10
Transport and the environment

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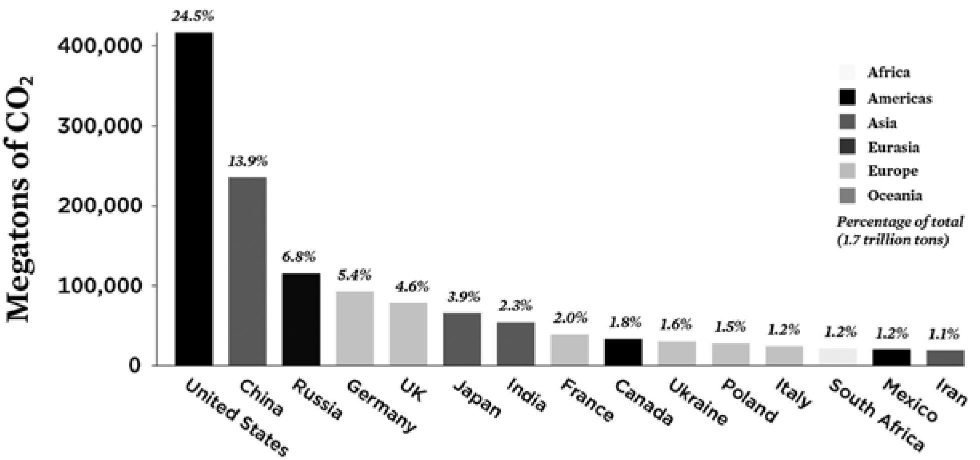
10.1. INTRODUCTION

Transport has diverse environmental impacts. These negative impacts have been found harmful to biodiversity, air quality, and public health. Table 10.1 gives an overview of the dominant environmental impacts per transport mode. It is nearly impossible to discuss all these harmful environmental effects of the transport system in one chapter, therefore, the focus will primarily fall on the road-related climate change impacts, measures, and mitigation strategies with also some attention on air pollution and noise. The reason to assess transport in the context of climate change is because of the huge role it plays in the overall emissions. The ongoing challenges, coupled with the Paris Agreement[1] goals that legally bound carbon dioxide (CO_2) emission reduction, provide an underlying framework needed to evaluate the environmental opportunities available for the transport sector.

Table 10.1 Dominant environmental impacts per transport mode

	Road	Rail	Air	Water
Climate change (carbon dioxide emissions)	*	*	*	*
Energy use (oil depleting)	*	*	*	*
Use of raw materials and waste production	*	*	*	*
Air pollution: NO_x (nitrogen oxides), particulate matter (PM) and others	*	*	*	*
Soil and water pollution	*			*
Odor pollution	*		*	
Noise pollution	*	*	*	

Improvements in the road transportation system and technologies have delivered countless benefits to society and made travel easier and, in many cases, less expensive. Some of the positive effects of transportation such as economic growth, job creation, or technological progress cause negative externalities in other domains. Economic growth and employment opportunities are very beneficial to communities, however accessing these economic opportunities often leads to long and auto-dependent commutes and consequently brings negative environmental impacts. Much of this growth and harmful impacts have been a consequence of inexpensive and abundant oil that is used for powering the vehicles that emit a variety of pollutants and gasses. While the transportation sector is responsible for non-CO_2 pollutants including methane, volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), F-gasses, black carbon, and non-absorbing aerosols (Sims et al., 2014), lately – as noted before – much attention goes to CO_2 emissions. CO_2 is the most important gas that contributes to raising global temperatures. CO_2 emissions have steeply increased since 1900, with this becoming exponential since around the 1950s. The steady growth after the 1950s can be mainly attributed to the increased reliance on fossil fuel-driven transportation and industry. Although the annual CO_2 emissions from burning fossil fuels have been increasing globally, not all countries contribute to this equally. Figure 10.1 shows how much different countries contributed to the overall emissions between 1970 to 2020 in the total number of tons of CO_2 (not per capita).



Source: UCSUSA (2022).

Figure 10.1 Top CO_2 emitting countries from 1975 to 2020

Although there are multiple key sectors that contribute to the overall emissions, the transportation sector plays a significant role by producing 24% of direct CO_2 emissions from fuel combustion (International Energy Agency, 2020). In developed economies these contributions are driven by road transportation and become even more significant, reaching around 30% of their national total (Sims et al., 2014). In general, electricity (29%) and transportation (27%)

have been the main contributors to greenhouse gas emissions in the United States (EPA, 2017; Van Fan et al., 2018).

The history of environmental concerns in transport will be discussed in a broader context in Section 10.2. In 10.3 the trends in transport related CO_2 emissions will be examined and in 10.4 the relationship between transport and air and noise pollution will be presented. In 10.5 this chapter returns to transport's CO_2 emissions and introduces some innovations to mitigate them. The environmental performance of different transport modes is treated in 10.6, using CO_2 emissions as criterion for comparison. In 10.7 some key environmental policy instruments for transport are discussed and Section 10.8 gives some ideas how to evaluate these policies and is followed by conclusions in the final Section 10.9.

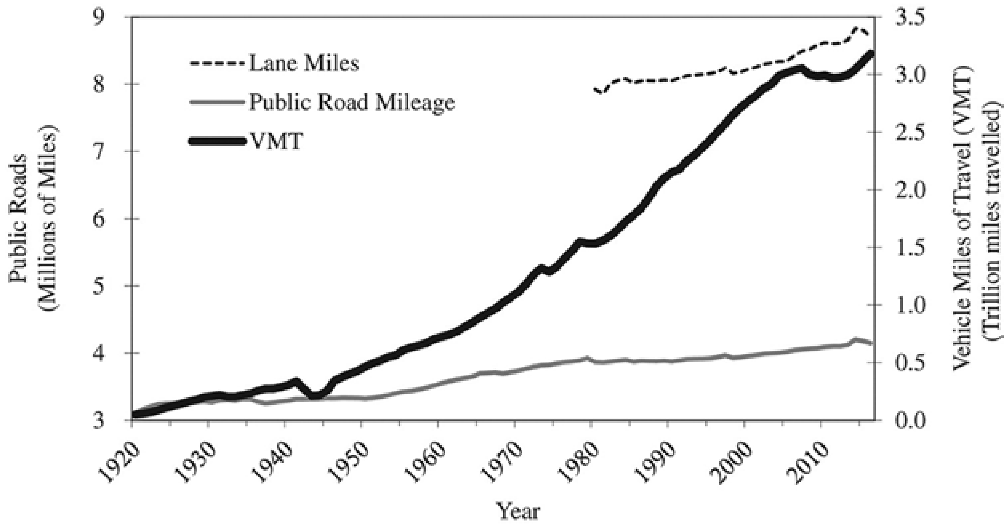
10.2 THE HISTORY OF ENVIRONMENTAL CONCERNS IN TRANSPORT IN A BROAD CONTEXT

Concern over environmental problems increased rapidly in the late 1960s, mainly because of the rapid growth in population, industrialization, incomes, and consumption levels. In 1972 the Club of Rome produced an influential report titled *The Limits to Growth* (Meadows et al., 1972; see Meadows et al., 2005, for an update) that discussed ecological footprints for humanity in the context of the capacity of the Earth and the concept of limits to growth. After decades of gas, oil, coal exploitation these resources were found shrinking. Within the fossil fuel economy and high levels of exhaust emissions, the transportation sector was also shown to contribute to high levels of noise pollution as well as non-exhaust emissions coming primarily from tire and brake wear.

The growth in emissions can be generally linked to increased travel. Figure 10.2 shows growth in vehicle miles travelled (VMT) in the United States from 1920. Today, the United States is one of the most motorized nations, at 816 vehicles per 1,000 people in 2019 (Federal Highway Administration, 2017). Over the last century, other developed countries have been following similar trends and increasing their auto-dependence. In 2019, Luxembourg had the highest number of passenger cars per inhabitant in the EU, with 681 cars per thousand inhabitants (Eurostat, 2021).

In *The Limits to Growth* it is argued that the environment should be protected for future worldwide growth of the population and the economy. The unequal distribution of welfare could be a source of conflicts and ecological destruction, which could lead to stagnation in social, economic, and technological development. Because of its environmental and societal impacts, the transportation sector has been in the center of these discussions.

