant vehicles. This scenario has to both optimize technology choices over the time horizon to minimize the overall discounted compliance cost for the 2030 target and comply with the minimal requirements of the vehicle emissions regulation. The vehicle emission regulation is based on EURO standard with a two consecutive increase on stringency in 2020 and 2025.

— The ZEV Mandate scenario corresponds to a combined strategy on CO_2 emissions with a fuel economy standard and a minimum requirement on low emission vehicles as seen in China and California. This scenario looks at satisfying both an average emissions target in 2030 an a minimum low emissions vehicles (BEV and PHEV) quota in 2030.

— The CO_2 and LEZ ICE ban scenario corresponds to a strategy that would optimize technology choices for a national scale policy on CO_2 emissions and a local scale policy led by local policymakers that will progressively ban the use of ICE vehicles in urban areas. The ban starts with diesel followed by an all ICE vehicles ban 5 years later.

— The CO_2 and LEZ ZEV force scenario corresponds to a strategy that has the same aim of CO_2 and LEZ ICE ban scenario that is to reduce local air pollution in urban areas. However, this scenario goes beyond on technology ban and only allows low emission vehicles in urban areas from 2030. The difference relies on HEV that are allowed on LEZ ICE ban scenario but are not allowed on LEZ ZEV scenario.

Table 5.7 and 5.8 summarize the scenarios and environmental policies considered. There is a difference in the nature of policies that affects how a car manufacturer prepares for each policy. On the one hand, the CO_2 policy, CAFE is based on the average of new vehicle sales. On the other hand, all other policies are at technology or vehicle level in various forms a ban, a quota of technologies or a minimal requirement of local pollutants regulated.

Scenario	Climate Change Policy	Urban Pollution Policy	Target	Horizon	Other
No policy	None	None	-	-	CAFE target fixed at initial CAFE
CO_2 only	CAFE target in 2030		60-80 gCO_2/km	2030	without Mass-indexed*
Air Quality standard	None intended	EURO standard	6dFull and 7	2020 and 2025	
ZEV Mandate	Quota for ZEV		25-37 credits	2030	1 credit/EV 1/2 credit/PHEV
LEZ ICE ban	fossil-fuel engines ban	tech restriction in cities	start:Paris +10%/year	Diesel start:2022-2025 Gasoline start:2027-2030	Max coverage varies
LEZ ZEV force	ZEV push	tech restriction in cities	start:Paris +10%/year	ZEV start:2027-2030	Max coverage varies

TABLE 5.7 – Scenarios of Environmental Policies for Passenger Vehicles. For each Scenario, we separate policies that aim at a Climate Change mitigation and policies that aim at reducing air pollution in urban areas. *CAFE standard is also modeled with mass-index mechanism in Appendix E

Scenario	Climate Change Policy	Urban Pollution Policy
CO_2 & Air Quality Standard	CAFE target	EURO standard
CO_2 & ZEV Mandate	CAFE target and quota for ZEV	None
CO_2 & LEZ ICE ban	CAFE target	tech restriction in cities
CO_2 & LEZ ZEV force	CAFE target	tech restriction in cities

TABLE 5.8 – Scenarios of Combination of Environmental Policies for Passenger Vehicles. For each Scenario, there is a fuel economy standard component common to all. Target values and time horizons are the same of the application of a single policy in Table 5.7.

5.3 Results

In this first part of Results we will model a CAFE target of 77 gCO_2/km, a ZEV target of 37 credits as defined in 5.2.2, an introduction of LEZ ICE ban for Diesel in 2022 vehicles and Gasoline and Diesel vehicles in 2027 and an introduction of LEZ ZEV force in 2027. From these assumptions we have varied the CAFE target in Figures 5.2, 5.3 and 5.6.

The application of an environmental policy on passenger vehicles has an impact on the overall carbon emission performance of a technology mix. In order to assess this impact we have isolated the effect of a policy by applying one policy at a time and comparing it with the application of a two policy package with CAFE. Figure 5.2 shows the gap to the CAFE target in 2030 of 4 scenarios with CAFE policy. If the gap is negative the scenario has an average emissions lower than the CAFE target meaning that CAFE is not the restrictive policy. The application of the policy requires efforts that go beyond the application of CAFE target only.

The conditions that can explain a need for lower emissions of the technology mix are related to the policies objectives: a quota of ZEV at a national or local scale and a ban on ICE vehicles in LEZ. The CO_2 & AQ scenario produces always an emission level equal to the CAFE target, this means that for all targets, CAFE is binding. For CO_2 & LEZ ZEV force and CO_2 & ZEV Mandate scenarios, the minimum quota for ZEVs reduces carbon emission levels below the CAFE target. The same effect is seen in the CO_2 & LEZ ICE ban scenario because of a need to transition out from Diesel and Gasoline engines locally. Figure 5.2 is an indicator of which policy is more demanding in terms of CO_2 emissions.

To check if technology choices are different between the two policy package scenario and the CO_2 only scenario we analyze the gap on sales share for selected technologies from the CO_2 only scenario in 2030 in Figure 5.3. If the gap is zero, it means that the CO_2 only scenario and the combined scenario have made the same choices. We can see that for stringent targets of CAFE, the gap is small which means that choices are closer together. But for less stringent targets, the gap is large and the logic of the policy that is not the fuel economy standard prevails. The CO_2 + LEZ ICE ban scenario is different in Gasoline and Diesel share because it can not develop the share of optimal Gasoline and Diesel due to the technology ban thus developing other types of engines, more HEV and PHEV, as seen in Figure 5.4 with the dynamic mixes of technologies. The only scenario that always produces less EVs is CO_2 & AQ standard because it is using less cost efficient technologies for reducing carbon emissions, it is the only scenario that develops the second level of compliance of the Gasoline variant which is more expensive.

When two policies demand for the same type of technologies independently, the application of these two policies results in a similar output than the result where the policy was applied independently. On the contrary when the technology requirements to comply with a policy differ from another policy, the combination of both results in a technology mix that is different or a technology that is the same of one of the policies thus suggesting that one of the policies is not binding.

Looking more closely at how each policy responds to reduce average carbon emissions, we investigate how efforts are distributed in the technology mix. We can look at the distribution of technologies according to CO_2 emission levels. Fig. 5.5 shows that when applying a ZEV Mandate the share of BEV is highest which is the intended objective of the policy but the share of the dirtiest (highest CO_2) emission technology Gasoline is also highest. Therefore, the distribution of efforts is not uniform as opposed to the case of CAFE only where the share of the dirtiest technology is lower. This is seen in other policies similar to the ZEV mandate in the energy sector when applying energy renewable quotas in combination with an ETS sector (Böhringer and Rosendahl, 2010). The difference between these policy mechanisms is that CAFE does not regulate actual total emissions but only fuel economy or emissions/km (on a normalized cycle). Actual emissions will depend on how

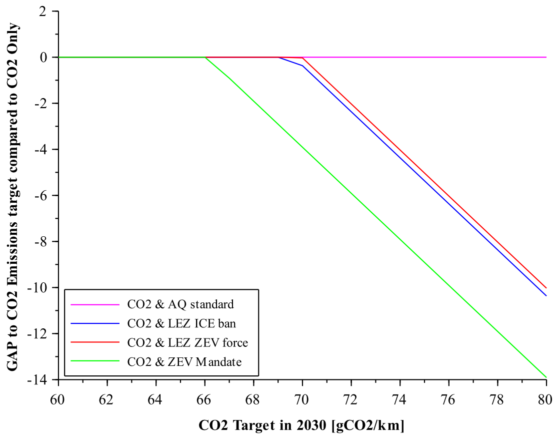


FIGURE 5.2 – 2030 CAFE Gap of a Scenario compared to the target. There are two types of scenarios: Policy only scenarios: a CO_2 only policy and two package scenarios: that include a CO_2 policy + other policies. Positive values mean that a Scenario has a higher CAFE performance than the target.

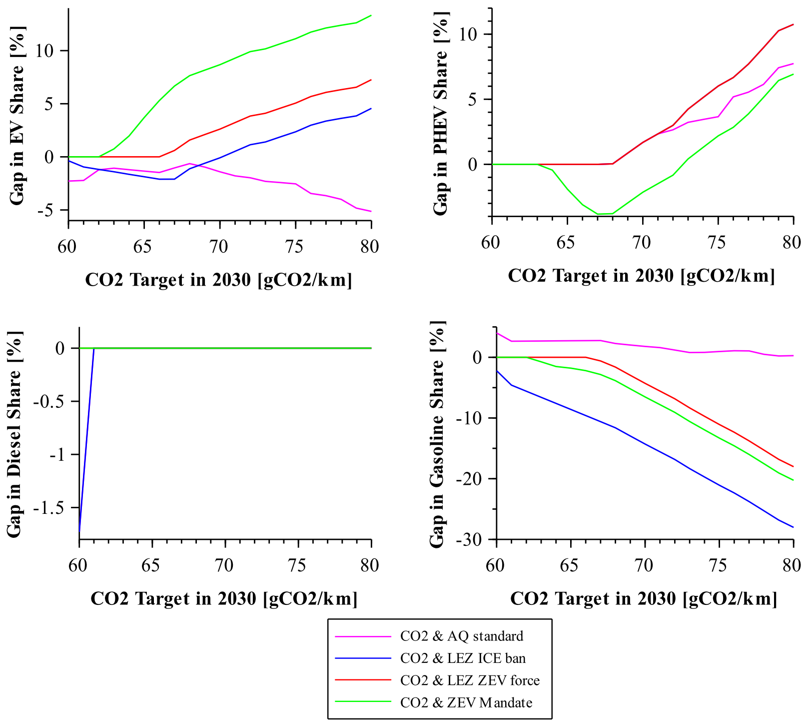


FIGURE 5.3 – 2030 Technology choice Gap between the CO_2 only Scenario and the selection of two policies Scenario. Positive values mean that the technology share in the two policy scenario is higher than the share of that technology in the CO_2 only Scenario.

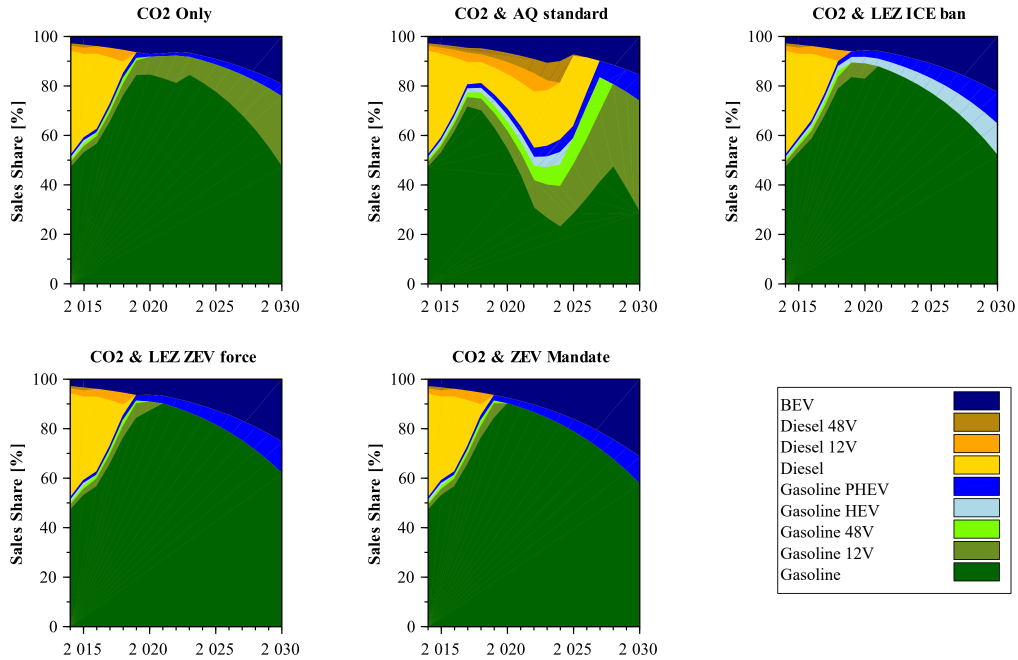


FIGURE 5.4 – Dynamic technology mixes of selected two policy scenarios compared to the CO_2 only scenario.

many km driven by each type of vehicle and on the gap between on road emissions and normalized cycle emissions. In the ETS case, emissions do not change because the scheme is built to act on emissions at electric energy supply. With a CAFE policy, emissions can be more than what the fuel economy average says if the dirtiest vehicles are driven more.

In the same figure we can see that a LEZ ZEV force scenario is close to a ZEV Mandate policy. In absolute terms a ZEV Mandate does not constraint the place of use of a ZEV whereas a LEZ policy requires using the low emission vehicles in urban areas. The Air Quality policy changes the type of Gasoline technologies compared to the CO_2 only scenario where Gasoline technologies are not compliant with a second Air Quality standard. We have said above in the scenario definition that an HEV is allowed in a LEZ in scenario LEZ ICE ban but it is not allowed in the LEZ ZEV force scenario. This is why we can see HEV appearing in CO_2 and LEZ ICE ban scenario.

To see the effect of policy compliance on the overall environmental performance: air pollution + climate change, we have first analyzed what is the tendency of the combination of policies compared to the application of the policy alone in terms of two criteria: the CAFE performance and emissions performance measured in share of polluting vehicles. The pollutant emissions performance is represented with a note that is high for a more polluting mix and lower for a more clean mix, as described in section 5.2.3. On the one hand, we have compared the single application of X policy with CO_2 only scenario. On the other hand, we have compared the two policy package policies: CO_2 + X policy with CAFE only scenario.

