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How to reduce CO_2 emissions from cars?

Scenario simulations applied to Belgium

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Master's Thesis Submitted for the Degree of
Master of Business Administration
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Academic Year: 2018–2019
May 2019

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Abstract
The transport sector is responsible for a quarter of the European Union’s greenhouse gas emissions. If we are to mitigate climate change and improve air quality, these emissions will have to be reduced rapidly and substantially. This study explores ways in which such a reduction may be brought about in the market of passenger cars. It does so by simulating three scenarios that are able to reduce carbon dioxide emissions from passenger cars: carsharing, steel recycling, and electrification of Belgium’s vast salary cars fleet. Drawing on data about the Belgian car market, we conclude that steel recycling, carsharing and the transition from diesel cars to electric vehicles are certainly conducive to the reduction of carbon dioxide by the Belgian transport sector. However, if Belgium is to meet the European goals, much more needs to be done. We argue that a faster transition to electric vehicles combined with an integrated mobility network can make cars cleaner while causing a modal shift to more sustainable modes of transportation. In closing, this study delineates policy measures and incentives that may render individual mobility services powered by combustion engines less attractive.

Keywords: Q51 Valuation of Environmental Effects; Q53 Air Pollution, Recycling; Q54 Global Warming; Q56 Sustainability; L91 Transportation: General

1 Introduction

In December 2015, the Paris Agreement was signed by 196 parties with the objective to respond to the threat of climate change. In order to reach this objective, the Agreement calls for international cooperation to limit the rise in the global average temperature to 1.5 °C above pre-industrial levels. The Intergovernmental Panel on Climate Change (2018) published a special report, requested by the Paris Agreement, on the impact of global warming of 1.5 °C above pre-industrial levels. The report emphasizes that global warming is happening today, with an estimated increase of 0.2 °C per decade as a result of past and current emissions. Some adverse effects from global warming are already undeniable. They include losses of biodiversity and ecosystems, sea level rise and an increase in extreme weather events. Deep cuts in emissions are required to reduce the risk of climate change on ecosystems and human health. This is why the European Union set progressive targets to reach a climate-neutral Europe by mid-century: a 20% cut in greenhouse gas (GHG) emissions by 2020 and at least a 40% cut by 2030, compared to 1990 levels (European Commission, 2011). By 2050, GHG emissions need to be 80 to 95% lower than in 1990 in order to keep climate change below 2 °C. In addition, the EU set targets to improve energy efficiency and to increase the penetration of renewable energy. Reaching these key targets will significantly improve air quality and public health. The low-carbon economy roadmap of the Commission also contains emission targets for the most polluting sectors. About one quarter of the EU’s total GHG emissions originates from the transport sector (European Commission, 2016). This encourages the EU to prioritize low-emission mobility in the transition to a low-carbon, circular economy. By 2050, GHG emissions from transport need to be at least 60% lower relative to 1990. Furthermore, air pollutants harmful to human health need to be drastically reduced since the transport sector is the main cause of air pollution in cities, resulting in numerous deaths every year.

Despite ambitious targets, emissions from the EU transport sector have been increasing again since 2014 and are even 26% higher than in 1990, as reported by the European Environment Agency (EEA, 2018a). Data from the EEA show that the transport sector is the only key European economic sector in which GHG emissions are higher compared to 1990 levels. Road transport is responsible for about 82% of total GHG emissions from transport. This implies one fifth of the EU's total GHG emissions. The latest annual report of the Belgian federal government department of mobility and transport shows similar results for Belgium. The Belgian transport sector accounted for 23% of the country's total GHG emissions in 2016 and road transport represents more than 80% of all kilometers traveled by passengers, excluding aviation (FOD Mobiliteit en Vervoer, 2018a). The car is by far the most dominant mode of transport in the market.

It is obvious that if we are to mitigate climate change and improve air quality, reducing the environmental impact of road transport is of the utmost importance. The objective of this study is to explore ways in which such a reduction may be brought about by simulating different scenarios that are able to reduce GHG emissions from passenger cars. We focus on the emission of carbon dioxide (CO_2), since greenhouse gases are usually expressed in terms of the equivalent amount of CO_2 (CO_2-eq) to measure their contribution to global warming. Carbon dioxide is the main greenhouse gas. It is responsible for 85% of the total greenhouse effect of Belgium in 2017, according to the Belgian federal website on climate change "Klimaat.be" (2019). We will draw on these scenario simulations to make suggestions that lower the carbon footprint of transport by passenger cars.

The paper is structured as follows: Section 2 presents a profound literature review of relevant concepts to provide useful background information. Section 3 explains the methodology of scenario simulations. In Section 4, the results of the scenario simulations are analyzed and discussed. Finally, Section 5 formulates conclusions as well as suggestions for further research.

2 Literature review

2.1 Dieselization

For many years, diesel engines have been favored by European regulations which led to a dieselization. Figure 1 illustrates the share of diesel in new passenger cars in Belgium and in all of Western Europe. The share of new diesel car registrations in Belgium has increased from 32.7% in 1990 to a peak of 79% in 2008. The Financial Crisis in 2008 caused a short decline in the diesel share in some European countries, but the downward growth was strongly accelerated only later, by the dieselgate scandal in 2015. This scandal highlighted the dark side of diesel cars: they contain higher levels of toxic nitrogen oxides (NO_x) than reported, which cause air pollution and as a result many deaths from breathing toxic air (Transport & Environment, 2017). The exact diesel NO_x emissions were kept under the radar for a long time. However, in 2017, diesel cars still represented about half of new passenger cars sold in both Europe and Belgium. Hooftman, Messagie, Van Mierlo, & Coosemans (2018) present a review of how the current air quality situation in Europe is a consequence of emission-related European regulations. They state that the historical decisions favoring diesel engines turned Europe into a diesel island. About 70% of all diesel cars and vans worldwide are sold in Europe, compared to only 1% in the US and 2% in China (Transport & Environment, 2017). Belgium is one of the leading European countries in terms of diesel share, together with Spain and France. The question is why diesel cars received a preferential treatment for such a long time and what the consequences are of this dieselization.

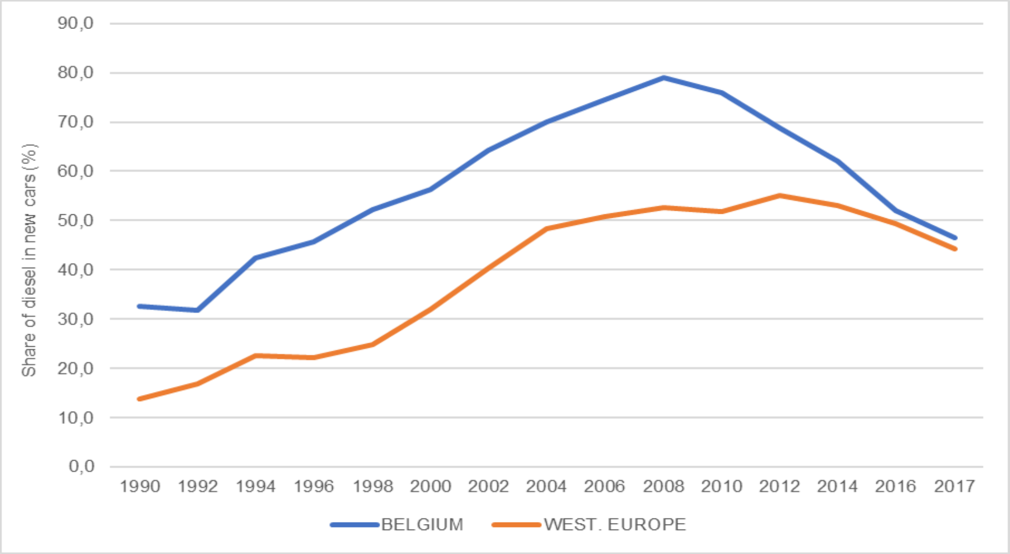

Figure 1: Share of diesel in new passenger car sales 1990-2017. Source: ACEA (n.d.)

According to Transport & Environment (2017), there are different reasons why Europe encouraged diesel cars. A liter of diesel contains more energy than a liter of gasoline because of a higher energy density and, aside from being more solid and durable, diesel engines are also more efficient. This means that, in general, they consume less fuel than comparable gasoline engines for the same number of kilometers driven. The last element is a crucial one. A lower consumption convinced people that more diesel cars would reduce CO_2 emissions from road transport and as a result reduce the impact on global warming. Tovar (2011) confirms that the higher efficiency of diesel engines was the main reason why European countries encouraged diesel vehicles as a strategy to reduce CO_2 emissions from the transport sector. The author concludes that improvements in energy efficiency cause an adverse effect though, which is a higher intensity of using diesel cars. Diesel promoting policies made diesel relatively cheaper, which eventually increased energy consumption and CO_2 emissions. Hooftman et al. (2018) notice that Europe turned into a diesel island in an attempt to become the world leader of CO_2 reductions by passenger cars. In many European countries, people paid lower taxes on diesel cars and enjoyed lower fuel prices at the pump. Europe developed a unique gap between diesel and gasoline taxes during post-war times (Transport & Environment, 2015). When governments needed more tax revenues, they increased taxes on gasoline because it was widely used by wealthier people with cars, whereas diesel was only used by trucks, so it was taxed lightly. The comparison of passenger car taxation in 30 European countries from Kunert (2018) still shows significant differences, among countries as well as between diesel and gasoline taxation. For many years, cars with diesel engines were taxed less than cars with gasoline engines. Years of incentivizing diesel cars reversed the composition of the vehicle stock in Belgium. The number of diesel and gasoline cars in 1990 was equal to respectively 1 014 905 and 2 744 249 (FOD Mobiliteit en Vervoer, 2018b). In 2015, diesel cars more than tripled to a total of 3 466 974, whereas the number of gasoline cars decreased by 22%, to 2 152 335.

In Belgium, the gap between diesel and gasoline taxes has been narrowed in recent years. As a result, fuel prices at the pump are also converging. In 2004, the price of one liter diesel was on average €0.82 compared to €1.13 for gasoline 95 (FOD Mobiliteit en Vervoer, 2018a). Today, the playing field has been levelled more or less in Belgium, even favoring gasoline cars. The latest article from VAB Magazine (2019) regarding fuel prices presents an increase to an average of €1.45 per liter diesel, while one liter of gasoline costs on average €1.36. This tendency appears to push the market in the opposite direction: since 2015, the number of gasoline cars is on the rise again at the expense of diesel cars, which are more and more de-stimulated since the dieselgate scandal.

