8

Transport technology

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8.1 INTRODUCTION

Mobility has changed tremendously over history. About 200 years ago, people walked, rode horses, sat in carriages, and used barges. At the same time, goods and mail were transported on people's backs, in carriages, and by barge and boat. Two centuries later the transport system has revolutionized, as can be illustrated with three examples.

In 2018, around 1.42 billion cars travelled the streets and the roads of the world (rfidtires.com). In 1900 this number was nearly zero. In 1950 containers did not exist. Seventy years later 1.83 billion metric tons of goods are carried by containers (Placek, 2021). The modern container has indeed transformed worldwide trade and economy (Levinson, 2008). According to Levinson, by making shipping so inexpensive the container paved the way for Asia to become the world's workshop, and brought consumers a previously unimaginable variety of low-cost products from around the globe. Finally, one of the first jet airliners (Boeing 707) was introduced in 1959. In 2019, the world's airlines carried around an amazing 4.7 billion passengers on scheduled services (Mazareanu, 2021).

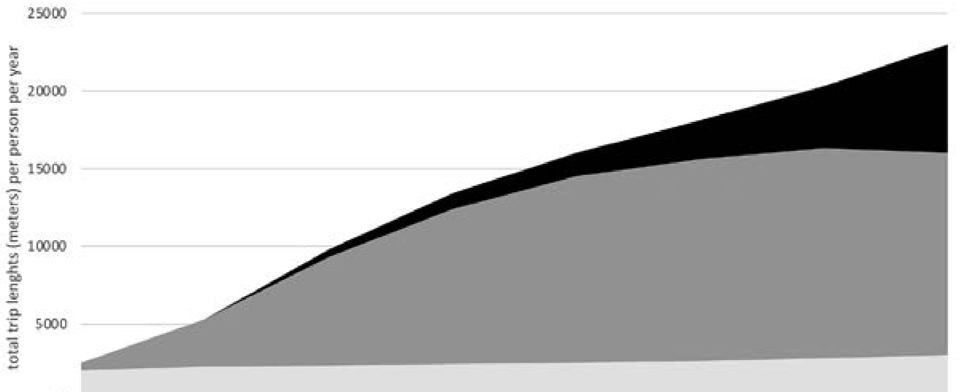
Technological progress in vehicles and infrastructure (see next section) has resulted in more speed – thus, reducing travel times – cheaper transport and more comfort. Related to the themes of Chapter 2 and Chapter 6 of this book, this means that transport technology progress, broadly speaking, often has lowered transport resistance and, thereby, increased transport volumes. At the same time, this increase has resulted in some societal issues such as safety (see Chapter 11 on safety) and environmental damage (see Chapter 10 on environment).

This chapter is mainly about three transport technical innovations which are aimed, amongst others, to reduce these transports drawbacks. The three innovations are alternative powertrains and fuels; Intelligent Transport Systems (ITS) including fully automated vehicles; and vehicle sharing systems. We have chosen these three innovations because at the time of writing this chapter in June 2022, these three, what Fulton et al. (2017) call transportation revolutions, are expected to change the transport system. Vehicle sharing systems such as Mobility as a Service (MaaS) are transport service innovations that require ICT. In the book of van Wee et al. (2022) a larger spectrum of transport innovations is discussed. The goal of this chapter is to explain the potential role of these technological innovations to decrease transport's external effects (see Chapter 13 for an explanation of this concept).

The strong focus on the three innovations selected and external effects is a limited approach. Therefore, this chapter starts with a brief description of the evolution of transport technologies in general (8.2). In Section 8.3 we start by focusing on transport's external effects by explaining why a technologically imperfect transport system has emerged, and what is required from a political-economy perspective to implement new technologies aimed at decreasing the undesirable negative impacts of transport. In Sections 8.4 to 8.6 the three technological innovations are described: alternative powertrains and fuels in 8.4, ITS in 8.5, and vehicle sharing systems in 8.6. In 8.7 some conclusions are drawn.

8.2 THE EVOLUTION OF TRANSPORT TECHNOLOGY

Figure 8.1 shows the development of the average total distance travelled per person per year between 1950 and 2019 in Sweden (in km) (Eliasson, 2022).



Source: Eliasson (2022).

Figure 8.1 Average total distance travelled by mode in Sweden, km per person per year

From a transport technological perspective, we can observe from Figure 8.1 that the past trend in Sweden is relatively straightforward: they increasingly have used higher-speed technologies. In 1950, the Swedes travelled, on average, 2500km per person per year mainly using the active modes (walk/bicycle) and bus. Seventy years later they travel on average almost ten times more per year mainly by car and international air. The Swedes are no exception. Other and older studies have also shown this trend: e.g., Americans have increased their total mobility by

4.6% each year (kilometres travelled per person per year) since 1870 (Ausubel et al., 1998), and Gruebler (1990) has estimated that the French increased their mobility by about 4% per year since 1800. As already explained in Chapter 6, travel time is an important resistance factor for transport. Thus, humankind apparently has chosen (consciously or unconsciously) to reduce this resistance factor by developing higher-speed transport vehicles and infrastructure. By doing so, people have increased their mobility without violating the 'law' of the constant travel time budget (see Chapter 6).

New transport technology for the future is highly uncertain. Nevertheless, increased demand for (high) speed transport technologies is expected to continue in the next decades. For example, Schäfer (2017) estimated that US travel demand per person could increase by 30–50% by 2100 over the 2010 level, mainly due to an increase in air travel. Perhaps suborbital space travel may grow significantly in the twenty-first century (Cohen and Spector, 2020). Another high-speed technology for the future as discussed in the literature is the vacuum train concept, better known as the hyperloop system (see, for example, Nøland, 2021). In this system, passenger or freight capsules are propelled inside an airless vacuum tube at a very high speed. Currently, no commercial applications of the hyperloop exist.

8.3 IMPLEMENTING NEW TRANSPORTATION TECHNOLOGY TO SOLVE NEGATIVE IMPACTS: A POLICY PERSPECTIVE

From the early 1950s, the car started to dominate the Western world transport system (as shown for Sweden in Figure 8.1) with the US as the frontrunner. Sperling and Gordon (2009) talk about the US baby boom generation which came of age in comfortable car-dependent families already in the late 1950s. However, as these authors point out, the 1960s and 1970s also brought about a rather sudden new attitude and new consciousness. In the 1960s, Ralph Nader campaigned against the reluctance of the car manufacturers to spend money on safety measures (Nader, 1965). Jacobs (1961) observed already in 1961 that 'healthy' cities are ones where the physical environment is organized in a way that strengthens the social networks of streets and communities. Meadows et al. (1972) published their famous book with the telling title *Limit to Growth*. This book, commissioned by the Club of Rome, modelled future population growth and the use of natural resources, showing that oil is a finite resource. Indeed, two worldwide oil crises in 1973 and 1979, and an oil-price peak in 2008, showed the Western world that the supply of cheap oil is less self-evident than perhaps previously thought.

Despite new thinking and a greater awareness of the challenges facing transport and the need for technological change, the system is still not perfect (Table 8.1). Economists explain transport imperfections by pointing toward the existence of external costs (see also Chapter 13).

Evolutionary economics can help to explain how we have ended up with an imperfect transport system as depicted in Table 8.1. The theory can also help to explain why it is so difficult for governments and private parties to change it.