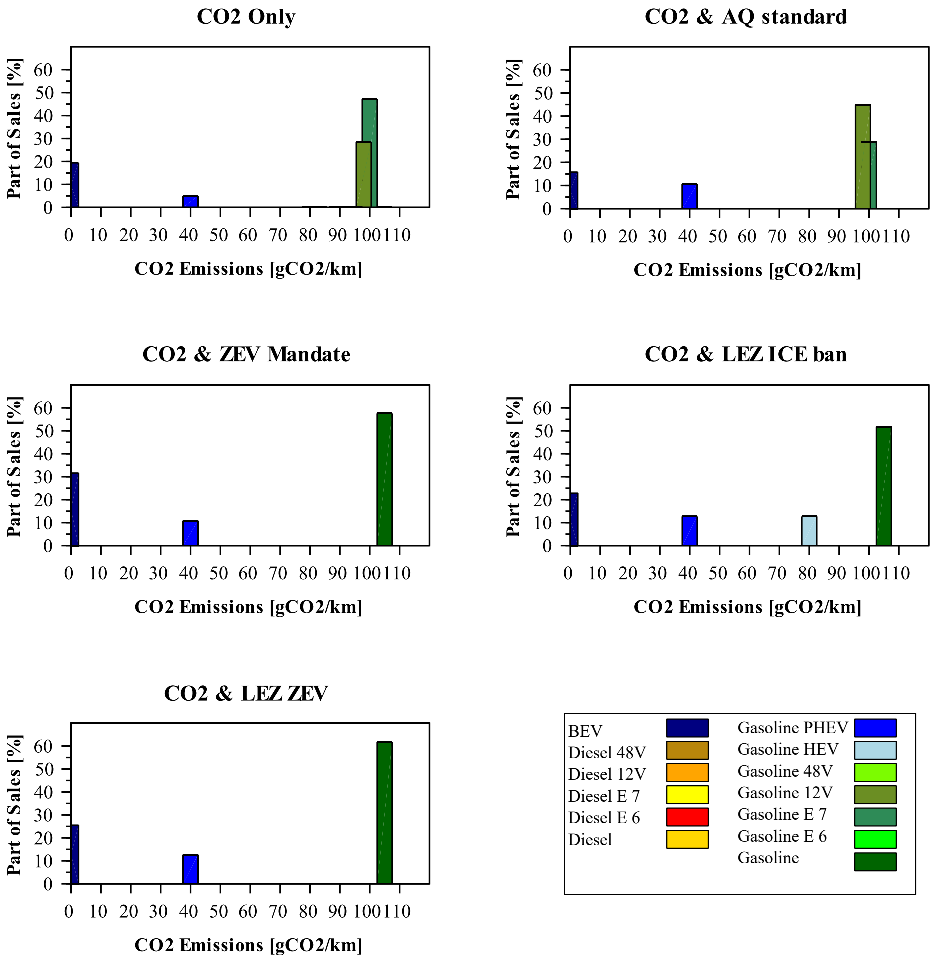


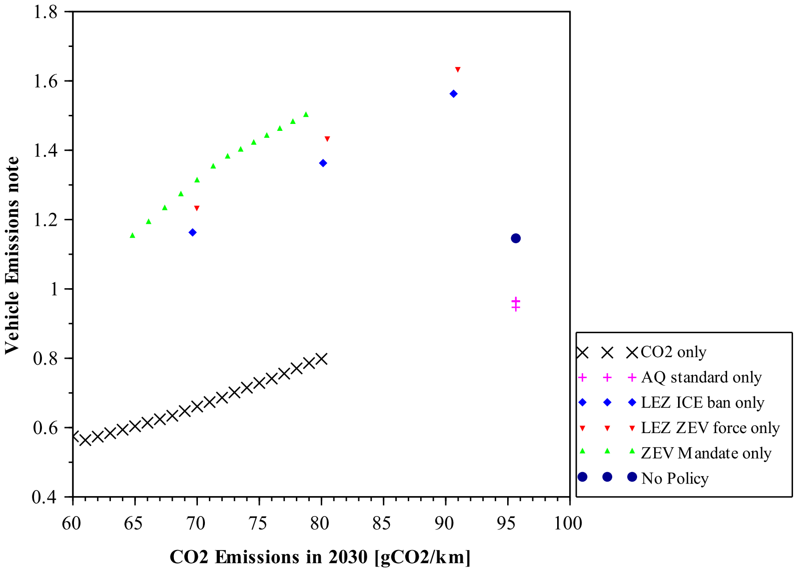
FIGURE 5.5 – Comparison of the distribution of technology choices in a CO_2 emissions dimension for 4 Scenarios: CO_2 only and selected two policy scenarios.

First, when modeling policies independently in panel a of Figure 5.6 the difference in each point of the figure is a different stringency for the policy modeled for example in the case of ZEV Mandate it is a change on the ZEV target. A ZEV Mandate, a LEZ ICE ban and a LEZ ZEV force have all a positive trend meaning that the CO_2 Target and Vehicle's emissions note improve when the other policy condition improves. A CAFE only policy always positively relates CO_2 and other pollutants which means a policy that focuses on climate change only can produce an improvement of air pollutant emissions too. A more stringent CAFE target will improve the CO_2 emissions performance and Other Pollutants emissions too. The AQ standard only scenario is different, for a variation of the policy condition there is no improvement in CO_2 emissions. Compared to the baseline scenario without any policies, the AQ scenario produces the same CO_2 emissions in 2030 but only a better air pollution note. Therefore this policy alone does not produce any effect on CO_2 emissions.

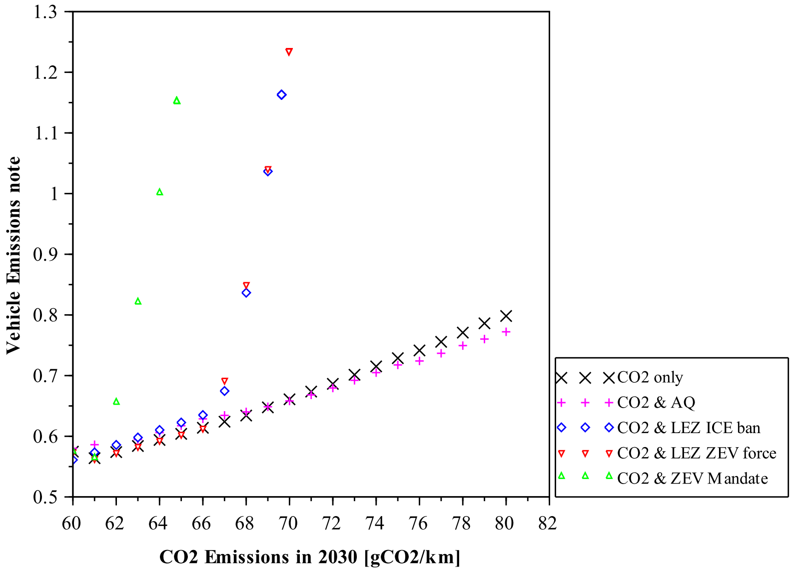
Second, we focus now on panel b of Figure 5.6 to analyze the combined effect of policies. In this second figure, the policy condition are the same as before defined in the introduction of this section. The variation of each point in the figure comes from a change in the CAFE target. We can see that an Emission standard appears to have a positive effect with CAFE for all targets but the trend is almost equal to the scenario of CAFE only, thus the effect is minimal. For the CO_2 + ZEV Mandate, CO_2 + LEZ ZEV force and CO_2 + LEZ ZEV ban there is a change in the relationship between the air pollutant note and CO_2 emissions. There is a point where the slope is steeper, meaning that when the CAFE target gets less stringent the pollutant emission note gets worse but the CO_2 emissions perform better than the expected target. If we relate to Figure 5.3 we can see that the turning point correspond with the point where the gap in BEV share is higher in both ZEV Mandate and LEZ ZEV force Scenarios. Since a BEV has the lowest pollutant emission note one should expect that the note should be better, however the share of pollutant Gasoline variant is highest in these scenarios which makes the average pollutant emission note increase more rapidly.

The fact that both the LEZ policies and the ZEV mandate have higher air pollutant emissions is surprising because all three policies are intended to reduce local air pollution. The difference lies on where does the air pollution occur, in the case of the ZEV mandate we have already seen that it contained the dirtiest technology in terms of CO_2, Figure 5.6 shows that it also contains a high share of polluting vehicles, specially when the CAFE target is less stringent. For the case of LEZ, the difference is that only a part of new vehicles sales is bound by the policy. Which means that the other part of new vehicles sales does not have a requirement to have low pollutant emissions.

To complete the study of the impact of policy application for a car manufacturer, we perform an analysis of the Total Cost of Possessions of a vehicle that will tell the cost for society of the application of a policy. This cost is divided in two



(A) Single Policies



(B) Combination of two policies

FIGURE 5.6 – CO_2 Performance and Other Vehicle's emissions with Environmental policies with different levels of stringency. (A) Application of a single policy at each time. An increase of stringency in each case is: CAFE policy: a lower target, ZEV Mandate: a higher target, both LEZ and QA (Emission Standard): a year earlier. (B) Application of a combination of CAFE with other policies. The increase of stringency in Scenarios is only due to a change in the CAFE target.

components the cost of technology and the cost of mobility of a vehicle. This analysis uses the same framework employed in Chapter 4 to obtain the cost of fuel, the kilometers driven and fuel consumption. In Table 5.9 we show that a CO_2 only scenario is the least cost scenario when preparing a CAFE policy in terms of cost of production which is expected since this model has fewer constraints than the other scenarios. However, in terms of Cost of Mobility a CO_2 only scenario produces the worst performance, the cost of usage of a car fleet deriving from this scenario will be higher. Combining all costs it is still the CO_2 only policy scenario that is the best in terms of cost of usage and cost of production. Other externalities such as pollutant emissions are not monetarized and might change the result.

When the overcost is higher than any of the single policy scenarios, both policies are binding. In the absence of an increase in cost of the two policy scenario compared to either one of the single policy scenarios we can deduce that a policy dominating is the other, meaning that one policy has stricter technology conditions that are also compatible with the other policy.

When comparing the single policy cost and the combination with CAFE Fig. 5.7, the Total Cost of Production per vehicle is higher when combining policies due to an increase in constraints. First of all, we can see that for the case of LEZ policies and ZEV Mandate, the combination with CAFE yields the same cost, the emission level of the LEZ policy scenario applied independently already complies with the CAFE target thus the CAFE policy is not really adding any constraint. The overcost for complying with a CAFE policy is the lowest among these three policies, in these conditions we also saw that all these policies overcomplied with the CAFE target thus adding a CAFE policy does not changes the result and there is no impact on cost. For policies that are compatible, it is expected that the Total Cost of Production also read as the total cost of compliance will be lower than the sum of the application of the two policies. We see this degree of shared effort between the policies when the cost of application of the two policy package is smaller than the sum of compliance cost of each policy independently. CAFE and LEZ ICE ban policy, CAFE and LEZ ZEV force and CAFE and the ZEV Mandate show this behavior. In Fig. 5.8 we perform the same comparison of Scenarios from the No Policy Scenario basis but with a more stringent CAFE target of 62 gCO_2/km in 2030. In this more stringent case, the CAFE target is binding, adding a policy to the CAFE policy does not produce a significant increase in cost. The air quality emission standard shows a very different behavior, the compliance of both policies costs more than the sum of each policy applied independently showing that between these policies there are no shared efforts.

Appendix E will describe the effect of CAFE indexed to mass when combined with the policies treated in this Chapter. We show that the mass indexation favors heavier vehicles which creates more compatible conditions in technology choice

Scenario	Total Cost of Production in k€	Total Cost of Mobility in k€	Total Cost of Possession in k€
CO_2 only	2.01	1.37	3.38
CO_2 & Air Quality standard	2.26	1.31	3.57
CO_2 & ZEV Mandate	2.17	1.33	3.50
CO_2 & LEZ ICE ban	2.14	1.35	3.48
CO_2 & LEZ ZEV force	2.10	1.35	3.45

TABLE 5.9 – All Scenarios without mass index. Summary of Total Cost of Possession per vehicle: sum of Total Cost of Mobility and Total Cost of Production.

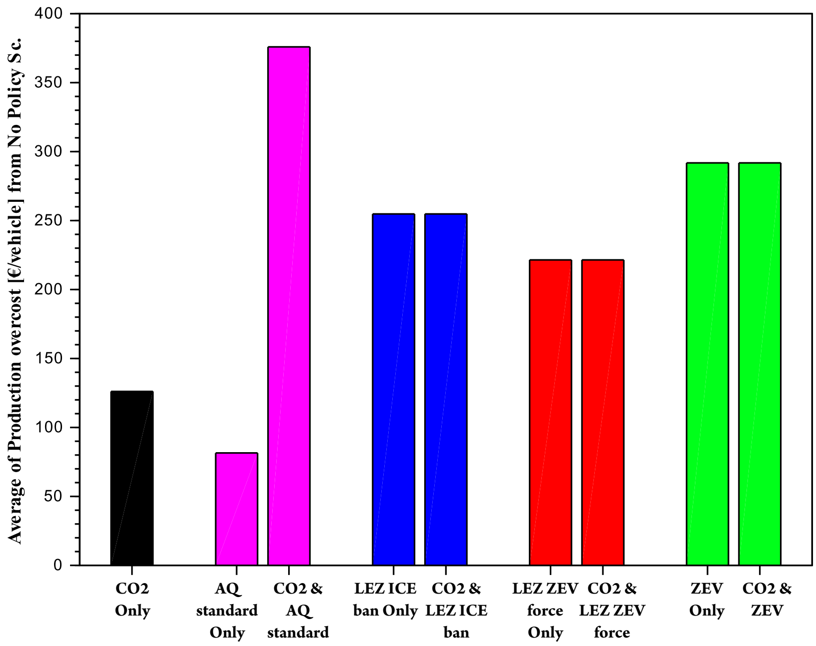


FIGURE 5.7 – Comparison of the overcost of compliance with one single policy and the combination with CAFE policy from a policy Scenario.

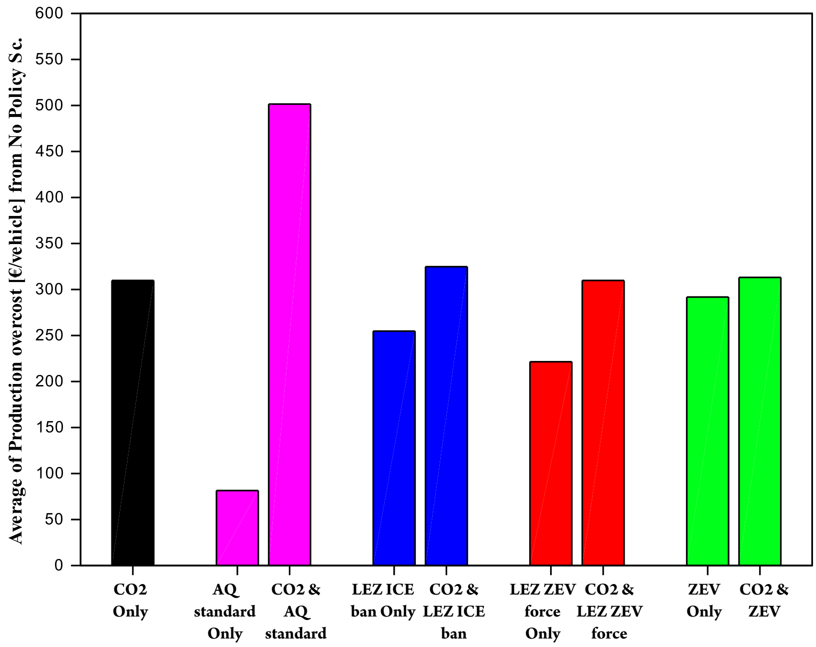


FIGURE 5.8 – Comparison of the overcost of compliance with one single policy and the combination with CAFE policy from a policy Scenario with a CAFE target of 62 gCO_2/km.

with two policies: LEZ ZEV force and the ZEV Mandate but it reduces the compatibility of LEZ ICE ban and worsens the differences of an Air Quality Standard and CAFE.

5.4 Discussion and Conclusion

Environmental policies have an impact on carmaker's technology choices, the abatement of carbon emissions and the reduction of pollutant emissions. Today there is a growing number of policy instruments that focus on a fraction of emissions but not all emissions. We have analyzed the independent and combined effect of policies and found that the selection of technologies is different from policy to policy, thus a several conditions are key to determine what is the effect of the combination of policies. Stringency and timing are elements that determine whether a policy will be more difficult to comply. The reasons of these differences in choice are also due to the nature of the policy if it is a technology-based instrument or not and the technologies at disposal that are more or less adapted to policy criteria.

When policies are combined more criteria is included to assess the cost-optimal technology thus making the selection of technologies more challenging since there will be less adapted solutions for the given constraints. The impact of the ZEV Mandate and LEZ ZEV force policies on technology choices has two implications: first, it is a technology specific policy that produces a high share of EV and second, they do not push for incremental improvements of ICEV. Therefore, it has a path dependency on EVs and do not decrease the carbon emissions of conventional vehicles. A

CAFE standard and a LEZ ICE ban distribute abatement efforts more evenly. Such a behavior is similar to a Renewable quota combined with an emission trading scheme in the energy sector where an increase in the share of Renewable energy is compensate with an increase in non renewable energy such as carbon plants, this effect is defined as "the green promotes the dirtiest"(Böhringer and Rosendahl, 2010). The fuel economy standard combined with a policy promoting plug-in vehicles (ZEV Mandate and LEZ ZEV force) produce the same effect. However, the difference with the energy sector is that CAFE applies on fuel economy and does not bind real emissions driven by vehicles. Final emissions from vehicle's usage will depend on how many km they are driven and the gap between test cycle fuel economy and real fuel economy.