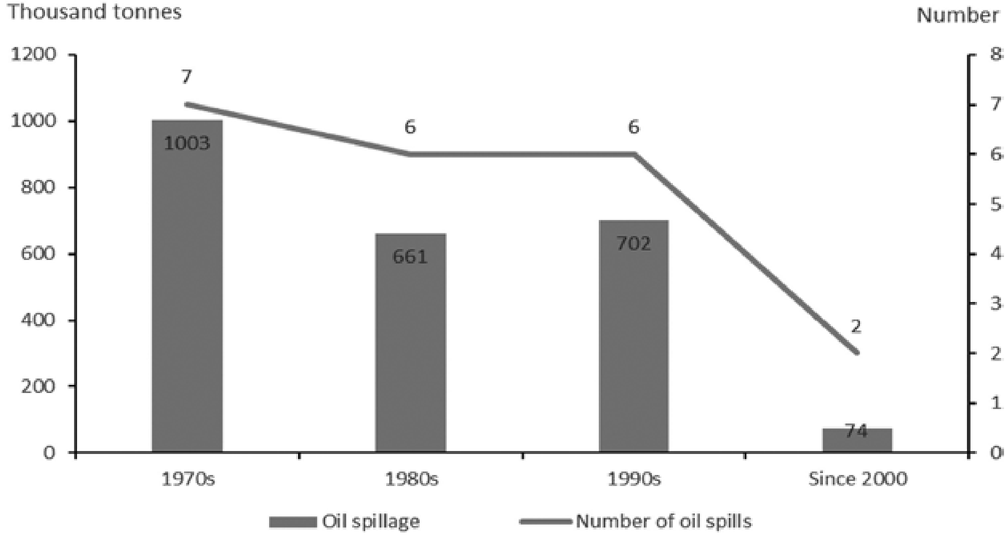
Air pollution and greenhouse gas emissions resulting from burning gasoline or diesel fuels for transportation (primary environmental effects) steal the headlines. The so-called secondary environmental effects of oil extraction are also not trivial and are related to drilling, fracking, and mining operations that generate enormous volumes of wastewater, which can be contaminated with heavy metals, radioactive materials, and other pollutants. Industries store this waste in open-air pits or underground wells that can leak or overflow into waterways and contaminate aquifers with pollutants linked to cancer, birth defects, neurological damage, and



Source: Federal Highway Administration (2017); Frey (2018).

Figure 10.2 Growth in vehicle miles travelled (VMT), public road mileage, and public road lane miles in the United States 1920–2016

much more. Land and wildlife degradation are also some of the undesired and irreversible consequences of fossil fuel extraction. Although the number of oil spills has been decreasing since 1970 (Figure 10.3), the spilled oil has already created a permanent damage to the ecosystem.



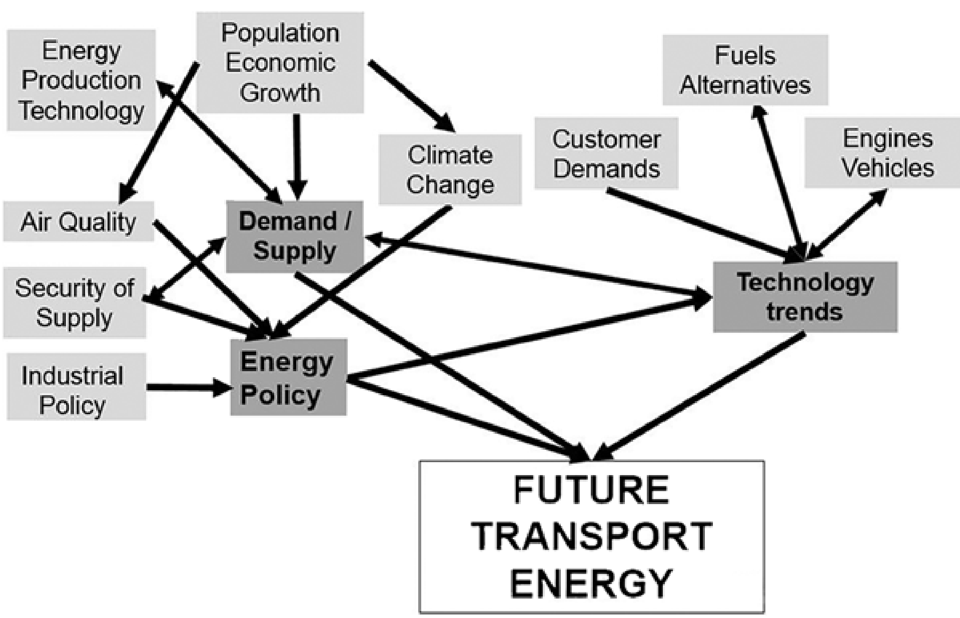
Source: Chen et al. (2019).

Figure 10.3 Oil spillage by major oil spill accidents 1970–2017

Furthermore, fossil fuels are non-renewable meaning that there is a certain amount of them left, and once depleted, they cannot be easily produced. Depletion of cheap and easily accessible fossil fuels, more specifically oil, raises major concerns.

Inexpensive oil that contributed to high reliance on automobiles has also brought many unintended consequences relating to livability. Past research has concluded that the quality of the urban environment is positively associated with individual well-being (Dong and Qin, 2017). Although there is still no unified definition and measurement of urban livability in the literature due to its complex and multi-dimensional nature (Zhan et al., 2018), car-centric designs, traffic, or exposure to pollution have been found to negatively impact livability and well-being (Park and Kwan, 2017). Natural environment, followed by transportation convenience and environmental health are some of the key factors affecting overall satisfaction with urban livability (Zhan et al., 2018). Lastly, neighborhood level of livability is particularly important in the context of space allocation and creating car-free and car-lite spaces where citizens of all ages and abilities can participate in urban mobility. Past studies argued that a livable city accommodates a healthy life and increases the chance for easy mobility (Hahlweg, 1997).

Given the wide scope of the environmental concerns, there are various ways to address them. Policy instruments to reduce the environmental impacts of transport will be discussed in Section 10.7. Other chapters in this book also address transport technology (Chapter 8), land-use and infrastructure (Chapter 5), and driving behavior (Chapter 8). Legislative measures often aim to increase transport resistance for motorized vehicles (Chapter 6), which



Source: Kalghatgi (2018).

Figure 10.4 Factors in future transport energy reduces environmental impact via lower transport volumes or modal shares of motorized vehicles.

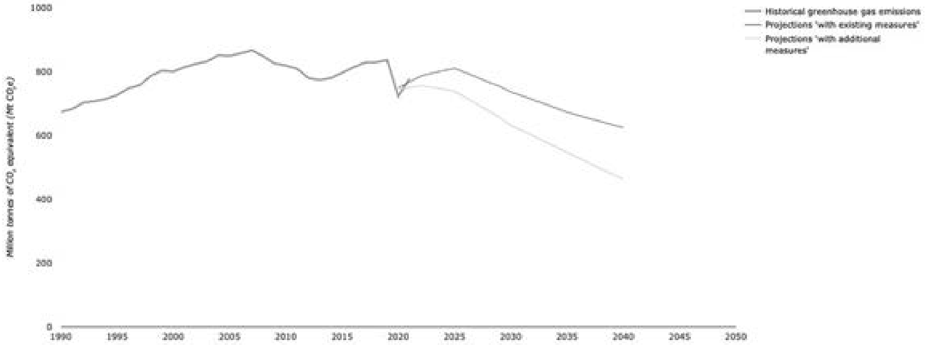
Lastly, the technical solutions for the environmental impact of transport are also related to the future energy system. The future energy system for transport is dependent on many factors. Kalghatgi (2018) identified these factors and their relationships in Figure 10.4. Energy production, security of supply, policy, available fuel alternatives among others, will ultimately impact the direction of innovation and fossil-free energy transition in the transport sector.