Table 8.1 Examples of external costs of transport which might be (partly) solved by technological innovations

	Current statistics, some examples from all over the world	Historic and expected future trends
Traffic jams	In and around large cities all over the world, a car traveller may lose more than 100 hours in congestion in a year with London, for example, on top with 148 hours lost (INRIX, 2022).	An increasing trend in the past. Without additional policies increase in traffic jams in urbanized areas is to be expected.
Oil dependency	Worldwide transportation is responsible for approximately 60% of oil consumption. The transport sector is the most exposed part of the economy to oil prices. The transport sector accounts for more than two-thirds of the EU's final demand for oil and petroleum products (McGovern et al., 2020).	Technologies such as greater engine efficiency, hybrid cars, electric vehicles, biofuels, and hydrogen (see below) could significantly reduce overall oil demand in transport.
Climate change	In 2019, approximately 15% of total net anthropogenic greenhouse gas (GHG) emissions worldwide came from transport (IPCC, 2022).	According to IPCC (2022), the average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in total but remained roughly constant at about 2% per year in the transport sector. Also here, technologies such as greater engine efficiency, hybrid cars, electric vehicles, biofuels, and hydrogen could significantly reduce GHG emissions.
Acidification and local air pollution (NO_x and PM)	In European cities, the transport sector contributes roughly 40–50% to overall nitrogen oxides emissions (NO_x emissions) and 10–15% to particulate matter (PM) emissions (Hoen et al., 2021).	The end-of-pipe emissions of these road transport air pollutants decreased by roughly 50–60% between 1990 and 2018 mainly due to technical progress (Hoen et al., 2021). A further emission reduction is expected because of the penetration of cleaner fossil fuel-based vehicles and alternative powertrains and fuels in the fleet; see before.
Traffic safety	Worldwide an estimated 1.35 million people are killed on roads each year (WHO, 2018).	The future of traffic safety is uncertain and very diverse among the different regions of the world. It is expected that road fatalities will increase in the near future, especially in low- and middle-income countries. Improved technology such as Intelligent Transport Systems (ITS) can contribute to improved traffic safety.
Noise nuisance	Mapping of EU shows that 25% of the population in Europe are exposed to road traffic noise exceeding the EU guideline limit of 55 dB (L_{DEN}: average over a whole day) (Sorensen et al., 2020).	In OECD countries road noise burdens have remained relatively constant since the 1990s; aircraft noise burdens have increased. In the future, a further increase in transport noise is expected in business-as-usual because of expected road and air volume growth. The reduction potential of technologies (e.g., noise barriers, quieter tyres, quieter planes, low-noise road surfaces) is not expected to be strong enough to beat the volume growth.

8.3.1 Innovation and Selection Towards an Imperfect System[1]

In evolutionary economics, all actors are assumed to have bounded rationality (Simon, 1957). Bounded rationality implies that actors, amongst others, have routines, habits, that they are satisfiers rather than optimizers, and that they have a limited time horizon. Bounded rationality results in heterogeneity in behavioural strategies. Innovation is the result of this diversity. Sovacool (2009) describes how by the end of the nineteenth century a person seeking transport in the United States (and many other corners of the world) could choose between a bewildering array of different options: the horse, bicycles, trains, subways, the new steam-powered horseless 'carriages', gasoline automobiles and electric-powered vehicles.

In evolutionary economics, serendipity plays an important role in explaining the innovation process. This means that a combination of chance, luck, and knowledge results in an invention. Knowledge is important because empirical evidence shows that creative innovations are in most cases the result of a new combination of existing knowledge, techniques, or concepts.

Within the scope of behavioural diversity, 'knowledge' has many faces and it is unavoidable that much knowledge, and therefore money will be wasted. This means that knowledge 'waste' in the form of trial-and-error and cul-de-sacs is needed to get 'fit' technologies (one may even wonder if 'waste' is the right phrase here). In other words, according to evolutionary economics, gasoline and diesel vehicles have emerged as a fit technology in the competition with the train, the steam-powered carriage, and electric-powered vehicles.

Selection processes reduce the innovation diversity. The innovation and selection processes together determine the 'fitness' of a certain new technological alternative. Fitness is a measure of survival and reproduction. In the selection process, the new innovations are put to the test for survival. Selection relates to many different factors: physical possibilities or impossibilities of new technology, technical usage pros and cons, economic factors such as price and the possibilities to produce the technology on a large scale, psychological factors (do people actually like the new invention?), institutional barriers (will governments allow the new invention to enter the market?), and so forth. Sovacool (2009) in his history of early modes of transport in the US argues that all of these factors have played a role in explaining why the gasoline automobile finally became the winner. For example, he shows that even though the electric-powered vehicles initially (1895–1905) had many advantages, they did not break through because they were more expensive than gasoline cars, had slower top speeds, were difficult to charge, were mostly confined to urban areas, and came to be seen, amongst others, as old fashioned.

8.3.2 Path Dependency, Lock-In, and Co-Evolution

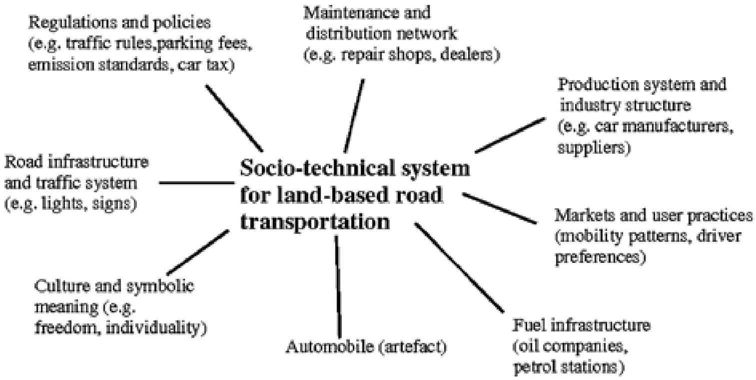
The dynamics of evolutionary systems as described here result in three important concepts for this chapter: path dependency, lock-in, and co-evolution. Path dependency means that for a certain technology, as a result of increasing economies of scale, a self-reinforcing feedback loop may emerge which ends up in the dominance of that technology. With economies of scale economists mean that the more one specific technology is used and produced, the lower the average cost will be to produce or use one unit of that technology (e.g., a fossil-fuelled car). For example, all people and shippers using internal combustion engines share the same fuel network and make use of the same maintenance and distribution networks (repair shops and dealers). For car producers, many types of economies of scale exist. One of these is that building cars require large fixed costs such as factories, assembly lines, and so forth. Using such factories to full capacity lowers the average costs of making a car. Thus, economies of scale result in substantially lower costs.

Unfortunately, the consequence of path dependency means that there may be a historically unavoidable path towards the complete dominance of one technology. Disadvantages that did not occur, or were not seen as disadvantages at the early start of its development, can make it difficult to change technologies. A situation of so-called technological 'lock-in' has unintentionally been created. In many ways, the current dominant transport technology (the internal combustion engine fuelled by oil products) can be regarded as such a lock-in situation that has, on the one hand, led to economies of scale and, thus, relatively cheap ways of transportation for many people around the world. However, on the other hand, it has led to many negative externalities (Table 8.1).