The combination of policies were studied from three perspectives: technology choices, overcost of policy compliance and environmental performance on both dimensions of vehicle's emissions. Analyzing technology choice determines how close the requirements of a policy are to other policies. We show that depending on the stringency of a policy, the technology requirements can be more or less demanding which in turn can change how similar technology choices of two policies are. Looking at the portfolio of technologies we saw that some technology mixes are very similar to the scenario with a CAFE policy only. This proofs that the CAFE policy is the dominant policy, the one that constraints the most.

In terms of social cost of the policy we have obtained the technology cost and the cost of usage for different policy scenarios. We found that for a CAFE policy not stringent, there is no overcost for a policy package combining a fuel economy standard with another policy. For the case of a very stringent CAFE policy target, there is an overcost to comply with the fuel economy standard because it is more difficult to comply. For all cases, low or high stringency CO_2 targets, the emission standard with a CAFE policy requires the most expensive social cost showing that the air quality emission standard and the CAFE policy do not help each other.

In the case of the two main dimensions of vehicle emissions CO_2 and air pollutants we have studied how a change in policy stringency changes the performance on these dimensions and what happens when they are combined with a CAFE target. In the CO_2 dimension we observed that a change in policy stringency produces lower CO_2 emissions for all cases except for an emission standard. In the air quality dimension, a change in policy stringency produces a better air quality note. When policies are combined we have lower performance on the air quality dimension for the two types of LEZ and ZEV Mandate but better performance for some CO_2 targets after the threshold. The combination of a fuel economy standard and an emission standard produces very little variation from the scenario of a CAFE only application. When the emission standard is applied alone there is no effect on CO_2 emissions.

The model of a LEZ is based on the assumption that all urban areas in a country will apply the same type of scheme. Although some countries do apply similar policies in cities such as the "vignette" (labels) restrictions in French cities, Italy does not have a common framework. Thus a common model of LEZ is not adapted for regions with high diversity of LEZ. The application of LEZ are related to local government willingness to control air pollution. The LEZ policy produces an impact on the entire vehicle fleet, although we consider a large impact of the policy in departmental sales, further research on the consumer reaction to a LEZ policy is necessary. Despite increasing concern on air pollution there is no certainty that LEZ scheme will spread to other cities or will become more restrictive.

Our model of local policy impact estimates that the departmental sales are affected by the urban policy. In practice, this assumption holds for people driving in and out the restricted area. However for people doing peripheral driving outside the restricted zone they might not be limited to choose a technology that is more expensive but allows them to enter the city-centers. To check if this assumption holds a detailed analysis of mobility of passenger vehicles is required to check for the share of vehicles affected by a LEZ in a department. Data on community level will reduce the mesh of vehicle registrations and can improve the model.

The assessment of vehicle usage is only focused on fuel consumption and the cost of usage is derived from how much fuel is burned during a vehicle service. The other externality that we treat in this Chapter, air pollution, is not quantified we do not know the quantity of a given pollutant emitted by vehicle usage. We could make an assumption on the policy limits of the Air Quality emission standard. Nonetheless real driving performance of technologies on each type of pollutant is required to make an assessment on air pollution. The challenge of quantifying air pollution is that, unlike carbon emissions, the location of the source is important to determine the concentration of emissions at a given location. Thus a vehicle sales model at the community level is a potential tool to make an air pollution assessment.

Different policy mechanisms are implemented to correct a variety of externalities resulting from vehicles emissions. These mechanisms induce technology change in vehicles that increases vehicle cost. The technology solutions that solve for more than one externality: CO_2 and air pollution perform better than those focusing on a single externality. When preparing a future portfolio of technologies a firm should choose technologies that have good performance among all externality indicators to avoid the risk of having a technology that is not adapted to a policy. The emission standard is a policy that has technology requirements different from other policies, neglecting adaptation for this policy might put the technology portfolio at risk if a future change in the policy package includes an emission standard. With more policy pressure on environmental externalities car manufacturers will face a future of more overlapping policies that will reduce the margin to maneuver the technology portfolio. In this Thesis with the current assumptions the best solution from the perspective of climate change and air pollution is a BEV.

A policymaker has different tools to regulate the passenger vehicle market, they vary in scope, stringency and mechanism. The scope of policies should be as large as possible to avoid compensating effects seen in a technology specific policy such as the ZEV Mandate. When policies apply to all vehicles there is less risk that very polluting vehicles are still present in the market. The effect of a ZEV Mandate alone does not guarantee that the average emissions of a fleet reduce year by year. The advantage of a ZEV Mandate is that it sets a strong signal to develop a plug-in vehicle ecosystem (Fox, Axsen, and Jaccard, 2017) that requires a joint effort of technology development, infrastructure deployment and change in consumer behavior.

Policies on new vehicle sales are based on estimations on the vehicle usage that can be wrong, emission test cycle have failed to capture real driving emissions. Thus a policymaker should create instruments that are as wider as possible including the new and existing fleet. A fuel economy standard and an emission standard are designed from assumptions on vehicle mileage and environmental performance on test-cycles. These policies work best if the assumed vehicle mileage is close to real vehicle mileage and the assumed performance on test-cycles is close to on road performance. After vehicle sales there is room for policy instruments that regulate the entire vehicle fleet.

Stringency of policy instruments can considerably change the difficulty of complying with an objective, when preparing a new target an assessment on the impact on other policies is necessary to understand how the technology change will be oriented. Various mechanisms are applied in the passenger vehicle market that are not always complementary. When there are opposing selection criteria between policies the final policy package cost will be high, thus a policymaker should consider how to effectively solve a group of externalities without creating these type of effects as much as possible. In some cases this is challenging since technology requirements might be very different between policies, we saw this type of situation in the combination of a fuel economy standard and an emission standard.

The four challenges that a policymaker face are a selection challenge that is intended or unintended bias on technologies favored by the policy, an stringency challenge that is the policy goal, a stability challenge that is the coherence of policy over an extended period of time and a scale challenge that is the balance of the policy budget (Bergek and Berggren, 2014).

Time horizon of various policy instruments is different with some policies producing long term signals and other policies only having a shortsighted objective. The difference in planning makes a policy more urgent than the others. Timing technological change such that it suits all policy objectives requires studying different policy outcomes and promoting solutions that are compatible with a large range of objectives.

The overlapping of policies is not limited to two policies, in current markets there are more than two policies on vehicle's emissions that can produce less obvious implications. In the French market, three distinctive policies are applied to vehicle emissions: a CO_2 emission regulation, an Air Quality emission standard and a fee and rebate based on CO_2 emission. We have not analyzed the combination of three policies, further research should investigate what are the implications of a larger policy package. There are policy announcements that show a willing to transition from fossil-fuel vehicles to electric vehicles. These policy signals are more severe policy constraints, in France the government plans to ban all ICE vehicles in 2040. The Netherlands and Norway plan to ban the same category of vehicles as early as 2030 and 2025 respectively.

Recent efforts from the Global Fuel Economy Initiative (GFEI) have considered a label of a larger set of externalities upon a notation mechanism which considers tailpipe emissions, energy efficiency and noise called GreenNCAP. Although this program is based on safety New Car Assessment Programme (NCAP) tests which rates vehicle's safety but do not require specific compliance for a carmaker, it can be a potential multidimensional indicator of environmental performance. With such a label, the impact of such policy mechanism depends on consumer's value of a vehicle's note. Such mechanism deserves further research to check if it is complementary with existing instruments and how it will steer current automotive technologies.

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Chapter 6

Conclusion

The future technology mix of light-duty vehicles will determine if car manufacturers are successful in developing a clean vehicle fleet, and ultimately the emissions externalities associated with the vehicle fleet use to provide mobility services. This thesis has shed some light on the evolution of technology choices under emissions policy and technology diffusion inertia constraints, with three perspectives applying a technologies choices optimization model developed within the thesis. All three perspectives study a specific aspect of the corporate average emissions standards that regulate car manufacturers. The first focused on the dynamic aspect of the standards with consecutive targets that increase in stringency over time. It studied how the anticipation (or not) of a long-term target changes short-term technology choices, and how how reaching short-term targets enables or hinders the attainment of long-term targets. The second perspective focused on the design of the standard that in some jurisdictions, notably Europe and China, indexes the target on the average mass of vehicles sold, making it less stringent for heavier vehicles. It analyzed how such indexation influences technology choices, emissions and the cost of respecting the regulation. The third perspective was centered on the overlap of several policy instruments, the CO_2 emissions standard, zero emissions vehicles mandates and local air quality policies. This last section of the thesis will summarize the main results in section 6.1 then it will cover the potential improvements and further paths for this work in section 6.2. To conclude this thesis I will discuss the implications for an automotive firm and for policymakers in section 6.3.

6.1 Summary of Results

The policy instruments that are implemented in the automotive market try to solve the externalities of the negative impacts of vehicle's emissions. We have focused on two impacts: global warming and air pollution. The fuel economy standard is the central policy of this thesis that has been studied under three perspectives. First, the anticipation of long term fuel economy targets defines how a firm will prepare for an intermediate target. Second, the fuel economy standard when indexed to mass does not give an incentive to develop all low carbon technologies but leads to limited additional compliance cost. Third, overlapping policies with different objectives can collide or help each other, some combinations of the fuel economy standard with other policies do not produce a significant change in the optimal technology choices and some others require a new solution to fit two policies.

The anticipation of consecutive targets

The first perspective on policy issues of the fuel economy standard showed the implications of the type of anticipation of consecutive targets in the future. When a firm prepares a portfolio for the near term if the long term policy signals are strong they will consider a near and long term targets to optimize technology solutions. In contrast when there is no long term signal or there is doubt about the stringency of the final target a firm can prepare for a near term waiting for the long term to be strong enough to perform a change in the mix of technologies. We showed that when firms do not anticipate the long term target, there is a technological lock-in that emerge on low abatement technologies that are cheaper to produce. The path dependency on this short term technology portfolio leads to unfeasible long term targets. Our estimates showed that these conditions occur for a range of possible long term targets, and result from the inter-temporal dynamics of technology diffusion.

We illustrated that the type of choices made in the near term condition the achievement of a long term target. We showed that neglecting the long term target would prioritize the least cost technologies for a lenient target. However when using this very same portfolio of technologies to prepare stringent long term targets, it reveals ill prepared. The mix has chosen technologies that have low abatement potential thus creating a lock-in in high carbon technologies.

The indexation of the stringency of the target on the vehicles average mass

The second application on policy issues of the fuel economy standard quantifies the impact of the mass indexation of the target on technology choices, emissions, compliance cost and total mobility costs. The principle of indexing the stringency of the target on the average mass of the vehicles sold aims at being more acceptable for car manufacturers that specialize on heavier types of vehicles. It obviously introduces an incentive to increase vehicles mass, or, at least, a disincentive to reduce vehicles mass. Because different powertrain technologies imply mass changes, in particular battery vehicles are heavier, and because lightweight technologies constitute an abatement option, the standard is not technology-neutral when its stringency is indexed on the mass. The mass-indexed fuel economy standard conditions the scope of technologies that can be chosen by a firm in favor of heavy technologies. There is an incentive to develop heavier technologies that causes a reduction of the overall stringency of the target. We studied how indexing the stringency of the target on the average mass of vehicles changes the overall emissions, the technology choices, the compliance cost for the car manufacturer and the social cost of mobility. We illustrated with a quantified example taking plausible numbers for the

CAFE target, the coefficient of mass-indexation and the technologies characteristics in terms of mass, emissions and costs.

We found that mass-indexation of the target does lead to higher emissions of the cost-optimal technology mix complying with the target, and quantified the increase on an illustrative case where it amounts to 5% increase of emissions. When comparing cases where the overall emissions are forced to be equal, we found that technology choices are significantly different when the target is indexed on the mass or not. The lightweight variant of a mainstream technology is only developed in the case without mass indexation. In our illustrative case, it reaches about 20% of the sales. However, we find only very limited differences on the compliance cost and on the social cost of mobility when preparing a CAFE policy with or without a mass index.

Fossil fuels vehicles that are heavy consume more fuel than lighter versions thus a policy that incites heavy technologies should also be more expensive. Our result does not find a significant difference in social cost because plug-in vehicles are heavy technologies favored by a mass indexed standard that do not follow the logic stated above. A BEV is heavier than all fossil fueled vehicles but it is cheaper to use due to a difference in fuel price: electricity is cheaper than gasoline or diesel. Thus there are two compensation effects. First, in terms of technology costs a mass-indexed policy develops more plug-in vehicles which enables the absence of lightweight technology. Second, in terms of cost of usage a mass-indexed policy develops a cheap BEV which compensates a more costly fossil-fuel vehicle without lightweight. Overall these two compensation effects make the gap between a fuel economy standard with and without mass index very small.

The small difference found for total social cost is subject to a number of assumptions that might change the result. First, we do not model an evolution of energy prices, our fuel cost is always constant thus we can not tell how future electricity cost and oil prices will affect cost in usage in the end of period. Second, we assumed that all vehicles are driven the same mileage and they are owned the same number of years. In practice, consumers that have higher mileage are sensitive to fuel economy and tend to choose a vehicle that has high fuel economy, with high driving range and easy access to refueling/recharging infrastructure. The best cost in usage technology is a BEV however range anxiety and a lack of infrastructure does not push high mileage drivers to choose plug-in vehicles. The effect of different driving behaviors, and years of possessions for different technology types might affect the cost in usage assessment.

Overlapping policy instruments

The third perspective analyzed the effect of overlapping policy instruments with multiple objectives on technology choices. We have considered two types of vehicle emissions externalities: climate change and air pollution. On top of CAFE standards, we have modeled four other passenger vehicle policies to show the diversity of mechanisms: a Zero Emission Vehicle (ZEV) Mandate, a local pollutants emission standard and two types of Low Emission Zones (LEZ).

We showed that when stringency in CO_2 emissions related policies increases, the air pollution performance of vehicles also improves. In contrast when stringency in air pollution ambition increases, we did not see improvement on climate change ambition. We also found that when LEZ policies and ZEV Mandate are binding they improve the average climate change performance but they deteriorate the average air pollution performance compared to a fuel economy standard alone. In the case of LEZ, urban vehicles have a different technology mix than non urban vehicles but in the case of a ZEV Mandate this condition is not guaranteed.

We showed that for each policy there is a portfolio of technologies that is the least cost solution to comply with the policy. Comparing the least-cost choices for each policy instrument shows that some policies require the same type of technologies. The reasons why are a similar type of policy mechanism or an equivalent stringency on the amount of low carbon technologies. Stringency and technology specific requirements such as a share of low emission vehicles determine how close CO_2 emission policies are. Policies treating air pollutants demand different types of technologies.