10.3 TRENDS IN CO_2 EMISSIONS FROM TRANSPORT

It was relatively recently when CO_2 became the center of conversations around transportation and its impact on the environment. Although the Swedish scientist Arrhenius had first speculated about the greenhouse gas effect over 100 years ago, climate change has not been globally addressed until a few decades ago. Since the 1990s climate change has been prominent on the international agenda of researchers and policy makers, and the reports of the Intergovernmental Panel on Climate Change (IPCC) provide the best-known and most influential overviews about state-of-the-art scientific knowledge. The IPCC (151; 2014) concluded that 'Human influence on climate change is clear and recent anthropogenic emissions of greenhouse gasses are the highest in the history. Recent climate changes have had widespread impacts on human and natural systems.'

Global trends in the transportation sector greenhouse gas emissions have been dominated by the road transport, international shipping, and aviation. With regard to regional differences, Northern America and Europe have been the largest emitters since 1900.

Although in Europe, historical greenhouse gas emissions have been increasing, given the current policies, the projections accounting for existing and future measures have downward trends (Figure 10.5). The European Environment Agency (EEA, 2021) predicts a significant decrease in emissions from transport by mid-century.



Source: European Environment Agency (2021).

Figure 10.5 Greenhouse gas emissions from transport in Europe

Transport emits CO_2 because of the high use of fossil fuels. In the internal combustion engines of cars, vans, lorries, ships, and planes the fossil fuels are burned, resulting in the desired energy for propulsion and in the undesired waste product CO_2. The popularity of oil as a transport fuel can be explained technically because of its high energy content. This means that, with a relatively low fuel volume on board, vehicles can cover many kilometers. Furthermore, inexpensive fuel has led to its wide adoption, particularly in passenger cars and vans, and therefore resulted in high emissions from these vehicles.

Even though there have been concerns over the price and availability of oil since the 1970s, it is only recently that more fundamental questions have been raised over its future. Transport has been almost totally dependent on oil, and the world price of oil has fluctuated between an average annual price of $27 and $110 a barrel between 2000 and 2020 (with even wider daily fluctuations). It is uncertain how that might change in the short or longer term. The oil price has historically had an impact on travel demand and on the adoption of alternative technologies and will likely remain one of the key players in the energy transition. In addition, there is the question of the availability of oil, which again influences the price of travel.

In essence, the trends in CO_2 emissions and fuel use in road transport are a function of the number of vehicles on the road (affected by affordability and consumer incomes and preference, see Chapter 3, and fuel price), distances driven (affected by infrastructure characteristics, see Chapter 5), prices such as fuel price and tax policies such as car taxation, tolls or congestion charge (see also Chapter 6), land-use (see Chapter 5), and the level of fuel economy of the cars (amount of motor fuel consumed per kilometer driven per year; see also Chapter 8) *see* Chapter 2 of this book for a general overview of links between the determinants. The personal vehicle has impeded the decarbonization of world transport activity because of, among other things, the increase in vehicle size (which requires more energy input; see Chapter 8 of this book for more details).

10.4 OTHER TYPES OF POLLUTION AND THEIR CAUSES

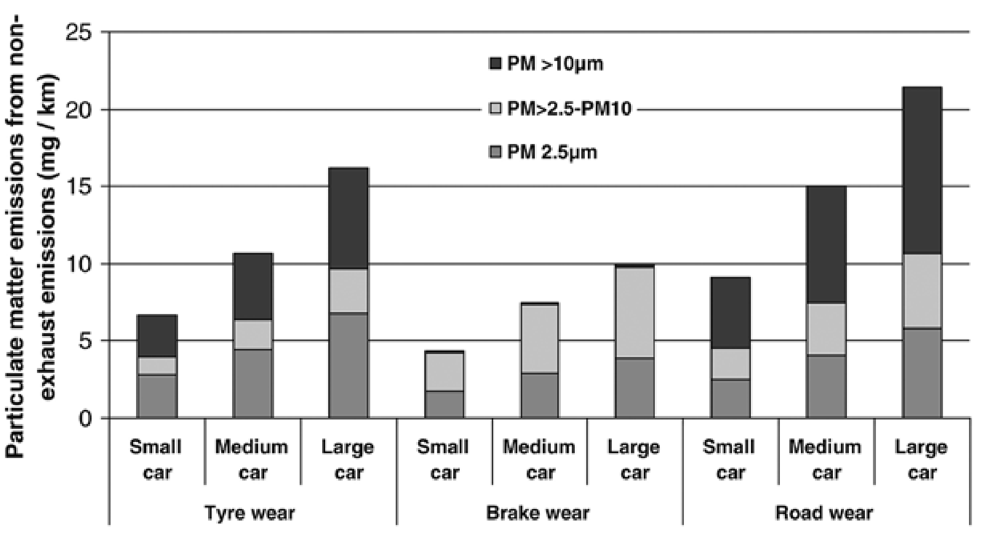
As already noted in Section 10.1 of this Chapter, CO_2 emissions have gained the most attention in conversations around creating more environmentally friendly transportation systems. Nevertheless, limiting emissions of CO_2 is not the only problem the sector is currently facing. Other pollutants include, but are not limited to, particulate matter (often noted as PM), nitrogen oxide (NO_x), carbon monoxide (CO), as well as noise.

The exhaust air pollution has been the focus of policy makers leaving the other types of air pollution (non-exhaust) often unregulated. Non-exhaust air pollution is a result of particles (PM) coming from breaking and tire wear. Noise pollution is a consequence of engines (dominant at slower speeds) and tires making contact with the road surface at high speeds (dominant at speeds higher than roughly 50 km/h), see below.

Traffic is one of the main reasons why PM levels are high as well as being the primary source of PM emissions in urban areas (Charron et al., 2007; Kousoulidou et al., 2008; Pant and Harrison, 2013). Vehicles emit PM through their exhaust and non-exhaust sources, such as tire wear, brake wear, road surface wear, and resuspension of road dust (Thorpe et al., 2007;

Shi et al., 2017). The numbers next to PM in $PM_{2.5}$ and PM_{10} stand for different PM fractions. 'Particulate matter' is a term for very small particles floating in the air, which humans can deeply inhale. The suffix 2.5 points at the fraction of particles that are smaller than 2.5 mm (micrometers); the suffix 10 means smaller than 10 mm.

It has been speculated that vehicle weight largely determines the rate of non-exhaust emissions per vehicle, however, there is very little research that directly links non-exhaust PM emissions to the vehicle weight (Timmers and Achten, 2016). Because electric vehicles (EVs) are 24% heavier than their conventional counterparts, Timmers and Achten (2016) concluded that the increased popularity of EVs will likely not have a beneficial effect on the non-exhaust PM levels. The same authors also stated that the non-exhaust emissions already account for over 90% of PM_{10} and 85% of $PM_{2.5}$ emissions from road traffic and cautioned that these proportions will continue to increase as exhaust standards improve and average vehicle weight increases. Figure 10.6 shows the relationship between PM non-exhaust emissions and car size.



Source: Simons (2013); Ntziachristos and Boulter (2009).

Figure 10.6 Non-exhaust particulate matter emissions by source and car size

According to the European Environmental Agency (EEA), PM is one of Europe's most problematic pollutants in terms of harm to human health (European Environment Agency, 2021). Deep inhalation of PM has been linked to severe health impacts (respiratory problems and even premature deaths) (Wu et al., 2018). Exposure to both $PM_{2.5}$ and PM_{10}, especially, affects people's health (Pope and Dockery, 2006; Grahame and Schlesinger, 2010). Epidemiologic studies have provided strong evidence for associations of PM inhalation with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence of the adverse effects related to short-term exposure, whereas fewer studies have addressed the longer-term health effects (Simoni et al., 2015). Although the generally coherent link between the ambient PM and pulmonary disease is perhaps not surprising, it is remarkable that the association between PM and inflammation-related cardiovascular diseases, such as heart disease, cardiac dysrhythmias, congestive heart failure, and stroke, has been also consistently found in medical literature (Langrish et al., 2012).