Co-evolution is related to the evolutionary notion that innovations are in most cases the consequence of combining already existing ideas or systems. Co-evolution focuses on the ways partial systems (such as, on one hand, cars, vans, and lorries, and on the other hand, the road or the fuel network) develop, work together, and to an increasing extent influence each other's evolution. One may say that co-evolution of different partial technical systems working increasingly together will often result in improved synchronization and extra benefits for the users. However, if the resulting co-evolutionized system has societal disadvantages (Table 8.1), it seems even more difficult to escape the 'lock-in' of the closely intertwined system.

8.3.3 System Innovations (Transitions)

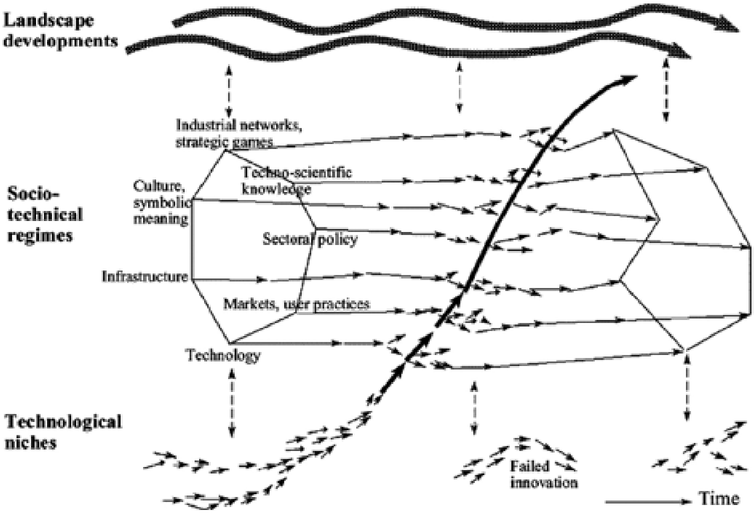
Systems can change via system innovation or transition according to system innovations theory (e.g., Geels, 2005). Central in this theory are so-called socio-technical systems. For example, Figure 8.2 illustrates the socio-technical system for road transport. The picture shows interrelated entities within this socio-technical system and explains the embeddedness of transport technology in society in terms of physical infrastructure, institutions, markets, and culture. The notion of a co-evolutionized closely intertwined system is clearly recognizable in Figure 8.2.



Source: Geels (2005).

Figure 8.2 Socio-technical system for road transport

System innovation is a transition from one socio-technical system to another, potentially characterized by a technological change (e.g., from sailing ships to steamships). Transition is a process that can be explained by using the *multi-level perspective (MLP)* (e.g., Geels, 2002). The multi-level perspective (see Figure 8.3) combines insights from evolutionary economics, innovation studies, and science and technology studies, in order to understand transitions and the dynamics in system innovation.



Source: Geels (2002)

Figure 8.3 Multi-level model of system innovations

An existing socio-technical system is depicted as a heptagon somewhere left to the middle of Figure 8.3. The changed socio-technical system is symbolized on the right side (later in time) of Figure 8.3 as a differently shaped heptagon. In the multi-level model of system innovations three levels are distinguished:

1. The middle level is the **socio-technical regimes**, see Figure 8.2 for an example. The crux in the MLP theory is that this level is stable and that innovations will not happen here. As already mentioned, socio-technical systems are locked-in.
2. However, at the lower level, **technological niches** may exist (represented as small arrows) that try to penetrate the middle level of the socio-technical regimes. Some niches succeed and change or become a new socio-technical system, some fail. Niches 'act as incubation rooms for radical innovations nurturing their early development' (Geels, 2002, p. 1261). A niche can be a specific market segment (e.g., car racing where new technologies are tried), R&D projects, pilot programmes, and so forth. The crux is that niches are unstable because they are per definition small with limited user practices, high policy uncertainties (e.g., will electric vehicle subsidy programmes be continued?), and not yet consisting of mature networks between actors.

3. **Landscape developments** are conceptualized as the high level. These are 'a set of deep structural trends external to the regime' (Geels, 2005; p. 78). Landscapes cannot be changed by actors within the socio-technical regime (middle level), in our case transportation. The landscape developments include both tangible (such as the built environment) and non-tangible aspects (such as economic growth, culture, attention for environmental problems, and pandemics). There are slow developments in the landscape (e.g., demographical changes) as well as rapid developments (e.g., oil crises, COVID-19 pandemic). Some landscape developments may help a technical niche to successfully penetrate the socio-technical regime, but other landscape developments may result in failed penetration.

Public authorities often play a role in the technological niche level (for example, 'protect' some early but very promising niches by giving subsidies or by carrying out pilot programmes), but they are also a regime player. This means public authorities can have an accelerating as well as a decelerating role in system innovations.

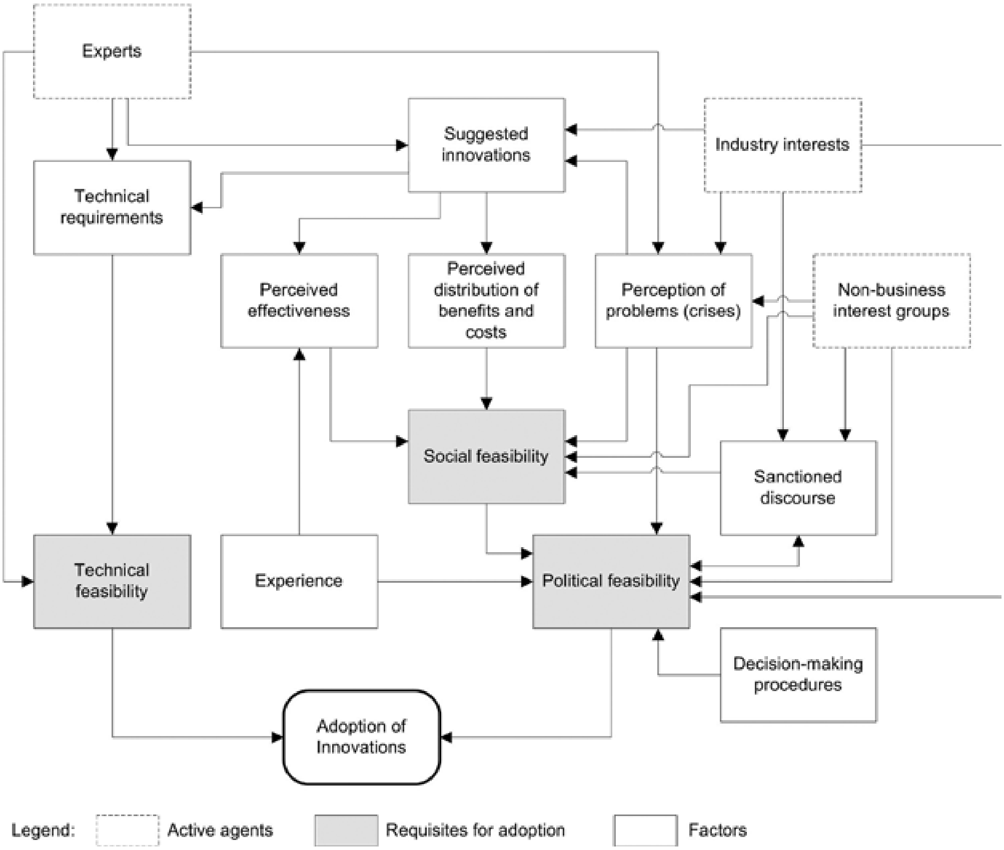
8.3.4 A Political-Economy Model

A view on transport innovations and the role of public authorities is advanced by Feitelson and Salomon (2004). They have developed a political-economy framework for analysing the adoption of transport innovations (Figure 8.4).