The combination of a LEZ where only ZEV are permitted or a ZEV Mandate with a fuel economy standard produce the highest share of low carbon technologies which is expected by the objective of the policy. However because the CAFE standard regulates the average emissions of vehicles sold, the increase of ZEV shares are compensated by an increase in the share of high emitting technologies. Therefore, this type of overlapping policies cause a polarized distribution of emission reduction efforts where only low carbon technologies are making the abatement efforts for the entire technology mix. We have seen this same behavior appear in the electricity sector where a renewable quota combined with an emission trading scheme produce an increase in the share of renewable energy but produce also an increase in high emitting energy from fossil-fuels, such as coal power plants. In the automotive sector the difference lies in the scope of application, in electricity the emission trading scheme is applied to direct emissions unlike the automotive sector where the policy applies to fuel economy based on tank-to-wheel assessment on a test cycle. Actual emissions resulting from the usage of the vehicles sold are not directly regulated and will depend on vehicles mileage and on the gap between real emissions on the road and emissions measured on a test cycle.

We investigated the impact of overlapping policies on the additional cost of the technology mix compared to a baseline without policies. We found that if one of the overlapped policies is not binding or demands little change then the cost of compliance is determined by the more binding policy. We saw that depending on target stringency a policy can change from binding policy to not binding policy. This type of behavior was found for all policies except the emission standard that is always binding and implies an additional cost that is more than the sum of the compliance costs of each policy applied alone.

6.2 Discussion of limitations and avenues for further research

In this section, we will discuss the limitations of our modelling approach and sketch out some avenues for further research.

The modelling approach we developed rests on, and our results are driven by, the representation of a limit to the speed at which a technology diffuses in the market. A change in the automotive ecosystem is not only limited to technology research and development, it impacts all actors related to a vehicle passenger mobility. The rate of change of the ecosystem is difficult to estimate since there are supply-side and demand-side dynamics that affect how fast a technology can diffuse. Our simplifying assumption was that such complex process of the diffusion of technologies can be approximated with an S-shaped function. This assumption allowed us to capture the inertia limiting technology diffusion in a simplified model that is focused on the choices in a technology portfolio. However, it is a first approximation that captures the stylized fact but does not represent in detail the underlying mechanisms of actual technology diffusion process. Moreover, the S-shaped function used to represent the constraint on technology diffusion that is sensible to two parameters: speed of diffusion and initial sales share. The assumption of modeling a new technology under a given speed defines how fast a technology will diffuse in the future. If the market conditions for diffusion of a technology are more difficult to implement than expected, then the actual speed will be slower than predicted. Conversely, if a market is capable of putting all market conditions to get a faster pace, then the actual speed will be faster. We are limited in our approach to fit a technology diffusion speed to an observed diffusion speed seen in the past. In addition, the initial share of a technology in new vehicles sales determines the start point of diffusion. Our model does not allow instant growth of a technology, this conditions affects more those technologies with a low sales share. Thus, our results are sensible to the initial sales share of the technology mix. Varying the initial share will result in more or less growth of low carbon technology, the shape of diffusion will remain the same but it can start sooner or later. In extreme cases where the initial share of a cost-effective solution is too low, the model will have to find additional technologies to comply with policy objectives. Therefore, this modeling approach is not suited to include completely new technologies that do not exist in the market yet, such as fuel cell technologies for instance.

Second, our model of technology choices is based on the principle that a firm would minimize technology production costs to comply with a policy scenario (or compliance costs), without pricing and volume of sales adjustments. However an automotive firm does not sell technology, a firm sells vehicles that have different margin of profits. According to the type of technology a firm can raise or decrease the margin of profits, this element of price adjustment does not appear in our model. Each car manufacturer can have different strategies to put a higher or lower price on certain types of technologies depending on its own technology costs and expertise. We have modeled a single vehicle segment of a car manufacturer but in reality a car manufacturer produces more than one segment, thus it can develop those segments that are more profitable than others. We model a single segment with constant volume, a complete model of a car manufacturer would include different segments and allow a change in size although it will not change our results on policy mechanisms.

Third, the mechanism of technology choice of a car manufacturer models a firm that acts based on cost optimal choices of its own portfolio of technologies. The automotive market is a very competitive market where technology trends and expectations on technology pathways are high. Therefore choices made by a different car manufacturer influence the rationale of the technology choice of car manufacturer. Some firms decide to bet on a single technology such as Tesla developing plug-in vehicles. We model a single car manufacturer that is independent of choices made by others. This is limiting in the diversity of technology solutions, a promising solution that is cost optimal can fail to diffuse if there is no car manufacturer supporting its development. For example, hydrogen vehicles are suffering from a lack of support because all manufacturers are turning massively to plug-in vehicles.

Furthermore, we have a model of partial equilibrium where an automotive firm minimizes technology costs but faces a non responsive demand. We assume that the increase in vehicle cost due to the introduction of low carbon technologies does not affect vehicle demand. This is a limitation of scope of our model that do not consider how consumers will react to the increase in vehicle price, and to the different characteristics of alternative powertrain, such as limited autonomy of battery electric vehicle. Considering both vehicle price and cost in use, low carbon vehicles are not more costly than conventional vehicles because they are cheaper to use. A consumer that completely neglects potential savings in cost in use of low carbon technologies will be more resistant to adopt these type of vehicles. In contrast if a consumer considers the reduction in future cost in use, demand of low carbon vehicles will not suffer. Thus how consumers see future costs is important in the acceptability of low carbon vehicles. We have assumed that the demand is only limited by technology diffusion constraints but we did not include an explicit reaction of price.

We have shown three policy issues using the same framework of technology choices under technology diffusion and vehicle emissions policy constraints. Each application focuses on a distinct aspect of policy construction. We have not cover all potential issues next we list some further hints that can assess other policies or perspectives.

We centered our policy analysis on the fuel economy standard. However other policies have the goal to reduce vehicle emissions. The assessment of more policies will contrast the result of the fuel economy standard and can also study which instrument is more effective on the scope of a car manufacturer. Therefore a policy that could be implemented in the model is a feebate scheme. This instrument focuses mainly on consumer adoption, it is less adapted to our model since we do not maximize the utility of a consumer thus we can only take into account the profit maximization of a car manufacturer. To assess the welfare effects of the policy we have to combine the model of this thesis with an consumer utility model.

We have limited the scope of the model to 2030 to coincide with policy ambitions that are visible up to 2030. After 2030 the policy scenario is less clear, however a growing number of countries and cities are announcing their engagement to the objective of carbon neutrality at horizons varying between 2035 and 2050. This objective concerns all sectors and would not necessarily be directly translated to a carbon neutrality for the transport sector, but would imply very stringent emissions reductions from all sectors. In this same movement, several countries have announced goals to end ICE vehicles sales in the coming decades. If the status of these announcements are yet unclear, and it remains to be seen if and how they would be translated in legally binding policies, these announcements are a signal that future policies are likely to become more stringent. Therefore, the 2030 horizon we have adopted in our studies is not an end-point in itself but rather an intermediate transition point. The dynamics beyond 2030 implies further issues of technology diffusion, but also innovations and disruptions. Increasing the time span of the model would allow to explore those dynamics, but would require lifting a number of limitations. In particular, it poses the question of how to represent technological learning and the assumption of constant technology costs would not hold anymore. Furthermore, it would require modeling the innovations and how new technologies enter the market. Finally, policy mechanisms that would imply a ban of certain types of vehicles, and possible a large class such as all ICE, would radically change the market conditions in which technology choices would be made, both on the car manufacturer side and on the consumer side.

We have applied the model to a single vehicle segment of a particular car manufacturer that is large enough to represent the vehicle market but it is still more or less competitive in some areas. To assess a firm strategy the model will need to study all vehicle segments produced and distribute efforts between segments under different strategies. Likewise the role of game theory between car manufacturers under a policy context is key to determine whether some actors might become free riders. Our stylized model could provide a simple supply-side perspective of policy compliance to be used in game theory models. On the same note, an application of the model to another main automotive market should help challenging the results from another start point with less Diesel vehicles such as Japan and the USA.

The impact of urban policies on new vehicle sales can be improved to find which type of sales are affected. To do so, first an assessment on the mobility of the urban area and non urban area is required to identify the daily trips that enter a potential restricted area. Second, the relationship between new vehicle registrations and the place of usage is important to check the assumption that a vehicle registered in a given community is used in that place. Third, some LEZ are already announced but do not immediately affect new vehicle sales, therefore some consumers might be aware that a future car restriction will impact them and some others might not know or neglect such impact. The consumer perception of the LEZ policy signal determines the share of consumers thinking about choosing other types of powertrains because of LEZ. Finally applying the LEZ restriction to other countries with different types of LEZ will help identify or confirm trends on technology choice.

The model used in this thesis is focused on new vehicle sales of a car manufacturer. To have the complete emission assessment of passenger vehicles a stock model is needed to obtain the vehicle emissions from the entire fleet stock, new and used car. Such assessment requires studying new vehicle sales from all firms and data of the existing fleet stock, to be in position to model the dynamics of the vehicles stock evolution. We have only used a simplified assessment of car usage but many improvements are possible in the estimation of distance driven, the change in price of energy and the effect of policies of vehicle usage.

6.3 Implications of our results

Notwithstanding these limitations, and recognizing that our results constitute an illustration of stylized mechanisms concerning technology choices under emissions policy and technology diffusion constraints, this last section concludes the thesis by drawing some implications of our results, for an automotive firm and for policy makers.

Implications for an Automotive Firm

The model developed in this thesis allows a greater technological detail of low carbon technology families. It allows to assess how cost optimal a low carbon technology is compared to others when preparing for a policy target. A car manufacturer requires such information to orient investments on new resources to be able to produce new vehicles at the expected rate.

The industry has been structured to optimize each vehicle component to reduce costs to increase profits, it has developed a specialized know how on each subsystem. This silos structure favors incremental improvements on the incumbent technology that retrofit existing architectures. Disruptive technologies that change how the automotive firm is organized create a discontinuity and need more efforts to diffuse. There is no silver bullet technology to solve all requirements, constant trade-offs are made to obtain a final product that is compliant with the policy framework and competitive. Despite basing it success on increasing returns on development of ICEV, the car maker faces major challenges to engage a low carbon transition. An equilibrium is required between solidifying a new solution to produce economies of scales and searching for new niches that can help the low carbon transition. Past evidence on technological transition shows that disruptive technologies rarely develop inside the dominant system, they are exogenous and develop in niches that later find applications in the dominant system to offer an improved performance. When studying the potential of low carbon technology the constraint on technology diffusion is also a measure of how fast does the existing structure of a car manufacturer can change to deliver low carbon vehicles in a mass market. The inertia of the structure of a car manufacturer is difficult to measure but we have modeled different diffusion speeds for technologies that require less change.

An automotive firm develops a business plan which defines the portfolio of technologies for the following five years in general with a more precise vision for the next three years. This anticipation of the future contrast with a long-term ambition of policymakers to engage a low carbon transition that aims at limiting global warming to 2ºC by the end of the century. Even though long term signals exist, planning for the firm's future only occurs in the near term. When the long term context is not clear, a firm will find more difficult to fix a target. What seems to be a profitable plan for a near term target can lead to an unfitted portfolio of technologies in the future when more stringent policy targets are decided. A car manufacturer can decide to take into account weak policy signals in the future and anticipate changes in technologies. Or, it can wait and see how policy negotiations evolve and defend a less ambitious target in the future. The result of our first application study, on the anticipation of consecutive targets, highlights the risk of lock-in that a strategy that would not account for a long-term target.

The fuel economy standard when indexed to mass produces an incentive to develop heavy technologies. Lightweight technology is the field most penalized because it reduces vehicle's mass. The indexation parameter of a fuel economy standard produces an advantage, a penalty or no effect on emission reduction technologies. When a firm chooses to exploit this incentive, it is risking the chance to achieve real emission reductions instead of some reductions and a relaxation of the target thanks to a change in the parameter. If the policymaker were to change the parameter or reduce the advantage of exploiting mass instead of emission reductions, a firm focused on heavy technologies to reduce stringency of target will be in a difficult position to adapt to a new policy. The mass indexed fuel economy standard also produces an incentive to develop plug-in vehicles because they emit less and are heavy although the increase in share for plug-in vehicles comes with a decrease in the development of incremental technologies for fossil fuel vehicles. A car manufacturer that is positioned to develop a large number of plug-in vehicles will be favored by the fuel economy standard at the condition that consumers choose plug-in vehicles massively. In contrast a car manufacturer that is focused on incremental improvements of fossil-fuel vehicles does not depend on plug-in vehicles adoption but can suffer from a more stringent fuel economy target.

We have identified a similar effect with a different kind of policy, the ZEV Mandate and a LEZ ZEV force are two policies that also incite diffusion of plug-in vehicles. The difference with a mass-indexed fuel economy standard is that there are other ways to comply with the fuel economy standard in contrast the minimum quota on zero emission vehicles does not leave other possibilities to comply. Both the ZEV Mandate and the LEZ ZEV force are policies that send a clear signal for the development of zero emission vehicles, the mass-index fuel economy standard is not a clear signal, plug-in vehicles are favored because they contribute to reducing average emissions and they reduce target stringency.

When different policies overlap to regulate vehicle emissions, car manufacturers need to assess what are the adapted solutions for multi-objective policy framework. There technologies that are more or less adapted to solve one type of externality. The technology that seems to be adapted to a large source of externalities is a BEV since it does not produce direct emissions in use. There are not yet automotive policies that consider well-to-wheel emissions except for a fuel tax. There are combination of policies that require more costly technologies to respect policy limits. This is the case when the emission standard is combined with CO_2 emissions standard. To comply with the double challenge of vehicle emissions current technology mix needs to drastically change. Today we see that such rapid changes are occurring in the automotive market. In France the diesel share of new vehicles sales has fallen from 70 % in 2010 to 39 % in 2018.

Implications for Policymakers

Emissions policies have a regulatory role to push car manufacturers to develop low carbon technologies and low air pollution technologies. They also have the role to pull consumer to incentive adoption of such technologies. Our results can give some insights for the former.

Determining future policy targets requires an assessment on the low carbon pathways to evaluate how to share abatement efforts among energy sectors. The policy ambition of vehicle passengers abatement depends on how fast the energy system changes in other sectors. The long term goal can be estimated but how fast should the sector move is a matter of debate. A policymaker is asked for intermediate targets to orient technological change in the near future, the industry requires a signal that can be interpreted in the present context. Setting this intermediate target has to balance between a feasible near term technological change and a compatible milestone with a long term goal. Moreover, in energy sectors where there is a risk of carbon lock-in there are two elements that have to be monitored: the compliance of the target and how the sector has selected technologies to reduce emissions. These two elements are necessary to avoid creating carbon lock-ins.

To set an adequate intermediate target a policymaker should take into account the consequences of near term technology choices on long term technology choices. To prepare for a long term target, we found that in some plausible cases the compliance to the near term target is not a sufficient nor necessary condition to comply for a range of long term targets in the fuel economy standard. Setting the short-term target is a difficult task since it requires fine evaluation of abatement technology potentials. This information is produced by the automotive sector thus a policymaker only has partial information of future technology potential. Therefore, if setting a short-term target is necessary, it also calls for caution and for the need to announce and construct the credibility of the long-term target. From the monitoring point of view, our result also calls for caution: respecting the aggregate emission target on the short-term may not be a reliable indication that the structural changes are on the right track to meet the longer-term target. This calls for indicators that go beyond the aggregate result in terms of emissions, to be able to monitor and track structural changes.

Some policies are thought to be technology-neutral, and aim at letting the firms choose the most adequate technologies to meet an environmental target. However, some details in the design of the policy can in practice render the instrument technology-oriented. We illustrated an example of such mechanism: the mass-index fuel economy standard which produces an incentive to increase mass to reduce stringency of the target and favor technologies such as electrified vehicles but excludes technologies that reduce vehicles weight. A policy instrument can prematurely close the door for promising low carbon technologies before they have been tested to evaluate their potential. An equilibrium between cost-effective policies that are market instruments to obtain a cost-effective abatement solution and research or technology incentives that are targeted policies on specific technologies to develop a niche market is needed at an early stage of the low carbon transition.