As mentioned above, increasing the market share of diesel cars was a strategy to reduce CO_2 emissions from passenger cars. Although many countries embraced this strategy, it is not sure whether diesel cars actually produce less CO_2 than gasoline cars over their entire lifetime. The Belgian car federation FEBIAC (2018) estimates that diesel cars emit on average 10 g CO_2 less per kilometer than comparable gasoline-powered cars. The European Automobile Manufacturers' Association ACEA (2016) claims that this gap can go up to 20% less CO_2 emissions per kilometer for diesel cars. But this concerns solely the use phase, which is only one part of the life cycle of a vehicle. The complete life cycle is explained in detail in Section 3. Transport & Environment (2017) believes that diesel cars produce more CO_2 than gasoline cars, instead of less, because of three reasons. The first reason is that diesel cars usually have a higher accumulated mileage than gasoline cars over their lifespan. Data from FOD Mobiliteit en Vervoer (2018b) show that in Belgium, a diesel car ran on average 18 480 km in 2017, compared to only 9 861 km for a gasoline car. So the benefit of a lower CO_2/km emission during the use phase may in fact be neutralized by the higher number of kilometers driven if diesel cars reach more or less the same age. The second reason, according to Transport & Environment, is that the refinery process is more carbon intensive for diesel fuel. Leduc, Mongelli, Uihlein, & Nemry (2010) find higher emissions required for producing, refining and distributing diesel fuel, although the difference is rather small. These emissions are indirect emissions, whereas the emissions during the use phase are direct emissions. Diesel cars have thus lower direct emissions than gasoline cars, but the indirect emissions appear to be higher. The third mentioned reason is the fact that diesel cars are heavier so they require more materials for manufacturing. Especially steel, which according to Leduc et al. (2010) accounts for an additional weight of 217 kg in the material composition of a diesel car. This leaves them with a higher carbon footprint in the production phase. Taken together, these three elements undo the advantages generally ascribed to the lower emissions of diesel cars in their use phase, as reported by the study of Transport & Environment.

To monitor the fuel consumption and emissions of pollutants from vehicles on the road, Europe introduced the New European Driving Cycle (NEDC) and corresponding test procedure (Fontaras, Ciuffo, et al., 2017). This driving cycle was supposed to reflect typical car use in Europe. However, the test turned out to be not representative at all for on-road driving conditions, as shown by many authors (Degraeuwe & Weiss, 2017; Fontaras & Dilara, 2012; Marotta, Pavlovic, Ciuffo, Serra, & Fontaras, 2015; Weiss et al., 2012). The NEDC test results clearly underestimate the real-world passenger car emissions. A short literature review from Fontaras et al. (2017) reveals that the gap between reality and laboratory results has been widening over the years, ranging from 15% up to 40%. Fontaras, Zacharof, & Ciuffo (2017) find real-world vehicle CO_2 emissions to be 12% higher in 2005, compared to 44% in 2014. The authors study the factors that influence this gap and they claim that no test procedure will ever be able to properly capture the real-world performance of vehicles. Pavlovic, Marotta, & Ciuffo (2016) believe that the European targets regarding emission reductions, imposed by the European Commission in 2009, stimulated OEMs to exploit the flaws of the outdated NEDC test protocol. To bridge this gap, the European Commission introduced a new Worldwide Harmonized Light Vehicle Test Procedure (WLTP) to replace NEDC. In-use driving data creates a more realistic driving profile, complemented by a 'real driving emissions' (RDE) test to reflect emissions more accurately (Degraeuwe & Weiss, 2017; Pavlovic et al., 2016). Fontaras, Ciuffo, et al. (2017) conclude that WLTP shows improvements, but a gap of about 10-15% is likely to remain.

An increasing share of diesel vehicles combined with an inaccurate driving cycle to monitor emissions, results in a significant underestimation of emissions for diesel cars (Hooftman, Oliveira, Messagie, Coosemans, & Van Mierlo, 2016). In addition, underestimating the actual NO_x emission factors for diesel passenger cars leads to another consequence of the dieselization: the deterioration of air quality. The road transport sector is not only a major contributor of carbon dioxide, but also of NO_x and particulate matter ($PM_{2.5}$ and PM_{10}) (Hooftman et al., 2018). NO_x is the combination of nitric oxide (NO) and nitrogen dioxide (NO_2). Weiss et al. (2011) find that the share of NO_2 in the total NO_x emissions is significantly higher for diesel than for gasoline cars. This is threatening since NO_2 is a toxic nitrogen with adverse effects on human health and the environment. Nitrogen oxides and particulate matter are the main air pollutants (Bourguignon, 2018). The sequential 'Euro' standards on the emission of air pollutants failed to decrease the NO_x emission for diesel cars, while for gasoline cars it remained very low. Hooftman et al. (2018) confirm that no actual NO_x emission reductions are found for diesel cars between Euro 1 and Euro 5, while Euro 6 vehicles still surpass the 0.08 g/km limit by a factor of 5-7. Yang et al. (2015) compare seventy-three Euro 6 diesel passenger cars with three different types of NO_x control technologies over the NEDC test procedure and over the WLTP. They find average NO_x emissions to be five times larger over WLTP than over NEDC. 88% of all vehicles tested met the Euro 6 legislative limit of 0.08 g/km of NO_x over NEDC, compared to only 27% over WLTP. Anenberg et al., (2017) estimate that actual NO_x emissions are respectively 3.2 and 5.7 times the emission limits for Euro 4 and Euro 6 diesel passenger cars.

While the encouragement of diesel cars in order to mitigate climate change may not have produced the intended results, it certainly has had other noxious effects. A repeated violation of the emission limit of NO_x lead to a substantial deterioration of air quality. The World Health Organization (WHO) distinguishes between ambient air pollution (outdoor) and household air pollution (indoor). Emissions from vehicles are related to outdoor air pollution. Together they are responsible for one in every nine deaths annually (WHO, 2016). This makes air pollution the biggest environmental risk to human health on earth. The WHO estimates that more than 90% of people breathe air that does not comply with their Air Quality Guidelines (AQG). The report of the WHO concludes that about three million people are killed annually by ambient air pollution, affecting all regions of the world, primarily Western Pacific and Southeast Asia. Within Europe, central and eastern Europe and Italy are affected more than other parts of the continent (Bourguignon, 2018). Every year, the EEA publishes an updated analysis of the air quality in Europe. The most recent report covers the period between 2000 and 2016. It appears that Europe’s most harmful pollutants to human health are $PM_{2.5}$, NO_2 and ground-level ozone (O_3), responsible for respectively about 422 000, 79 000 and 17 700 premature deaths in 2015 (EEA, 2018b). In Belgium in the same year, 7 400 premature deaths were attributable to $PM_{2.5}$ exposure, 1 500 to NO_2 exposure and 220 to O_3 exposure. Furthermore, the EEA emphasizes that air pollution also has a large impact on ecosystems, affecting vegetation and fauna and the quality of water and soil. Their 2018 report states that although emissions of key pollutants from the transport sector have decreased significantly between 2000 and 2016, transport is still the largest contributor to total NO_x emissions and a major contributor of $PM_{2.5}$ and carbon oxides (CO). This implies that many premature deaths as a result of exposure to the aforementioned pollutants are attributable to the transport sector.

2.2 Electrification of road transport

Given that the transport sector is such a major contributor to global warming and air pollution, reducing the environmental impact of transport provides a huge opportunity to address these problems. FEBIAC (2018) acknowledges that the automotive industry faces two major challenges today: improving air quality and decreasing CO_2 emissions. In this context, researchers believe that the transition to electromobility can play an important role. Many studies make a comparison between the environmental performance of conventional vehicles and electric vehicles (EVs). Athanasopoulou, Bikas, & Stavropoulos (2018) observe that battery electric vehicles (BEVs) are an attractive alternative since they have no tailpipe emissions. However, BEVs still require fossil fuels in order to generate electricity to power the battery. This implies that a higher share of fossil fuels in the electricity generation mix causes higher CO_2 emissions. Belgium has a high ratio of nuclear energy in its electricity mix which has a low carbon intensity, so BEVs are significantly more environmentally friendly than ICEVs. Increasing the ratio of renewable energy in the electricity mix makes electricity generation less carbon intensive and as a result BEVs become greener. Boureima et al. (2009) compare the greenhouse effect of electric, hybrid, LPG and gasoline cars in a Belgian context and find the effect to be the lowest for BEVs and the highest for gasoline cars. The same is true for the impact on human health. Hawkins, Singh, Majeau-Bettez, & Strømman (2013) confirm that EVs are able to reduce GHG emissions and exposure to tailpipe emissions, if they are connected with low-carbon electricity. Zero tailpipe emissions offer a decrease in global warming potential (GWP) and reduce urban air pollution compared to conventional ICEVs. Siskos, Zazias, Petropoulos, Evangelopoulou, & Capros (2018) believe that the decade 2020-

2030 will be crucial in the decarbonization process of the transport sector. This transformation requires an increased penetration of technologies with a low carbon footprint. In addition to BEVs, there are other types of EVs which can lower the CO_2 emissions from the transport sector. The EEA (2016) presents an overview of the main types of electric vehicle technology in Europe. Hybrid electric vehicles (HEVs) are a combination of ICEVs and BEVs, since they combine an internal combustion engine with an electric motor. HEVs are most of the time powered by the combustion engine, but the battery assists the conventional engine when the vehicle is accelerating to increase fuel efficiency. Plug-in hybrid electric vehicles (PHEVs) also combine an internal combustion engine and an electric motor, but unlike HEVs, their battery can be charged from the grid. The battery of HEVs is usually charged during regenerative braking which recovers energy. PHEVs have a longer driving range and the combustion engine supports the electric motor when the battery is low or when the vehicle requires more power. The fuel efficiency of PHEVs depends on the extent to which they can rely on the electric motor and the carbon intensity of the electricity mix. Range-extended electric vehicles (REEVs), as the name suggests, have a longer driving range than HEVs and PHEVs. They are powered by an electric motor and plug-in battery, but still possess an internal combustion engine which is used to recharge the battery as soon as the vehicle exceeds its electric driving range. The battery of REEVs can also be charged from the grid, so they are in fact a type of PHEV with a longer driving range. The last type of electric vehicle technology is fuel cell electric vehicles (FCEVs). FCEVs and BEVs are both entirely powered by electricity, but while BEVs store energy in a rechargeable battery, FCEVs draw energy from a fuel cell ‘stack’ which combines hydrogen from an on-board tank with oxygen from the air. They have a longer driving range and faster refueling process than BEVs, but fuel cell technology is not fully developed yet. This is why the commercial availability is still limited. The aforementioned electric vehicle technologies are all related to electrically-chargeable vehicles (ECVs), except for HEVs, which are only charged while driving and not from the grid.

In Belgium, the share of ECVs in new passenger car registrations decreased in 2018 because of a drop in PHEV sales (ACEA, 2019). The share of BEVs in new passenger car sales was 34% higher in 2018 than in 2017. The press release from ACEA shows that in general, more EVs were sold in the EU in 2018 than in 2017, but they still account for merely 5.8% of annual vehicle sales. If we only take into account the ECVs, the share goes down to 2% of new passenger car registrations in 2018 for the EU. Also in terms of market share, EVs remain a tiny proportion of the total passenger cars. In Belgium in 2017, all types of EVs together represent a market share of 1.43%, compared to 41.02% for gasoline cars and 56.83% for diesel cars (FOD Mobiliteit en Vervoer, 2018b). A higher share of EVs in new car registrations will boost its market share, but the penetration of EVs needs to go faster if it is to have a significant impact on the environment. Norway is considered a frontrunner in the transition to electromobility. This is the result of a wide range of incentives which makes EVs not only economically accessible but also attractive to use (Figenbaum, Assum, & Kolbenstvedt, 2015). In 2015, already 22.5% of all new cars sold were electric (EEA, 2016). BEVs and PHEVs together almost accounted for 50% of new passenger car registrations in 2018, according to the European Alternative Fuels Observatory (2019). This is more than eight times the share of 2013. The market share of EVs in Norway now approaches 10%. The press release from ACEA indicates that, when comparing Norway to the EU, Denmark is the only country that is, just like Norway, capable to increase the share of ECVs in new passenger car registrations while reducing the share of both diesel and gasoline cars. However, this transition happens a lot slower in Denmark than in Norway. In Belgium, the share of diesel cars in new passenger car registrations was 23% lower in 2018 than in 2017, but the share of gasoline cars in vehicle sales increased by 22%. The ING Economics Department (2017) identifies three major barriers to the demand of BEVs: charging infrastructure, driving range and pricing. The authors of the report are confident that all three barriers “are about to be broken”. If this is the case, a scenario in which BEVs account for 100% of all new car sales by 2035 is considered realistic by the authors.