Despite the transportation sector being not the only sector emitting PM to the atmosphere, transport's share in negative effects is high, as (on average) the distance between road traffic and the people exposed is much shorter than from other emission sources of pollution, such as power plants. Traffic emissions, therefore, have a greater health impact per kilogram than average emissions, as people live close to the sources of pollution and are exposed to continuous levels, particularly along busy roads (Eyre et al., 1997).

Due to the chemical differences between non-exhaust and exhaust emissions, many of the non-exhaust emissions include different secondary PM. Secondary PM is formed in the atmosphere through chemical reactions, rather than being directly emitted by a source. The volatile organic compounds in the exhaust gasses react with sunlight in the atmosphere to form secondary organic aerosols, whereas non-exhaust emissions are mainly inorganic and therefore form secondary inorganic aerosols, which ultimately lead to increased difficulty in modeling secondary organic aerosols and secondary inorganic aerosols emissions regardless of the location (Hoogerbrugge et al., 2015; Timmers and Achten, 2016).

In addition to CO_2 and PM emissions, other polluting substances such as NO_x (nitrogen oxide), CO (carbon monoxide), SO_2 (sulfur dioxide), O_3 (ozone), as well as other non-methane gasses are included in the transportation sector emission inventory. On a global scale, these emissions are often unregulated, and the allowed amounts of pollutants can vary by region. Figure 10.7 shows the differences in emission regulations for key pollutants between the USA and the European Union.

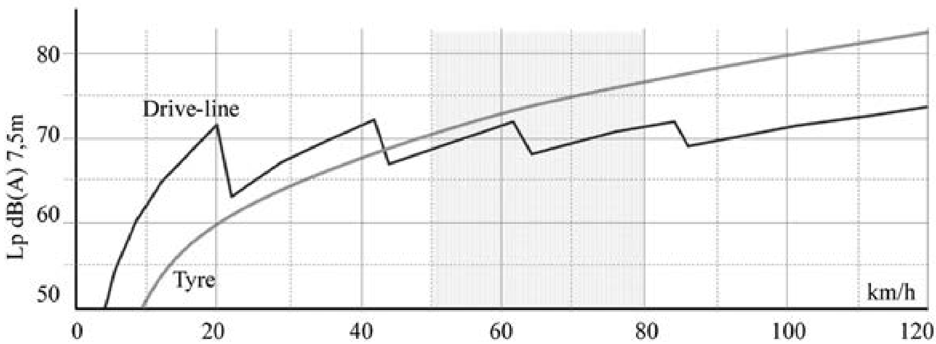
Vehicle emission pollutants	USA	European Union
Nitrogen oxide (NO_x)	0.04 g/mi	0.06/0.08* g/mi
Carbon monoxide (CO)	2.61 g/mi	1.0/0.5* g/mi
Carbon dioxide (CO_2)	155 g/mi	130 g/mi
Particulate matter (PM)	0.003 g/m	0.008 g/mi
Non-methane organic gases	0.06 g/mi	0.07/na* g/mi

Source: Gruzieva et al. (2013); Hime et al. (2018); Glanzer and Khreis (2019).
Note: *Petrol/diesel fuels

Figure 10.7 Comparison of the vehicle emission regulations per pollutant between the USA and the EU for light duty vehicles set to last until 2025

Given that only the exhaust pollutants are regulated, it is essential that policies should focus on setting clear global standards for both exhaust and non-exhaust emissions. Some researchers suggest that encouraging weight reduction of all vehicles has the potential to significantly reduce emissions from traffic, particularly in the context of PM emissions (Timmers and Achten, 2016).

Transport-related emissions are a function of the number of vehicles on the roads. Even if all vehicles become electric, the non-exhaust pollution will remain problematic. Similar concerns apply to noise pollution that cannot be mitigated by electrifying the fleet (Figure 10.8). The figure shows that drive-line noise (motor) – the black line – is the dominant source of noise below 45 km/h speeds. From this speed level, tire-road surface contact noise becomes dominant which also grows for EVs. The ‘bumps’ in the black line signify the moment that gears are shifted.



Source: den Boer and Schroten (2007); Jacyna et al. (2017).

Figure 10.8 Correlation between velocity and noise emitted by car

Studies from the US have shown a fairly consistent relationship between individuals or communities of lower socioeconomic position and increased exposure to noise pollution (Hajat et al., 2015). Evidence on noise pollution exposure from Europe has been mixed (Temam et al., 2017) and shown to have potential to affect all socio-demographic groups. Individuals with high socioeconomic positions living in city centers can also disproportionally experience high exposures to noise pollution (Goodman et al., 2011; Havard et al., 2011). Nevertheless, transport-related air and noise pollution has been consistently linked to adverse health outcomes and found to often vary within cities, potentially resulting in exposure inequalities *see* Chapter 12 for more information on the relationships between transport and health. Relatively little is known regarding inequalities in personal exposure to air pollution or transport-related noise pollution (Tonne et al., 2018).

10.5 CO_2-DRIVEN INNOVATIONS IN THE TRANSPORT SECTOR

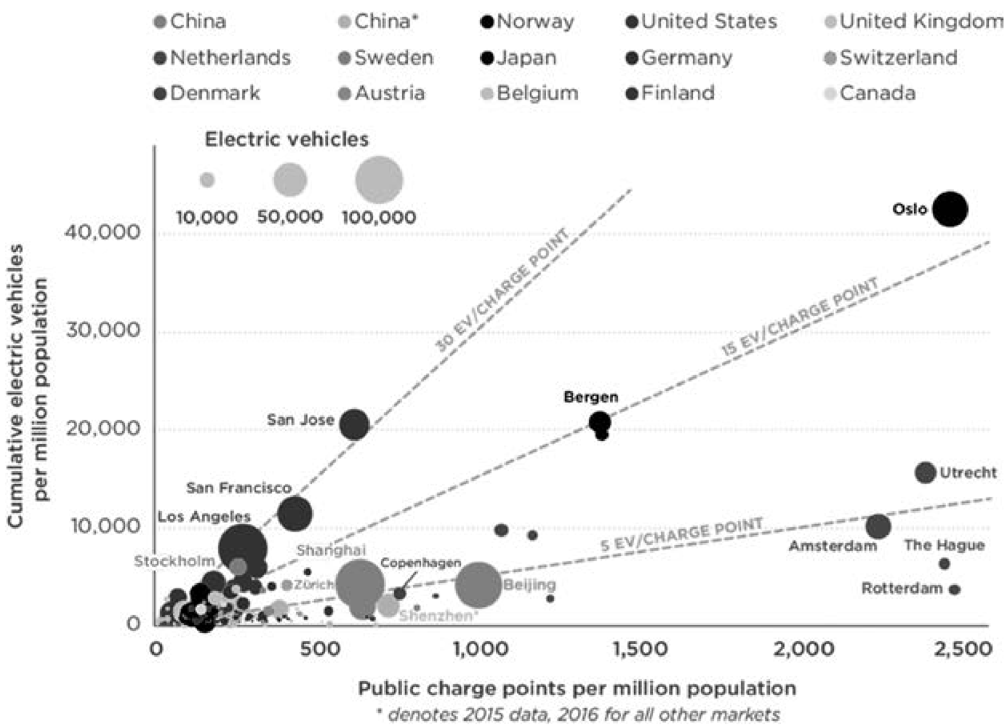
To address the increasing CO_2 emissions and to activate behavioral changes that would pave the way to decarbonizing the transport sector, there have been many innovations. They can be divided into different categories. In this chapter, two distinctive categories which may play a huge role in CO_2 emission reduction will be discussed. The first category includes all the technical innovations that relate to electrification, battery capacities and durability, charging infrastructure, the use of hydrogen, to name a few (Section 10.5.1). The other category, while it is enabled by technological progress, aims to target the behavioral component (lowering kilometers travelled) in transportation such as applications allowing easy access to carsharing, Mobility-as-a-Service (MaaS), ridesharing, etc. (Section 10.5.2). Both have the same goal of lowering the emissions, however, they approach achieving this goal from different angles.