The overlap of policies, with multiple objectives, can create unintended consequences. For instance, we illustrated that an overlap of corporate average fuel economy standards and a zero emissions vehicles standard may lead to the polarization of emissions reduction creating a fleet of vehicles split into zero emissions vehicles, or very low emissions vehicles, and high-emitting vehicles. Because the CAFE standards regulate the emissions on a test-cycle of vehicles sold, but not directly the actual emissions on the road, there is a risk that resulting emissions are higher than expected. Furthermore, such polarization may lead to inequalities between households and territories with different access to the very low emissions vehicles.

Vehicle emissions cause multiple negative externalities the climate change and air pollution impacts have been addressed by policy instruments. There are policy mechanisms that produce higher compliance costs than others. Some elements that require attention are potential carbon lock-ins, a polarized distribution of emission reduction and the risk to exclude potential solutions. We have illustrated all three of these elements.

The policy environment is a combination of different instruments that have different mechanisms. In the case of climate change and air pollution externalities, the actors engaged for each policy are different and may have different interests. There are actors that are common such as the car manufacturer and vehicle clients but the policymaker changes. There are multiple regulators or public offices that dictate policies affecting car technology. Overlapping policies produce an effect on the technology mix but overlapping policymakers are also a challenge that creates multiple and simultaneous debates on different externalities. The coordination effort of different network of actors is difficult to correct multiple market failures.

Appendix A

Difference in diffusion modeling in optimization models:

We have compared the optimal abatement technology choices of three models: a model with learning without constraint on speed of diffusion, a model without learning with constant constraint on speed of diffusion and OMLCAT which has no learning and a endogenous constraint on speed of diffusion.

(Goulder and Mathai, 2000) The difference between the R&D problem and the Learning By Doing model is the change in the $\Psi()$ function: for learning-by-doing induced knowledge growth is a function of the current level of abatement rather than R&D investment. In the learning by doing formulation of a cost-effective model of abatement policies, there are three effects in the value of the implied reduction in the CO_2 concentration. The negative shadow-cost effect, the positives effects of knowledge-growth effect and learning-by-doing effects.

The optimization problem is defined as follows:

$$\begin{aligned} min_{A_t} \int_0^{\infty} C\{A_t, H_t\} e^{-rt} dt \\ s.t.\ \dot{S}_t = -\delta S_t + E_t^0 - A_t \\ \dot{H}_t = \alpha_t H_t + k\Psi(A_t, H_t) \\ S_0, H_0\ given \\ and\ S_t \leq \bar{S}\ \forall t \leq T \end{aligned} \tag{A.1}$$

where C is the cost of abatement, A_t is the abatement of emission, H_t is the knowledge stock, r is the discount rate, δ is the natural rate of removal of atmospheric CO_2, E_t^0 is the baseline emissions, α_t is the rate of autonomous technological progress, k indicates the degree of induced technological change, Ψ is the knowledge accumulation function, $\bar{S}$ is the target concentration and S_t the CO_2 concentration The Hamiltonian associated of this problem is:

$$\begin{aligned} \mathcal{H}_t = -(C(A_t, H_t) - \tau_t(-\delta S_t + E_t^0 - A_t) - \mu_t(\alpha_t + k\psi(A_t, H_t)) \\ + \eta_t(\bar{S} - S_t) \end{aligned} \tag{A.2}$$

where τ, μ and η are the Lagrangian multipliers. The firs-order condition for abatement is given by:

$$\begin{aligned} C_A(\cdot) - \mu_t k \Psi_A(\cdot) &= \tau_t \\ \dot{\tau}_t &= (r+\delta)\tau_t - \eta_t \\ \dot{\mu}_t = \mu_t(r - \alpha_t - k\Psi_H()) &+ C_H(\cdot) \end{aligned} \tag{A.3}$$

(Vogt-Schilb and Hallegatte, 2014) The optimization problem does have learning instead it has a limit on the available abatement at a point in time.

$$\begin{aligned} min_{x_t} \int_0^\infty C\{x_t\} e^{-rt} dt \\ s.t.\ m_t \leq B \\ \dot{m}_t = e_{ref} - a_t \\ \dot{a}_t = x_t - \delta a_t \\ a_t \leq e_{ref} \end{aligned} \tag{A.4}$$

where r is the discount rate, m_t are cumulative emissions at date t, B is the carbon budget, $\dot{m}_t$ is the emissions at date t, e_{ref} are baseline emissions, a_t is the abatement at time t, $\dot{a}_t$ is marginal abatement or speed of abatement, x_t is investment and δ is the depreciation rate. The Hamiltonian associated to this problem is

$$\begin{aligned} \mathcal{H}_t = e^{-rt}(C(x_t) + \lambda_t(a_t - e_{ref}) + \nu_t(\delta a_t - x_t) \\ + \mu_t(e_{ref} - a_t) + \phi_t(m_t - B)) \end{aligned} \tag{A.5}$$

where λ, ν,μ and ϕ are the Lagrangian multipliers. The firs-order condition for abatement is given by:

$$\begin{aligned} C_x(\cdot) &= \nu_t \\ \dot{\nu}_t = (r+\delta)\nu_t &- \mu_t \\ \dot{\mu}_t = r\mu_t &- \phi_t \end{aligned} \tag{A.6}$$

The optimization problem applied to optimal allocation of abatement investment results in different abatement options.

$$\begin{aligned} min_{x_{it}} \int_0^\infty \sum_i C_i\{x_{it}\} e^{-rt} dt \\ s.t.\ m_t \leq B \\ \dot{m}_t = \sum_i (\bar{a}_i - a_{it} \\ \dot{a}_{it} = x_{it} - \delta a_{it} \\ a_{it} \leq \bar{a}_i \end{aligned} \tag{A.7}$$

where $\bar{a}_{it}$ is the abatement potential of sector i. The Hamiltonian associated to this problem is

$$\begin{aligned}\mathcal{H}_t = e^{-rt}(\sum_i C_i(x_{it}) + \sum_i \lambda_{it}(a_{it} - \bar{a}_i) \\ + \sum_i \nu_{it}(\delta a_{it} - x_t) + \mu_t \sum_i (\bar{a}_i - a_{it}) + \phi_t(m_t - B))\end{aligned} \tag{A.8}$$

The firs-order condition for abatement is given by:

$$\begin{aligned}C_{x_i}(\cdot) &= \nu_{it} \\ \dot{\nu}_{it} &= (r+\delta)\nu_{it} - \mu_t \\ \dot{\mu}_t &= r\mu_t - \phi_t\end{aligned} \tag{A.9}$$

(Vogt-Schilb, Hallegatte, and De Gouvello, 2015) When applied to one variable of abatement and definition of a speed of abatement the resulting optimization problem is describes as follows:

$$\begin{aligned}min_{x_{it}} \int_0^\infty \sum_i C_i a_{it} e^{-rt} dt \\ s.t. \sum_i a_{iT} = a^* \\ a_{it+1} \leq a_{it} + v_i \\ a_{it} \leq A_{it}\end{aligned} \tag{A.10}$$

where C_i is the cost of abatement i, a_i is the abatement potential of i, A_i is the maximum potential of i, v_i is the speed of diffusion of i and a^* is the abatement target. The Hamiltonian associated to this problem is

$$\begin{aligned}\mathcal{H}_t = e^{-rt}(\sum_i C_i a_{it} + \sum_i \lambda_{it}(a_{it} - A_{ij}) \\ + \phi_t \sum_i (a_i T - a^*))\end{aligned} \tag{A.11}$$

where λ and ϕ are the Lagrangian multipliers. The firs-order condition for abatement is given by:

$$\dot{\nu}_{it} = (r + v_i)\nu_{it} + \lambda_{it} - \phi_t + C_i \tag{A.12}$$

OMLCAT: In our model to technology choice the resulting optimization problem is describes as follows:

$$\begin{aligned} min_{x_{it}} \int_0^\infty \sum_i C_i x_{it} e^{-rt} dt \\ s.t. \frac{\sum_i x_{iT} * e_i}{\sum_i x_{iT}} = E^* \\ x_{it+1} \leq x_{it} + V_{x_{it}} \\ \sum_i x_{it} \leq \bar{R} \end{aligned} \tag{A.13}$$

where e_i is the emission level of i, E^* is the emission target: fuel economy standard, $V(x_i)$ is a function of speed of diffusion and $\bar{R}$ is the volume target. The Hamiltonian associated to this problem is

$$\begin{aligned} \mathcal{H}_t = e^{-rt}(\sum_i C_i x_{it} + \sum_i \lambda_{it}(\sum_i x_{it} - \bar{R}) \\ + \sum_i \nu_{it}(V(x_{it}) + \phi_t \sum_i x_{iT} e_i - E^* \sum_i x_{iT})) \end{aligned} \tag{A.14}$$

The firs-order condition for abatement is given by:

$$\dot{\nu}_{it} = (r + V_{x_{it}})(x_{it})\nu_{it} + \lambda_{it} - \phi_t(e_i - E^*) + C_{it} \tag{A.15}$$

Appendix B

Variant of Myopic Scenario:

The Myopic Scenario used in Chapter 3 is built in a two step fashion defined as follows: a firm finds the optimal mix from 2014 to 2020 under a policy constraint in 2020. Then, the mix in 2020 of the first step is the input of a second optimization of technology choices from 2020 to 2030 under a policy constraint in 2030. The first period does not take into account the technology costs after 2020, this is a short-sighted perception of the future. What if the firm is able to see beyond 2020 but do not considers the policy target in 2030.

We tested a variant of the Myopic Scenario that we call Myopic v2 where a firm also has a two-step optimization of the technology mix but the first step is extended until 2030 with a policy constraint in 2030 equal to the target in 2020. This implies that in 2014 a firm considers technology costs between 2020 and 2030. This is different from the first version of Myopic. In 2020, a firm in the Myopic v2 Scenario will run a second optimization that starts from the 2020 technology mix of the first step and includes the more stringent 2030 policy target. In 2020, the firm is aware or assumes that the 2030 target is close enough to be prepared, before 2020 the 2030 target is not considered. The impact of Myopic v2 Scenario on the regions of the compliance of the 2030 target is that it reduces the size of Region 2 in Fig. B.1 and B.5 because Myopic v2 is able to comply with more stringent targets in 2030.

Myopic v2 Scenario considers both long-term technology costs and optimal compliance in 2020. The effect of Myopic v2 on 2020 technology choices is different from Myopic Scenario because of the type of anticipation of future technology costs. The resulting technology mix shows a higher share of Gasoline that is cheaper in the long-term without any increase in policy stringency. We show the comparison of the two Myopic Scenarios and the Foresight Scenario in Fig. B.2. The Myopic v2 Scenario produces the same technology mix in 2020 as the Foresight Scenario that has a 2030 target equal to the 2020 target. We can see in Fig. B.2 that as the 2030 target becomes less stringent the technology mixes in 2020 are more similar.

In 2030, we have still different choices in 2030 with the Myopic v2 Scenario, the gap is slightly reduced between the new Myopic and Foresight seen in Fig. B.3. The new Myopic v2 is in fact a step between Myopic and Foresight because it fails to

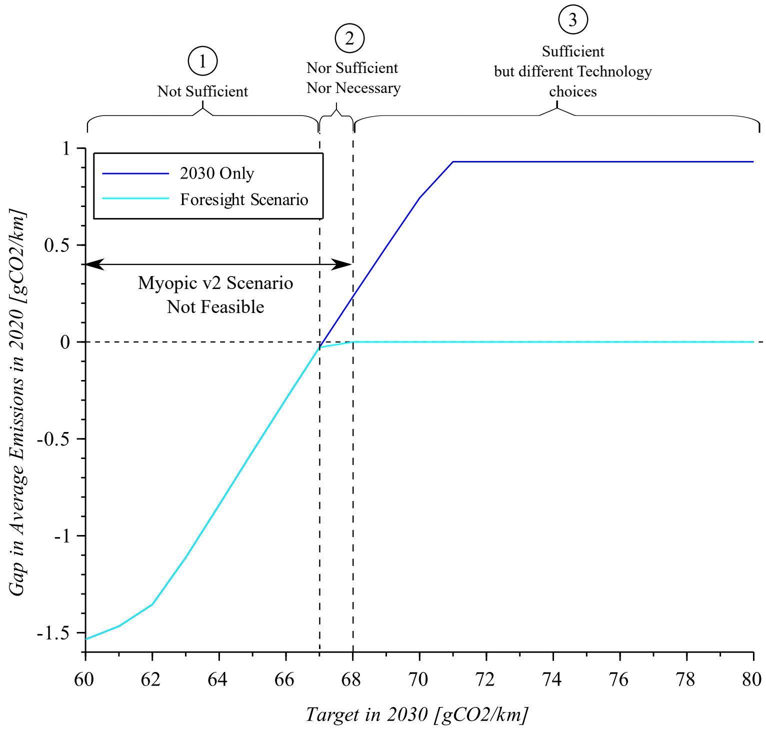


FIGURE B.1 – CO_2 emissions gap in 2020 between the 2020 CAFE Target of 95 gCO_2/km and two Scenarios - the 2030 Only Scenario and the Foresight Scenario - as a function of the 2030 target. A positive gap means that emissions in the scenario considered are higher in 2020 than the CAFE Target, a negative gap means that the scenario over-complies with the target in 2020. The Myopic v2 Scenario is able to comply with the 68 gCO_2/km target.

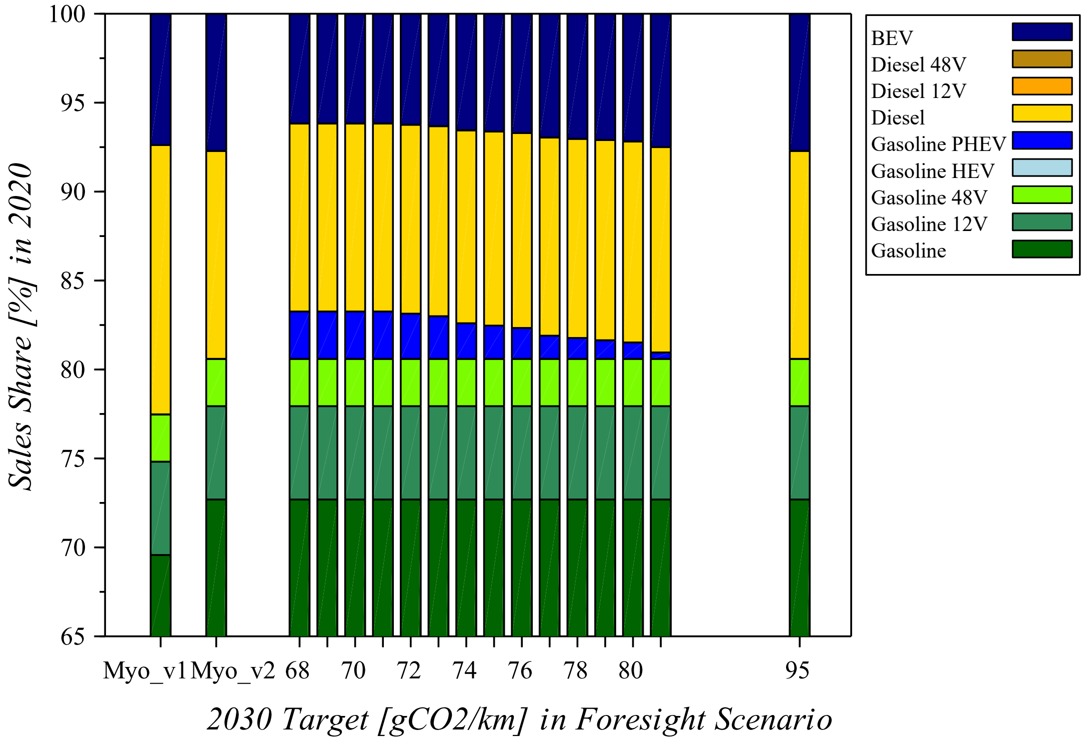


FIGURE B.2 – Technology mix in 2020 of Foresight Scenario for different 2030 targets and two Myopic Scenarios for a common 95 gCO_2/km target in 2020. Myopic v1 Scenario only sees up to 2020 and the 2020 target. Myopic v2 Scenario sees from 2014 to 2030, the 2020 target but does not sees the 2030 target.

take into account the 2030 fuel economy target in 2014 but it is capable of anticipating future technology costs.