The spectrum of incentives that enabled Norway to obtain the largest electric vehicle fleet per capita in the world is summarized in Table 1. The exemption from VAT and purchase taxes appear to be the strongest incentives for buying a BEV (Bjerkan, Nørbech, & Nordtømme, 2016). Norway does not intend to slow down its electrification of road transport, given that the country aims to stop the sales of non-zero emission vehicles as from 2025 (Saele & Petersen, 2018). In order to reach this goal, Norway set up an interim target of 85 g CO_2 emission per kilometer for new passenger cars by 2020 (Figenbaum et al., 2015). The EEA (2018c) monitors CO_2 emissions from new passenger cars and finds an average of 82.6 g CO_2/km for new passenger cars in Norway in 2017. This implies that the rapid growth of EVs permits Norway to reach its target earlier than expected. Meanwhile, Figure 2 indicates that the EU transport sector is not on track to reach the policy target of 95 g CO_2/km by 2021. Although the rise of EVs has led to a substantial reduction in CO_2 emissions in Norway, Aasness & Odeck (2015) also find some adverse effects of the numerous incentives. For example, a decrease in toll revenues following the exemption from toll charges and an increased travel time for public transport users since EVs are allowed to use transit lanes, leading to more congestion on these lanes. The authors conclude that every country should take the adverse effects into account as well as the electricity source. Singh & Strømman (2013) confirm that Norway benefits from substantial GHG reductions because the main energy source for EVs is hydropower, which is carbon free. A more carbon intensive electricity mix, for example if the main energy source is coal or gas, will reduce the environmental benefits of EVs over conventional vehicles.

Table 1. Zero emission incentives in Norway[a]

Incentive	Date	Incentive	Date
No purchase/import taxes	1990 - Present	Access to bus lanes	2005 - Present
Exemption from 25% VAT on purchase	2001 - Present	New rules allow local authorities to limit the access to only include EVs that carry one or more passengers	2016 - Present
No annual road tax	1996 - Present	50 % reduced company car tax	2000 - 2018
No charges on toll roads or ferries	1997 - 2017	Company car tax reduction was lowered to 40%	2018 - Present
Charges were introduced on ferries with upper limit of maximum 50% of full price	2018 - Present	Exemption from 25% VAT on leasing	2015 - Present
Charges on toll roads were introduced with upper limit of maximum 50% of full price	2019 - Present	Fiscal compensation for scrapping of fossil vans when converting to a zero emission van	2018 - Present
Free municipal parking	1999 - 2017	Allowing holders of driver license class B to drive electric vans class C1 (light lorries) up to 2450 kg	2019 - Present
Parking fee for EVs was introduced locally with an upper limit of maximum 50% of full price	2018 - Present		

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[a] Overview of the Norwegian electric vehicle policy is retrieved from http://elbil.no/english/norwegian-ev-policy/

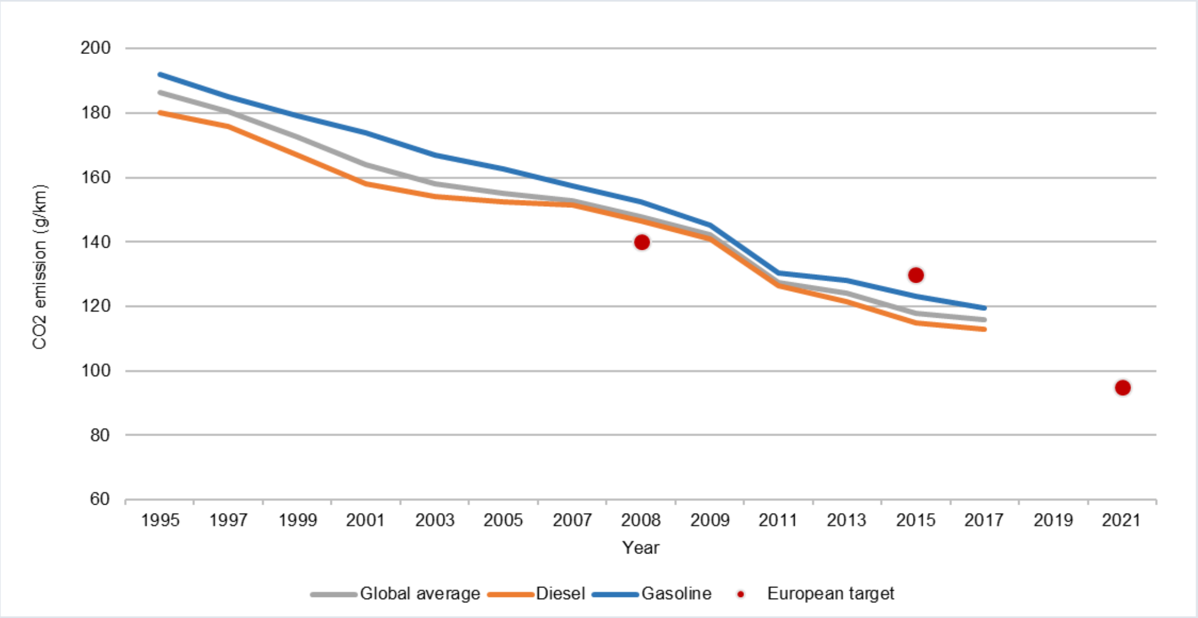

Figure 2: Average CO_2 emission of newly registered cars. Reproduced from FOD Mobiliteit en Vervoer (2018a)

2.3 Circular economy

Kirchherr, Reike, & Hekkert (2017) gather a comprehensive set of 114 CE definitions to offer a better understanding of the circular economy. The most popular definition in the authors' set is the following definition of the Ellen MacArthur Foundation (2013):

> A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models. (p. 7)

This definition is also supported by Geissdoerfer et al. (2017) and will be used throughout this paper. The cited authors mention that the circular economy concept is an emerging topic among scholars, policymakers and companies. They are all increasingly aware of the need for more sustainable solutions to environmental issues. The CE offers a set of opportunities to address these problems. It aims at overcoming the dominant linear *take, make, dispose* economy model (Urbinati, Chiaroni, & Chiesa, 2017). According to the European Commission (p.1, 2018), shifting to a CE is a "tremendous opportunity to transform our economy and make it more sustainable, contribute to climate goals and the preservation of the world's resources, create local jobs and generate competitive advantages for Europe in a world that is undergoing profound changes".

Although EVs offer drastic reductions of GHG emissions and improve air quality, Hawkins et al. (2013) warn for potential problem shifts to "increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication and metal depletion". EVs require the extraction of different materials like copper, and sometimes nickel, for the production of electronic equipment. The authors claim that this raises concerns about toxicity. Furthermore, using scarce materials can pose a challenge for recycling. The EEA (2018d) published a report in which they study electric vehicles from life cycle and circular economy perspectives. The report explores how a transition to a CE can reduce this detrimental environmental impact, associated with the life cycle of BEVs. The environmental impact refers to the impact on climate change, on health and on ecosystems and is based on the findings of Hawkins et al. (2013).

The EEA (2018d) claims that the CE can optimize the environmental benefits of BEVs by addressing the following elements: vehicle design, reuse and recycling, vehicle use and choice, and low-carbon electricity sources. The standardization of battery design can facilitate reuse and recycling in the future. Reuse and recycling strategies should therefore be taken into account in the vehicle design from the start to allow for a more efficient use of materials. If we are able to reuse and recycle key components, we need less primary material extraction and as a result reduce the environmental impact. A standardized battery design would also facilitate the ease of maintenance which enables a higher driving range. Furthermore, the EEA report stimulates car manufacturers to increase the driving range of BEVs without making batteries larger, since these require more energy and more raw materials to produce. Literature on the use of BEVs regarding lifetime mileage and trip purposes is still limited, though the EEA believes that shared mobility could be a huge opportunity for BEVs in the transition to sustainable mobility. Shared mobility allows people to choose from different operating systems such as taxis, short-term rental or carsharing. This scenario implies that people no longer have to own cars, but that they are able to use cars only when they need them. This is the main idea behind circular business models. People do not pay for the possession of products, but only for the use (Urbinati et al., 2017). Circular business models are able to eliminate the costs of ownership and shift the “pay-per-own” approach to a “pay-per-use” approach. In this way, a circular economy is a rather functional economy, in which consumers buy mobility instead of cars (Mont, 2002). This is called a ‘product-service system’, meaning that people buy in fact a product in order to receive a service. Shared mobility is thus based on the idea that people do not want to own cars, but they want the service that is provided by a car. Passenger cars are produced to move people and not to be owned. Privately owned cars sit idle for long periods throughout the day, whereas shared mobility offers the possibility to make better use of cars. According to the ING Economics Department (2017), the value shift from products to services is beneficial for BEVs, which have low costs of operation. The higher price can thus be spread among multiple users. This can also make people more familiar with the battery technology of BEVs.

There is an important distinction with linear business models. Circular business models encourage manufacturers to design for durability because if their products have a longer lifetime, the use phase is extended and when people pay-per-use, this results in more revenues. On the other hand, linear business models have the opposite effect. If consumers only pay to own a product, a shorter lifetime implies that they need to replace their product sooner, which encourages manufacturers to shorten the lifetime. Shared mobility can significantly increase the intensity of car use, since fewer cars are required to fulfil the same needs as car ownership.

The essential role of low-carbon electricity, discussed earlier in this paper, is also emphasized by the EEA (2018d). Increasing the share of renewable energy sources in the electricity mix reduces the environmental impact of a BEV in every life cycle stage. Lowering the share of coal reduces human ecotoxicity and adverse ecosystem impacts. Overall, studies suggest that EVs, and especially BEVs, reduce GHG emissions and improve air quality, primarily in urban areas, but we should not neglect the potential adverse effects. For one, the extraction of raw materials like copper may be toxic. There is still a lot of uncertainty, particularly regarding the environmental impact of the end-of-life process of BEVs, but the transition to a CE could be an opportunity to solve the adverse effects of the electrification of road transport.