10.5.1 Towards Electrification

Electrification as a mitigation strategy to combat climate change has been stealing the headlines. There are different battery technologies currently available and depending on their composition, they will have a unique set of operational characteristics, limitations, and applications. One of the most common types is a lithium-ion battery (LIB) but there are also others like lithium-sulphur batteries, lithium-air batteries, or pre-LIB batteries. Although the wide application of batteries in the automotive sector does provide a substantial reduction in emissions as they do not require burning fossil fuels for vehicle operations, they come with their own set of constraints.

One is the weight of the battery, which has implications on the weight of the vehicle and thus non-exhaust emissions (discussed in Section 10.4), and the other one is sourcing of the raw materials needed for battery production. As outlined in the newest IPCC report (Jaramillo et al., 2022), for EVs sold in 2018, 11 kilotons (kt) of lithium, 15 kt of cobalt, 33 kt of manganese, and 34 kt of nickel were used (International Energy Agency, 2019). International Energy Agency projections for 2030 show that the demand for these materials would increase by 30 times for lithium and around 25 times for cobalt. There are efforts to move away from expensive materials such as cobalt (International Energy Agency, 2019). The dependence on lithium will remain, which causes concerns relating to its high demand and mining practices (You and Manthiram, 2018; Olivetti et al., 2017).

To maintain the efforts of decarbonization of the transport sector, battery technologies must be supported by charging infrastructure. Studies in this space found that without proper and widely available charging infrastructure, the adoption of electric mobility will be challenging, and consumers will be less likely to purchase an EV (Nicholas et al., 2017). Ongoing research tries to also capture and address user preferences and key attributes regarding charging preferences and vehicle purchases. Past research found that for light vehicles, the majority of charging (75–90%) has been reported to be done near homes (Figenbaum, 2017; Webb et al., 2019; Wenig et al., 2019). A reliable and comprehensive network of public charging infrastructure is essential to support the transition to an EV fleet (Gnann et al., 2018). Public charging infrastructure and EV registrations per million of the population by metropolitan area are shown in Figure 10.9.



Source: Hall and Lutsey (2020).

Figure 10.9 Public charging infrastructure and electric vehicle registration per million population by metropolitan areas, with size of circles indicating total number of electric vehicles

Much attention has also been paid to studying the potential of hydrogen fuel cell vehicles particularly to support heavy and long-haul freight or marine shipping. So far this has been only emerging technology and its direction and success have not yet been determined, partly because it is very much dependent on the advancements in the energy sector. Hydrogen is expected to play an important role as an energy carrier for supporting the decarbonization of the heavy vehicle sector (Tokimatsu et al., 2016). There are, however, a few main barriers that the sector needs to overcome. Producing hydrogen from renewable resources and using it in vehicles has been found less efficient than directly charging electric batteries. Substantial losses happen on the pathway from the 'well to tank' and 'tank to wheel' and therefore this fueling method has not been found as efficient as direct electrification (although charging times are in favor of hydrogen fuel cell vehicles compared to EVs). The main challenges of hydrogen fuel cell mobility are similar to the ones that are faced by the standard EV sector and include charging infrastructure, price, and maturity of the technology (Transport and Environment, 2020).

Biofuels are another fuel technology that has been seen to play a role in the transportation sector and particularly in freight, marine, and aviation domains. Biofuels are considered to complement measures aimed at constraining the sector's energy needs and the enhanced role of electrification in urban and other shorter-haul transport applications (Jaramillo et al., 2022). While some biofuels such as ethanol from fermentation of sugars and biodiesel from oil crops have already achieved commercial scale in many countries, this sector has been facing many challenges in adoption on a global scale and rather limited technology development to produce biofuels derived from lignocellulosic feedstocks (agricultural crop residues, forest residues, and grass materials that are relatively inexpensive and highly abundant in nature), which are still struggling to achieve full commercial scale.

Achieving low-carbon transport implies a strong link between the transport and energy sector. First, regardless of which non-carbon energy carrier is used for rail, urban transport, and medium-distance transport (electricity or hydrogen), it has to be produced with low carbon emissions. Without a low-carbon energy sector, low-carbon transport is not feasible. Second, failure to decrease CO_2 emissions from transport will most likely need to be compensated in the energy sector. Third, electrification has been the most promising thus far, however the key will be to assure that the electricity for transportation is derived from renewable sources.

The use of non-renewable raw materials that are essential for battery production has recently received increasing attention. Emerging technologies needed for electric mobility often need 'rare' materials that are expensive, scarce, and can only be found in a few places worldwide. Given the increased production of rechargeable batteries, there have been discussions on the continued availability of materials like cobalt. Furthermore, there are a lot of concerns regarding extraction of these materials and unethical labor laws in countries where they occur. On the other hand, it is always a possibility that scarce materials may in the future be substituted by other materials that are currently being developed, researched, and tested.

10.5.2 Behavioral and Shared Mobility Innovations Enabled by Technology

Aside from innovation in technology, reducing emissions can be also achieved through large scale behavioral changes that are promoted by incentives, campaigns, and designs for new ways of transporting. In addition to the vehicle related innovations, MaaS (Mobility-as-a-Service) has been gaining popularity and reshaping urban mobility. (MaaS is a concept that bundles personal mobility services from multiple mobility providers into a combined interface through which the services can be searched, booked, and purchased.) There have also been innovations in public transport (e.g., related to travel information–showing the expected train occupancy on selected routes and real-time arrivals and delays), advances in micromobility (e-scooters, bikesharing), or other behavioral changes related to the infrastructure (real-time parking availability and reservation or smart infrastructure).

Many innovations around personal mobility aim to reduce car ownership and car travel. Given that a significant part of total emissions from the transport sector has been linked to car and road travel, policy makers and city officials have targeted car travel the most. Some of the strategies include reducing car travel through schemes like congestion pricing, reducing car ownership through taxes, reducing available parking, and increasing the prices of the existing one, as well as incentivizing sharing of the already existing vehicles. Sharing economy and in particular shared mobility have experienced a steady growth over the last years.

Although sharing is not a behavioral innovation, it depends on the technological progress. In particular, the mobile applications allow vehicle owners to connect to people outside of their immediate communities. Sharing can be simultaneous like sharing a ride when two people sit in the same vehicle going to the same destination, or sequential when the same vehicle is used by different customers one after another. Over the last decade, ridesourcing companies together with bike- and e-scooter sharing companies have revolutionized how mobility works and how it is perceived. The growth in mobility solutions was once again stimulated by advancements in technology, a decrease in prices of mobile devices, and the availability of internet connections.

Ultimately, any new mobility adoption (regardless of whether it is shared or not) is linked to household income as well as other socio-demographic and residential location characteristics. Often, differences in behavior may also depend on the differences in gender, age, norms, values, and social status. Simićević et al. (2013) concluded that women were more sensitive to parking prices than men, which then can be translated in their other mobility preferences. The price of the emerging services has also a very strong relationship to their adoption, which is often captured in the elasticity value (more on elasticity can be found in Chapter 3). Shared mobility modes are already a part of the mobility paradigm in many parts of the world; however, their maturity and adoption rates still vary by regions. The largest number of carsharing memberships is in Asia and is responsible for 58% of worldwide memberships (Dhar et al., 2019), followed by Europe, which accounts for 29% of worldwide members (Shaheen et al., 2018).

Over the last decade the disruptions in technology and usage have been seen in ridesourcing, carsharing, and micromobility spaces. Cuevas et al. (2016) concluded that carsharing could provide the same level of service as taxis, however the taxis could be three times more expensive. The shared mobility sector that includes bikesharing, carsharing, and on-demand mobility services has been rapidly growing over the last decade (Greenblatt and Shaheen, 2015). The use of micromobility services depends on various factors such as age, gender, social and economic inequalities, time of day, or weather conditions. It has been shown that men and women do not follow the same usage patterns. In the e-scooter sector, it was found that the users were predominantly young men while low-income neighborhoods were underrepresented in the existing studies and trials (Latinopoulos et al., 2021; Bai and Jiao, 2020). Similarly, researchers have been studying the adoption of shared mobility and micromobility services (Barbour et al., 2019; Barbour et al., 2020). Because the needs of the users are not homogeneous, the adoption will likely take place in phases and different users will adopt using these services and technologies in different moments of time. Recent studies also point towards the intended adoption patterns of automated and shared automated vehicles varying by gender, age, presence of children, education, or residential location (Menon et al., 2017; Barbour et al., 2019).