The box 'perception of problems' (see Figure 8.4 top right) is an important factor in the successful adoption of new technology, as will be shown in the subsequent paragraphs on technological innovations aimed at reducing the external costs of transport. The oil crises (in 1973 and 1979), severe smog periods in Los Angeles and London, and a continually increasing amount of traffic casualties in the 1960s have all spurred technical changes in transport. Also, experts such as scientists, advisers, and consultants play a role in their framework (see Figure 8.4 top left). Experts suggest technical innovations and the means to implement these innovations. They research technical issues and societal problems such as congestion, climate change, and air pollution. They also perform formal cost–benefit analysis showing, for example, that certain policies such as implementing nationwide road charging using GPS technology will have a positive benefit-to-cost ratio. Nevertheless, the Feitelson and Salomon framework shows clearly that a favourable benefit-to-cost ratio for a policy does not mean that this policy will be adopted. For politicians the perceived effectiveness and the perceived distribution of benefits and costs (who wins, who loses) of policy also play an important role in their decision-making.

Most important in their framework is that they think that the adoption of innovations is predicated on the economic, social, political, and technical feasibility. Thus, it is insufficient that innovation is technologically superior, that it meets a strict benefit–cost criterion or that there is a majority of voters supporting it. In their view, only a particular combination of these feasibility issues will result in successful innovation.

The Feitelson and Salomon political-economy framework, with its emphasis on the importance of social and political feasibility for explaining the successful adoption of innovations, relates to the notions of the current transport system as a co-evolved lock-in situation or as a socio-technical regime. Both concepts imply that the current situation not only means a strong dependence on one dominant technology but also a strong position for the defenders of the existing socio-technical regime, such as vehicle manufacturers, the oil industry, unions, and billions of consumers worldwide who by using their voice and vote influence the position of non-business interest groups and political parties (Figure 8.4). To illustrate the political power of certain actors: according to the European Automobile Manufacturers' Association (ACEA, 2022) the European automobile industry accounts for 8.5% of total direct EU manufacturing employment. In countries such as Germany (11.1%), Sweden (14.4%), and Slovakia (16%) this share is even higher, representing a workforce amounting to more than the population size of a country such as Belgium. This passage is not meant to blame the defenders of an imperfect system. After all, it is clear that the current dominant transport technology has also many advantages related to economies of scale. So, it seems obvious that industries and people profiting from these advantages are reluctant advocates for a fast and radical change.



Source: Feitelson and Salomon (2004)

Figure 8.4 A political-economy model for explaining the adoption of innovations

In the next three sections, three technological innovations will be discussed that potentially can change the current socio-technical transport system.

8.4 ALTERNATIVE POWERTRAINS AND FUELS

The ‘text box air pollutants’ (see below) demonstrates how the policy of vehicle emission standards implemented in the past decades all over the world has spurred the implementation of many technologies in conventional fossil-fuel-based vehicles that reduced emissions. However, it is widely acknowledged that fossil-free technologies are the way forward (IPCC, 2022). Electric cars and vans are considered an important solution for reducing transportation’s GHG (carbon dioxide, CO_2) emissions and air pollution (e.g., nitrogen oxides, NO_x and particulate matter, PM). For trucks, lorries, ships, and planes other carbon-free options are also studied (see below in this section).

BOX 8.1 AIR POLLUTANTS REDUCTION WITH CONVENTIONAL TECHNOLOGIES

Air pollutant emissions from conventional fossil-fuel-based vehicles decreased considerably in the past (Table 8.1). All large economies of the world have implemented air pollution emission standards for all kinds of road vehicles (cars, vans, and lorries) since around 1990. A comprehensive overview of these vehicle standards from all over the world can be found on Dieselnet (2022). One of their overviews gives the EU emission standards for passenger cars (see Table 8.2). An important feature of this policy as shown in the table is that the standards are tightened over time.

Table 8.2 EU air pollutant emission standards for passengers cars

Stage*	Date	CO	HC	HC+NO_x	NO_x	PM	PN
		g/km					*#/km*
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	–	0.97 (1.13)	–	–	–
Euro 2	1996.01	2.2	–	0.5	–	–	–
Euro 3	2000.01	2.30	0.20	–	0.15	–	–
Euro 4	2005.01	1.0	0.10	–	0.08	–	–
Euro 5	2009.09[b]	1.0	0.10[d]	–	0.06	0.005[e,f]	–
Euro 6	2014.09	1.0	0.10[d]	–	0.06	0.005[e,f]	6.0×10^{11} [e,g]
Compression Ignition (Diesel)							
Euro 1†	1992.07	2072 (3.16)	–	0.97 (1.13)	–	0.14 (0.18)	–
Euro 2, IDI	1996.01	1.0	–	0.7	–	0.08	–
Euro 2, DI	1996.01[a]	1.0	–	0.9	–	0.10	–
Euro 3	2000.01	0.64	–	0.56	0.50	0.05	–
Euro 4	2005.01	0.50	–	0.30	0.25	0.025	–

Stage*	Date	CO	HC	HC+NO_x	NO_x	PM	PN
		g/km					*#/km*
Euro 5a	2009.09[b]	0.50	–	0.23	0.18	0.005[f]	–
Euro 5b	2011.09[c]	0.50	–	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	–	0.17	0.08	0.005[f]	6.0×10^{11}

Notes:
CO = carbon monoxide; HC = hydrocarbons; NO_x = nitrogen oxides; PM = particulate matter (in weight); PN = particulate matter in number of particles
* At the Euro 1–4 stages, passenger vehicles > 2500kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the Particle Measurement Programme (PMP) measurement procedure
g. 6.0×10^{12} 1/km within the first three years from Euro 6 effective dates

With improved motor management and all kinds of end-of-pipe-technologies such as three-way-catalysts, particulate soot filters, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR) technologies, vehicle manufacturers have been able to meet these standards. Kuklinska et al. (2015) give a comprehensive review of air quality policies in the U.S. and the EU, including vehicle emission regulations. Hooftman et al. (2018) have also reviewed the European passenger car regulations including the technologies implemented. Implementing the vehicle emission reduction technologies for air polluting substances such as nitrogen oxides (NO_x) and particulate matter (PM_{10}) has been a relatively smooth adoption process of new technologies because these technologies can be regarded as purely technological innovations, not as systems innovations. When we refer back to Figure 8.2, the only element in the socio-technical system really affected by implementing these end-of-pipe technologies is the vehicle production system. And although vehicle manufacturers have opposed stricter standards and the speed of implementing the next stricter rule (and some even cheated on meeting the emission standards, Bouzzine and Lueg, 2020), they have always complied in the end.