2.4 Carsharing

As discussed above, shared mobility includes different operating systems which enhance the efficiency of car use and as a result reduce the environmental impact. In this paper, we discuss the potential effect of carsharing on reducing CO_2 emissions from passenger cars. Carsharing gives people access to a shared fleet of vehicles on an as-needed basis which eliminates costs and responsibilities of car ownership (S. A. Shaheen, 1999). The traditional type of carsharing is station-based, which means that cars are picked up and dropped off at predefined, fixed stations (Ferrero, Perboli, Rosano, & Vesco, 2018). The more flexible type of carsharing is free-floating, which allows users to pick up and park a car anywhere within a defined area (Firnkorn & Müller, 2011). In both cases, the vehicle fleet is owned by the company. Some studies include peer-to-peer as a third type of carsharing, in which cars are privately owned and shared between individuals (Ballús-Armet, Shaheen, Clonts, & Weinzimmer, 2014). Bert, Collie, Gerrits, & Xu (2016) write in a report for the Boston Consulting Group that carsharing users pay more per trip than they would pay with their own car, but car ownership involves a lot of fixed costs, such as maintenance, insurance and depreciation, whereas carsharing users only pay when they need a car. Therefore, the authors of the report calculate how many people in Europe would pay less to share than to own. Based on their annual mileage, 17% of city-car drivers, 46% of compact drivers, and the majority of midsize and large-car drivers would be better off with carsharing instead of owning a car, from a financial perspective.

The main objective of carsharing is to reduce traffic congestion and air pollution (S. A. Shaheen, 1999). Sharing vehicles should lead to less traffic and even fewer cars in general. Not only should carsharing cause a decrease in vehicle usage, but also in demand for parking space (Litman, 1999; S. Shaheen, Sperling, & Wagner, 1998). It is not sure, however, whether carsharing really reduces the stock of cars and if so, to what extent. Studies differ in their projected impact of carsharing on car ownership. According to Martin & Shaheen (2011a), every shared car in North America takes 9 to 13 vehicles off the road, even though 60% of all households joining carsharing did not have a car in the first place. In their sample, the average number of vehicles per household drops from 0.47 to 0.24 after joining carsharing. Rydén and Morin, cited in S. A. Shaheen & Cohen (2007), estimate a decrease of 6 to 23 privately owned cars for every shared car in North America and 4 to 10 in Europe. They also predict a significant reduction in vehicle kilometers traveled (VKT) between 28 and 45%. Giesel & Nobis (2016) study the impact of carsharing on car ownership in German cities and find out that many people consider free-floating and station-based carsharing as a valid alternative for car ownership if there is a good availability of carsharing vehicles. Nevertheless, a large group of car owners is not willing to give up their private car. Therefore, Sprei & Ginnebaugh (2018) explore a business model where consumers combine a private vehicle to fulfil their daily needs with the possibility to use carsharing for infrequent use. They conclude that carsharing is not ready to serve as a vehicle for infrequent use, due to a lack of a variety of models in the carsharing fleet. In order to make this variety profitable for carsharing providers, they need to grow in terms of size and customer base. The impact of carsharing on new-car sales in 2021 is estimated by Bert et al. (2016) based on three scenarios. The most likely scenario is that a significant part of lost car sales will be offset by an expansion in carsharing fleets. This expansion is necessary in order to deal with times of peak demand. More specifically, the authors predict that carsharing will decrease projected new-car sales in Europe by only 1.3% in 2021. They conclude that carsharing will continue to grow in the coming years, but that the social importance of private ownership will remain too big for carsharing to become a real game changer. Grosse-Ophoff, Hausler, Heineke, & Möller (2017) are more optimistic, predicting that shared mobility will eliminate about a third of the projected increase in car sales by 2030. However, as mentioned before, shared mobility involves more merely carsharing. Moreover, the authors aniticipate that increasing car sales in developing countries in the near future may reduce the positive impact of fewer vehicles resulting from carsharing.

Either way, Martin & Shaheen (2011b) emphasize that participating in carsharing can also cause a beneficial side effect, namely a shift in travel behavior towards more sustainable transport modes. This is known as a modal shift. Carsharing members, who were not carless before joining carsharing, tend to drive less and travel more by walking, bicycling and public transport. Baptista, Melo, & Rolim (2014) confirm that carsharing leads to “a more efficient and rational mobility”, if it serves as a complement to public transport. Jung & Koo (2018) question the positive effect of this change in behavior after joining carsharing. Their research shows that there is also a negative modal shift as carless individuals may shift from public transport to carsharing, because of an improved flexibility of carsharing. This would lead to an increase in VKT, instead of a decrease. The cited authors conclude that a larger proportion of fuel-efficient EVs in car sharing fleets is required to avoid a negative environmental effect of carsharing.

Although carsharing can have a positive impact on the environment, it is clearly still a niche market. Thus the number of shared cars and carsharing users needs to grow before it can play an important role in the mobility market (Nobis, 2006). Firnkorn & Müller (2012) emphasize the responsibility of policymakers, who should support carsharing by allocating more public space to carsharing schemes. According to a recent report from ING Economics Department (2018), the number of 'registered users' in Europe doubled from 2016 to 2018, 5.1 million to 11.5 million. Most private cars are parked 95% of the time, yet only 0.13% of all passenger cars in Europe are shared. This is far from an economically rational approach, but carsharing still needs to overcome many barriers before it can be a worthy alternative to ownership. ING defines the improvement of the user experience and the cost competitiveness as the most important barriers. This means that there must be a sufficient supply of cars at any time so that people can always rely on carsharing when they need to, and carsharing must become relatively cheaper compared to car ownership.

2.5 Research questions

Based on the literature review, we can conclude that the transport sector is a major contributor to global warming and air pollution because of the emission of CO_2 and other key pollutants. Therefore, reducing the environmental impact of road transport provides a huge opportunity to address these environmental problems. The aim of this paper is to explore how we can reduce CO_2 emissions from passenger cars in Belgium. We simulate different scenarios and draw on the outcomes to make suggestions for the transition to a lower-emission mobility. This objective can be divided into more specific research questions that will be addressed in this paper:

- How can we measure a service, such as mobility?
- How can we measure environmental impact?
- How can growing carsharing activity contribute to a smaller environmental impact of cars?
- Will an electrification of road transport reduce the CO_2 emissions from cars?
- How can growing steel recycling activity reduce the CO_2 emissions from cars?
- Which scenario has the largest potential to reduce the CO_2 emissions from cars?
- How can policy-makers contribute to the transition towards sustainable mobility?

3 Data and method

We use a three-step method in this study. In the first part we estimate the current environmental impact of cars. In the second step we simulate different scenarios that reduce CO_2 emissions from cars. In the third and final step we interpret the results of the simulated scenarios and offer some policy recommendations. This section explains which data we use for each step, how we estimate the environmental impact and how we simulate every scenario.

3.1 Vehicle specification

GHG emissions from road transport depend on the composition of the vehicle stock. According to the Federal Planning Bureau (2019), the emission intensity depends on a car's age, fuel type and size. It is necessary, then, to clarify the assumed characteristics of the car models analyzed in this study, before estimating their environmental impact. Changing these characteristics results in a different outcome of the estimated environmental impact. We distinguish between ICEVs, fueled by gasoline or diesel, and BEVs, which are fully electric cars, and model an average vehicle for every type. The average models are illustrated in Table 2. ICEVs are the most representative vehicles and BEVs have the potential to obtain this title in the future (Qiao, Zhao, Liu, Jiang, & Hao, 2017). About 99% of all passenger cars in Belgium in 2017 were ICEVs fueled by either diesel or gasoline, compared to less than 1% of BEVs

(FOD Mobiliteit en Vervoer, 2018b). Despite still being very small in absolute numbers, BEVs grew at a percentage of 1177% between 2012 and 2017.

Table 2. Assumed vehicle characteristics with different total mileages

PARAMETER	Unit	ICEV	ICEV	BEV
Energy source	na	Gasoline	Diesel	Lithium-ion battery
Age of retirement	years	15	15	10
Accumulated mileage[a]	km	160 000	208 000	150 000
Average consumption[b]	l/100km	5.3	4.5	na
Average consumption[c]	kWh/100km	na	na	20.6
Battery capacity[d]	kWh	na	na	40

na: not applicable

There are no reliable data regarding the retirement age and accumulated mileage of vehicles in Belgium (Federal Planning Bureau, 2019). According to Nemry, Leduc, Mongelli, & Uihlein (2008), the average lifetime of a car is between 12 and 15 years in Europe. Transport & Environment (2018) believes the typical lifetime of cars today is 15 to 20 years. We assume that both diesel and gasoline cars reach the end-of-life stage at the age of 15 and BEVs at the age of 10. In one scenario we measure the environmental impact based on an equal accumulated mileage of 150 000 km for every vehicle type and in another scenario, we assume the accumulated mileages to be equal to the observations of Dun et al. (2015) for ICEVs. For BEVs, there is more uncertainty about the total mileage. They are still rather new to the market which means that not enough BEVs have come to the end of their lifetime yet in order to make precise estimates. Hawkins et al. (2013) expect that battery lifetime is equal to the BEV lifetime. The authors assume 150 000 km driven over the entire lifetime, even though they admit that it is a challenge to make an appropriate lifetime assumption for EVs. This is mainly due to uncertainty regarding the battery design, driving patterns and ease of maintenance. Notter et al. (2010) also assume a lifetime of 150 000 km for a BEV that is comparable to a Volkswagen Golf in terms of size and power, according to the authors. In 2017, a BEV ran on average 18 951 km in Belgium (FOD Mobiliteit en Vervoer, 2018b), but generally cars are used more in the first years of their lifetime. On the assumption that the average km per year will decrease for BEVs over their lifetime, an accumulated mileage of 150 000 km seems realistic when considering a lifetime of eight to ten years.

3.2 Environmental impact

To estimate the environmental impact, we focus on the production and ‘well-to-wheel’ (WTW) phase. Moro & Helmers (2017) describe WTW as a “simplified life cycle assessment (LCA) that focuses on the energy consumption and CO_2 emissions only for the fuel being consumed, ignoring other stages of a vehicle’s life cycle”. LCA on the other hand, is a standardized methodology, constructed by the International Organization for Standardization (ISO), that is far more complex since it takes into account the footprint of every process over the entire lifetime of a product (Edwards, Mahieu, Griesemann, Larivé, & Rickeard, 2004). Leduc, Mongelli, Uihlein, & Nemry (2010) perform a life cycle assessment to

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[a] Dun, Horton, & Kollamthodi (2015) for ICEVs. Hawkins, Singh, Majeau-Bettez, & Strømman (2013) for BEVs

[b] Test results from Test-aankoop (2015) for gasoline Volkswagen Golf VI TSI and diesel Volkswagen Golf VI TDI

[c] Based on WLTP results for the second-generation Nissan Leaf. Retrieved from http://ev-database.nl/auto/1106/Nissan-Leaf#charging

[d] Based on second-generation Nissan Leaf. Retrieved from http://ev-database.nl/auto/1106/Nissan-Leaf#charging

study the environmental improvement potential of gasoline and diesel cars. They identify five life cycle stages:

- Production phase
- Spare parts production
- Well-to-Tank
- Tank-to-Wheel (Use phase)
- End-of-life phase

The authors remark that the spare parts production and the end-of-life (EOL) phase only have a minor impact on global warming potential (GWP), which is measured in terms of CO_2 emissions. This is why we do not include these two phases. Furthermore, BEVs are relatively new to the market, so very few of them have already reached the recycling stage (Romare & Dahllöf, 2017). Although data about BEVs' EOL impact are currently too scarce to allow for significant scientific conclusions and projections, it is obvious that this will have to be taken into account in future research.