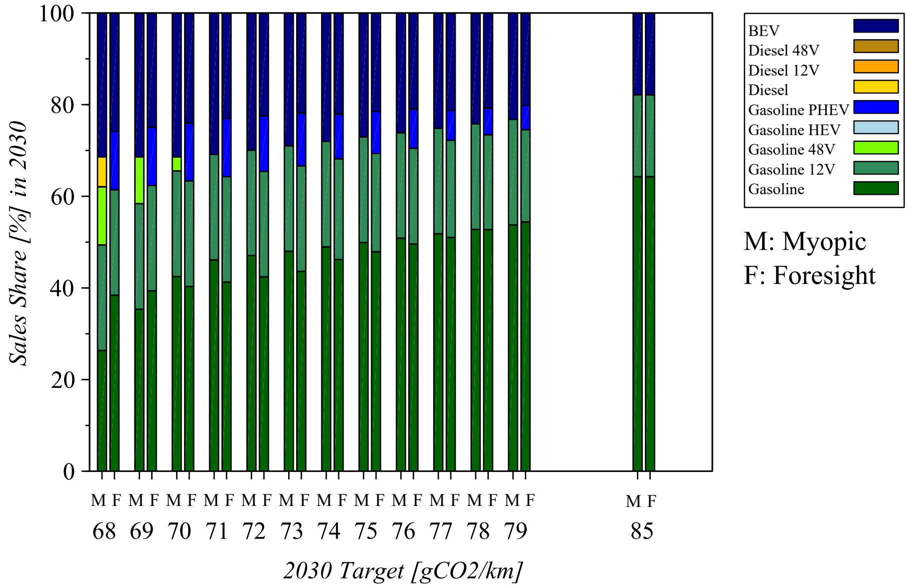


FIGURE B.3 – Technology mix in 2030 of Myopic v2 Scenario (left) and Foresight Scenario (right) for each 2030 target from 68 to 79 gCO_2/km.

In terms of the gap of technology cost of the Myopic v2 Scenario with the 2030

Only Scenario, we show that there is convergence between Foresight and Myopic Scenarios for low stringent 2030 targets. We saw that the technology choices were identical in this region therefore overall costs are also the same. This is different from the result found with the first version of the Myopic Scenario where there was always a gap in cost, although small, between Myopic and Foresight Scenarios in Fig. B.4.

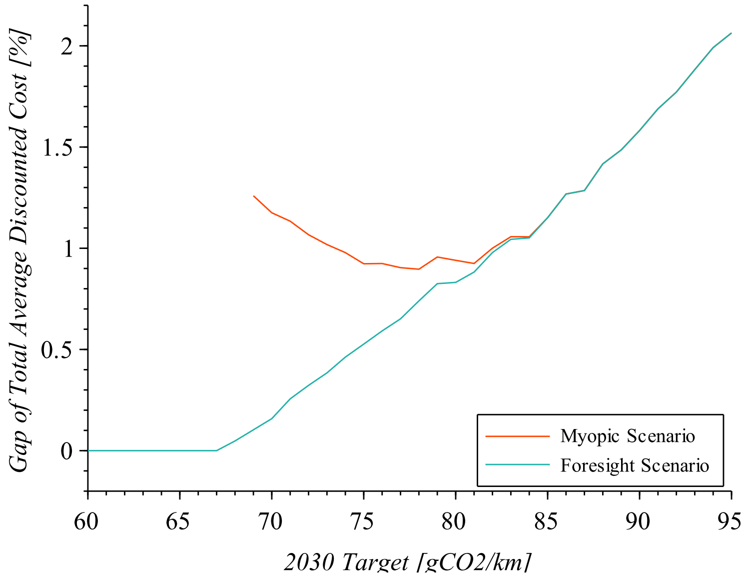


FIGURE B.4 – Gap of Total Discounted Cost of technologies between Scenarios Myopic (version 2) and Foresight to Scenario 2030 Only. The gap is the relative difference of cost of Myopic v2 and Foresight Scenarios to 2030 only Scenario for a range of 2030 CAFE targets.

The Compliance conditions of the 2020 target with Myopic v2 Scenario do not change very much in Fig.B.5. Region 1 based on the gap between Foresight Scenario and the 2020 target is identical. Region 2 is smaller than with the first version of Myopic, there are more cases where the 2030 target is feasible. This is because the Myopic v2 Scenario has a fraction more of BEV sales share in 2020 which allows for more stringent targets in 2030. In Region 3, since Foresight and Myopic v2 Scenarios are similar for low stringent 2030 targets we found cases were technology choices are identical in 2020 which did not happen with the first version of Myopic. This is consistent with the convergence in cost gap seen in Fig.B.4 between Myopic v2 and Foresight.

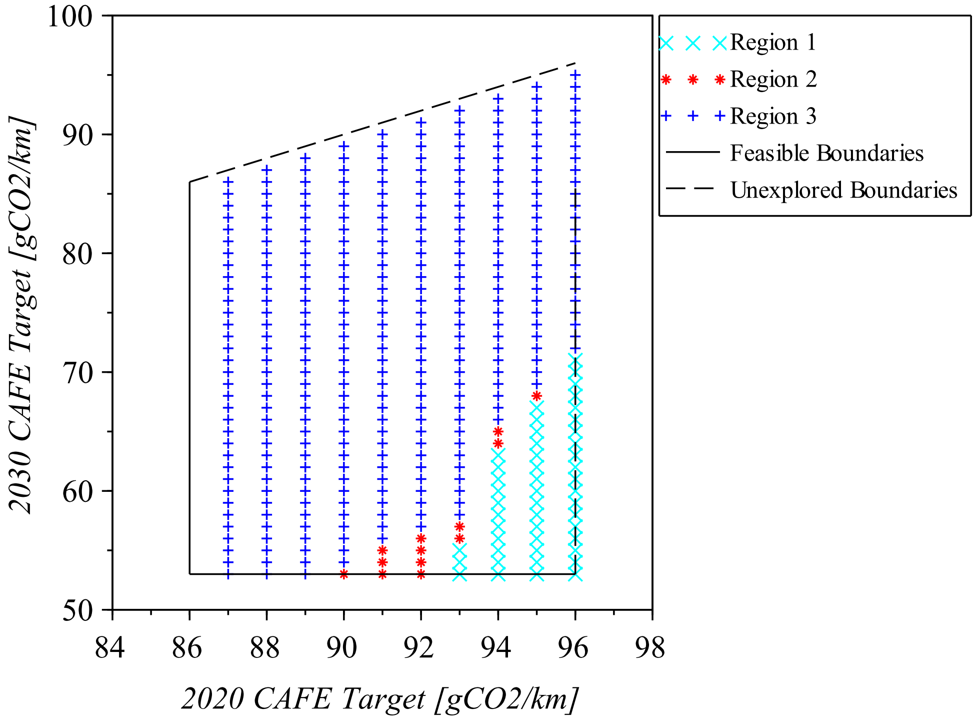


FIGURE B.5 – Change in the conditions of compliance of the 2030 target for a range of 2020 and 2030 targets. The three regions identified are described above in Fig. B.1 which describes in detail the case for 95 gCO_2/km target.

Appendix C

Additional Description on Lagrangian Multipliers

C.1 Optimization of Technologies under simplified fuel standard constraint without mass

The optimization function is the sum of technology costs and the optimization constraints are: a volume constraint, a fuel economy standard constraint and a non negative constraint.

$$\begin{gathered} min \quad \sum_{j=1}^{n} x_j * C_j \\ s.t. \quad \sum_{j=1}^{n} x_j = SALES \\ \frac{\sum_{j=1}^{n} x_j E_j}{SALES} \leq TARGET \\ for \quad every \quad technology \quad x_j \geq 0 \end{gathered}$$

Where n is the total number of technologies in the simplified case this is 3. The corresponding Lagrangian of this optimization problem is the following:

$$L(x_1, x_2, x_3, \lambda_k) = \sum_{j=1}^{n} x_j * C_j - \lambda_1(\sum_{j=1}^{n} x_j - SALES) - \lambda_2(TARGET * SALES - \sum_{j=1}^{n} x_j E_j) \\ -\lambda_3 x_1 - \lambda_4 x_2 - \lambda_5 x_3 \tag{C.1}$$

Let's assume that x_1 and x_2 will be positive and that the constraint on the fuel economy standard is binding. In this case the Lagrangian multipliers are:

$$\begin{gathered} \lambda_1 = C_2 + (\frac{C_1 - C_2}{E_2 - E_1}) \\ \lambda_2 = \frac{C_1 - C_2}{E_2 - E_1} \\ \lambda_3 = 0 \\ \lambda_4 = 0 \\ \lambda_5 = C_3 + C_2 + E_2(\frac{C_1 - C_2}{E_2 - E_1}) + E_3(\frac{C_1 - C_2}{E_2 - E_1}) \end{gathered}$$

The Lagrangian multipliers that will define the optimal choice are based on the ratio of cost over emissions. If we now assume that x_1 and x_3 will be positive and that the constraint on the fuel economy standard is binding, the Lagrangian multipliers are:

$$\lambda_1 = C_3 + (\frac{C_1 - C_3}{E_3 - E_1})$$
$$\lambda_2 = \frac{C_1 - C_3}{E_3 - E_1}$$
$$\lambda_3 = 0$$
$$\lambda_5 = 0$$
$$\lambda_4 = C_2 + C_3 + E_3(\frac{C_1 - C_3}{E_3 - E_1}) + E_2(\frac{C_1 - C_3}{E_3 - E_1})$$

We are interest at the Lagrangian that compares a low carbon technology with the baseline technology if the baseline technology is 1 the lagrangian of interest to rank the abatement technologies as a function of abatement cost is in the form of:

$$\lambda_i = \frac{C_1 - C_i}{E_i - E_1}$$

This equation defines the Abatement ratio that enable us to compare different low carbon solutions.

C.2 Optimization of technologies under complete fuel standard constraint

We have changed the fuel economy standard constraint to include mass as the index parameter.

$$\frac{\sum_{j=1}^{n} X_j E_j}{SALES} - a(\frac{\sum_{j=1}^{n} x_j M_j}{SALES}) \leq TARGET - aM_0$$

All other constraints remain equal, the resulting Lagrangian is:

$$L(x_1, x_2, x_3, \lambda_k) = \sum_{j=1}^{n} x_j * C_j - \lambda_1(\sum_{j=1}^{n} x_j - SALES)$$
$$-\lambda_2((TARGET - aM_0) * SALES - \sum_{j=1}^{n} x_j(E_j - aM_j) - \lambda_3 x_1 - \lambda_4 x_2 - \lambda_5 x_3 \quad \text{(C.2)}$$

Let's assume again that x_1 and x_2 will be positive and that the constraint on the fuel economy standard is binding. In this case the lagrangian multipliers are:

$$\lambda_1 = C_2 + (E_2 - aM_2)(\frac{C_1 - C_2}{E_2 - E_1 + a(M_1 - M_2)})$$
$$\lambda_2 = \frac{C_1 - C_2}{E_2 - E_1 + a(M_1 - M_2)}($$
$$\lambda_3 = 0$$
$$\lambda_4 = 0$$
$$\lambda_5 = C_3 + C_2 + (E_2 - aM_2)(\frac{C_1 - C_2}{E_2 - E_1 + a(M_1 - M_2)}) + (E_3 - aM_3)(\frac{C_1 - C_2}{E_2 - E_1 + a(M_1 - M_2)})$$

Again if we change the non negative assumption to x_1 and x_3 and assume that the fuel economy standard is binding, the resulting Lagrangian multipliers are:

$$\lambda_1 = C_3 + (E_3 - aM_3)(\frac{C_1 - C_3}{E_3 - E_1 + a(M_1 - M_3)})$$

$$\lambda_2 = \frac{C_1 - C_3}{E_3 - E_1 + a(M_1 - M_3)}($$
$$\lambda_3 = 0$$
$$\lambda_5 = 0$$
$$\lambda_4 = C_2 + C_3 + (E_3 - aM_3)(\frac{C_1 - C_3}{E_3 - E_1 + a(M_1 - M_3)}) + (E_2 - aM_2)(\frac{C_1 - C_3}{E_3 - E_1 + a(M_1 - M_3)})$$

The Lagrangian multiplier that compares a low carbon technology with the baseline technology is key to rank all abatement options in the case of the fuel economy standard indexed to mass this lagrangian multiplier is of the type:

$$\lambda_i = \frac{C_1 - C_i}{E_i - E_1 + a(M_1 - M_i)}$$

This equation defines the CAFE ratio that enable us to compare different low carbon solutions in the case of mass indexed fuel economy standard.

Appendix D

Scenario of 9 Powertrain Technologies and 1 Powertrain+Lightweight Technology

Additional information on technology choices from Chapter 4.

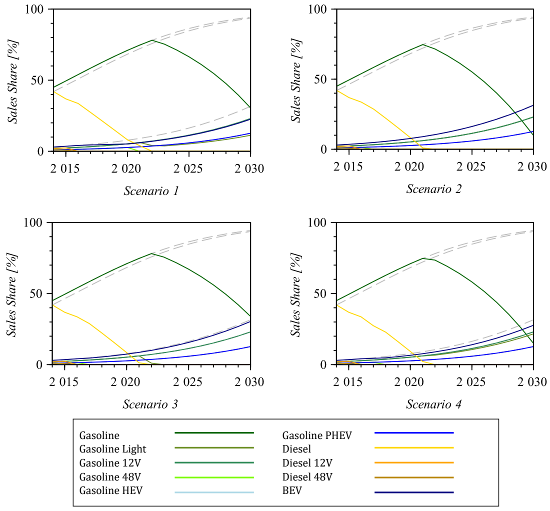


FIGURE D.1 – Technology pathways of the 9 powertrain technologies and one powertrain and lightweight option for the 4 Scenarios with Diffusion Constraints: (top left) Scenario 1: no mass constraint, (bottom left) Scenario 2: no mass constraint but target corrected to initial mass, (top right) Scenario 3: mass constraint and (bottom right) Scenario 4: no mass constraint but target corrected with final mass of Scenario 3. In dash lines: the maximum allowed diffusion of technologies.