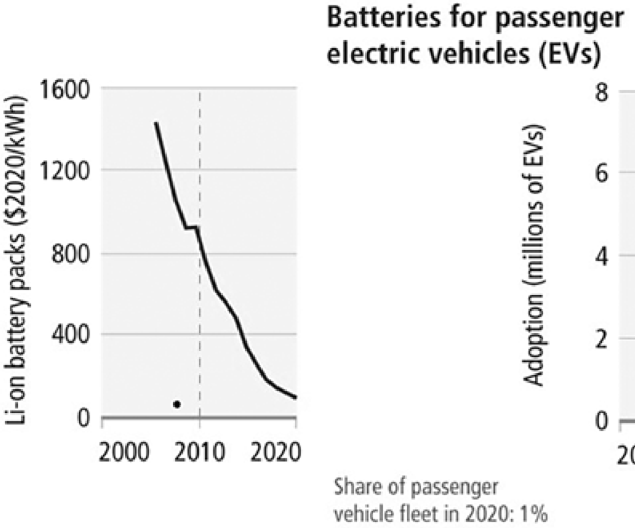
8.4.1 Cars and Vans

The crux of the electrification of cars is that instead of burning fossil fuel products such as petrol, diesel, LPG in an internal combustion engine (ICE) to produce the propulsion energy for the vehicles, electricity is used in an electromotor. The burning of fossil fuels results in unwanted side products such as CO_2 and air pollutants. When using the vehicle's electricity no emissions take place. However, the electricity and electric vehicle components may still produce emissions, and this is discussed below.

Different types of electric vehicles can be distinguished. Battery electric vehicles (EVs) contain a battery that has to be charged using an outside electricity source. In so-called hybrid electric vehicles and plug-in hybrid electric vehicles, the electromotor is combined with an ICE. The difference between these two hybrid vehicles is that plug-in hybrid vehicles' batteries are charged via an outside electricity source (and by using braking energy), while a hybrid vehicle uses its ICE (and also braking energy) to charge the battery. Fuel cell electric vehicles are also considered electric vehicles but their energy source is special. These types of vehicles generate electricity in a fuel cell by using compressed hydrogen and oxygen (from the air). The chemical reaction between hydrogen and oxygen results in electricity and water. So, these vehicles have to be fuelled with hydrogen which has to be produced (see below). Finally, extended-range vehicles are produced to some extent which is quite similar to EVs but they have a (small) ICE that can be used to charge the battery if an extra range is required and no charging options are available.

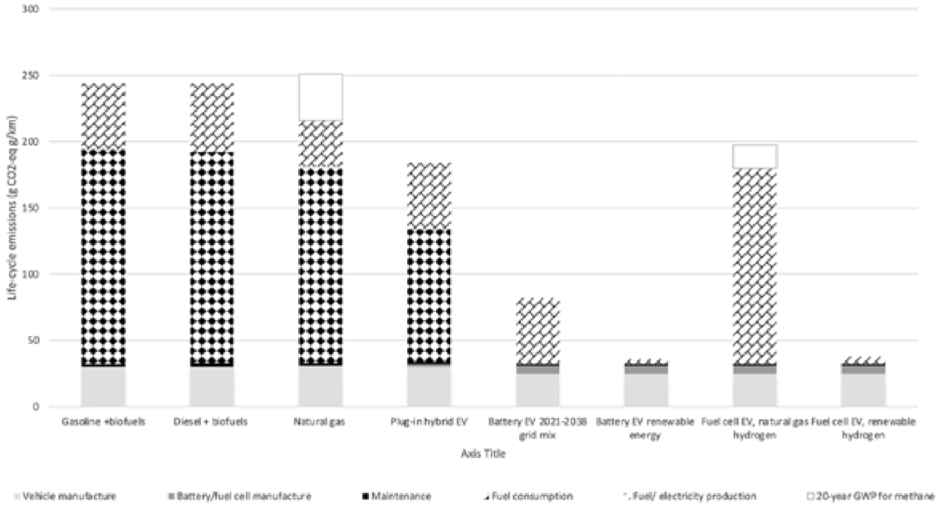
The sales of EVs have increased rapidly worldwide (Figure 8.5). In Norway, in 2020, more EVs are sold compared to ICEs. It should be noted that these sales are mainly policy driven. When we relate to the political-economy model of Feitelson and Salomon (2004), EVs can be seen as technically feasible and the stimulating policies as being social and politically feasible. Governments across the world support EV sales with all kinds of policies such as tax exemptions, subsidies, and facilitating public charging to contribute to reducing transport externalities. In 2020 governments worldwide spent 14 billion USD to support electric car sales (IEA, 2021). The reason for these policies is that consumers experience barriers in purchasing EVs which are related to their higher purchase costs, range anxiety issues, lack of charging infrastructure, and also more intangible barriers related to emotions (e.g., 'lack of fun', 'no cool noise') (Krishna, 2021). So, without government support, this technology would probably be adopted very slowly, because within the socio-technical regime (Figure 8.2) long-ingrained market preferences and cultural meaning within the old regime (fossil fuel) will have to change due to EV adoption. Thanks to the support EV registration increased globally to almost seven million in 2020 (IPCC, 2022). Due to the resulting economies of scale (see Section 8.3), it seems that some important barriers are slowly disappearing. For example, the total cost of ownership (TCO; includes purchase costs, maintenance costs, and operational costs) of EVs is expected to become lower in 2023–25 for smaller and medium-sized cars and for the bigger cars segment some years later (Element Energy, 2021). Even for the fuel cell electric cars, which in 2020 were far more expensive in TCO terms compared to comparable ICEs, it is expected in this study that around the year 2030 they may break even. The TCO decreases are fuelled by lower battery and fuel cell prices and energy costs. Figure 8.5 shows that the lithium-ion (Li-ion) battery packs unit price has dropped by roughly 90% in the period 2005 to 2020. Also, the range has improved considerably with roughly 40% of the average EVs sold worldwide in the period 2015–20 (IEA, 2021).

Decreasing CO_2 emissions is an important reason for governments worldwide to stimulate EV adoption. As noted before, during the use of EVs no CO_2 emissions will take place but what about producing electricity and hydrogen? In so-called Life Cycle Analysis (LCA) a full comparison between technologies is made. In LCA studies also the CO_2 emissions are taken into account when producing the vehicles and vehicle components (such as the battery), when maintaining the vehicles, and when producing and distributing the fuels. In some LCA studies also the environmental impacts of the end-of-life treatment of vehicles and components (e.g., demolition, recycling) are considered but this stage is not included in the LCA example we give in Figure 8.6 (Bieker, 2021). Figure 8.6 gives the EU the life-cycle GHG emissions in g CO_2-eq[2] per kilometre driven for different car technologies.



Source: IPCC (2022)

Figure 8.5 Adoption of EVs worldwide and the development of the Li-ion battery unit price



Source: Bieker (2021)

Figure 8.6 Life-cycle GHG emissions of lower medium segment cars (e.g., Ford Focus) with different technologies registered in Europe in 2021

Some observations can be made related to Figure 8.6. The first is that the currently dominant technologies petrol (gasoline) and diesel cars in the EU emit around 250g CO_2-eq/km over the full life cycle. Conventional gasoline and diesel fuels contain some biofuels. The EU has promoted the use of biofuels since the 1990s, amongst others, to save GHG emissions (Puricelli et al., 2021). According to this study around 4.5% of the energy consumption in road transport and non-road mobile machinery is biofuel, mainly ethanol from crops. The idea of biofuels is that plants while growing absorb CO_2. When these plants are converted into liquid fuels and burned, this CO_2 is released and can 'immediately' again be taken up by new plants for biofuel production, and so forth. Puricelli et al. (2021) reviewed many LCA studies on biofuels and conclude that the climate change impacts of biofuels are indeed broadly speaking lower than fossil fuels. However, they also point out that direct and indirect land-use changes due to growing biofuel feedstocks are not always taken into account in these CO_2 emission impact estimations. Additionally, these land-use changes can be harmful, e.g., biodiversity can be lost. It is for these reasons that electrification policies for light-duty vehicles have become more popular, but for heavy vehicles, ships, and aeroplanes biofuels are still seen as a potentially viable option albeit many researchers recommend a shift in producing biofuels towards using non-edible feedstocks, waste, and industrial by-products to avoid the land-use change issues (see below).