Figure 3 illustrates the life cycle of cars, without the spare parts production phase which comprises repair and maintenance and causes so-called 'non-exhaust' emissions. Messagie, Macharis, & Van Mierlo (2013) study the outcomes from many life cycle assessments of vehicles through a profound literature review. The large variety in results is mainly due to differences in goal and scope definition of various studies, and the uncertainty regarding battery and vehicle production, energy consumption and electricity source. The fact that the LCA methodology has been used so often to measure and compare the environmental performance of vehicles, suggests that it is the most suitable approach. Given that the objective of this paper is not to measure nor to compare the environmental impact of cars, but to explore the potential reduction of CO_2 emissions through a simulation of different scenarios, we use a shortened LCA approach that covers an average vehicle for ICEVs and BEVs. This is similar to Moro & Helmers (2017), who use a hybrid approach between WTW and LCA to study the carbon footprint of electric vehicles.

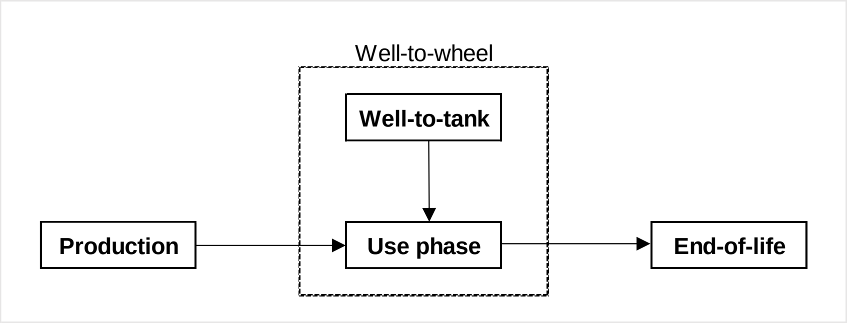

Figure 3: Life cycle of cars, reproduced from Patterson (2018)

3.2.1 Production phase

Leduc et al. (2010) subdivide the production phase into raw material mining, material processing and car assembling. The differences in terms of GHG emissions between gasoline and diesel cars are rather small during this phase. Diesel cars tend to be heavier because of the higher amount of steel that is required for them. This results in slightly higher emissions compared to lighter gasoline cars. However, the authors of the cited study write that making a detailed study of the environmental impact of car production based on the material composition is difficult because of a lack of data. This is confirmed by Messagie et al. (2013), who state that modelling the vehicle production usually requires a detailed life cycle inventory list which includes all materials and production processes. The authors suggest that modelling the vehicle production of an average vehicle is an alternative method, since the vehicle fleet is heterogeneous so the inventory list is different for each vehicle. For scenario analysis purposes, we only distinguish based on source of power and not on size. This is why we draw on the life cycle inventory (LCI) list provided by Volkswagen AG (2010) for an average vehicle to study the environmental impact of production. The average vehicle is a VW Golf VI 1.6 TDI for diesel cars and a VW Golf VI 1.2 TSI for gasoline cars.

The environmental impact of the production phase of BEVs is different because of the battery production. The International Council on Clean Transportation surveys studies that analyze the emissions of battery manufacturing in terms of carbon dioxides per kilowatt-hour of battery capacity (ICCT, 2018). The report shows that the impact of battery manufacturing on the overall emissions of BEVs is a complex subject and that it depends on the methods and materials that are used for manufacturing. Especially the energy used during the manufacturing process plays an important role. The ICTT therefore suggests that using cleaner energy significantly reduces the emissions of battery manufacturing. Values from the analyzed studies range from 56 to 494 kg CO_2-eq/kWh of battery capacity. We draw on the findings of Kim et al. (2016), who use primary data from the battery industry and apply this to a 24kWh lithium-ion battery from a Ford Focus Electric. They find GHG emissions to be 140 kg CO_2-eq per kWh of battery capacity, which lies in the midrange of the literature values for BEV batteries, according to the authors. Romare & Dahllöf (2017) confirm that the main driver for GHG emissions during the production of lithium-ion batteries is energy use. Since production energy is mostly electricity, carbon emissions in the battery manufacturing process depend to a great extent on the electricity mix at the production location. According to Patterson (2018), the vehicle production of ICEVs represents at most 30% of the total lifecycle GHG emissions, compared to 60% for BEVs. In general, the environmental impact of this phase is the highest for BEVs because of the carbon intensive battery production (Qiao et al., 2017). Since car manufacturers have not yet released a full life cycle inventory list for a BEV, we rely on the same LCI as for our average diesel model, provided by Volkswagen AG (2010), and add to this the separate manufacturing of a 40kWh battery.

3.2.2 Well-to-Wheel

The well-to-wheel approach, or fuel-cycle, consists of two parts: the well-to-tank (WTT) and the tank-to-wheel (TTW) phase. Both phases are different for ICEVs on the one hand and BEVs on the other. This is illustrated in Figure 4. The WTT includes the indirect emissions from the fuel production and distribution for ICEVs, or from the electricity generation in the case of BEVs. The TTW, or use phase, is related to direct emissions from the tailpipe, so this is only valid for ICEVs. The well-to-wheel approach for BEVs is thus limited to the well-to-tank phase.

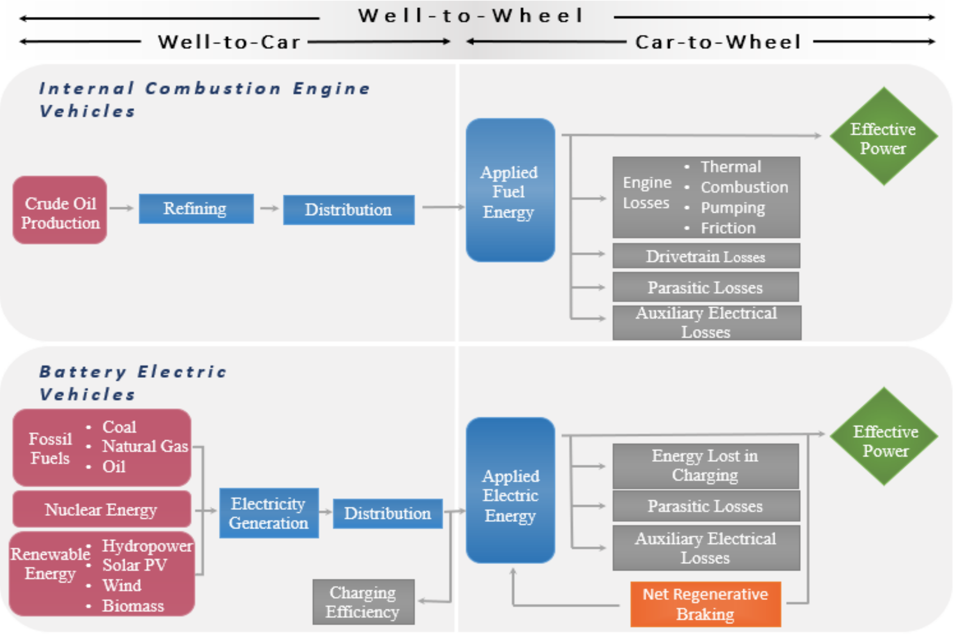

Figure 4: Well-to-wheel approach for ICEVs and BEVs. Source: Athanasopoulou et al. (p. 26, 2018)

Before fuels come into an ICEV and are burned to power the vehicle, they need to be produced and transported. This well-to-tank process starts with the extraction of primary energy, followed by the fuel production, conditioning, transportation and distribution (Leduc et al., 2010). We retrieve data from the Federal Planning Bureau (2019) for the indirect emission factors of fuel production and distribution, expressed in terms of megajoules (MJ), and from IOR Energy (n.d.) for the energy density of gasoline and diesel. Fuel consumption and accumulated mileage are based on the assumed vehicle characteristics illustrated in Table 2. We use formula (1) to measure the well-to-tank phase of diesel and gasoline cars:

$$WTT = \frac{CO_2}{MJ} \times \frac{MJ}{L} \times \frac{L}{KM} \times KM \tag{1}$$

An important difference between the production and use phase (TTW) of ICEVs is the fact that GHG emissions during the production phase take place only once for every car, while in the use phase a car emits every time it is on the road. To estimate the environmental impact of ICEVs during the tank-to-wheel phase, we retrieve data from FOD Mobiliteit en Vervoer (2018a). The carbon intensity per kilometer (CO_2/KM) is measured as a weighted mean over the last 20 years, meaning that the average CO_2 emission of newly registered cars in a certain year is multiplied by the amount of cars registered in the same year. However, the CO_2 emissions per kilometer are based on the inaccurate NEDC test protocol which underestimates the emissions. To come closer to real driving emissions, we increase the CO_2 emissions per kilometer by 11%, based on WLTP results from Pavlovic et al. (2016). We use formula (2) to measure the tank-to-wheel phase of diesel and gasoline cars:

$$TTW = \frac{CO_2}{KM} \times \frac{KM}{CAR} \times CAR \tag{2}$$

Despite having no tailpipe emissions, BEVs also emit carbon dioxides indirectly, when generating energy to charge their battery. This is measured by the well-to-tank phase for BEVs. The carbon intensity of electricity consumption depends on the electricity mix of a country. For example, nuclear energy has a low carbon footprint, whereas coal has a very high carbon footprint. Thus relying on coal to generate electricity can completely offset the environmental benefits of electric vehicles. The electricity mix of Belgium and the European Union is illustrated in Table 3.

The carbon intensity of the Belgian electricity mix is lower than the average of the EU because of the larger share of nuclear energy and smaller share of coal. The carbon intensity of Belgium's electricity mix in 2018 is retrieved from Agora Energiewende and Sandbag (2019), who analyze the European power sector. The energy consumption of the modelled BEV is based on WLTP results for the second-generation Nissan Leaf and illustrated in Table 2. We use formula (3) for the well-to-tank phase of BEVs:

$$WTT = \frac{CO_2}{kWh} \times \frac{kWh}{KM} \times KM \tag{3}$$

Table 3. Share of electricity generation by fuel in 2016. Source: IEA Electricity Information (2018)

Region	Renewables	Nuclear	Coal and lignite	Natural and derived gas	Oil	Other fuels
Belgium	17%	51.2%	3.1%	26%	0.2%	2.5%
European Union	29.4%	25.8%	22.6%	18.8%	1.8%	1.6%

3.3 Scenario simulation

In the second part of this study, we simulate different scenarios that reduce CO_2 emissions from cars. Material Economics (2018) published a report about the climate potential of a circular economy. The report states that existing literature is mainly focused on the supply side, by studying how to reduce emissions from production processes. The demand side is often ignored, despite being economically attractive: “Can we make better use of the materials already produced,” the authors ask, “and so reduce our need for new production?”. They believe that the answer to this question can be found in a circular economy. As explained in the literature review, a circular economy provides opportunities to reduce CO_2 emissions from road transport by applying concepts such as reuse, recycling and shared mobility. This is why we measure the environmental impact of using more recycled steel in the production process of cars as well as the impact of carsharing, which is a form of shared mobility. Material Economics set up a framework which contains three circular strategies that reduce the amount of new materials required by increasing efficient use of materials. The framework is illustrated in Figure 5. In this section we explain why steel recycling and carsharing fit into this framework.