Although they offer a great potential, shared mobility solutions are not without their legislative issues that include regulations and policies not being able to keep up with the fast pace of technological innovations. Shared mobility research is expanding but the literature has not yet been consistent on how much this sector will contribute to decarbonization or how much it will impact the ridership from transit or active modes like walking.

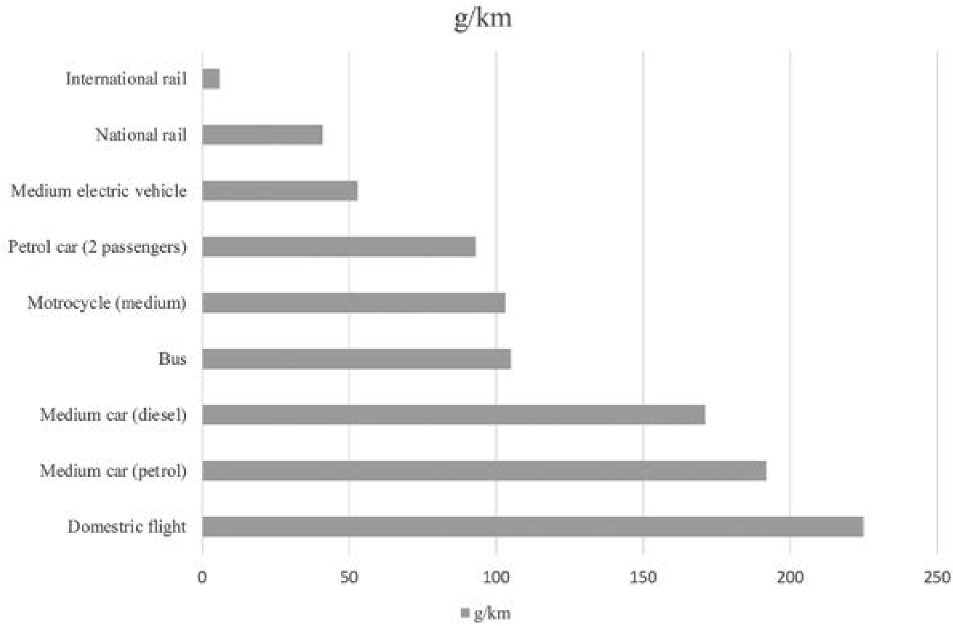
10.6 A COMPARISON OF THE ENVIRONMENTAL PERFORMANCE OF TRANSPORT MODES

From a policy perspective, it is interesting to know the environmental performance of different transport modes. The focus in Sections 10.2, 10.3, and 10.4 was on their environmental impacts, but electric mobility also uses the energy and produces emissions, and all direct and indirect impacts of a mode should be evaluated for a proper analysis.

Walking, bicycle, or train are the most efficient and the least pollution intensive modes. Department for Business, Energy & Industrial Strategy (2020) concluded that substituting a car for a bike for short trips would reduce travel emissions to negligible amounts of CO_2. Taking a train instead of a car for medium-length distances has a potential to cut emissions by ~80% and travelling by train instead of a taking a domestic flight would reduce emissions by ~84%.

Despite many studies delivering promising results, comparing the emissions performance of transport modes is not straightforward because of the differences in methods applied to perform the analysis (Figure 10.10), as can be demonstrated through the following range of questions (based on van Wee et al., 2005):

1. Which emissions are selected for the comparison?
2. Which emissions are compared: only direct emissions in the use stage, or also indirect emissions, such as those arising from the production of vehicles, even infrastructure, breaking or tires?
3. In the case of direct emissions, are emissions of electricity production and of refineries included?
4. For which year(s) are emissions compared?
5. Are average emissions compared, or emissions for sub-segments (such as for short- or long-distance travel only, or for containers only)?
6. Are average emissions compared or marginal emissions (extra emissions due to extra travel – Rietveld, 2002)?
7. Are average emissions compared, or for specific time periods (e.g., rush hour versus off-peak hours)? Note that, in the case of public transport, the choice for peak versus off-peak interacts with marginal versus average values: marginal peak hour emissions are relatively high, whereas average peak hour emissions are relatively low. The difference is linked to the level of ridership, meaning the more passengers on a bus, the lower the average emissions. For off-peak hours the opposite is true.
8. For the operational use of vehicles (e.g., driving circumstances of road vehicles), are real-world circumstances assumed, or test circumstances?
9. Which load factors or occupancy rates are assumed (real-world averages versus assumed factors)?



Source: Department for Business, Energy & Industrial Strategy (2020).

Figure 10.10 Carbon footprint of travel per kilometer in 2018

An alternative evaluation to emissions per kilometer (or passenger kilometer of travel), like in the Figure 10.10 above (based on the United Kingdom's values), is to use life cycle assessment (LCA) methods, which were developed in the 1960s and have been used in transport since the late 1990s. They take account of the non-negligible impacts of transport activity through vehicle production and scrapping, energy (fuel) extraction, and production and the full environmental impacts associated with infrastructure such as land take, materials use, and the construction itself (Chester and Horvath, 2009). LCA has demonstrated the full range of transport activities associated with the entire supply chain of products (Browne et al., 2005). Even if these life cycle factors are included in the costs of transport (internalized), they have little effect on transport volumes (Maibach et al., 2007), as the demand elasticities for travel are low and rising income levels reduce the effectiveness of higher prices (Goodwin et al., 2004; Graham and Glaister, 2004; see also Chapter 6).

10.7 POLICY INSTRUMENTS TO REDUCE THE ENVIRONMENTAL IMPACT OF TRANSPORT

This section focuses on the different types of policy measures – regulations, pricing, land-use planning, infrastructure policies, marketing, information, and communication. These types of policy measures have been implemented all over the world, albeit every country or region differs in the specific policies chosen. More information on transport policy can be found in Chapter 13.

Regulations with respect to the access of motorized vehicles to central urban areas have been successful in improving the attractiveness of these areas by changing at least the modal shift, and probably also the total transport volumes (owing to the increased travel times and costs of traveling by car). The distribution over time and space of transport volumes has also been influenced by regulations (e.g., limitations for access of trucks and vans, and loading and unloading times for these vehicles). In other words, the regulations can sometimes directly impact mobility behavior, transport, and traffic flows, depicted in Figure 2.1 (Chapter 2).

Although one policy measure often addresses cross-sectional domains (Santos et al., 2010), policies could be also classified into three types: physical, soft, and knowledge policies. Physical policies are related to building and maintaining infrastructure for public transport, walking and cycling, and freight transport. Soft policies include more non-tangible measures aiming to bring about behavioral change by informing actors about the consequences of their transport choices and potentially persuading them to change their behavior and they include e.g., incentives, pricing, regulations. These measures often try to boost more efficient use of vehicles and incentivize behaviors like carsharing and carpooling, teleworking and teleshopping, eco-driving, as well as provide general information and advertising campaigns. And lastly, knowledge policies emphasize the important role of investment in research and development for a sustainable model of mobility for the future. In the next sections, some of the most common environmental policy instruments will be introduced.

10.7.1 Regulations

It is clear (at least in Organization for Economic Co-operation and Development (OECD) countries) that emission regulations for road vehicles have been successful in reducing transport emissions of pollutants. Emissions of CO, VOC (volatile organic compounds) and NO_x per car and truck kilometer have all decreased by a factor of between 5 and 10 or even more between 1980 and 2020s (see Chapter 8). Lead emissions from petrol cars have decreased to almost zero because of regulations in the 1970s and 1980s to ban lead in petrol. Regulations have also included speed regulations and therefore indirectly impacted emissions.

However, not all interventions have been this successful. Vehicle regulations for noise emissions have been much less effective. Although the emission standards have been tightened and vehicles should have become much quieter, the reality is different, the car fleets have not become quieter (1980–96), and the noise from fleets of trucks has only reduced by 3 dB(A) (van der Toorn et al., 1997).