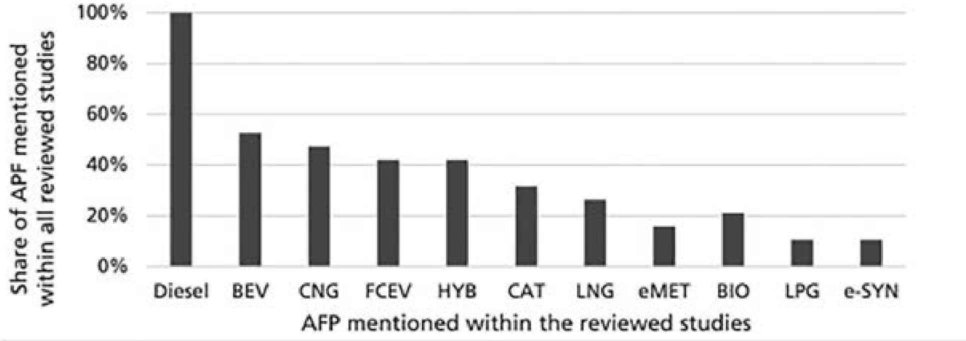
The second observation (Figure 8.6) is that natural gas cars do not perform better than conventional petrol and diesel cars. Important reasons are that the obtaining and distribution of natural gas (which is in essence methane) result in methane emissions and also when methane is used in cars some methane will be emitted ('slip'). Methane is a strong GHG, see endnote 2.

The third observation is that plug-in hybrids, EVs, and fuel cell electric cars perform also from an LCA perspective better than the fossil-fuel-based variants (Figure 8.6). The figure shows that the extent of this improvement is highly dependent on the way electricity and hydrogen are produced. Bieker (2021) assumes that in the EU electricity grid mix coal and natural gas (and to a small extent oil) are still used to produce electricity which, compared to a renewable mix, results in a higher CO_2-eq/km value for EVs. Countries that have a higher share of, for example, coal will have higher CO_2-eq per kilometre emission factors compared to the EU, to state the obvious. For fuel cell electric cars natural gas (methane) is seen as a relatively cheap feedstock to produce hydrogen but this choice will result in not much improvement CO_2-eq-wise compared to the conventional fossil fuel cars due to the methane emission problems just mentioned (Figure 8.5). Using renewables such as solar and wind to produce hydrogen from water will result in a far better emission factor.

Next to cars, there is a huge and increasing market for urban transport vehicles (such as vans). The global online retail sales market, for example, quadrupled in the period 2014 to 2020 to around 4200 billion USD (4.2 trillion USD) (Apex Insight, 2021). This implies an enormous growth in the use of delivery vehicles, and, thus, in emissions. For the conventional vans, Castillo et al. (2020) have analysed that full electric battery-powered vehicles seem to be the best-placed solution for reducing these externalities, although they also note that driving range and recharge options are still barriers that need to be solved. Another kind of technology development in the delivery market is the increasing use of 'light electric freight vehicles (LEFV)'. These are bikes, mopeds, or compact vehicles with electric support or drive mechanisms, equipped for the delivery of goods, and goods and people with limited speed (van Duin et al., 2022). Verlinghieri et al. (2021) and van Duin et al. (2022) expect significant growth in LEFVs usage within urban areas all over the world.

8.4.2 Heavy duty vehicles

For heavier vehicles such as trucks and lorries (HDVs), the discussion on alternative powertrains to reduce GHG emissions is still going on (as at 2022). Kluschke et al. (2019) reviewed 19 studies on potential market penetration of alternative fuel powertrains (AFPs) in HDVs, see Figure 8.7. Battery-electric vehicles (BEVs) were mentioned the most but also interesting is to see that many different AFPs are studied and suggested. Ten AFP technologies are considered: six alternative fuels (liquid petroleum gas (LPG), liquid natural gas (LNG), compressed natural gas (CNG), electric methane (eMET), electric Synfuel (eSYN), and biofuels, (BIO)) and four electrified powertrains (catenary (CAT), battery-electric (BEV), hybrid (HYB), and fuel cell electricity (FCEV)). eMET is synthetic methane generated from hydrogen (produced by using electricity) and CO_2. eSYN are any kind of hydrocarbons (e.g., methanol, or more complex products such as diesel or kerosene) also made out of hydrogen (produced by using water and electricity) and $CO_{2.}$ Which of these technologies or set of technologies will become the AFP or AFPs of the future for HDVs is dependent on many factors, such as their CO_2 performance (see Figure 8.6), costs, energy supply factors, infrastructure development, and user acceptance. Referring to the multi-level model of system innovations, the AFPs HDV can be regarded as niches. Which one (or perhaps two or three) will breakthrough eventually in the socio-technical regime of heavy-duty transport is, at the time of writing this chapter, unknown.



Source: Kluschke et al. (2019)

Figure 8.7 Share of alternative fuel powertrains (AFPs) in HDVs mentioned in reviewed studies

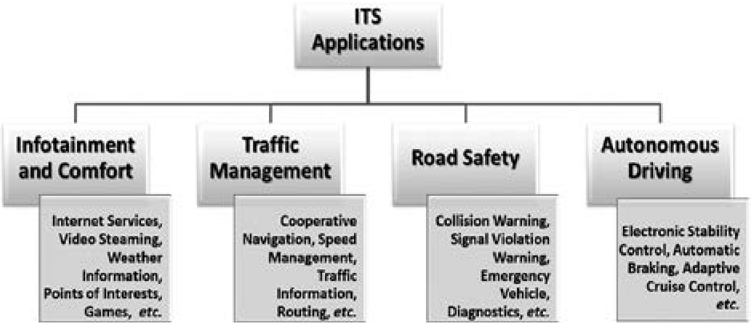
The same kind of uncertainties about the suitability of AFP or AFPs for HDVs in the future also play an important role in other transportation markets such as aviation and inland and sea-going shipping. Dahal et al. (2021) performed a techno-economic review of alternative fuels and propulsion systems for the aviation sector. They assess bio-jet fuels (hydro-processed esters and fatty acids and alcohol-to-jet) as most promising in the near term and electrofuels (eSYN fuels) and hydrogen in the long term. They see the costs of producing these fuels and the design and development of appropriate propulsion systems and aircraft as the major challenge. In relation to the question of whether biofuels are actually sustainable (see before), Dahlah et al. (2021) also see an important issue in the limited supply potential of feedstocks for the bio-jet fuels such as cooking oil, animal fats, vegetable oils, and waste oils. The same kinds of uncertainties about alternative fuels can be found in the literature on the maritime sector. Foretich et al. (2021) map the challenges and opportunities of low-carbon fuels in the maritime sector. Again fuels such as LNG, biodiesel, ammonia (as a source for onboard hydrogen), and various e-synthetic fuels are discussed. Supply issues, costs, safety concerns, spill risks, and actual LCA GHG emission reductions are still important challenges.

Åkerman et al. (2021) present five scenarios for long-distance travel in 2060 which are consistent with a 67% probability of limiting global warming to 1.8 degrees. Foremost is their conclusion is that to meet this global warming goal, (huge) reductions in air travel demand are required but this notion is outside this technology chapter. Additionally, they see also an important role for alternative fuels with biofuels, electrofuels, and liquid hydrogen offering the best options.