				Material recirculation		**Product material efficiency**		**Circular business models**
GHG EMISSIONS	=	USEFUL SERVICE	X	$\frac{\text{GHG}}{\text{MATERIALS}}$	X	$\frac{\text{MATERIALS}}{\text{PRODUCT}}$	X	$\frac{\text{PRODUCT}}{\text{USEFUL SERVICE}}$

Figure 5: Three circular economy strategies make more productive use of materials and products to reduce GHG emissions, reproduced from Material Economics (2018)

First, we reproduce this framework to measure CO_2 emissions of passenger cars. GHG emissions are expressed in terms of the equivalent CO_2 emissions and the provided useful service is defined as road transport by passenger cars. Other types of road transport such as public transport or freight transport are not taken into account. In order to measure the CO_2 emissions of producing a certain material according to this framework, it is necessary to quantify the useful service. The number of kilometers driven with passenger cars is the most relevant criterion, since this indicates how much people use this mode of transport. Formula (4) expresses the CO_2 emissions of each produced material for every vehicle type, based on Figure 5:

$$CO_2 = \frac{CO_2}{MATERIAL} \times \frac{MATERIAL}{CAR} \times \frac{CAR}{KM} \times KM \qquad (4)$$

An increased recycling activity of steel leads to a lower need for primary steel and as a result lower CO_2 emissions per ton of steel since recycled steel has a lower carbon footprint. Total CO_2 emissions of steel production are hereby reduced without changing the provided service, measured by the number of kilometers driven (*KM*). This is an example of making better use of a material which results in a lower need for primary production.

There are two common ways to produce steel: basic oxygen furnace (BOF) and electric arc furnace (EAF) (Hasanbeigi, Arens, Cardenas, Price, & Triolo, 2016). BOF uses iron ore to produce steel, which is an energy-intensive process with a much higher CO_2-intensity than EAF steel production, which re-melts recycled steel scrap. To simulate this scenario, we rely on the material composition of gasoline and diesel cars from the study of Leduc et al. (2010), who distinguish between both steel production methods. The carbon intensity of BOF and EAF steel production is retrieved from Material Economics (2018), on the assumption that the BOF-route contains the best available technology. The authors of Material Economics are confident that nearly all the emissions from steel production can be eliminated within the EU by 2050 if we move to a fully circular steel economy. To reach this objective, the authors admit that some important issues related to steel recycling need to be addressed first. More steel scrap should become available for recycling through a reduction of steel losses and avoiding downgrading.

Too often, large amounts of steel are lost during the use cycle or steel is contaminated with other materials such as copper, which downgrades the quality of secondary steel. We measure the environmental impact of steel recycling through a gradual transition from the BOF-route to the EAF-route. According to Yellishetty, Ranjith, & Tharumarajah (2010), despite the fact that steel is the most recycled material, most steel production still follows the energy-intensive BOF-route. However, the authors expect that the share of EAF in the total steel production will grow rapidly.

The main idea of carsharing is that it allows for a more efficient use of cars by providing the same service with fewer cars. As a result the required number of cars to drive a certain number of kilometers decreases, expressed in the formula above by *CAR/KM*. This is called the product intensity of service delivery. Meanwhile, if the same number of km is driven, but with fewer cars, the average number of km driven per car increases. This is the product intensity of car use. So carsharing enables each car to be used more intensively, but with fewer cars in total. The literature review on carsharing shows that it is usually associated with reduced vehicle ownership as well as reduced VKT. Literature on the extent to which VKT are reduced as a result of carsharing is very limited. On one hand, there are individuals who forgo car ownership because they shift to carsharing and combine this with other transport modes such as public transport, walking and biking so they drive less than before. This is a positive modal shift. On the other, there are also carless individuals who join carsharing and as a result drive more, because initially they would use public transport or other sustainable transport modes. This is a rather negative modal shift. The net effect of the modal shift depends on the characteristics and preferences of people whether joining carsharing will increase or decrease their number of VKT. This is why we focus on the other key environmental benefit associated with carsharing, which is a reduction in vehicle ownership. The literature review proves that the reduction in vehicle ownership can be compensated by potential setbacks too, such as an expansion in the car sharing fleet. Sharing more vehicles should reduce the required total number of cars in the market. It is very unlikely that carsharing alone will ever be able to replace car ownership, although it can slow down the growth of the car stock. The idea behind this deceleration is that individuals who join carsharing would have bought a car otherwise. If more people share cars instead of buying them, there are more forgone purchases and the demand for ownership declines. Similar to a reduction in VKT, the size of this effect is again doubtful since individuals who join carsharing may use it solely for occasional use as a second or third car, or maybe they did not even possess a car in the first place. Not every individual who joins carsharing will shed his car. It is thus fair to say that the extent to which carsharing can reduce CO_2 emissions from cars is unclear.

We use data concerning the actual car stock of Belgium from the FOD Mobiliteit en Vervoer (2018b) and its expected growth rate from the Federal Planning Bureau (2019) to predict the Belgian car stock by 2025 and 2035. Due to a lack of data regarding the projected growth of ICEVs and BEVs in Belgium, we make projections for each fuel type based on recent trends. Until 2025, we expect that the share of diesel cars will further decrease at the same pace as after the dieselgate scandal in 2015. This scandal caused serious damage to the reputation of diesel cars. On the short term, the largest part of this decrease will be compensated by a rise in the share of gasoline cars. BEVs are expected to grow rapidly until 2025 in terms of percentages, but remain rather small in absolute numbers. After 2025 though, the expected growth of gasoline cars is lower and diesel cars will further decrease, although at a slower pace. If the tipping point of electric vehicles occurs in this period of time, BEVs will benefit heavily from the slowdown of ICEVs and should be able to reach one million cars in the Belgian vehicle stock by 2035.

Since the impact of carsharing on car ownership is open to discussion, we measure the effect of carsharing based on a worst-case and a best-case scenario. In a worst-case scenario, every shared car replaces four privately owned cars and in a best-case scenario, every shared car replaces ten privately owned cars. These numbers correspond to the findings of S. A. Shaheen & Cohen (2013) for Europe. Both scenarios lead to a slowdown in the growth of the Belgian car stock. This is why we predict the composition of the Belgian car stock again in 2025 and 2035, considering the effect of carsharing in the worst-case and best-case scenario. The current number of shared cars in Belgium is unknown, so we rely on the report from the ING Economics Department (2018) for the actual and projected market share of carsharing in Europe and apply this to Belgium. According to ING, an increase in the fleet of shared cars can lead to a ‘peak car moment’, “at which point the total number of cars in Europe will fall and new car sales will also decline”. The authors believe that this moment will occur between 2025 and 2035. They expect carsharing to slow down the growth in the European passenger car fleet until 2025. After this year, carsharing should be able to meet the increasing demand for car use thanks to an improved user experience and cost competitiveness, resulting in a decline of the total number of cars. In the final step, the environmental impact of carsharing is measured as the difference between the CO_2 emissions of the originally forecasted car stock and the CO_2 emissions of the forecasted car stock considering the impact of carsharing.

The aforementioned scenarios assume that the number of kilometers driven remains constant. In this case, the emission of CO_2 will not decrease during the use phase, on the assumption that cars do not become significantly more fuel-efficient. The adverse environmental impact during the use phase is caused by tailpipe emissions. In order to reduce this impact, cars need to drive less or they need to become more fuel-efficient. Therefore, we develop another scenario, which is a more fuel-efficient fleet of company cars. Belgium has a relatively large number of company cars, which can be divided into two types. On one hand, there are company cars which are required for work purposes and registered on behalf of the company for which the employee works. On the other, there are so-called ‘salary cars’ which can be used for private purposes too. In fact, according to the ‘Company Car Taxation’ report from the European Commission (2010), up to 67% of company car use in Belgium is for private purposes or work-home commutes instead of being purely business-related. This is due to the fact that they are promoted through a favorable tax regime, making it often more interesting for employers to give a salary car instead of a pay raise. Belgium appears to be one of the largest providers of subsidies to private use of company cars in the EU, even encouraging purchases of larger cars rather than smaller ones, boosting fuel consumption and CO_2 emissions. The authors of the report conclude that the under-taxation of company cars within the EU aggravates the adverse environmental impact of the transport sector. The annual report from FOD Mobiliteit en Vervoer (2018b) shows that salary cars represent 8% of all passenger cars and 16% of all VKT. Despite the overall decline in diesel cars, they still account for 91% of the salary cars, whereas BEVs are even below 0.10%. This scenario estimates the environmental impact of a gradual transition from diesel cars to BEVs in the fleet of salary cars.

Recycling leads to less primary material production, which lowers the CO_2 emissions per ton of material. Carsharing reduces CO_2 emissions by requiring fewer cars to deliver the same service, so the number of cars per kilometer driven decreases. Electric vehicles reduce CO_2 emissions since they have no tailpipe emissions, which more than offsets their higher emissions during the production phase. These scenarios are thus able to reduce CO_2 emissions from passenger cars without causing a decrease in the number of kilometers driven. The only way to reduce CO_2 emissions from passenger cars through a decrease in kilometers driven, is by driving less kilometers. This can be obtained by a modal shift from private cars to transport modes such as walking, biking and public transport. The environmental effect of this shift to a more sustainable mobility in Belgium is studied by Delhaye, Vanherle, & Zeebroeck (2019). The authors conclude that their simulated shift alone will not be sufficient to reach the targeted emission reductions by 2035. Their study is based on a scenario simulation which involves banning salary cars, introducing road pricing and investing more in infrastructure for public transit, walking and biking. Therefore they suggest additional policy measures that can further reduce the demand for private cars or accelerate the transition to electric cars. A series of case studies from the EEA (2018e) proves that in European countries where targeted taxes and incentives were applied, the “consumer adoption of lower CO_2 emitting vehicles followed”.

4 Results and discussion

4.1 Environmental impact

The estimated environmental impact is illustrated in Table 4 and Table 5, based on a shortened LCA for the modelled average gasoline car, diesel car and BEV. Table 4 contains the environmental impact in case of the assumed characteristics of Table 2. Table 5 assumes an equal accumulated mileage of 150 000 km for each vehicle and an equal lifespan of 15 years. One must consider Table 5 to compare the environmental impact of the modelled vehicles. The higher lifetime mileage for diesel cars may result in a higher carbon footprint compared to gasoline cars, but it also implies that the diesel car provides more useful services. If we thus assume an equal accumulated mileage of 150 000 km, gasoline cars emit slightly more CO_2 than diesel cars, but both gasoline and diesel cars produce over 80% higher CO_2 emissions compared to BEVs over an equal lifetime. In fact, a higher accumulated mileage further increases the environmental benefit of BEVs over ICEVs, since they are carbon-free on the road. This would reduce the relative impact of the production phase, which is more significant for BEVs because of the carbon-intensive battery production. According to our estimates, the battery production accounts for 50% of the CO_2 emissions during the production phase.