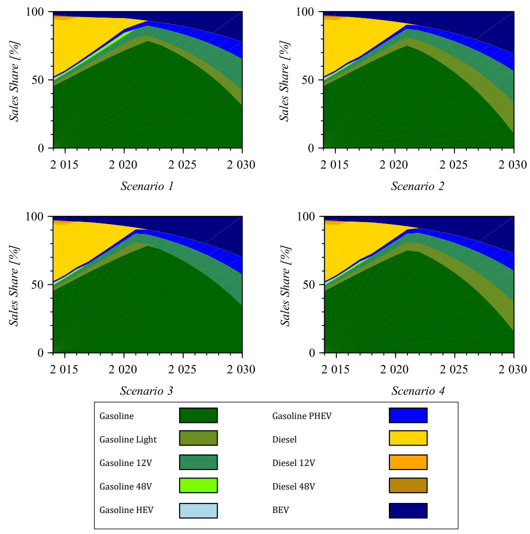


FIGURE D.2 – Technology Mix of the 9 powertrain technologies and one powertrain and lightweight option for the 4 Scenarios: (top left) Scenario 1: no mass constraint, (bottom left) Scenario 2: no mass constraint but target corrected to initial mass, (top right) Scenario 3: mass constraint and (bottom right) Scenario 4: no mass constraint but target corrected with final mass of Scenario 3.

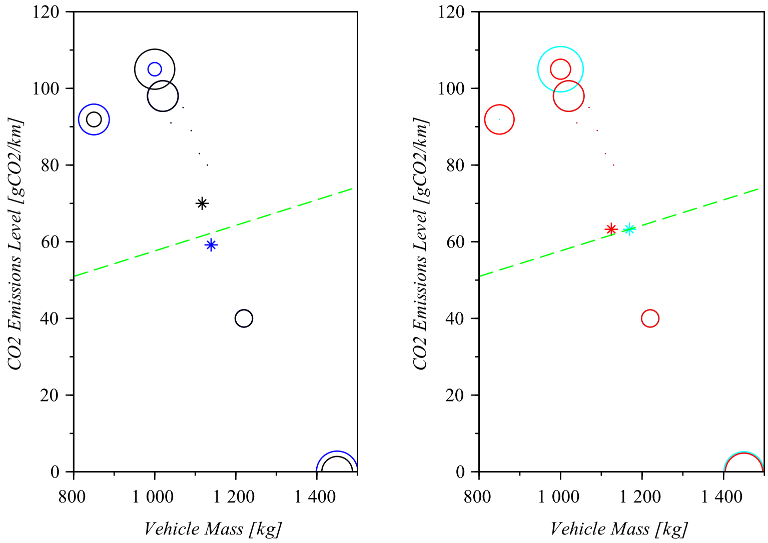


FIGURE D.3 – Scatter plot of Weighted Sales of the technology mix of powertrain mix with lightweight from Scenario 1 in black and Scenario 2 (left) and Scenario 3 in cyan and Scenario 4 in red (left) and in green the CAFE compliance line indexed to the mass.

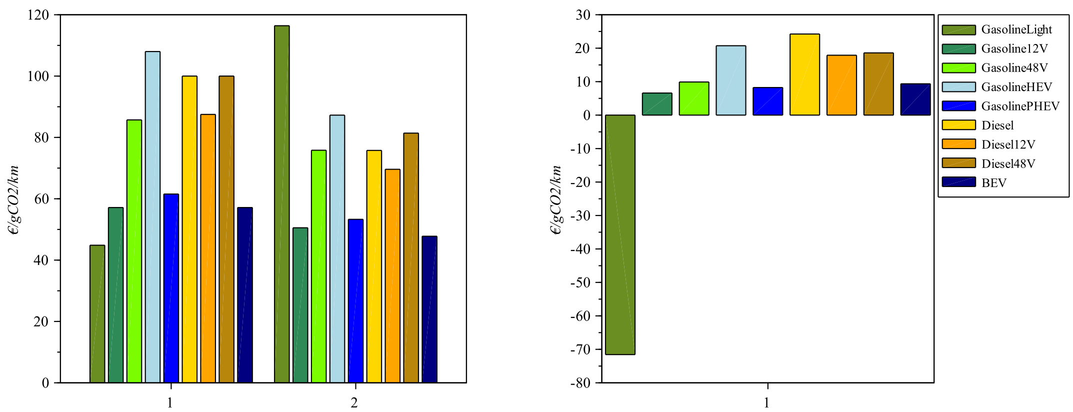


FIGURE D.4 – Comparison of Abatement and CAFE Ratios for the abatement technologies (powertrain and a lightweight alternative of Gasoline), left and Difference between Abatement and CAFE ratios, right.

Appendix E

Additional Results of Environmental Policy impacts with a CAFE indexed to mass

Chapter 5 has treated the combination of a fuel economy standard with other policies. To capture the full effect of the CAFE policy we introduce the mass indexation in the same manner modeled in Chapter 4. Here we will describe the differences in results with the modified fuel economy constraint. Vehicle's mass is an important parameter for this constraint, Table E.1 shows the vehicle's mass of the technologies treated in this section.

Technology	Mass in kg
Gasoline	1000
Gasoline EURO 6d Full	1010
Gasoline EURO 7	1020
Gasoline 12V	1020
Gasoline 48V	1040
Gasoline HEV	1130
Gasoline PHEV	1230
Diesel	1070
Diesel Euro 6d Full	1095
Diesel Euro 7	1095
Diesel 12V	1090
Diesel 48V	1110
BEV	1450

TABLE E.1 – Vehicle's mass assumptions for a lower-medium segment.

First, we will check if there is any difference in CO_2 emissions, second we focus on technology choice and third we will see if there is any difference in tradeoff and synergy effects. What we expect is to see heavier vehicles in the technology mix.

E.1 Results

The fuel economy standard indexed to mass has an incentive to develop heavier vehicles in order to reduce stringency of the CAFE target, recall E.1. In this section we have modeled the same CAFE targets than the case without indexation. However due to the mass indexed constraint, the actual emission target is lower because average mass is below market average. Thus the scenarios in this chapter will search for lower CO_2 emissions. Therefore when we show a CAFE target it means the policy target and conversely when talking about CO_2 emissions target we mean the real target. In 5 both of these targets were equivalent.

$$CAFE_i = TARGET_i + a\left(M_{corporate} - M_0\right) \tag{E.1}$$

where $TARGET_i$ is the enacted European target in $gCO_2/km$for year i
$a = 0.0457 \quad gCO_2/km/kg$ in 2015 and 0.0333 from 2020 is the mass index coefficient
$M_{corporate}$ is the average mass in kg of corporate sales for year i
M_0 is the estimated average mass in kg of all new vehicles by the regulator

First, to check for a deviation from all scenarios compared to their CAFE targets we obtain the gap of the CAFE performance to the actual target in E.1. The difference lies in the section that remains common for all Scenarios, up to 73 gCO_2/km all Scenarios perform equally. This is due to the mass correction that makes a CAFE target with a mass indexation coefficient more difficult to achieve for a light car manufacturer.

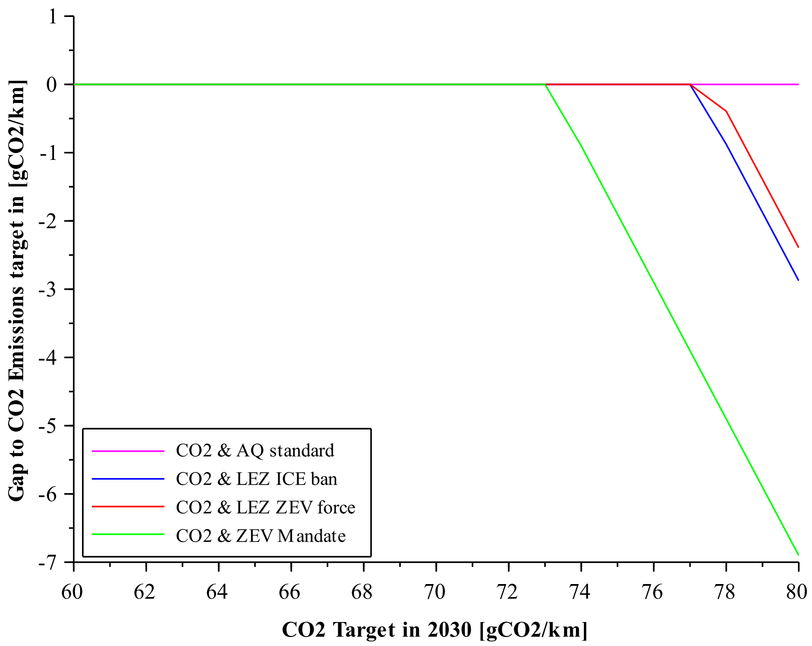


FIGURE E.1 – 2030 CAFE Gap of a Scenario compared to the target. There are two types of scenarios: Policy only scenarios: CAFE only and two package scenarios: that include a CAFE policy + other policies. Positive values mean that a Scenario has a higher CAFE performance than the target.

Second, technology choices will vary more for stringent CAFE targets because these targets are more severe and require significant mix adaption that will oppose to the other policies constraint. For example the EURO standard does not allow high pollutant emitters therefore the share of Diesel family that is the technology that has more problems to adapt for the standard is well below the other scenarios. Likewise, the share of ICE engines in LEZ limited by ICE scenario is lower for stringent CAFE targets due to the stringency of the LEZ standard.

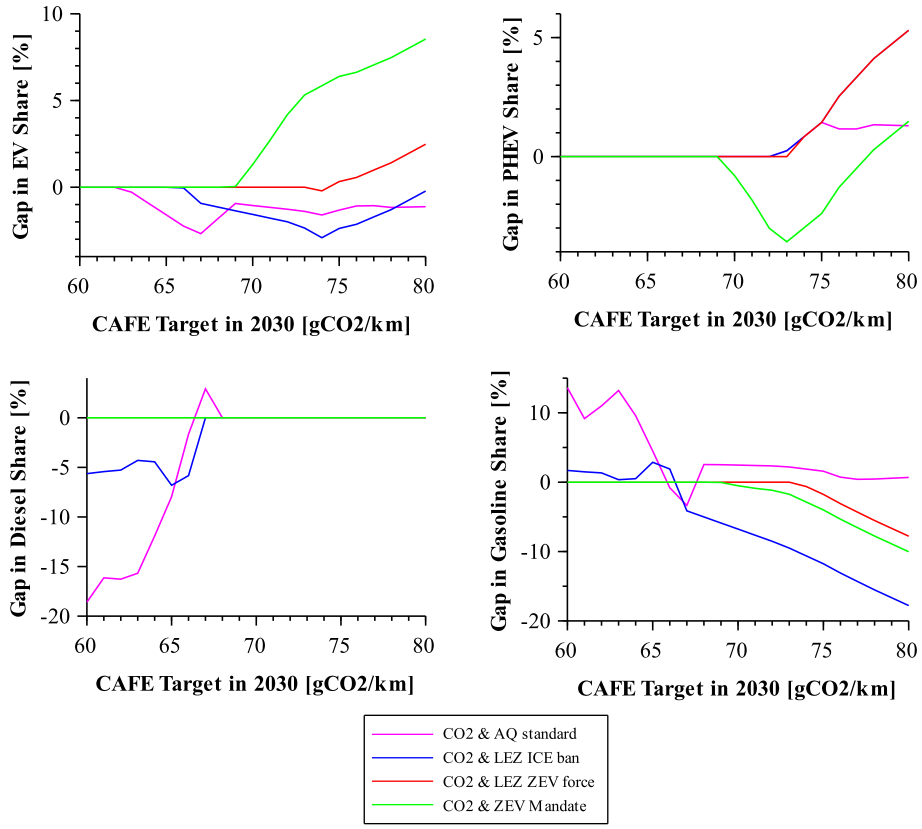


FIGURE E.2 – 2030 Technology choice Gap between the CAFE only Scenario and the selection of two policies Scenario. Positive values mean that the technology share in the two policy scenario is higher than the share of that technology in the CAFE only Scenario.

In this Appendix we will also model a CAFE target of 77 gCO_2/km, a ZEV target of 36 credits, an introduction of LEZ limited by ICE for Diesel in 2022 vehicles and Gasoline and Diesel vehicles in 2027 and an introduction of LEZ limited by NEV in 2027. From these assumptions we have varied the CAFE target in Figures E.1, E.2 and **??**. The technology mix with mass indexation does show a different trend compared to the technology mix without mass indexation. The share of EV is higher, we will check this in Fig. E.4

Looking more closely on how each policy responds to reduce average carbon emissions. We can look at the distribution of technologies according to CO_2 emission levels. Fig. E.4 shows the effects of policies: a ZEV Mandate and ICE limited by NEV develops zero and high emissions technologies. The stringent carbon emissions targets requires a higher share of low carbon technologies. From all options

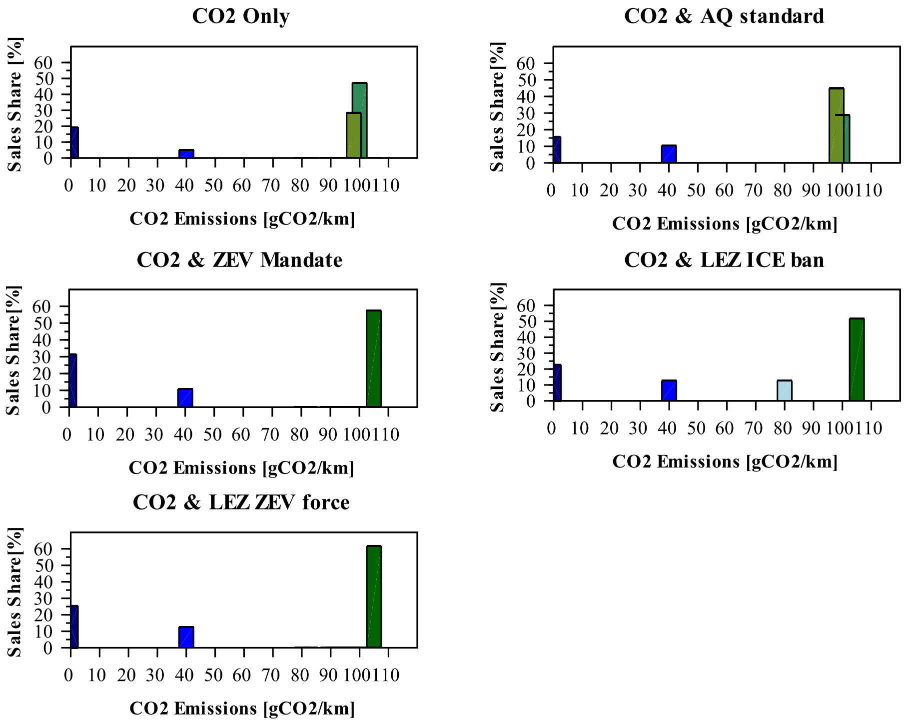


FIGURE E.3 – Dynamic technology mixes of selected two policy scenarios compared with the CAFE only scenario.

available, the one that is prefered is EV : all Scenarios have a higher share of EVs when CAFE is indexed to mass.

To analyze the synergy and trade-off effects, we will distinguish two comparisons: policy focused compliance and policy efficient. In the first case we check for the trade off and synergy of policies in the policy context in the second case we will show the real performance and analyze policy efficiency in terms of real performance. Fig.E.5 treats the tradeoff in terms of CAFE targets and in absolute emissions reduction.

There is a change in the trend of trade off curb: this means that two policies have a trade off when the slope of the tradeoff curve is negative that becomes a synergy when the slope is positive. This threshold is located at a target of 66 gCO_2/km or a emissions level of 60 gCO_2/km and is true for the CAFE only, CAFE & QA, CAFE & LEZ limited by ICE, CAFE & LEX limited by NEV and CAFE & ZEV Mandate. The gap between CAFE and emissions level is 6 gCO_2/km, in the case of lower than average car manufacturer the impact of mass indexation is positive for policy efficiency because it requires lower emissions. However we do not check for the effect of all new vehicles.