Limiting speed reduces noise, especially between 50 and 80 km/h. Speed limits do not require investment and have a direct effect on noise pollution but the costs associated with travel time losses may be significant (Jacyna et al., 2017). Because the elements of the transport system are often closely related to each other (like in this case speed and noise), the environmental policies in transport can address multiple layers of concerns if phrased and implemented properly. Going back to the conceptual model from Chapter 2, reducing speed limits would not only help in reducing noise pollution but lower speeds could also consequently impact safety – both frequency and severity of vehicle crashes.

10.7.2 Pricing

Pricing is one of the most powerful policy tools. Pricing policies include subsidies for public transport, taxes on vehicles and fuels, prices for parking, and road pricing. Subsidies on public transport (PT) have reduced the fares for public transit, decreased transport resistance (Chapter 6), and increased public transit usage. The stated political reasons for subsidies have often included environmental improvement (by changing modal choice from car to public transit), reduced congestion (also because of the change in modal choice), or improved access for people not having a car available (reduced social exclusion). The effectiveness discussion then becomes more complicated. For the impact of public transit subsidies on the environment, the substitution effects (from car to public transit) are important, as are the potential generation effects of additional travel ('induced demand' – see Chapter 6, and Goodwin, 1996). Because of the limited overlap in markets between public transit and cars (Bovy et al., 1991), overall decreases in public transit pricing could have a negative impact on the environment, as the positive effect of mode change is more than compensated for by the negative effect of the generation of additional travel, at least for energy use and CO_2 emissions (van Wee et al., 2005).

Taxes on fuels can change the share between different fuel types and address, to some extent, environmental concerns. As there are differences between countries in types of taxes, the share of diesel cars is much lower in some countries, such as the UK or the Netherlands, as compared with others, such as Belgium and France. A higher share of diesel reduces CO_2 emissions (at least on a per-kilometer basis) and increases emissions of PM and NO_x. Secondly, such taxes increase transport resistance (see Chapter 6) and have an impact on the overall level of car use and on modal split.

Looking in the past, long-term fuel price elasticity for car use was in the magnitude of −0.25 (see Graham and Glaister, 2004, for a review of elasticities), which means that a 1% increase in fuel prices reduces car use in the longer term by approximately 0.25%. Note that most of the studies reviewed used data from the 1980s and 1990s, under conditions of lower incomes. Because people with higher incomes are less sensitive to price increases, the impact of fuel price increases now and in the future could be lower. Nevertheless, these values indicate that prices do matter. Dargay et al. (2007) estimated the car price elasticity of ownership to be −0.12. For energy use and CO_2 emissions, elasticity values are higher than the fuel price elasticities because, in addition to the effect on car use, people buy more fuel-efficient cars and tend to drive a little bit more efficiently if prices are higher (see Graham and Glaister, 2004), leading to an elasticity of approximately −0.77. Higher prices are a stimulus for higher load factors for transport.

In 2021, Goetzke and Vance compared the fuel price elasticity values on miles driven in the United States. In 2017, the fuel price elasticity was estimated to be equal to −0.29. The same authors also found that those who drive the most are the least responsive to fuel prices. More information on fuel price elasticities and their values relating to the car use or car ownership can be found in Section 6.3.

To address environmental concerns, negative externalities of driving, and to improve air quality several cities and towns introduced parking charges in the 1960s and 1970s, often in combination with a reduction in the number of parking places in central urban areas. If parking is expensive, this increases transport resistance, leading to less car use and an increase in the use of alternatives.

Road pricing is probably the most controversial of all the categories of pricing policies. The controversy is not so much related to its effects but more to the difficulties in implementation (Nikitas et al., 2018). Nevertheless, several examples of real-world implementation of road pricing schemes can be found, including Singapore, some Norwegian cities, London, and Stockholm. Once road pricing is introduced, it may change transport resistance and how people move around.

Singapore was the first city to implement congestion pricing. It successfully reduced congestion by lowering peak hour traffic by 65%. About a decade later Electronic Road Pricing was implemented in 1998, which reduced traffic volume in the restricted zone by an additional 15% (Wilson, 1988; Phang and Toh, 1997; Santos and Fraser, 2006).

London implemented its road pricing scheme in 2003. It was an area licensing system with a fixed fee for all vehicles entering the congestion zone. This was one of the differences between the London initial scheme and Singapore's, as the charges in Singapore were imposed per trip, while in London a payment lasted for the entire day, allowing vehicles to enter and exit the zone multiple times. After the implementation of this scheme, traffic volume entering the zone when congestion pricing was in operation reduced by 18%. Travel time decreased by 30% during the first year of the implementation while bus riders increased by 18% (Santos et al., 2010). To further address air pollution, the pricing scheme in London was restructured, the area expanded, and consequently more improvements in the air quality were observed. The pricing scheme contributed to the number of Londoners living in areas with high levels of NO_x falling by 94% between 2016 and 2020 (Greater London Authority, 2020).

Stockholm adopted a slightly different approach and did not charge per trip or day but was using 18 entry and exit points. Congestion charges differed according to the time of day. Vehicle distance driven in the congestion zone decreased by 16%, while traffic volume also decreased by 5% outside the city center, and traffic emissions reduced by 10% to 15% between 2005 and 2006, which was the year of the launch of the congestion pricing scheme. The decrease in vehicle distance and traffic volume in the congestion zone and beyond could be due to the 24% of work trips by car that switched to transit, which would affect both traffic entering and surrounding the area (Santos et al., 2010; Eliasson, 2008). The road pricing has had an impact on other transportation-related areas such as parking or alternative travel modes and therefore impacted travel resistance or desires and needs.

Appropriate pricing schemes and incentive programs are not limited to only decrease auto usage but also stimulate uptake of cycling/e-cycling. In the case of the Netherlands, cycling is a very popular mode of travel, accounting for 26% of all national trips (KiM, 2015). Of all trips shorter than 7.5km, which is 70% of all trips, 35% are made by bicycle. Despite this high share of cycling trips, there is still considerable potential for an increase in cycling. De Kruijf et al. (2018) evaluated an incentive program to stimulate the shift from car commuting to e-cycling in the Netherlands and found that half of e-bike trips substitute car trips, while the other half substituted conventional bicycle trips. They also found that e-bike use by former car commuters in an e-cycling incentive program amounted to 73% after half a year of participation.

Another pricing strategy aiming to reduce emissions, kilometers driven, and improve air quality is carbon pricing. A price placed on carbon encourages travelers to use vehicle fuel types that pollute and cost less per mile or kilometer of travel. The idea behind carbon tax can be easily explained with an example of EVs.

To better understand the mechanisms of carbon pricing, let's consider a standard Toyota Camry and Model 3 Tesla with the following annual fuel costs: $950 for Toyota Camry and $500 for Tesla (Figure 10.11).

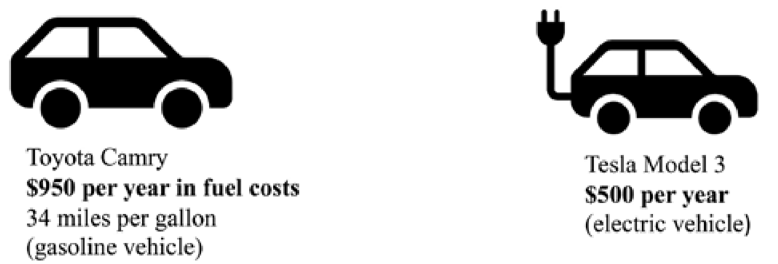


Figure 10.11 Fuel standards and annual fuel costs for Toyota Camry (gasoline vehicle) and Tesla Model 3 (electric vehicle)

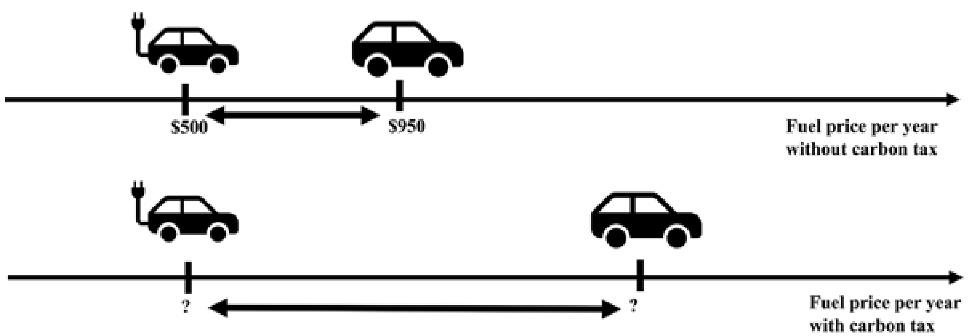


Figure 10.12 The change in fuel price per year with additional carbon tax

If additionally, the more carbon-intensive option is taxed, the price gap between refueling these two different models will widen. Many countries are considering this approach, however, the most important question that remains to be answered relates to the appropriate and stable price for carbon.