Table 4. Estimated environmental impact in kg CO_2-equivalent, based on a shortened life cycle assessment approach with different mileage and lifespan

TYPE PHASE	Gasoline car	Diesel Car	Battery electric vehicle
Production	5 300	5 600	11 200
Well-to-tank	5 510	7 587	7 262
Tank-to-wheel	25 867	30 730	0
Total CO_2-eq	36 677	43 917	18 462
CO_2-eq/year	2 445	2 928	1 846

Table 5. Estimated environmental impact in kg CO_2-equivalent, based on a shortened life cycle assessment approach with equal mileage and lifespan

TYPE PHASE	Gasoline car	Diesel Car	Battery Electric Vehicle
Production	5 300	5 600	11 200
Well-to-tank	5 166	5 472	7 262
Tank-to-wheel	24 251	22 161	0
Total CO_2-eq	34 717	33 233	18 462
CO_2-eq/year	2 314	2 216	1 231

4.2 Scenario simulation

4.2.1 Steel recycling

The steel industry is a major source of GHG emissions, so in order to reduce this environmental impact, a transition away from BOF towards EAF is a crucial step. The results of the effect of a gradual transition from steel production through the BOF-route towards the EAF-route for gasoline and diesel cars are presented in Table 6 and Table 7. The baseline scenario describes the current state of affairs. Every increase in steel production through the EAF-route at the expense of the BOF-route causes a decrease in the carbon intensity of steel production. Scenario 4 illustrates the most optimistic scenario. If we switch the current share of both production methods, meaning that only about one third of total steel from each car is produced by the BOF method and two-thirds by the EAF method, the CO_2 emissions from steel production decrease by 37% for gasoline cars and by 35% for diesel cars. For the complete production phase, this implies a reduction in CO_2 emissions of respectively 7.30% and 8.22%. Due to a lack of data regarding the material composition of BEVs, they are not included in the analysis. Nevertheless, we expect the effect of steel recycling for BEVs to be similar to the results of both ICEVs. The biggest challenge for steel recycling in the automotive industry is to ensure the quality of secondary steel, so it can be used not only for basic elements, but also for more structural elements of the material composition. If secondary steel producers tackle these barriers, recycled steel can cover a larger part of the demand for steel and thus reduce CO_2 emissions per ton of steel.

Table 6. Potential reduction of CO_2 emissions during production phase as a result of increased steel recycling activity for gasoline cars

	Total steel per car (in kg)	BOF-route	EAF-route	CO_2 emission per car (in kg)	Difference with baseline scenario (in %)
Baseline scenario	742	67%	33%	1046.80	0%
Scenario 1	742	57%	43%	935.50	-11%
Scenario 2	742	47%	53%	824.20	-21%
Scenario 3	742	37%	63%	712.90	-32%
Scenario 4	742	33%	67%	659.80	-37%

Table 7. Potential reduction of CO_2 emissions during production phase as a result of increased steel recycling activity for diesel cars

	Total steel per car (in kg)	BOF-route	EAF-route	CO_2 emission per car (in kg)	Difference with baseline scenario (in %)
Baseline scenario	959	66%	34%	1333.10	0%
Scenario 1	959	56%	44%	1189.25	-11%
Scenario 2	959	46%	54%	1045.40	-22%
Scenario 3	959	36%	64%	901.55	-32%
Scenario 4	959	34%	66%	872.60	-35%

4.2.2 Carsharing

Table 8 illustrates the predicted market shares of ICEVs and BEVs in the Belgian car stock by 2025 and 2035. These forecasts are based on recent trends and do not consider the potential slow down as a result of carsharing. The Flemish action plan 'Clean power for transport'[a] aims at a BEV-fleet of 60 500 in Flanders by 2020. Since there were only 7 548 BEVs in all of Belgium in 2017 (FOD Mobiliteit en Vervoer, 2018b), it is unlikely that this will be achieved. According to our estimates, there will be 60 500 BEVs in Belgium during the course of 2023. The market shares are calculated in terms of each share in the total number of cars and not in the total number of VKT. It is important to note that the share of alternatively-fueled vehicles is assumed to remain steady at 0.72%. Another limitation is the fact that gasoline and diesel cars also include hybrid models. The forecasts for every vehicle type until 2035 in terms of market share and in absolute numbers can be found in the Appendix A.

Table 8. Projected market share of different powertrains in Belgian car stock by 2025 and 2035

Year	Diesel	Gasoline	BEV	Other
2017	56.90%	42.25%	0.13%	0.72%
2025	41.64%	55.28%	2.36%	0.72%
2035	31.05%	53.61%	14.62%	0.72%

To estimate the environmental impact of carsharing by 2025 and 2035, it is necessary to have an idea about the composition of the vehicle stock in Belgium at this point of time. The change in the car stock is the net difference between car sales and cars leaving the market because they are either end-of-life or exported abroad. We aim to find out to what extent carsharing can reduce the growth of the Belgian car stock. Therefore we estimate the impact of carsharing on the projected growth of the car stock by 2025 and 2035, based on a worst-case and a best-case scenario. This effect is illustrated in Table 9. It turns out that in a worst-case scenario, about one third of the expected increase in the car stock by 2025 can be offset by an increase in shared cars. By 2035, carsharing can eliminate even half of the expected increase. In a best-case scenario, carsharing will nearly offset the whole increase in the car stock by 2025. The number of forgone purchases as a result of joining carsharing schemes even exceeds the projected increase in the car stock by 2035, causing a decline by 8.26%. The results of the best-case scenario correspond to the so-called 'peak car moment', occurring between 2025 and 2035, as expected by ING Economics Department (2018).

Table 9. Impact of carsharing projections on projected evolution of the Belgian car stock by 2025 and 2035

	Year	Projected increase in car stock	Projected increase in carsharing fleet	Private cars replaced per shared car	Forgone increase car stock	Net effect	Forgone increase car stock (in %)
Worst-case scenario	2025	386 140	40 482	4	161 929	264 693	31.45%
	2035	982 344	171 947	4	687 787	466 503	52.51%
Best-case scenario	2025	386 140	40 482	10	404 822	21 800	94.35%
	2035	982 344	171 947	10	1 719 468	-565 178	157.53%

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[a] For further explanation: https://www.milieuvriendelijkevoertuigen.be/sites/default/files/atoms/files/Actieplan%20CPT.pdf

The reduction in CO_2 emissions from the Belgian car stock is measured based on the difference between the emissions from the car stock before car sharing projections and after car sharing projections. For scenario purposes, we assume that every added shared car is a BEV and every shed private car is a gasoline car. This implies that diesel cars remain steady in absolute numbers, but their projected market share increases since the total number of cars is reduced by carsharing. In the worst-case scenario, CO_2 emissions from the car stock decrease by only 2.33% by 2025 and by 9.57% by 2035. In the best-case scenario, CO_2 emissions from the car stock decrease by respectively 6.37% and 26.13%. A detailed overview can be found in the Appendix B. The emissions from alternatively-fueled vehicles are not included since their impact is negligible.

An important limitation is that the projected composition of the car stock in 2025 and 2035 is multiplied by the estimated CO_2 emissions per year from Table 5, which are based on current practices and technologies. Cars will become more fuel-efficient overtime, leading to lower CO_2 emissions. Furthermore, Table 5 assumes an equal lifetime of 15 years for BEVs and ICEVs whereas it is not sure yet whether BEVs are able to reach this age. This will depend especially on the ease of maintenance and the reliability of the battery. Moreover, a more intense use of shared BEVs may shorten the lifespan of these cars and thus necessitate a faster replacement. This may severely limit the ecological benefit of this scenario, considering the high environmental cost of BEVs' production phase.

Similar to the steel recycling scenario, carsharing needs to address some important issues before it can cause a significant improvement in the environmental impact of cars. If we assume that the required improvements in user experience and cost competitiveness take place in the near future, carsharing could finally turn out to be a valid alternative to ownership for a larger group of people and reduce emissions.

4.2.3 Electrification salary cars

Almost one out of ten passenger cars in Belgium is a heavily subsidized company car, so making this fleet greener could contribute strongly to lower CO_2 emissions of the total car stock. Table 5 shows that diesel cars produce almost twice as much CO_2 emissions compared to BEVs over the same lifetime. Hence it is clear that a transition from diesel, or gasoline cars, to BEVs reduces the environmental impact of the transport sector. The environmental impact of a gradual transition from diesel salary cars to BEVs is illustrated in Table 10. The share of gasoline cars and the total number of salary cars are assumed to remain stable. The impact of alternatively-fueled vehicles, such as CNG, is negligible and therefore not included in the analysis. If BEVs would obtain the current market share of diesel cars, nearly all CO_2 emissions from the salary cars could be eliminated, illustrated by Scenario 4. This reduction in CO_2 emissions equals almost 10% of the projected CO_2 emissions from the car stock of 2017. Since every diesel car is replaced by a BEV, we assume people to drive the same number of km with the BEV. This is why it is necessary to estimate the CO_2 emissions per year for BEVs based on an equal lifespan and accumulated mileage as for diesel cars. We apply the lifespan of 15 years and 208 000 km from Table 4 for diesel cars to BEVs. This is beneficial for BEVs since a higher accumulated mileage increases the impact of the use phase, in which BEVs have no environmental impact. As a result the relative impact of the more significant production phase of BEVs is reduced. The reduction in CO_2 emissions would be larger if the transition relates to all passenger cars instead of solely salary cars. Diesel and gasoline cars are expected to become more fuel-efficient overtime as a response to regulated emission limits, so to sustain the environmental benefits of BEVs, the electricity mix should become less carbon intensive by investing more in renewable energy sources.

As in the previous scenario, it is not quite certain yet whether BEVs are already able to run the same number of kilometers and reach the same age as diesel cars. For example an early battery replacement would reduce the environmental benefit of BEVs as salary cars over diesel cars. A transition from diesel and gasoline cars to hybrid series is another option to reduce the environmental impact of the fleet. A final limitation refers to the number of salary cars, which is a rough estimate from FOD Mobiliteit en Vervoer (2018b). It is possible that there are many more company cars that are also used for private use, but not considered as salary cars. Especially company cars used by self-employed people are hard to factor in. Nevertheless, the estimated market shares for each fuel type are accurate representations of the total fleet of salary cars.

Table 10. Environmental impact of a transition from diesel engines to BEVs in fleet of salary cars, measured in terms of CO_2 emissions

	Total salary cars	Diesel market share	Gasoline market share	BEV market share	Equivalent CO_2 emissions per year (in ton)	Difference with baseline scenario (in %)
Baseline scenario	465 338	91%	9%	0%	1 293 145	0%
Scenario 1	465 338	66%	9%	25%	952 541	-26%
Scenario 2	465 338	41%	9%	50%	611 937	-53%
Scenario 3	465 338	16%	9%	75%	271 333	-79%
Scenario 4	465 338	0%	9%	91%	58 978	-95%

This section contains the third and final step of the analysis, which is an interpretation of the scenario outcomes as well as suggestions to reduce the environmental impact of passenger cars. It is clear that every simulated scenario is able to reduce CO_2 emissions from passenger cars in a different way. The most optimistic projections even lead to significant cuts in emissions. A nearly 10% reduction in CO_2 emissions of the production phase for each car as a result of more recycled steel. Causing a decline in the projected car stock of 2035 by 8%, in addition to a 26% cut in CO_2 emissions as a result of carsharing. Eliminating nearly all CO_2 emissions of the entire fleet of salary cars, which represent almost one out of ten passenger cars, through a transition from diesel cars to BEVs.