8.5 INTELLIGENT TRANSPORT SYSTEMS APPLICATIONS (INCLUDING AUTOMATED DRIVING)

This section covers a wide span of technologies which are summarized in the term 'intelligent transport systems' (ITS). Basically, common to all these technologies is the (sometimes huge amounts of) data generated from the road and public transport users and the infrastructure that are collected, stored, and processed with, increasingly, Artificial Intelligence techniques.[3] Figure 8.8 gives an overview of ITS applications (Shankar Iyer, 2021). Related to this chapter where the role of technologies is discussed to decrease externalities, two notions are important. First, implementing ITS has often a wider goal than solely decreasing externalities. Improving comfort, providing real-time travel information that lowers transport resistance factors (Chapter 6) and making vehicle driving effortless and accessible also to people without driving licences (when full automation is achieved; see below) are examples of these wider goals. Second, it is uncertain if ITS actually decrease externalities which we will illustrate below when we discuss automated vehicles.

One of the pillars in Figure 8.8 is road safety. Advanced driver assistance systems (ADAS) are one category of ITS that promote traffic safety. Applications in this ITS category are lane departure warning systems, automatic and adaptive cruise control systems, monitoring and warning systems for driver vigilance (intervenes when driver drowsiness, fatigue, and inattention occur), or night vision. Also, collision warning and avoidance systems are in use. Collision warning systems use radar and internal-vehicular information to detect any collision



Source: Shankar Iyer (2021)

Figure 8.8 An overview of ITS applications

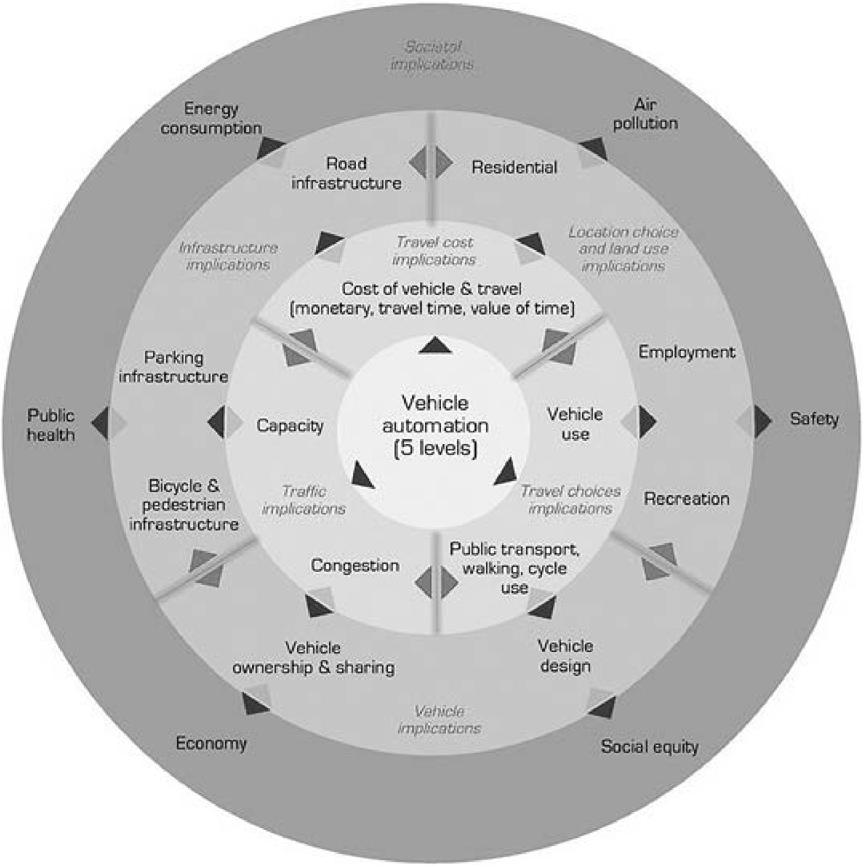
risk. Intelligent speed assistance (ISA) is another ITS application. In the EU ISA has to be fitted to all new vehicles from May 2022 (EC, 2022). With ISA the vehicle has information on the permitted or recommended maximum speed for the road along which it is travelling. The standard ISA system uses an in-vehicle digital road map onto which speed limits have been coded, combined with a satellite positioning system. If the driver exceeds the permitted or recommended maximum speed a system (which could be the navigation system) intervenes to control the speed of the vehicle. This intervention can have different forms of which actively preventing drivers from exceeding the speed limit is the strongest intervention. The European Commission is proposing a less strict intervention: ‘Cascade Auditory Warning System’. This auditory system warns only until the vehicle is well over the speed limit. Carsten (2021) indicates that such information and warning systems have life- and injury-saving potentials of around one-quarter of that of the strongest intervention, what Carsten calls ‘true ISA’.

A well-known ITS (in the pillar autonomous driving, Figure 8.8) is adaptive cruise control (ACC) whose use is increasing (Chen et al., 2019). ACC systems detect the position and speed of preceding vehicles on the road through various sensors and automatically adjust the speed according to the control strategy. ACC increases the safety and comfort of driving. The next step is so-called cooperative ACC (CACC) systems in which multi-vehicle information (using the vehicle-to-vehicle information based on advanced wireless communication) is produced and used which can shorten the following gap (see Chapter 7) on the basis of ensuring safety (Chen et al., 2019). CACC systems can potentially have positive impacts on congestion, safety, and energy (however, see below the discussion on autonomous vehicles and their societal impacts). From an energy perspective and, thus, CO_2 perspective, CACC systems seem an important next step as ACC impacts negatively on tractive energy efficiency (He et al., 2020) because unlike human drivers ACC followers lead to string instability.

ITS are also increasingly used in public transport (PT), in cycling, and by road authorities. PIARC (2022) mentions various ITS application terrains in PT such as management information systems (e.g., real-time management data collected from vehicle tracking and locations), en-route information for passengers about delays, disturbances, and changes that seats are available, and PT security information systems. For example, using CCTV PT authorities can monitor 24/7 stations, platforms, parking lots, bus stops, and so forth to gain real-time (manually or automatically) information about risky situations. For cycling examples of ITS are real-time information about parking availability in cycle storage facilities and cycle availability in bike-sharing systems. Road authorities use ITS increasingly to give en-route information about congestion, to instruct road users in real time to lower speed when road intensities approach capacity, to gather information (using sensors) about the quality of road pavements, bridges, viaducts in order to manage their maintenance programmes, and so forth. Also here PIARC (2022) is a very rich source of ITS applications.

One of the technologies that like electrification could potentially transform the transportation socio-technical system is full automated driving (see Figure 8.8). Automation is already extensively used in modern marine vessels and aeroplanes (use of autopilots), although human input is still required but in a more passive role. Unmanned aircraft in the form of drones are already used and ‘remotely piloted aircraft’ (RPA), whereby a pilot external to the aircraft (ground, ship, another aircraft) controls the plane but people (e.g., for monitoring, searching or inspection tasks) are on board, is foreseeable (ICAO, 2011). In public transport, automation has become more and more common, for example, with the use of communications-based train control (CBTB). The most challenging technology in this respect is automated driving on the road. SAE International distinguishes different levels of driving automation. In levels 0 to 2 people are driving but some of their tasks are automated (such as with an ACC or CACC; see above), in levels 3 to 5 people are not driving when autonomous driving features are engaged. In level 5 these features can drive the vehicle under all conditions. In levels 3 and 4 there are still some limited conditions such as automated driving is only possible on certain roads. Milakis et al. (2017) reviewed the literature to discuss policy and society-related implications of automated driving. They used the ripple model of automated driving (Figure 8.9).