The Total Cost of Possessions of a vehicle comparison results in E.2 in higher costs except for the ZEV Mandate and LEZ limited by NEV, the production costs are the same meaning that in presence of CAFE indexed by mass and these policies

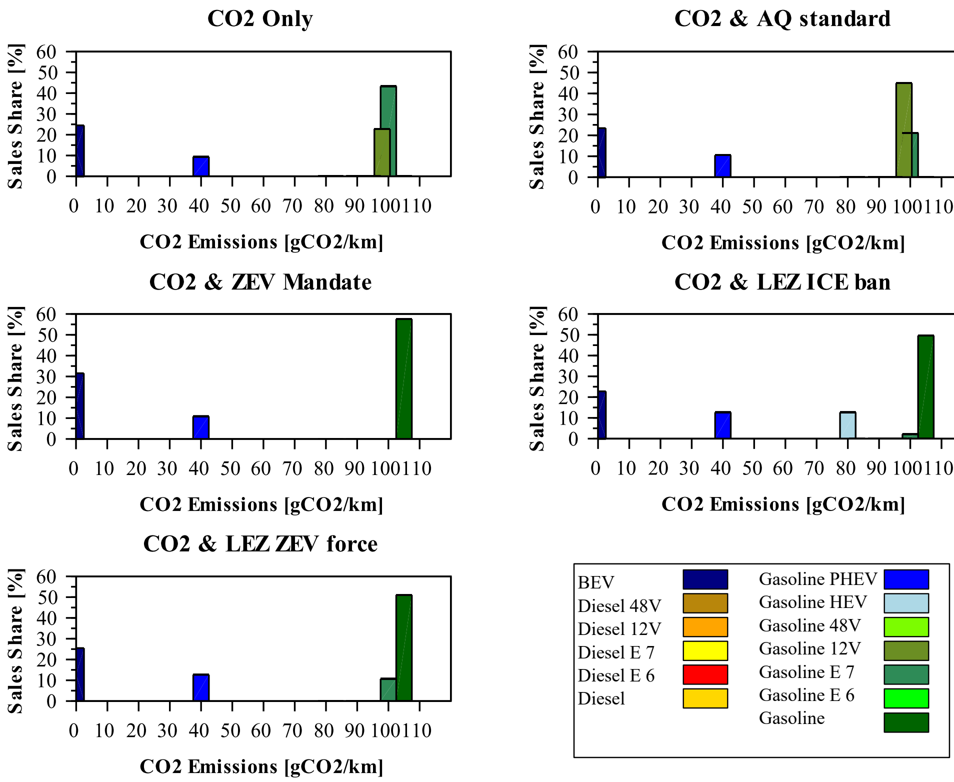


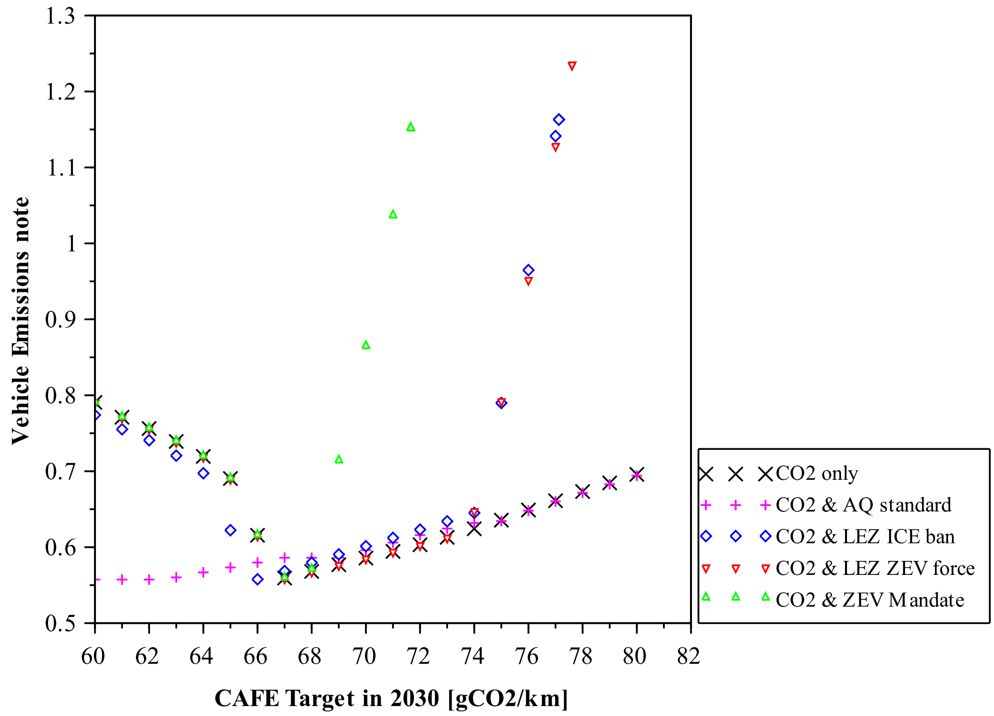
FIGURE E.4 – Comparison of the distribution of technology choices in a CO2 Emission dimension for 4 Scenarios: CAFE only and selected two policy scenarios.

there is no significant change in technology choices. This is what we expected since these two scenarios favor heavy baterry electric vehicles.

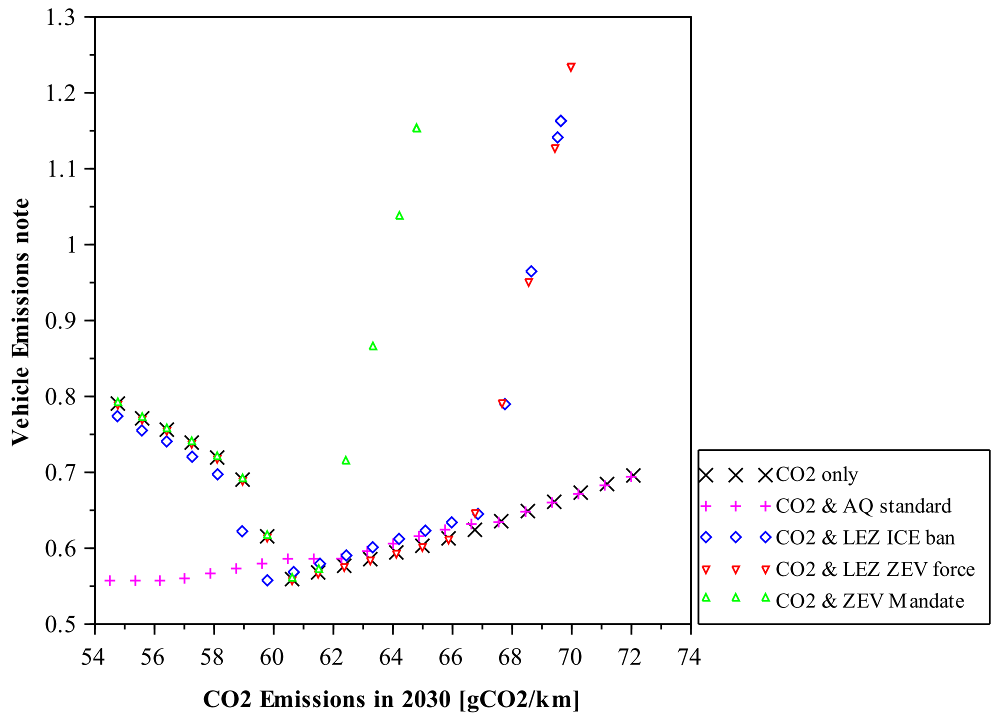
When comparing the single policy cost and the combination with CAFE Fig. 5.7, the Overcost comparison gives higher costs than the case without mass indexation which is expected because of the increase of the stringency on carbon emissions reductions and the same gaps between single and combined policies despite the increase in emissions target stringency, the exception is EURO standard which is more costly to comply when combined to CAFE with mass index E.6.

Scenario	Total Cost of Production in k€	Total Cost of Mobility in k€	Total Cost of Possession in k€
CO_2 only	2.09	1.35	3.44
CO_2 & Pollution regulation	2.32	1.29	3.61
CO_2 & ZEV Mandate	2.17	1.33	3.50
CO_2 & LEZ limited by ICE	2.14	1.35	3.48
CO_2 & LEZ limited by NEV	2.11	1.34	3.45

TABLE E.2 – Summary of Total Cost of Possession per vehicle: sum of Total Cost of Mobility and Total Cost of Production.



(A) CAFE target tradeoff



(B) CO2 emissions tradeoff

FIGURE E.5 – Tradeoff and Synergy effects of CO_2 Performance and Other Vehicle's emissions with Environmental policies with different levels of stringency. (A) Effects when compared to the policy targets. (B) Effects when compared with emissions levels.

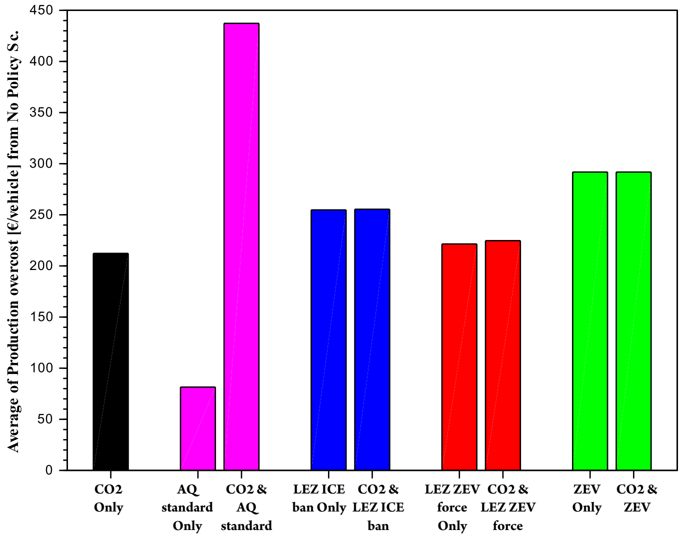


FIGURE E.6 – Comparison of the overcost of compliance with one single policy and the combination with CAFE policy from a policy Scenario.

This Appendix proved that the fuel economy standard indexed to mass changes the emissions target due to the index coefficient. The mass index has favored more heavy technologies and leads to better synergy between CO_2 policies and those policies favoring ZEVs.

ÉCOLE DOCTORALE
Agriculture, alimentation, biologie, environnement, santé (ABIES)

Titre : Choix des Technologies sous contraintes politiques sur les émissions et diffusion des technologies : le cas des véhicules légers.

Mots clés : technologies automobiles, inertie, diffusion, modèle d'offre, réglementations sur les émissions.

Résumé : Les instruments politiques sur les émissions de véhicules passagers visent à réduire les externalités négatives sur l'environnement causées par l'usage des véhicules. Des réglementations sur les émissions de CO_2 ont été mises en place en Europe, aux États-Unis, en Chine et ailleurs. La cible réglementaire basée sur la moyenne des émissions des véhicules vendus par un constructeur devient plus contraignante au fil du temps. Cette thèse analyse comment les constructeurs automobiles anticipent et préparent leurs futurs portefeuilles de technologies afin de respecter les futurs objectifs politiques. Pour conduire cette analyse, cette thèse développe un modèle d'optimisation des choix technologiques sous la contrainte de diffusion technologique.

Avec ce cadre de modélisation basé sur la limitation de la vitesse à laquelle une technologie peut se diffuser dans un marché, cette thèse étudie trois questions politiques. Dans un premier temps, nous analysons comment le type d'anticipation du futur peut modifier les choix technologiques faits à court et à long termes. Nous montrons qu'une anticipation du futur focalisée sur les objectifs de court terme peut empêcher l'atteinte de la cible à long terme. Respecter la cible à court terme n'est une condition ni nécessaire ni suffisante pour permettre le niveau d'émissions requis par la cible à long terme. De plus si l'anticipation du futur n'est pas parfaite, les choix technologiques vont être verrouillés dans des technologies à faible potentiel d'abattement créant ainsi une dépendance au sentier qui limite l'abattement potentiel à long terme.

Dans un deuxième temps, nous intéressons à évaluer quantitativement comment l'indexation sur la masse des véhicules de la réglementation CO_2 change les critères optimaux de choix. Nous montrons qu'il n'existe pas de différence significative dans le coût social de la mobilité entre les deux mécanismes de réglementation CO_2 avec et sans indexation sur la masse pour une même cible d'émissions. Cependant les choix technologiques entre ces mécanismes sont différents, la réglementation CO_2 indexée à la masse ne développe en aucun cas les technologies d'allègement.

Dans un troisième temps, nous étudions comment les choix technologiques changent quand des politiques à objectifs multiples se superposent. Nous centrons notre analyse sur deux externalités associées à la mobilité : les émissions CO_2 et la pollution de l'air locale. Nous montrons trois types d'impacts de la superposition de politiques. Premièrement, une politique technologiquement spécifique tel que le Mandat de Véhicule à Zéro Émission en combinaison avec la réglementation CO_2 provoque le développement de technologies vertes coûteuses et empêche les technologies sales et peu coûteuses de disparaître. Dans le cas de l'application de la réglementation CO_2 seule nous n'observons pas ce comportement. Deuxièmement, la superposition de politiques peut mener à un coût élevé quand les technologies adaptées à chacune des politiques sont très différentes. Troisièmement, nous trouvons un effet ambigu de la superposition de politiques relative à l'application d'une politique seule sur la performance environnementale.

Title : Technology Choices under Emissions Policy and Technology Diffusion constraints: the case of Passenger Vehicles

Keywords : automotive technologies, inertia, diffusion, supply model, air emission vehicle policy.

Abstract : Policy instruments on passenger vehicle emissions aim at reducing negative externalities on the environment from vehicles use. To regulate CO_2 emissions fuel economy standards have been put in place in Europe and in the US. These standards are made more stringent over time. This thesis analyzes how automotive firms anticipate and prepare their future technology portfolio to comply with expected future standards. To do so, we develop a model of optimal technology choices that captures technology diffusion constraints.

With this framework, this thesis investigates three policy questions. First, we ask how the type of anticipation of the future can affect near term and long term technology choices. We find that an anticipation of the future focused on near term objectives can lead to failure to comply with a long term target. Meeting the short term target is not a necessary nor a sufficient condition to satisfy long term compliance. Moreover if the anticipation of the future is not perfect, technology choices will be stuck with low abatement technologies creating a path dependency that limits long term abatement potential.

Second, we ask how much does the fuel economy standard index to mass change the optimal technology selection criteria. We show that there is no significant difference in the cost of usage and technology for an average vehicle between two mechanisms of the fuel economy standard with and without mass index for the same emission target. Thus a heavier vehicle fleet has the same cost than a lighter fleet. However the technology choices are different, the mass index fuel economy standard neglects lightweight technologies in all cases.

Third, we ask how does technology choices change when policies overlap with each other to answer multiple objectives. We focus on two dimensions of vehicle emission externalities: CO_2 emissions and air pollutants. We show three type of effects of overlapping policies. First, a technology specific policy such as the Zero Emission Vehicle Mandate in combination with a fuel economy standard develops more costly green technologies and prevents cheap dirty technologies to disappear compared to the case of a fuel economy standard alone. Second, the combination of policies can produce very high costs when technologies adapted for each policy are very different. Third, overlapping policies can improve or deteriorate the performance of one dimension of vehicle emissions from the cases of policy alone applications.

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