Despite the promising results, it is unrealistic to believe that one of these scenarios or even the combination of all three will be sufficient to reach the intended emission reductions of the whole transport sector. More, much more needs to be done. Our suggestions for cleaner road transport by passenger cars are summarized in Table 11, based on the scenario outcomes as well as on the literature review. According to this study, the key to environmental improvement of passenger cars is a combination of three elements, each requiring different strategies: drive less, fewer cars and cleaner cars. Less driving requires accurate policy measures which cause a modal shift to public transport, walking or biking. Appropriate taxation and incentives can reduce the attractiveness of driving in favor of the more sustainable alternatives. Taxation is a strong tool to guide human behavior. Ending the favorable tax regime of diesel cars led to a decline in the sales of diesel cars. Likewise, ending the financial advantages of salary cars may reduce the number of kilometers driven. A study of the effect of different policy instruments on the reduction in CO_2 emissions from passenger cars is a useful topic for further research. On the assumption that demand for transport will only increase, alternatives should become more attractive or cars should be used more efficiently in order to reduce the number of cars. Circular business models are able to deliver the same service while reducing the number of required cars. Shared mobility services such as carsharing make more intensive use of cars compared to car ownership. There should be a fully integrated mobility network in which carsharing serves as a complement to public transport, instead of being an alternative. Only then will increasing carsharing activity lead to a significant decrease in car ownership.

Another way to reduce the environmental impact of passenger cars is by making them cleaner. One example is making better use of materials so that less primary material production is required. Another option is a transition to electric vehicles which are substantially cleaner than conventional cars with combustion engines. There are many more options to reduce the adverse environmental impact of cars, but each strategy should focus on at least one of the following objectives: a reduction in kilometers driven, a reduction in the number of cars produced or a reduction in the carbon footprint of a car. The simulated scenario of carsharing is even able to combine all three. If ICEVs are replaced by shared BEVs, connected with an integrated mobility network, car ownership as well as the number of kilometers driven by passenger cars should go down.

Table 11. Summary of suggestions to reduce adverse environmental impact of passenger cars

Solutions	Strategies	Options
Drive less	Policy measures	Taxation
Fewer cars	Circular business models	Carsharing
Cleaner cars	Material recirculation	Steel recycling Electromobility

5 Conclusion

In this study we have examined different scenarios that may contribute towards a reduction in the CO_2 emissions from passenger cars. We have concluded that steel recycling, carsharing and the transition from diesel cars to BEVs are all able to cause significant emission reductions in the car stock of Belgium. Carsharing allows for a more efficient use of cars by providing the same service with a smaller number of cars. Steel recycling enables a more efficient use of steel by reducing the need for primary production. Electrification of salary cars may eliminate nearly all CO_2 emissions of the entire fleet.

Critically important though they are, these efforts and changes will not suffice to reach the key targets of the EU. If we are to meet the goals of the Paris agreement, political authorities will have to encourage and implement a fully integrated mobility network in which carsharing serves as a complement to public transport and individuals are encouraged to opt for BEVs when they choose to buy a vehicle of their own.

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Appendix A: Projected growth of diesel cars, gasoline cars and BEVs

Table A1: Forecasted growth of diesel cars until 2035

FORECAST DIESEL

Year	Total diesel cars	Market share	Total CAR	Other (constant market share)
2012	3 402 802	62.39%	5 453 857	
	1%	0%	1%	
2013	3 445 077	62.58%	5 504 810	
	0%	0%	1%	
2014	3 460 266	62.09%	5 572 573	
	0%	-1%	2%	
2015	3 466 974	61.24%	5 661 743	
	-2%	-2%	1%	
2016	3 399 453	59.32%	5 730 975	
	-3%	-2%	1%	
2017	3 299 580	56.90%	5 798 628	41 598
	-3%	-2%	1%	
2018	3 202 641	54.68%	5 856 614	
	-3%	-2%	0.92%	
2019	3 108 550	52.60%	5 910 279	
	-3%	-2%	0.92%	
2020	3 017 224	50.59%	5 964 436	
	-3%	-2%	0.92%	
2021	2 928 580	48.65%	6 019 089	
	-3%	-2%	0.92%	
2022	2 842 541	46.80%	6 074 242	
	-3%	-2%	0.92%	
2023	2 759 030	45.01%	6 129 901	
	-3%	-2%	0.92%	
2024	2 677 972	43.29%	6 186 070	
	-3%	-2%	0.92%	
2025	2 599 295	41.64%	6 242 754	44 784
	-2%	-1%	0.92%	
2026	2 547 309	40.43%	6 299 957	
	-2%	-1%	0.92%	
2027	2 496 363	39.27%	6 357 684	
	-2%	-1%	0.92%	
2028	2 446 436	38.13%	6 415 941	
	-2%	-1%	0.92%	
2029	2 397 507	37.03%	6 474 731	
	-2%	-1%	0.92%	
2030	2 349 557	35.96%	6 534 059	
	-2%	-1%	0.92%	
2031	2 302 566	34.92%	6 593 932	
	-2%	-1%	0.92%	
2032	2 256 515	33.91%	6 654 353	
	-2%	-1%	0.92%	
2033	2 211 384	32.93%	6 715 327	
	-2%	-1%	0.92%	
2034	2 167 157	31.98%	6 776 861	
	-2%	-1%	0.92%	
2035	2 123 814	31.05%	6 838 958	49 061

Table A2: Forecasted growth of gasoline cars until 2035

FORECAST GASOLINE

Year	Total gasoline cars	Market share	Total CAR	Other (constant market share)
2012	1 988 633	36.46%	5 453 857	
	1%	0%	1%	
2013	2 015 413	36.61%	5 504 810	
	3%	1%	1%	
2014	2 069 017	37.13%	5 572 573	
	4%	1%	2%	
2015	2 152 335	38.02%	5 661 743	
	6%	2%	1%	
2016	2 286 553	39.90%	5 730 975	
	7%	2%	1%	
2017	2 449 902	42.25%	5 798 628	41 598
	4%	1%	1%	
2018	2 557 109	43.66%	5 856 614	
	4%	1%	0.92%	
2019	2 669 007	45.16%	5 910 279	
	4%	2%	0.92%	
2020	2 785 802	46.71%	5 964 436	
	4%	2%	0.92%	
2021	2 907 708	48.31%	6 019 089	
	4%	2%	0.92%	
2022	3 034 948	49.96%	6 074 242	
	4%	2%	0.92%	
2023	3 167 757	51.68%	6 129 901	
	4%	2%	0.92%	
2024	3 306 377	53.45%	6 186 070	
	4%	2%	0.92%	
2025	3 451 063	55.28%	6 242 754	44 784
	1%	0%	0.92%	
2026	3 471 985	55.11%	6 299 957	
	1%	0%	0.92%	
2027	3 493 034	54.94%	6 357 684	
	1%	0%	0.92%	
2028	3 514 210	54.77%	6 415 941	
	1%	0%	0.92%	
2029	3 535 515	54.60%	6 474 731	
	1%	0%	0.92%	
2030	3 556 949	54.44%	6 534 059	
	1%	0%	0.92%	
2031	3 578 512	54.27%	6 593 932	
	1%	0%	0.92%	
2032	3 600 207	54.10%	6 654 353	
	1%	0%	0.92%	
2033	3 622 033	53.94%	6 715 327	
	1%	0%	0.92%	
2034	3 643 991	53.77%	6 776 861	
	1%	0%	0.92%	
2035	3 666 083	53.61%	6 838 958	49 061

Table A3: Forecasted growth of battery electric vehicles until 2035

FORECAST BEV

Year	Total BEVs	Market share	Total CAR	Other (constant market share)
2012	591	0.01%	5 453 857	
	104%	0.01%	1%	
2013	1 205	0.02%	5 504 810	
	82%	0.02%	1%	
2014	2 199	0.04%	5 572 573	
	51%	0.02%	2%	
2015	3 316	0.06%	5 661 743	
	57%	0.03%	1%	
2016	5 205	0.09%	5 730 975	
	45%	0.04%	1%	
2017	7 548	0.13%	5 798 628	41 598
	45%	0.06%	1%	
2018	10 946	0.19%	5 856 614	
	45%	0.08%	0.92%	
2019	15 873	0.27%	5 910 279	
	45%	0.12%	0.92%	
2020	23 018	0.39%	5 964 436	
	45%	0.17%	0.92%	
2021	33 379	0.55%	6 019 089	
	45%	0.24%	0.92%	
2022	48 405	0.80%	6 074 242	
	45%	0.35%	0.92%	
2023	70 194	1.15%	6 129 901	
	45%	0.50%	0.92%	
2024	101 791	1.65%	6 186 070	
	45%	0.72%	0.92%	
2025	147 612	2.36%	6 242 754	44 784
	21%	0.47%	0.92%	
2026	178 735	2.84%	6 299 957	
	21%	0.57%	0.92%	
2027	216 420	3.40%	6 357 684	
	21%	0.68%	0.92%	
2028	262 050	4.08%	6 415 941	
	21%	0.82%	0.92%	
2029	317 302	4.90%	6 474 731	
	21%	0.98%	0.92%	
2030	384 203	5.88%	6 534 059	
	21%	1.18%	0.92%	
2031	465 209	7.06%	6 593 932	
	21%	1.41%	0.92%	
2032	563 296	8.47%	6 654 353	
	21%	1.69%	0.92%	
2033	682 063	10.16%	6 715 327	
	21%	2.03%	0.92%	
2034	825 871	12.19%	6 776 861	
	21%	2.44%	0.92%	
2035	1 000 000	14.62%	6 838 958	49 061

Appendix B: Estimated impact of carsharing on the Belgian car stock

Table B1: Projected CO_2 emissions of the Belgian car stock by 2025 and 2035 without taking into account the effect of carsharing

Year	Diesel	Gasoline	BEV	Other	Total
2017	3 299 580	2 449 902	7 548	41 598	5 798 628
2025	2 599 295	3 451 063	147 612	44 784	6 242 754
2035	2 123 814	3 666 083	1 000 000	49 061	6 838 958
Ton CO2-eq/year	2.22	2.31	1.23	na	
2017	7 310 329	5 670 217	9 290		12 989 836
2025	5 758 825	7 987 370	181 681		13 927 876
2035	4 705 381	8 485 027	1 230 800		14 421 208

Table B2: Projected CO_2 emissions of the Belgian car stock by 2025 and 2035 after taking into account the effect of carsharing in a worst-case scenario

Year	Diesel	Gasoline	BEV	Other	Total
2017	3 299 580	2 449 902	7 548	41 598	5 798 628
2025	2 599 295	3 289 134	188 094	44 784	6 121 308
2035	2 123 814	2 978 296	1 171 947	49 061	6 323 117
Ton CO2-eq/year	2.22	2.31	1.23	na	
2025	5 758 825	7 612 592	231 506		13 602 923
Change (in %)	*0.00%*	*-4.69%*	*27.42%*		***-2.33%***
2035	4 705 381	6 893 166	1 442 432		13 040 979
Change (in %)	*0.00%*	*-18.76%*	*17.19%*		***-9.57%***

Table B3: Projected CO_2 emissions of the Belgian car stock by 2025 and 2035 after taking into account the effect of carsharing in a best-case scenario

Year	Diesel	Gasoline	BEV	Other	Total
2017	3 299 580	2 449 902	7 548	41 598	5 798 628
2025	2 599 295	3 046 241	188 094	44 784	5 878 415
2035	2 123 814	1 946 615	1 171 947	49 061	5 291 436
Ton CO2-eq/year	2.22	2.31	1.23	na	
2025	5 758 825	7 050 424	231 506		13 040 755
Change (in %)	*0.00%*	*-11.73%*	*27.42%*		***-6.37%***
2035	4 705 381	4 505 374	1 442 432		10 653 187
Change (in %)	*0.00%*	*-46.90%*	*17.19%*		***-26.13%***