The added fuel cost resulting from the carbon price would increase this price gap (Figure 10.12) and encourage consumers to consider EVs, although the effect would likely be small if the carbon price was equal to, say, \$50 per metric ton of CO_2.

The price of CO_2 per ton in emission trading systems has varied over the years. The price has also varied over time and regions but continues to remain relatively low. Historically, it varied between a few euros per ton to around 30 euros per ton. In November 2021, the price hit a record of more than 71 euros per ton (Buli, 2021).

As of now, many factors are playing a role in determining the price of carbon, and the carbon market is seen to be impacted by the geopolitical situation, climate policies, and technology development. The value of carbon price will then impact which vehicles people choose to travel by, where they live, and how much they travel (consider the conceptual model in Figure 2.1, Chapter 2).

10.7.3 Land-Use Planning

Land-use planning can have an impact on travel volumes and modal split (Chapter 5). Building at high densities can reduce travel distances and locating offices and residential neighborhoods close to railway stations can increase the share of public transit. Attractive neighborhood design can increase the share of slow modes, and mixed land-use (e.g., mixing housing, shops, schools, and services) can reduce transport distances and increase the share of slow modes. In addition, because land-use planning can change the distribution of vehicle kilometers of road types and related driving behaviors, it can have an impact on emissions and safety levels, and on distances between the source of emissions (noise, pollutants) and the recipients. There is still debate on the impacts of land-use planning on travel behaviors (see Chapter 5), and this is partly explained by the fact that the actual impacts on travel behaviors seem to be less than expected. This conclusion may be due to the problems of measurement and the long-term effects that land-use has on travel, but as with a lot of analysis it is the behavioral factors that are important, and current understanding of these responses is not sufficient.

10.7.4 Transport Infrastructure Policy

In almost all countries infrastructure provision is a public matter. Even in the case of toll roads, such as in France and Portugal, the government decides which motorways will be built and where they will be located, and the government sets the institutional context including regulations, tendering, and so on. It is beyond any doubt that the quality and quantity of road and rail networks have a major impact on transport volumes and modal split (see Chapters 3 and 6). In addition, these networks strongly influence the distribution of traffic across the networks, certainly in the case of roads, and therefore driving behaviors (Chapter 8), route choice (see Chapter 7), safety and emission levels, and distances between the source of emissions and receivers.

Furthermore, investments in infrastructure supporting alternative modes that include cycling, bikesharing, e-cycling, and walking are also a prominent and viable approach to reducing emissions. To support cycling, public agencies often invest in bicycle infrastructure networks to increase network connectivity and accessibility. These infrastructure investments include bike lanes, pavement maintenance, etc. In the past few years, bike-friendly initiatives have increased around the world and many improvements for cycling were made. Research has found that the installation of one additional mile of bike lanes in NYC led to an average increase of 102 bikesharing daily trips (Xu and Chow, 2020).

10.7.5 Public Transport Policies

Excluding policies involving public transport in one of the other categories (such as pricing or subsidizing and infrastructure policies), there are ways to make public transport more attractive. For example, routing and frequency of buses may be adjusted and facilities at railway stations may be improved. Investing in TODs (transit-oriented developments) could also make public transit more attractive and convenient.

10.7.6 Policies to Stimulate Work-from-Home

Particularly during the COVID-19 pandemic, the world has experienced a sudden change in commute patterns and consequently work-from-home was adopted virtually overnight. Most cities have seen a decrease in pollution and traffic. Since the transport sector emissions, and particularly CO_2 emissions, have grown steadily for the last three decades (International Transport Forum, 2021), it is essential to explore work-from-home as a viable alternative to auto commute. Many researchers have used the disruptions to transport systems caused by the COVID-19 pandemic to gain more insights into work-from-home adoption and study its relevance in relation to decreasing transportation-related environmental impacts (Barbour et al., 2021). It remains to be seen how the work-from-home paradigm will lead to stimulating work-from-home policies that may impact the environment, traffic patterns, and air quality in the long term and how cities decide to leverage the disruption in mobility caused by the pandemic. Flexible work hours or attractive tax deductions relating to the maintenance of home office or even new legislations to support telehealth and other fields where consumer privacy is an issue could further stimulate the uptake of work-from-home.

10.8 CRITERIA TO EVALUATE CANDIDATE ENVIRONMENTAL POLICY OPTIONS

Policy evaluation can take place before a policy is implemented (*ex-ante* evaluation) or after the policy has been in place for some time (*ex-post* evaluation). *Ex-ante* evaluation generally requires two separate actions; to estimate what will happen if the policy is not introduced and to estimate what will happen if it is introduced. *Ex-post* evaluation estimates what has happened with the introduction of the policy instrument. Additionally, an estimate still needs to be made of what would have happened if the policy instruments had not been introduced (Blok and Nieuwlaar, 2021).

To meet ambitious emissions reductions in the transport sector, multiple policies must be implemented, and their effectiveness continuously evaluated. As policies may be difficult to implement and may have various side-effects, an important question is which criteria should be used to evaluate the available options. Typically, the criteria include expectations with respect to all of the following, both individually and in combination:

1. CO_2 emission reductions;
2. Costs;
3. Other environmental impacts (such as emissions of other pollutants besides CO_2, noise);
4. Risks, or at least risk perceptions (these could be relevant in the case of hydrogen mobility adoption, available infrastructure, usage safety, and CO_2 capture and storage);
5. Land-use and spatial impacts (especially in the case of biofuels – the production of biofuels competes with food production and impacts nature and biodiversity);
6. Psychological factors (e.g., will the car driver accept hydrogen or EVs);
7. Legal, institutional, and political factors (important barriers might exist, e.g., legal barriers, the position of interest groups, political acceptability);
8. The position of important stakeholders, such as car producers, oil companies, and the agricultural sector (e.g., in the case of biofuels);
9. The question of whether transitions can take place evolutionarily starting with the current system, or if radical changes are needed, resulting in a 'difficult' transition phase (van Wee et al., 2013).

10.9 CONCLUSIONS

The most important conclusions of this chapter are:

1. Road transportation (including passenger transport and freight) that is a result of increased auto-dependency is one the biggest contributors to transport-related emissions.
2. The most problematic pollutants currently in transport are CO_2 and PM.
3. There are many policy instruments available to reduce the environmental impact of transport, including regulations, pricing, land-use planning, infrastructure policies, public transport policies, marketing, and information and communication. These instruments can influence the environmental pressure of transport by reducing transport volumes, changing modal split, and influencing the technologies used, the efficiency of vehicle use, and the way vehicles are used.
4. In many ways the options to decarbonize transport are clear, but the problem is the effective implementation of the measures so that desired environmental outcomes can be achieved.
5. In the future, the dominant environmental problems related to transport will probably continue to be the energy use, climate change, health, the use of raw materials, and noise nuisance. Raw material availability as well as harmful labor laws are particularly important for battery production.

6. The most challenging problems for the coming decades are mitigating CO_2 emissions and oil dependency as well as the largely unregulated non-exhaust emissions (like PM).
7. Pricing is a very powerful tool to change behavior. Examining how carbon tax schemes unfold in the coming years are especially important to mitigating climate change.
8. Improvements in technology need to be supported by its smart adoption and usage as well as timely regulated.

NOTE

1. The Paris Agreement is a legally binding international treaty on climate change (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, accessed February 2022). Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels.

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