In this model, three sequential impact circles can be distinguished. The first contains the first-order impacts of automated driving on travel resistance (Chapter 6), road capacity, and travel choices. These first-order effects are passed through to the second circle: second-order impacts on vehicle ownership and sharing, locations choices and land use, and transport infrastructure. Finally, in the third-order impacts circle, it is conceptualized what automated driving will have for societal implications. Feedbacks can occur in this ripple model in analogy with the central model in this book in Chapter 2. For example, automation can reduce all kinds of resistance factors (travel time, effort) in the first circle that influence location choices (second circle) which in turn might influence travel choices (first circle). The crux of their review is that it is not known if in the long term automated driving will increase or decrease transport’s externalities. The main issue is that automated vehicles are expected to induce road travel demand because of more and longer trips but to what extent is uncertain. They note that potential land use changes may induce additional road travel demand because of automation, but this has not been included in the literature reviewed. Their review shows that automated vehicles can have benefits compared to people-driven vehicles if travel distances remain constant. For example, they can be less risky, leading to less congestion and be more fuel-efficient. However, the unknown induced demand can decrease or even counteract the potential benefits on a system level in the long term. So, in a possible future world of full vehicle automation



Source: Milakis et al. (2017)

Figure 8.9 The ripple model of automated driving

on the road, transport policies such as pricing still seem required to decrease externalities (Chapter 13).

The ripple model indicates that automated driving, especially the higher levels, might be one of the hardest innovations to realize. The current socio-technical regime (Figure 8.2) will have to change in almost all elements, such as in the culture of being in the driver's seat, in rules and regulations, in infrastructure, in markets and user practices, and so forth.

8.6 SHARING AND NEW MOBILITY SERVICES SUCH AS MAAS

Vehicle sharing has gained popularity in transportation. Sharing can be considered an important change in the current socio-technical regime where private vehicle ownership is the dominant feature. Sharing is a bit of a misleading word because it is actually renting vehicles for a short period of time. There are real sharing schemes, where there is co-ownership of vehicles, but these are relatively uncommon. All over the world, various vehicle sharing systems (VSS) are in use or in development such as car sharing, e-car sharing, bike sharing, cargo-bike sharing, kick scooter sharing, scooter sharing, and so forth (Ataç et al., 2021). Although sharing can be introduced in principle without any advanced technological support, ICT plays an important role in building and maintaining modern VSS. Ticketing and reservations systems require advanced software and apps. Advanced wireless communication technologies are applied in order to open and close vehicles at their docking stations or somewhere on the street when a free-floating sharing system is used. Sometimes geo-fencing is used to make sure that the shared vehicles are parked in a designated area by the users, or to make sure that the use of the shared vehicle is limited to the area over which the vehicle is allowed to be used – a boundary to the scheme.

Like for ITS (previous section), vehicle sharing has wider goals than solely decreasing externalities. Sharing systems can be profitable for entrepreneurs and can be beneficial for users because it increases their accessibility. Still, most governments promote or actively support vehicle sharing systems because of their potential positive social impacts. Nijland and Van Meerkerk (2017) show in a survey amongst 363 car-sharing respondents in the Netherlands that they own 30% fewer cars than prior to car sharing and drive 15% to 20% fewer car kilometres. So, based on this research car sharing indeed has some potential to decrease car use and ownership externalities such as emission and use of public space. In a large review on the impacts of bike sharing, Teixeira et al. (2021) conclude that bike sharing is mostly replacing the sustainable modes PT and walking, with modest car replacing rates. This modest car shift will still have some positive impacts on emissions and noise. New trips generated by bike sharing might have positive health impacts (Chapter 12) due to more physical activity (Teixeira et al., 2021).

Urban planning authorities are looking for ways, such as providing or permitting VSS, that enable people to travel more sustainably (Alyavina et al., 2020). Among these options is MaaS. These are integrated systems that enable travellers to plan, book, and pay for trips through a single online interface. Basically, the idea is that in MaaS people buy their full trip through a single online interface instead of making the trip by using their self-owned vehicle or by having to organize the full trip themselves (e.g., walk to the station, buy a train ticket, rent a bike, buy a tram ticket, and so forth). Like in automated vehicles different levels of MaaS are distinguished in the literature: 0 no integration; 1 integration of information; 2 integration of booking and payment; 3 integration of the service offered, including contracts and responsibilities; 4 integration of societal goals (Sochor et al., 2017). In the highest level 4, people can choose between different mobility offers for a trip by online platforms based on out-of-pocket costs and time but also on information provided to them about the emissions and safety of the particular trip offer. The development of MaaS is still in its early stages, and the exact impact of MaaS on the current transport system is therefore unclear (Araghi et al., 2020). MaaS is expected by some to aid in promoting sustainable transportation modes at the expense of privately owned vehicles (Jittrapirom et al., 2017), potentially reducing the associated externalities of private vehicle ownership, such as climate change, air pollution, and public parking spaces (Butler et al., 2021). However, Casadó et al. (2020) and Alyavina et al.

(2020) also speculate MaaS to potentially be counterproductive by replacing current public or active transport trips (cycling and walking) with vehicle trips (e.g., using taxis or shared cars).

8.7 CONCLUSIONS

The conclusions of this chapter are:

1. It is difficult to change the dominant transportation technology. This can be explained with the concept of 'lock-in' from the theory of evolutionary economics or with the notion of transport as a socio-technical system from the theory of system dynamics. Socio-technical systems theory points at the embeddedness of transport technology in society in terms of physical infrastructure, institutions, markets, and culture.
2. Potential technological innovations that might change the socio-technical systems of transportation radically are alternative powertrains and fuels, automated driving and sharing.
3. It is uncertain for all three innovations paths identified whether they will succeed and what their societal implications will be. The innovations require policies and active governments to be realized and to steer them in such a way that they contribute to meeting sustainability goals.
4. For alternative powertrains and fuels, life cycle analysis gives the full CO_2 impacts.
5. For automated driving on the road, the long-term societal impacts are not known because it is unclear to what extent these vehicles will increase transport volumes.
6. Vehicle sharing systems might have positive societal impacts but can also substitute active modes and public transport.

NOTES

1. The most cited modern book in this area of economic research is by Nelson and Winter (1982). We will now only summarize some important notions (based on Van den Berg et al., 2005).
2. A CO_2-equivalent is a metric used to compare and add the emissions from various GHGs based on the so-called global-warming potential (GWP) of these gases. One ton of CO_2 has a GWP per definition of 1. For example, one ton of methane (CH4) is a stronger GHG with a GWP of 25. This implies that the emission of one ton of CH4 is equivalent to 25 tons of CO_2 emission.
3. Artificial Intelligence (AI) means that a machine is able to perceive, reason, learn, and to solve problems. According to Shankar Iyer (2021), AI methods that support transportation include Artificial Neural Networks (ANN), Genetic algorithms (GA), Simulated Annealing (SA), Fuzzy Logic Model (FLM), and Ant Colony Optimizer (ACO).

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